Oceanographic and Ecological Aspects of the Itajaí-açu River Plume During a High Discharge Period

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ABSTRACT

The Itajaí-açu River plume was investigated to evaluate its influence on the coastal waters during a period of high river discharge. An oceanographic cruise along a transect was carried out from 5.5 km inside the estuary to 15 km offshore. Data were obtained at seven stations, and included physical, chemical and biological (phyto and zooplankton) parameters. The river discharge during the cruise, as in the previous three months, was about 3 times the mean river discharge. The results have shown that most of the biogeochemical processes take place over the shelf, just after the early plume formation, about 10 km out from the inlet. A bottom nepheloid layer (BNL) was also observed over the shelf at the landward limit of the South Atlantic Central Water (SACW) upwelling. The presence of the BNL appears to have a close relationship with the plume evolution and the presence of SACW.

Key words: river plume, coastal processes, Itajaí-açu River.

INTRODUCTION

Coastal plumes are the first meso-scale features over the continental shelf in the continuous mass transfer process from continents towards oceans. They can be separated into river plumes and estuarine plumes. In the first case, there is dominance of river discharge over tidal effects resulting in direct release of continental fresh water into the adjacent sea, e.g., Mississippi River and Amazonas River. In the second case, tidal effects play a major role providing mixing energy inside the estuarine basin. Consequently, the brackish water released into the sea will have a significant contribution of salt water, e.g., Chesapeake Bay (Mann & Lazier, 1991).

Plumes are formed by density differences between lighter estuarine brackish waters and heavier coastal salty waters. They are driven by the river discharge, which will supply kinetic energy for dispersion along the coast (Chao & Boicourt, 1986). When the stratified estuarine structure becomes free of lateral basin constrictions, it is subjected to lateral pressure gradients generated by the water density differences. This will result in the spreading of brackish waters in a thin layer over coastal waters. The development of the phenomenon is highly related to the density gradient and to the kinetics acquired inside the estuary, which will determine the plume extension over the continental shelf (Wiseman Jr., 1986), as well as the associated coastal circulation (Weaver & Hsieh, 1987).

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Complex interactions between two water bodies with different properties on a continental shelf cause ecological responses at several trophic levels, from plankton to nekton (Kirchman *et al.*, 1989; Cochlan *et al.*, 1990; Gaudy *et al.*, 1990; Lohrenz *et al.*, 1990; Grimes & Finucane, 1991; Abreu *et al.*, 1995). The fresh water dispersion effects over the biota are separated by Mann & Lazier (1991) into: 1) direct effects of fresh water supply, 2) indirect effects due to the formation of a counter current that causes nutrient rich water upwelling, and 3) increase in water column stability, which decreases vertical mixing, thus the productivity is enhanced during spring blooms reduced during other periods. These effects play different roles, and are a function of other parameters such as coastal geomorphology, waves and current systems. The aim of the present study is to describe the evolution of the water mixing between estuarine and coastal waters during a period of high discharge of the Itajaí-açu River.

STUDY AREA

The Itajaí-açu River estuarine system is the most important along the Santa Catarina State coast. The river watershed is about 15,500 km^2, which represents 25% of the State area. Mean fresh water discharge, based on a 36 year daily dataset, is about 270 m^3.s^{-1}, with minimum values about 40 m^3.s^{-1} and maximum values about 2,000 m^3.s^{-1}. Extreme discharge peaks can reach up to 5,000 m^3.s^{-1}. The regional tide is microtidal, 0.8 m high on average, with maximum heights about 1.2 m occurring during spring tides. Winds are predominantly from the northeast all year, with an increase of southerly winds during the winter.

The estuarine physical characteristics have been described by Schettini *et al.* (1996), and the estuary has been classified, according to Hansen & Rattray (1966) stratification and circulation parameters, as a Type 4 salt wedge estuary. Estuarine nutrient dynamics assessment has been made by Bellotto *et al.* (1996).

The Itajaí-açu River plume plays an important role in the adjacent shelf waters. Its influence over the water mass structure and dissolved nutrients distribution has been described by Carvalho & Schettini (1996) and by Kuroshima *et al.* (1995), respectively. These results have shown that the plume is associated with fresh water pulses, becoming well developed after discharge peaks, and with an influence mainly northeastward from the estuary inlet. The plume can reach more than 20 km northeastward, observed as a thin surface layer (<2 m) of lower salinity. Near the estuary mouth, it shows well defined lateral boundaries which are noted by sharp color changes between the muddy brown brackish water and the relatively clean green coastal water. This characteristic allows visual observations of the plume behavior, and the northeast dispersion.

METHODS

Data used were obtained during a sampling cruise on March 26, 1996 onboard the South Fisheries Research Center (Cepsul/Ibama) "NPe Diadorim". Samples were collected at seven stations along a transect starting 5.5 km upstream from the estuarine inlet to 14 km offshore (Fig. 1). Stations #1 and #2 were located inside the estuary, at 5 and 1.5 km upstream. The other Stations (#3, #4, #5, #6 and #7) were located at 1.5 km, 3.5 km, 5.5 km, 7.5 km and 14 km offshore from the inlet.

Daily river discharge data were made available from the Water and Electric Energy National Bureau (DNAEE) at the Indaial Discharge Station. This station measures the discharge relative to 72% of the total watershed, and thus values used in the estuarine region must be corrected by a factor of 1.4. Salinity and temperature vertical profiles were recorded with a SensorData™ STD. Turbidity data were recorded every meter with a OBS3® turbiditymeter pre-calibrated for a range for 0 to 300 mg.l^{-1}. Light intensity was recorded every meter with a Li-cor™ probe for incident and reflected radiation. Water transparency estimates were obtained using a Secchi disk.

Water samples were collected at the surface, middle depth and near bottom with a Niskin bottle (5 ℓ) for chemical analysis and determination of phyto and protozooplankton concentrations. The pH was determined with an Orion™ pH meter and

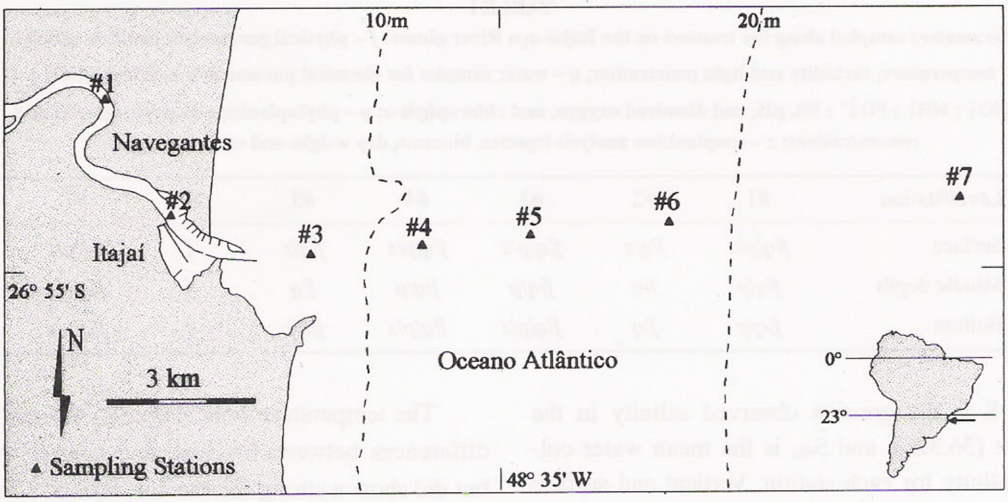


Fig. 1 — Map of the study area with the sampling stations.

