Land-sea interface features of four estuaries on the South America Atlantic coast

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Abstract

The Brazilian coastal zone extends from 4° N to 34° S latitude and because of its long extension, the interface zone from continent to ocean includes a high diversity of geomorphologic and oceanographic characteristics. The rivers from the Northeast and East regions are marked by a typical unimodal seasonal flux patterns but with different amplitudes. As the climate indicates, the rivers from the Northeast are subject to an accentuated seasonal variability with an elevated input and flood pulses during the rainy season and low to negligible fluxes during the dry season. Small-scale rivers usually present typical torrential behaviour. In the humid eastern region, the unimodal seasonal cycle is dampened with a more constant input supply. Recently, some studies have shown that the material supply from rivers along the Northeast and Eastern coasts is diluted by surface tropical waters of oceanic currents and that the estuarine plume dispersal is restricted to a narrow coastal belt. However, human impacts of course mask or even override both natural hydrological cycles and CO_2 emissions from terrestrial biomes, or depending on the nature of the human impact, can even increase extreme events. Henceforth this contribution addresses the typological, hydrological and biome diversity of the four estuarine systems fed and affected by the respective Amazon, São Francisco, Paraíba do Sul and Plata watersheds.

Keywords: anthropogenic impacts, climate changes, river discharge, geomorphology, coastal zone biomes.

Características da interface continente-oceano de quatro estuários da zona costeira da America do Sul

Resumo

A zona costeira brasileira se estende de 4° N a 34° S de latitude. Por causa de sua longa faixa de zona de interface do continente com o oceano, é encontrada uma grande diversidade nas características geomorfológicas e oceanográficas. Os rios das regiões nordeste e leste mostram um padrão de fluxo sazonal normalmente unimodal, mas diferentes em amplitude. Conforme o clima indica, os rios do nordeste estão sujeitos a uma acentuada variabilidade sazonal, com elevação da vazão em forma de pulsos de inundação durante a estação chuvosa e fluxos muito baixos ou mesmo negligentes durante a estação seca. Em rios de pequena escala, a vazão costuma apresentar um típico comportamento de eventos torrenciais. Na região leste, com clima tropical úmido, o ciclo unimodal sazonal se apresenta amortecido com uma entrada mais constante. Recentemente, alguns estudos mostram que a exportação de materiais pelos rios ao longo da costa leste e do nordeste é diluída a partir de águas tropicais superficiais de correntes oceânicas e que a dispersão das plumas estuarinas é restrita a uma estreita faixa costeira. No entanto, os impactos humanos mascaram ou mesmo substituem ambos os ciclos hidrológicos naturais e as emissões de CO_2 dos biomas terrestres ou, dependendo da natureza, podem até aumentar os eventos extremos. Doravante, esta contribuição aborda a diversidade, a tipologia hidrológica e os biomas dos quatro sistemas estuários.

Palavras-chave: impactos antrópicos, mudanças climáticas, vazão hidrológica, geomorfologia, biomas da zona costeira.

1. Introduction

Northeast Brazil (3° S to 13° S) of the tropical southwest Atlantic is a good example of a tropical passive continental shelf. The shelf is narrow and open to the sea, lies in the direct pathway of the oligotrophic South Equatorial Current (SEC), receives relatively little continental run-off, and is almost entirely covered by biogenic carbonate sediments (Milliman, 1975). The east Brazil shelf is more diverse and productive towards the south due to a gradual increase in run-off and enlargement of the shelf at the Abrolhos bank, which forms a topographic barrier to the southwest flowing Brazil Current (BC). This special topographic feature induces eddy spin-off and upwelling at the shelf edge and harbours the southernmost coral reef system of the southwest Atlantic (Leão, 1996; Castro and Miranda, 1998).

The main issue that has to be addressed is the definition of the coastal zone systems. Henceforth, the typology and the coastal biomes need to be defined, as well as whether they are sources or sinks of CO_2. These, will obviously be altered over time due to the predictions of precipitations (P) and temperature (T) for the extreme scenarios of P and T presented by Marengo et al. (2009a) for the South American and mainly Brazilian continental biomes within which four of the chosen estuarine deltas are embedded.

Problems arise with the definition of coastal zone biomes. According to the literature, the coastal zone integrates several biomes and estuarine deltas, in particular, even present seasonal shifts in the extension of biomes. For example: estuarine deltas of medium sized rivers with a natural unimodal seasonal pattern of run-off generally shift from 2D (low flow) to 3D (high flow) systems comprehending an estuarine system, mangroves and coastal plumes dominated by phytoplankton production.

Climatic and anthropogenic factors affecting river discharge to the global ocean over the last 50 years (1951-2000 according to Milliman et al., 2008) has shown that cumulative annual discharge from 137 rivers remains constant although annual discharge from about 1/3 of these rivers changed by more than 30%. With the notable exception of the Parana river (and for example for São Francisco River – SFR and Paraíba do Sul River – PSR), the annual discharge decreased by 30% due to anthropogenic impact effects including agricultural purposes and hydroelectric power generation.

The long and detailed discussion related to the carbon cycle and the role of continental shelves in the near shore ecosystems as being sources or sinks of atmospheric CO_2 has now being addressed by Chen and Borges (2009) attempting to reconcile the manifold opposing views. It now seems that continental shelves should be generally regarded as sinks and the near shore ecosystems as sources of CO_2. However, when addressing estuary biomes, which include mangrove and salt marshes of the tropics, they emit up to 0.9 Pg of C per year although they are still subject to large uncertainty due to poor total estimate of biomass distributions of these sub-biomes or habitats. Brazil, for example, harbours 13,000 km^2 of mangroves with 70% being concentrated in the north humid tropical sector of the Amazon estuary.