the dissolved oxygen was determined with an YSI™ oxymeter immediately after sampling. Samples were filtered and aliquots frozen for dissolved inorganic nutrient determination (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-} and Si) in the laboratory. In addition, filtered material was frozen for chlorophyll-*a* determination. Dissolved inorganic nutrients and chlorophyll-*a* were determined according to Strickland & Parsons (1972).

200 ml aliquots were fixed with 1% neutral lugol solution in amber flasks for quantification of phyto and protozooplankton organisms according to Utermöhl (1958). Organisms smaller than 10 μm were not counted due to the large amount of sediments and detritus in the samples. Vertical hauls were done with 25 μm mesh size plankton net for qualitative analysis, and samples were fixed with 4% formalin solution.

Zooplankton samples were obtained with a WP-2 net type, 1.8 m long, 0.3 m diameter of opening and 200 μm mesh size, equipped with a flowmeter and closing mechanism. Horizontal hauls were taken for two minutes on average, at near surface and near bottom. In the estuary, only surface hauls were taken. Mid-depth hauls were taken only at Station #7. The hauls were duplicated, one sample for species enumeration, and other for biomass determination. The former sample was fixed with 4% formalin solution, and the latter was fixed with 3% formalin solution and then frozen (Salonen & Sarvala, 1985). Biomass was determined according to Beers (1976), and organic carbon weight was determined according to Strickland & Parsons (1972).

Table I summarizes the parameters collected along the transect for each research area (physical and chemical oceanography, phytoplankton and zooplankton biology). It was not possible to collect all parameters at all stations and at all depths due to logistic reasons.

RESULTS

The mean daily river discharge during the first three months of 1996 were 740, 720 and 870 $m^3.s^{-1}$ for January, February and March, respectively. These values were about 3× the mean annual discharge of the Itajaí-açu river, of 270 $m^3.s^{-1}$. Daily river discharge values for the period previous to the sampling cruise are presented in Figure 2. The river discharge on March 28, when the cruise took place, was about 780 $m^3.s^{-1}$.

The salinity field along the transect (Fig. 3A) showed high stratification inside the estuary, with the upper brackish layer thickness decreasing towards the ocean. The plume gradually disappeared after a few kilometers offshore. Table II presents the fresh water contribution (%) along the transect, obtained by the ratio of $(S-S_{\#n})/S$ (Officer, 1975),

TABLE I

Parameters sampled along the transect on the Itajaí-açu River plume: *f* – physical parameters profiles: salinity, temperature, turbidity and light penetration; *q* – water samples for chemical parameters: nutrients (NO_3^- ; NO_2^- ; NH_4^+ ; PO_4^{3-} ; Si), pH, and dissolved oxygen, and chlorophyll-*a*; *p* – phytoplankton analysis (species and concentration); *z* – zooplankton analysis (species, biomass, dry weight and carbon weight).

Level/station	#1	#2	#3	#4	#5	#6	#7
Surface	*f/q/p/z*	*f/q/z*	*f/q/p/z*	*f/q/p/z*	*f/q/z*	*f*	*f/q/p/z*
Middle depth	*f/q/p*	*f/q*	*f/q/p*	*f/q/p*	*f/q*	*f*	*f/q/p/z*
Bottom	*f/q/p*	*f/q*	*f/q/p/z*	*f/q/p/z*	*f/q/z*	*f*	*f/q/p/z*

where S is the greatest observed salinity in the transect (36.3‰), and $\overline{S}_{\#n}$ is the mean water column salinity for each station. Vertical and surface horizontal salinity gradients, dS/dz and dS/dx respectively, were also calculated (Table II). The fresh water portion decreased from 73% at Station #1 to 3% at Station #7, showing a steep decline between Stations #2 and #4. The horizontal salinity gradient, evaluated in ‰ per km, showed the highest values also between Stations #2 and #4. The vertical salinity gradient, evaluated in ‰ per meter of water column, showed the highest values in the estuary, intermediate values in Stations #3 and #4, and small values at the offshore stations.

The temperature field (Fig. 3B) did not show differences between brackish and coastal waters, but did show a strong thermocline around 12 m between Coastal Water and South Atlantic Central Water (Castro Fo., 1990). Three water masses were distinguished along the transect using the TS diagram (Fig. 4). They are Estuarine Water (EW), Coastal Water (CW) and the South Atlantic Central Water (SACW). The EW was characterized by low salinity (<10‰) and warm waters (≈24°C); the CW was characterized by greater salinity (32-34‰) and warmer waters (24-26°C); and the SACW was characterized by higher salinity

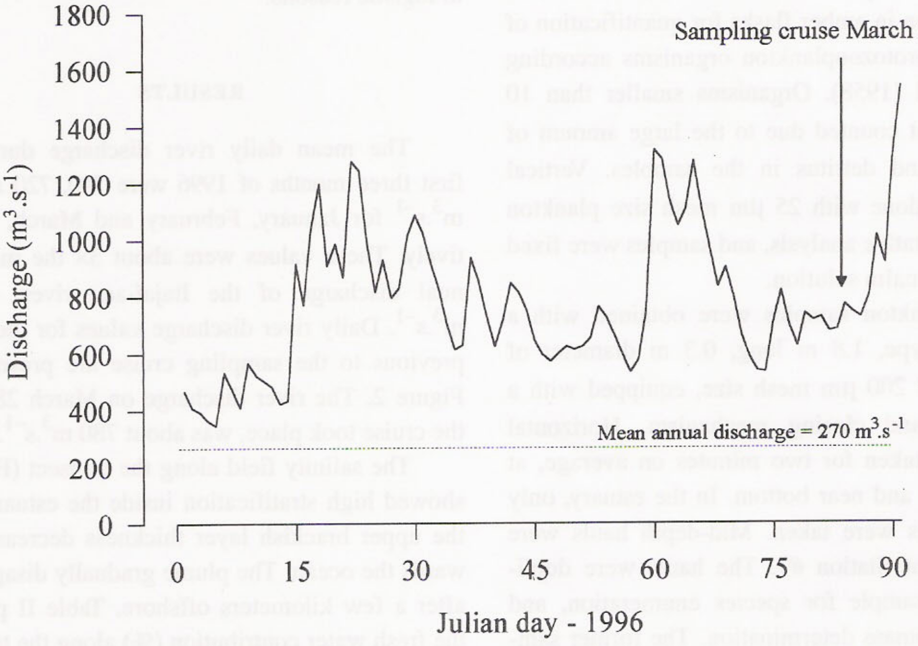


Fig. 2 — Daily Itajaí-açu River discharge in January, February and March of 1996.

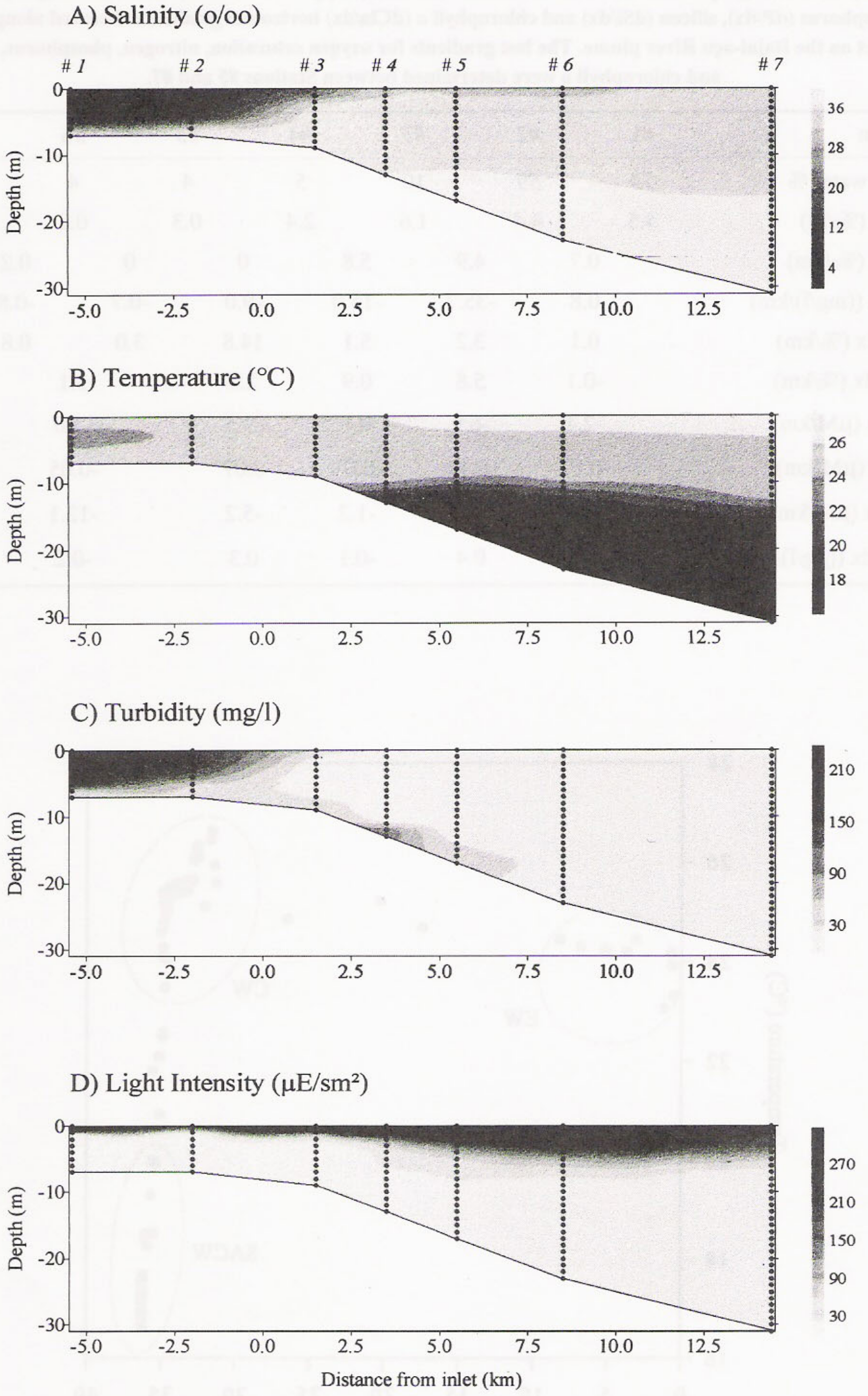


Fig. 3 — Distribution of the physical parameters along the Itajaí-açu River plume transect. (A) salinity; (B) temperature; (C) turbidity; and (D) light intensity.

TABLE II

Fresh water contribution (%) and vertical salinity gradient (dS/dz) at each station, and salinity (dS/dx), turbidity (dT/dx), light penetration in the first meter (dLP/dx), oxygen saturation (dOS/dx), nitrogen (dN/dx), phosphorus (dP/dx), silicon (dSi/dx) and chlorophyll *a* (dCla/dx) horizontal gradients observed along the transect on the Itajaí-açu River plume. The last gradients for oxygen saturation, nitrogen, phosphorus, silicon and chlorophyll a were determined between Stations #5 and #7.

Station	#1		#2		#3		#4		#5		#6		#7
Fresh water %	73		59		10		5		4		4		3
dS/dz (‰/m)	4.5		4.4		1.6		2.4		0.3		0.2		0.1
dS/dx (‰/km)		0.7		4.9		5.8		0		0		0.2	
dT/dx ((mg/l)/km)		0.8		-35.7		-15.0		-9.0		-0.7		-0.8	
dLP/dx (%/km)		0.1		3.2		5.1		14.8		3.0		0.8	
dOS/dx (%/km)		-0.1		5.8		0.9		2.5			3.1		
dN/dx (μM/km)		-2.4		-6.9		0.1		-3.5			-1.0		
dP/dx (μM/km)		-0.07		-0.19		-0.01		0.07			-0.05		
dSi/dx (μM/km)		-2.1		-18.2		-1.2		-5.2			-12.1		
dCla/dx ((μg/l)/km)		0.0		0.4		-0.1		0.3			-0.2		

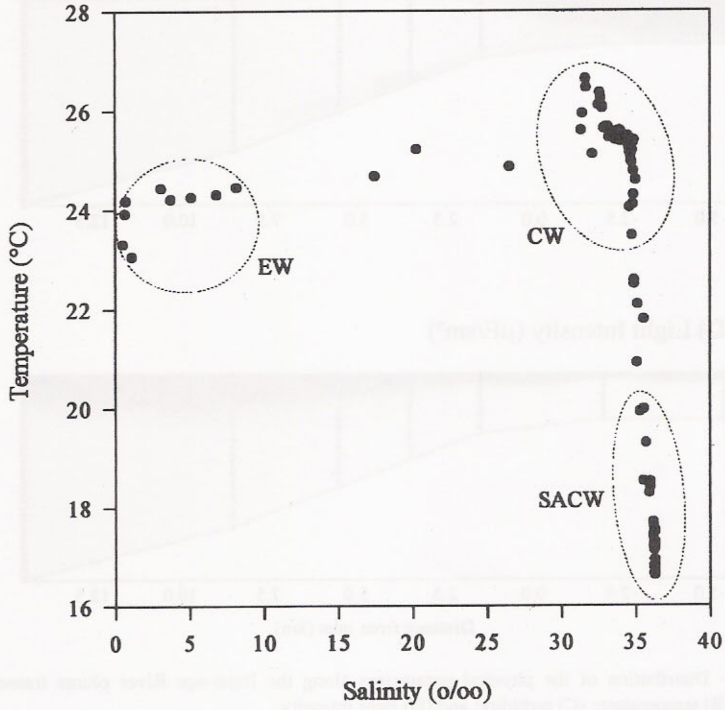


Fig. 4 — TS diagram of the salinity and temperature data recorded along the Itajaí-açu River plum transect, showing the point groups for the Estuarine Water EW, Coastal Water CW, and South Atlantic Central Water SACW.

(≈36‰) and cooler waters (16-20°C). The points clustered in three distinct regions of the diagram point out the high stratification of the plume system and the weak changes between CW and SACW. The presence of SACW is a common feature in the bottom layer along the north coast of Santa Catarina State, specially in the summer (Carvalho & Schettini, 1996).

The turbidity field (Fig. 3C) was strongly related to the salinity distribution. High concentrations were associated with river and brackish waters and lower concentrations were associated with seawater. Upper layer concentrations inside the estuary were up to 250 mg.l^{-1}, decreasing to 100 mg.l^{-1} in the plume and to values less than 50 mg.l^{-1} offshore. At subsurface, a bottom nepheloid layer (BNL) was observed near the estuarine inlet over the shelf, with concentrations up to 120 mg.l^{-1}. The light intensity distribution (Fig. 3D) showed a strong relationship with turbidity distribution. The light was strongly attenuated inside the estuary due to the high suspended matter concentrations, with penetration as low as 0.5% in the first meter of water column. The light penetration increased significantly towards the ocean, reaching 66.2% at Station #7. The surface longitudinal turbidity and light penetration gradient, mg.l^{-1} per km and % per km, are presented in Table II.

Dissolved nutrient surface concentrations decreased horizontally from the estuary to offsore stations. From Station #1 to Station #7, silicate (Si; Fig. 5A) ranged from 52.2 to 10.7 µM, nitrate (NO_3^- ; Fig. 5B) from 34.5 to 4.2 µM, and phosphate (PO_4^{3-} ; Fig. 5C) from 1.13 to 0.18 µM. The Si distribution was highly related to the turbidity distribution, and had relatively high values until Station #7. The nitrate and phosphate showed a rapid decrease just after the estuary inlet, which may be explained by biological consumption. The other nitrogen nutrients forms, ammonium (NH_4^+) and nitrite (NO_2^-) showed similar behavior.

The dissolved nutrients tended to decrease from surface to bottom. The highest gradients were observed inside the estuary, with differents of about 70 and 30 µM, for Si and NO_3^- respectively, while outside the estuary the vertical gradient diminished to 2 and 1 µM, respectively. The PO_4^{3-} did not show vertical gradient in the estuary, but showed a concentration increase to the bottom on the shelf. The mean vertical concentration of NH_4^+ , NO_2^- and PO_4^{3-} in Station #1 were 18.0, 0.4 and 1.0 µM, respectively, and 1.6, 0.1 and 0.6 µM at offshore Stations. The silicon, total nitrogen and phosphorus surface horizontal gradients, µM per km, are presented in Table II.

Dissolved oxygen saturation showed a horizontal increase from the estuary to the ocean (Fig. 5D), ranging from 73 to 108% of saturation. Vertically, the oxygen decreased from surface to bottom, with saturation differences of about 15% inside the estuary and 43% over the shelf. The higher concentrations of organic matter in the estuary may explain the lower values of oxygen saturation; the mineralization of organic compounds consumes oxygen, causing a deficit. The chlorophyll-*a* distribution (Fig. 6A) showed small values along the estuary, increasing at Stations #3, #4 and #5, and decreasing at Station #7. The maximum concentration was observed in the BNL, but high values were also found in all SACW samples. The oxygen saturation and chlorophyll horizontal gradients are presented in Table II.

The general surface behavior of salinity, turbidity, light penetration, nitrogen, phosphorus, silicon, oxygen saturation and chlorophyll-*a* from the estuary towards coastal waters are presented in Figure 7. The lines were made using a zero value for all parameters at Station #1 and adding the horizontal gradient values presented in Table II. All values were scaled to vary only from 0 to ±1. It is clear from this figure the development of the plume. Nutrients and turbidity decreased together coinciding with an increase in salinity, light penetration, chlorophyll-*a* and oxygen saturation.

The BNL showed a special relationship with the dissolved inorganic nutrients and oxygen saturation. All nutrient concentrations showed enhancement in the BNL, with an increase of the order of 6 × for the Si, 8 × for the PO_4^{-3}, and 18 times for the NO^-. Oxygen saturation decreased to

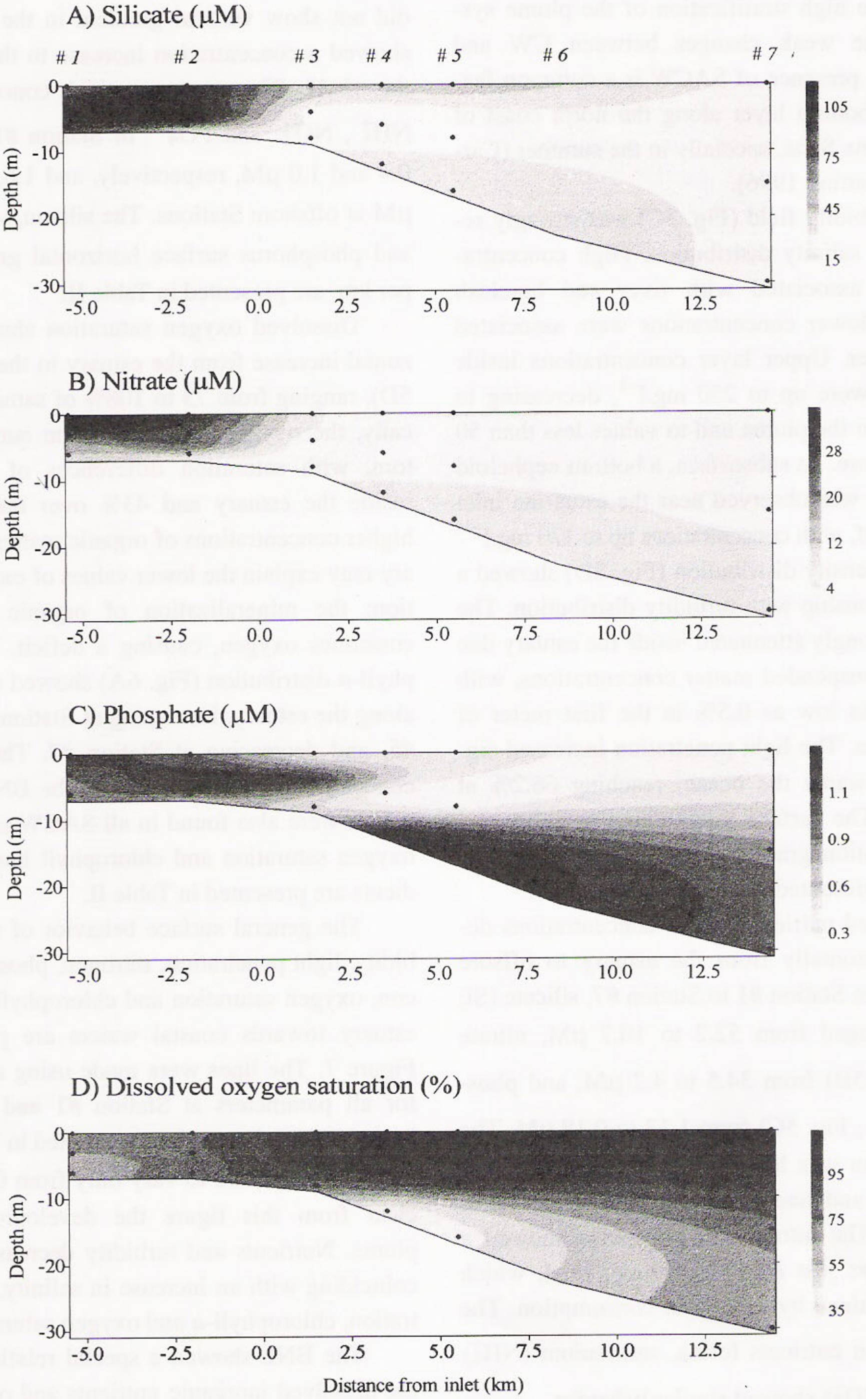
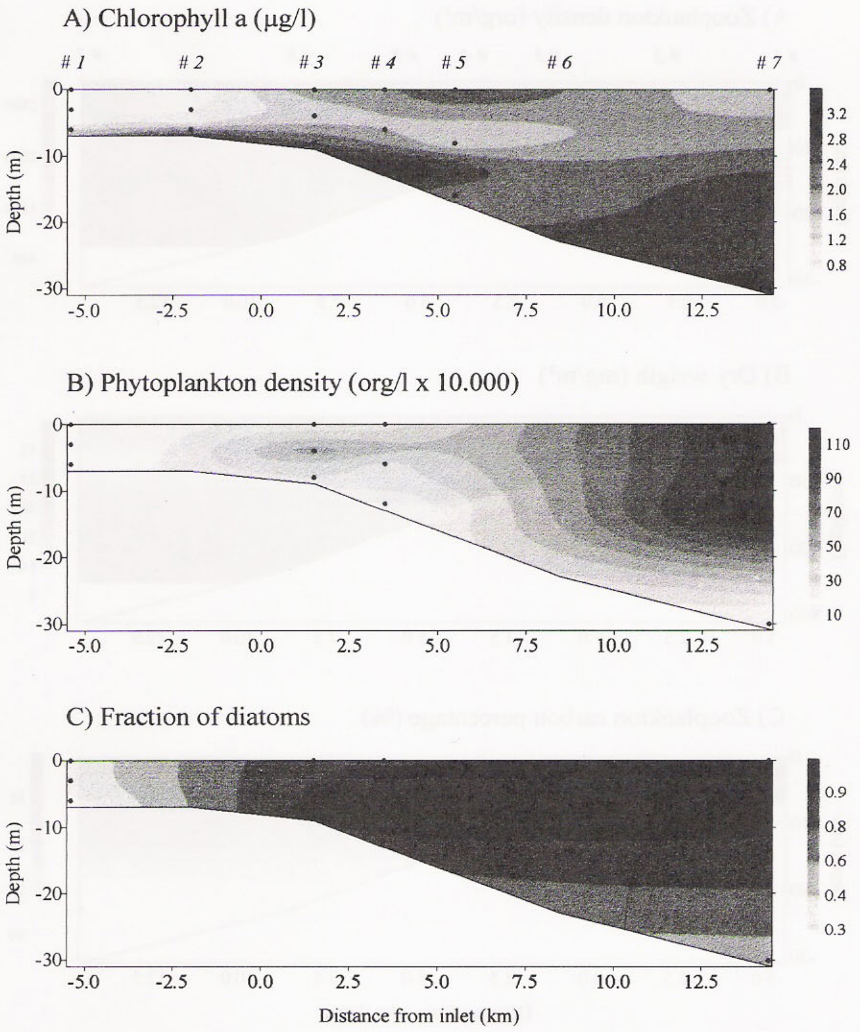


Fig. 5 — Distribution of the chemical parameters along the Itajaí-açu River plume transect. (A) silicate; (B) nitrate; (C) phosphate; and (D) oxygen saturation.



A) Chlorophyll a (μg/l)

B) Phytoplankton density (org/l x 10.000)

C) Fraction of diatoms

Fig. 6 — Distribution of the chlorophyll-*a* and phytoplankton parameters along the Itajaí-açu River plume transect. (A) chlorophyll-*a*; (B) phytoplankton density; and (C) fraction of diatoms.

29%, and the chlorophyll-*a* presented the highest value of the transect, 2.7 μg.l^{-1}.

Phyto and protozooplankton organisms (Fig. 6B) showed a clear gradient, increasing their concentration towards the ocean. There were low concentration of limnic species at the surface and marine species near the bottom inside the estuary. The limnic species were mainly heterotrophic, such as ciliates and dinoflagelates (Table III). Diatoms were the dominant phytoplankton organisms in the transect (Fig. 6C). *Asterionellopsis glacialis* was the dominant species in several samples (Stations #3 and #4 at surface and middle depth, and Station #7 at surface). This species is commonly found in the surf zone of Navegantes Beach, adjacent to the north border of the estuary. Another diatom found in the surf zone is *Anaulus australis* (Rörig *et al.*, 1997), which was also found in significant concentrations at Station #3 at the bottom. *Skeletonema costatum* together with *Chaetoceros* sp. were dominant at Station #7 at middle depth. *S. costatum* dominance was related to SACW presence. It is a highly productive diatom, dominating most spring blooms in temperate and subtropical coasts.

Phytoplankton associations were separated into three groups of generic assemblages: (1) low

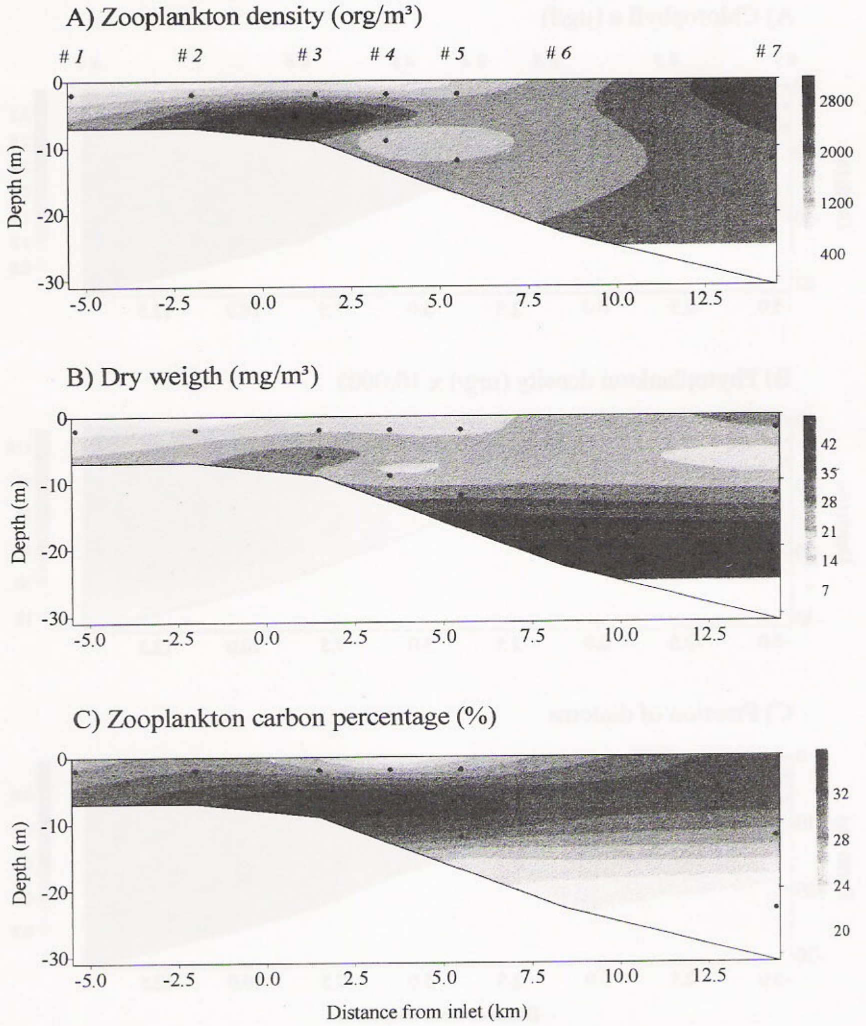


Fig. 7 — Relative variation of the physical and chemical parameters along the surface of Itajaí-açu River plume transect. The values were obtained from the longitudinal differential presented in Table II, considering all values in Station #1 at surface = 0, and adding the follow differentials. The values were re-scaled to vary from 0 to ± 1.

concentrations of organisms with limnic and mixohaline characteristics, that included surface and middle depth samples of Station #1; (2) neritic group of high densities, dominated by diatoms, that included all samples of Station #3, and surface and middle depth samples of Stations #4 and #7; and (3) low densities, that included all neritic samples situated below the euphotic zone, and bottom samples of Stations #4 and #7, which included planktonic and benthic autotrophic and heterotrophic flagellates.

Zooplankton concentration increased offshore (Fig. 7A), with maximum values at middle depth and at the bottom in Station #3, in the BNL. The specific composition of the zooplankton distribution was divided in three distinct groups: (1) estuarine fauna dominated by limnic organisms, such as Cladocera of the genus *Moina* and decapod larvae; (2) coastal marine fauna dominated by the copepod *Acartia lilljeborgi* (Bjornberg, 1981) and *Sagitta tenuis* (Resgalla Jr. & Montú, 1995), at Stations #3, #4 and #5; (3) oceanic fauna consisting of different species: copepods (*Paracalanus* spp.),

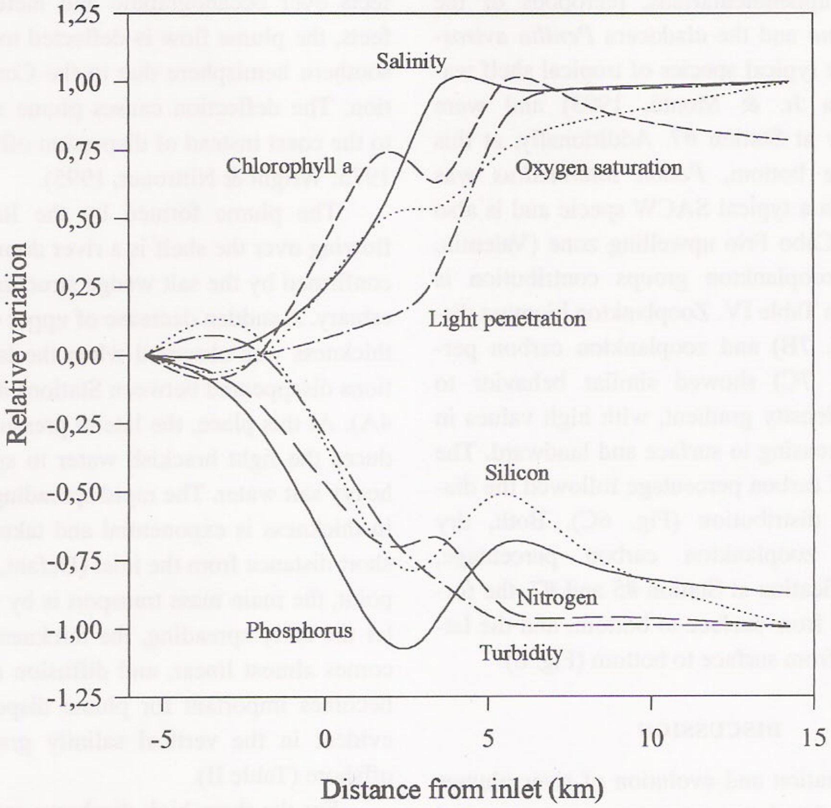


Fig. 8 — Distribution of the zooplankton parameters along the Itajaí-açu River plume transect. (A) zooplankton density; (B) dry weight; and (C) carbon percentage.

TABLE III

Phytoplankton dominant groups contribution (%) along the transect on the Itajaí-açu River plume. Ciano.: Cianophyceae; Cloro.: Chlorophyceae; Dino.: Dinoflagelates. S – surface; M – middle depth; B – near bottom.

#	Ciano.	Chloro.	Diatoms	Dino.	Ciliates	Other
1S	4	12	35	20	24	5
1M	—	15	32	21	30	2
1B	—	—	19	34	47	—
3S	—	—	89	3	8	—
3M	—	—	93	3	4	—
3B	—	—	97	1	2	—
4S	—	—	87	9	4	—
4M	—	1	97	1	1	—
4B	—	—	88	10	2	—
7S	1	—	95	3	1	—
7M	—	—	87	4	5	4
7B	26	—	57	17	—	—

copepodites, appendicularians, pteropods of the genus *Limacina* and the cladocera *Penilia avirostris*, which are typical species of tropical shelf waters (Resgalla Jr. & Montú, 1993) and were observed only at Station #7. Additionally, at this station at the bottom, *Podon intermedius* was found which is a typical SACW specie and is also found in the Cabo Frio upwelling zone (Valentin, 1988). The zooplankton groups contribution is summarized in Table IV. Zooplankton biomass distribution (Fig. 7B) and zooplankton carbon percentage (Fig. 7C) showed similar behavior to zooplankton density gradient, with high values in the BNL, decreasing to surface and landward. The distribution of carbon percentage followed the diatom fraction distribution (Fig. 6C). Both, dry weight and zooplankton carbon percentage, showed stratification at Station #5 and #7, the former increased from surface to bottom, and the latter decreased from surface to bottom (Fig. 8).

DISCUSSION

The formation and evolution of river plumes are highly related to estuarine processes and oceanographic and meteorological conditions on the continental shelf. With the addition of stratified flow characteristics, plume monitoring is a difficult task (Wiseman Jr. & Garvine, 1995). During periods when there is a dominance of the river effects over oceanographic and meteorological effects, the plume flow is deflected to the left in the southern hemisphere due to the Coriolis acceleration. The deflection causes plume retention close to the coast instead of dispersion offshore (Officer, 1975; Wright & Nittrouer, 1995).

The plume formed by the Itajaí-açu River flowing over the shelf is a river dominated system, confirmed by the salt wedge structure found in the estuary. A sudden decrease of upper estuarine layer thickness was observed when the lateral constrictions disappeared between Stations #2 and #3 (Fig. 4A). At this place, the lateral pressure gradient induces the light brackish water to spread over the heavy salt water. The rapid spreading and decrease in thickness is exponential and takes place over a short distance from the inlet (Defant, 1961). To this point, the main mass transport is by advection. After the early spreading, the thickness decrease becomes almost linear, and diffusion mass transport becomes important for plume dispersion. This is evident in the vertical salinity gradient towards offshore (Table II).

For the three high discharge months previous to the sampling cruise, the total water contribution of the Itajaí-açu River to the adjacent sea was about 4×10^9 m^3. Assuming that the physical and chemical properties of the fresh water had not changed significantly during this period, and that

TABLE IV

Zooplankton dominant groups contribution (%) along the transect on the Itajaí-açu River plume. VL: velliger larvae; Clad.: cladoceran; Cppd: copepods; DcpdL: decapod larvae; Chaet: chaetognath; Append: appendicularian; ELF: eggs and larvae of fish. S – surface, M – middle depth; B – near bottom.

#	VL	Clad	Cppd	DcpdL	Chaet	Append	ELF	Others
1S	—	64	11	15	—	—	5	5
2S	<1	39	9	39	—	—	11	2
3S	<1	1	92	3	2	<1	<1	—
3B	2	—	90	<1	8	—	—	—
4S	5	31	48	8	1	—	1	5
4B	10	6	56	2	19	2	—	4
5S	3	29	59	4	4	0	—	1
5B	6	7	70	0	8	2	<1	7
7S	5	31	34	2	5	19	<1	4
7M	3	20	50	6	3	9	1	10
7B	2	25	42	7	1	8	—	15

those properties at Station #1 are representative, we calculated a suspended sediment contribution of 7×10^5 tons, 110×10^3 kg of nitrogen and 30×10^3 kg of phosphorus exported to the coastal sea. Although those concentrations can vary through time, these values give us some idea about the magnitude of the mass transport to coastal waters during such a period.

The low densities of phytoplankton observed in the estuary, even with high nutrient concentrations, can be explained by the very low light penetration and high turbulence. The increasing density of organisms offshore was related to the plume thickness decrease and suspended particulated material dispersion and sedimentation. This allowed an increase of light penetration, resulting in productivity enhancement. The chlorophyll-*a* peak observed at Stations #3, #4 and #5 was probably related to a chlorophyll-*a* maximum expected in plumes (Mann & Lazier, 1991). High biological activity can explain the rapid decrease of nitrogen and phosphorus. High organism concentrations were also observed at middle depth in the thermocline between coastal waters and SACW. The SACW also shows relatively high concentrations of dissolved nutrients, though much smaller than the river plume.

The dominance of *A. glacialis* along the transect can be explained by the ecological characteristics of such an organism. It is a epi-benthic surf zone diatom, which commonly lives under low light conditions and has elevated photosynthetic capacity at low irradiance (Rörig, 1997). During the plume evolution, nutrient concentrations decreased and light penetration increased in the water column, allowing the rapid development of its population from the communities located along the beaches near the estuary mouth. *Skeletonema costatum* was another diatom observed in significant concentrations. It has the ability to grow in low salinity waters. The same dominant organisms were also observed in the Patos Lagoon estuarine plume, about 1,000 km southward (Abreu *et al.*, 1995).

Estuarine zooplankton organisms observed at Stations #3, #4 and #5 at the surface demonstrate the brackish water influence over the shelf fauna. Marine species found were predominantly warm water ones, being indicators of Coastal and Shelf Waters under Tropical Water influence. The high zooplankton concentrations observed in the BNL may be explained by physical retention or by active migration to graze. The abundant food could attract organisms from neighboring areas, and the high carbon percentage could indicate local intense biological activity. The carbon percentage may also reflect the high degree of contamination from suspended sediment and phytoplankton.

High zooplankton carbon percentage values agree with the distribution of *A. glacialis*, which was the dominant phytoplankton species at Stations #3, #4 and #5. Zooplankton composition at the shelf stations was dominated by small copepods and by nanoplankton feeders (appendicularins), suggesting a trophic structure response to food size change. A similar gradient structure has been also observed in the Gironde Estuary, France, where the phytoplankton and zooplankton have shown size decrease towards the ocean in response to the changing environmental conditions (Sautour *et al.*, 1996).

A conceptual model for the Itajaí-açu River plume evolution is presented in Figure 9. The three water masses occurring in the transect play different roles in the system, linking the surface plume to the subsurface BNL. The highly stratified water structure observed in the estuary is transferred offshore forming the plume, throught the spread of Estuarine Water over the Coastal Water and its deflection to the left due Coriolis acceleration. The estuarine kinetics is transferred to the Coastal Water, which follows the surface plume behavior. This results in a mass transport offshore and northeastward, inducing SACW upwelling. The Coastal Water offshore displacement causes friction in the upper SACW layer, inducing its upper layer to move offshore too. This movements creates a circulation cell in the upwelling water, and a zone with small horizontal currents and a predominance of upward displacements.

Particulate material exported from the estuary and organic matter generated by primary and secondary production at the surface will rapidly sediment following the water currents. When these

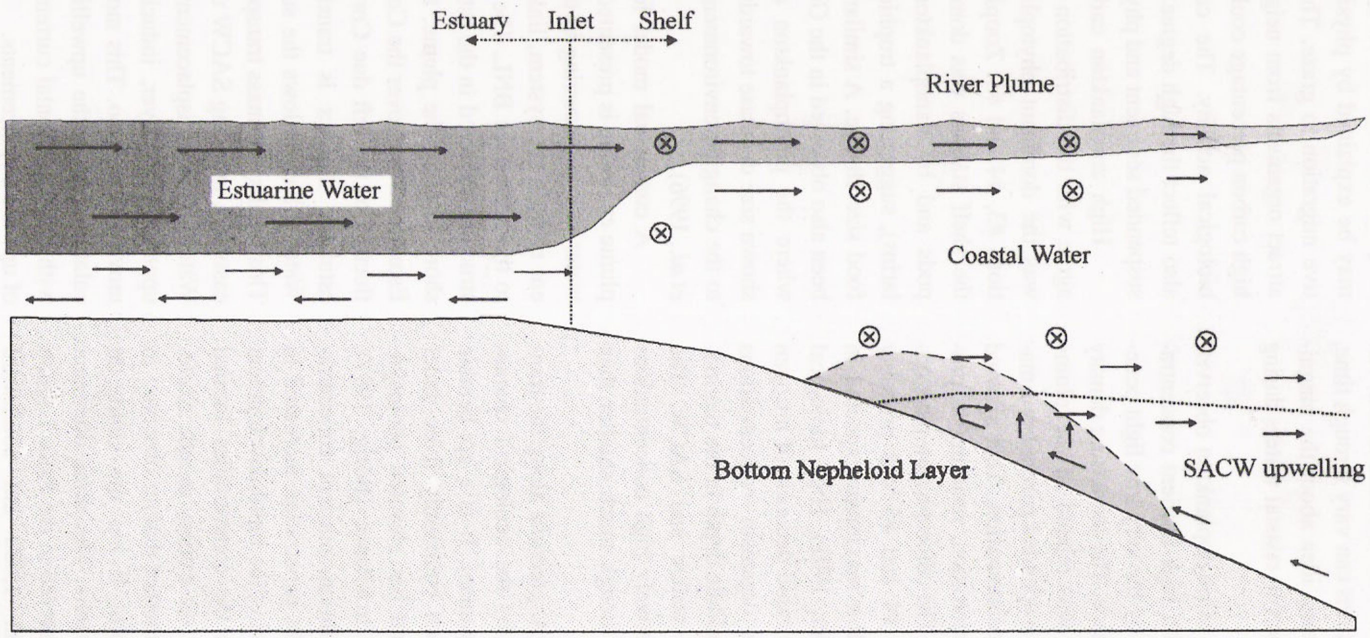


Fig. 9 — Conceptual model for the plume-bottom nepheloid layer evolution with the presence of South Atlantic Central Water. The circles with a cross inside represents the along shore current component entering into the paper.

materials slowly reach the bottom layer, they are transported back to the coast. Part of the material will reach the bottom, and will stay there until the environment becomes energetic enough to remobilize them. Part will reach the BNL at the SACW-CW interface in its shelf bottom limit, where suspensions are maintained by vertical currents. A similar mechanism explains the formation of the turbidity maximum zone in partially stratified estuaries (Dyer, 1986). When particles leave the BNL at the SACW-CW interface, they again sediment and return to the BNL. Such a cyclic mechanism increases the particle residence time in this region, which is evident by the lower oxygen saturation and higher dissolved nutrients concentrations.

The chlorophyll-*a* peak observed in the BNL can be explained by autogenus productivity or fresh sedimentation, because a long residence time could not allow high concentrations of such a short life molecules. The results pointed out for a phytoplankton cells density decreasing in the BNL, but the counting analysis did not cover the nanoplankton fraction which could be the dominant cells. Nevertheless, chlorophyll-*a* concentration per cell can increase under low light conditions, thus improving the primary production with less cells than it could be required under mean light conditions (Harris, 1980). The analytical procedure also could give misvalues, as it includes all fluorescent decay products of chlorophyll-*a* (Mantoura *et al.*, 1997).

The highly stratified flow characteristic of the Itajaí-açu River estuary does not allow mixing between the fluvial nutrient rich water with the ocean water inside the estuarine basin. Consequently the biogeochemical processes will take place mainly on the continental shelf, instead of inside the estuarine basin as is commonly found in partially stratified estuaries (Simenstad *et al.*, 1994). Figure 7 shows the sharp change of water characteristics from the estuarine basin to the adjacent shelf. The suspended sediment dispersion increases the light penetration which will allow biological productivity enhancement, consumption of dissolved nutrients, thus increasing chlorophyll-*a* and oxygen saturation. All these processes take place immediately after the plume formation. During long periods with high river discharge, as is the period assessed in this paper, the plume does not show well defined boundaries, but the gradients presented in Figure 7 permit us to estimate its outer limit about 10 km offshore in front the inlet. The plume extension northeastward was probably longer.

The presence of SACW in the profile appears to have great importance in the formation and maintenance of the BNL, either by carrying falling particles to the body or producing new biological particles which will also contribute to turbidity concentration. Future research has to account for the plume evolution under high discharge with the absence of the SACW. Current measurements in the estuary and on the shelf will give a estimate of the particle residence time in the BNL. A broad spatial approach will show how the BNL extends along the coast. It is also necessary to assess the BNL particle nature, considering their origin: 1) inorganic river sediments, 2) biological productivity in the plume, 3) biological productivity in the SACW, 4) ressuspension of bottom materials, and 5) autochthonous production.

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