However, human impacts of course mask or even override both the natural hydrological cycles and CO_2 emissions from terrestrial biomes, or, depending on the nature of the human impact, even enhance the extreme events proposed by modelling scenarios (like dams and increasing evaporation, deforestation, agricultural expansion, urbanisation on the coast).

Biome classification of the coastal zone and their role as source or sinks of carbon must be established in order to understand the continental climatic change effects as described from scenario modeling like that of Marengo et al. (2009b) (A2 scenario). Furthermore, it must be borne in mind that the coastal zone also responds to whatever changes of climatic and oceanic forcing functions which operate at different fashion than those of the continent.

Henceforth this contribution addresses the typological, hydrological and biome diversity of the four estuary systems fed and affected by the respective Amazon, São Francisco, Paraíba do Sul and Plata watersheds.

2. Material and Methods

2.1. The Amazon Estuary, N-Brazil (0,5° 00' S and 49° 30' W; 4° 00' N and 51° 00' W)

The Amazon River harbours one of the world's most unique estuaries. It is fed by the largest river in the world in terms of its freshwater discharge (Average Q_R = 209,000 $m^3.s^{-1}$; ANA, 2002) being about 20% of the global river water supply, and suspended sediments (Q_{TSS} = 7.7 × 10^{14} $g.yr^{-1}$) composed of 85-95% silt and clay particles attaining about 6% of the worldwide supply to the ocean margin. The drainage basin has an area of 6.93 × 10^6 km^2 (Table 2). Due to the large freshwater discharge, the main axis of the estuarine mixing zone and dispersal of the turbid river plume is offset beyond the geomorphological premises of the river mouth and is driven northwards parallel to the coast over the continental shelf (Figure 1). As such, it does not abide to the common definition of an estuary as a semi-enclosed body of water within which the mixing of fresh and marine waters occurs (Pritchard, 1967; Smoak et al., 2006), but may rather be regarded as an "external estuary". According to the definition adopted by AMASSEDS (A Multidisciplinary Amazon Shelf SEDiment Study; Nittrouer and Demaster, 1996), the southern limit of the estuarine waters and plume is located off the Amazon and Pará river mouths (49° 30' W and 0,5° 00' S) and its northern limit at the Brazilian/French Guiana border (51° 00' W and 4° 00' N). Its seawards extension over the shelf reaches about the 100 m isobath close to the shelf break and the entire system covers a total shelf area of 1.1 × 10^{11} m^2 (Figure 1) (Nittrouer and Demaster, 1996; Smoak et al., 2006). Furthermore, the influence of the Amazon is even noted beyond the above defined area, reaching thousands of kilometres into the Caribbean and Equatorial Atlantic (Muller-Karger et al.,

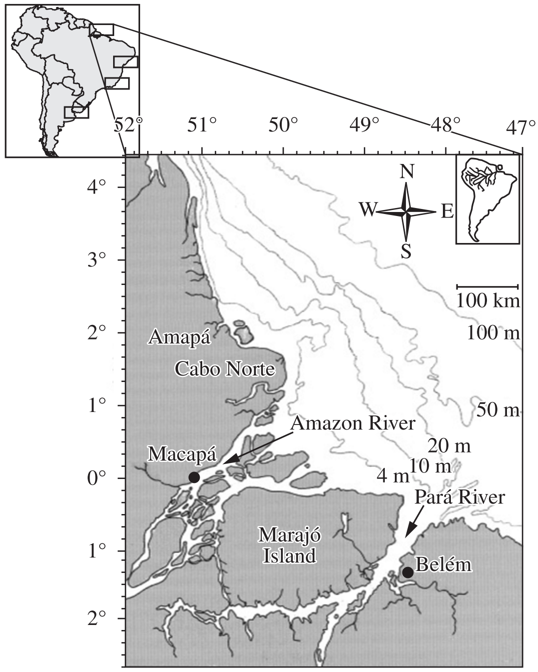

Figure 1. The Amazon Estuary, N-Brazil (0,5° 00' S and 49° 30' W; 4° 00' N and 51° 00' W).

1988) contributing to the material budget of the North Atlantic Ocean (Howarth, 1996).

Sediment accumulation on the shelf is deposited in a progressive delta subareas and northward currents export approximately 1.2×10^{14} g.yr^{-1} along the shelf (Kuehl et al., 1986; Smoak et al., 2006). These are actively reworked by the macrotidal regime and the bottom layer area is characterised by extensive areas of fluid muds which are unique to the Amazon and play a crucial role in the biogeochemical cycling of biogenic matter (Aller and Aller, 1986). The entire system is subject to a high physical energy regime and the outer premises of the shelf is governed by the northward flowing North Brazil Current (NBC) which may reach speeds of up to 75 cm.s^{-1} and at the mouth of the river tidal currents may reach 200 cm.s^{-1} (Beardsley et al., 1995). One of the most striking features is the entrainment (supply) of offshore waters upon the shelf and along the course of the mixing zone and plume with a water volume which may reach 10 times that of the river discharge (Smoak et al., 1996) and may contribute 38, 52 and 80% of nitrate, phosphorous and ammonium as compared to the river input (Demaster and Pope, 1996). Primary production is light limited due to turbidity down to about the middle sector of the mixing zone. The available nutrients from freshwater discharge concomitant to the entrainment of nutrients from the offshore waters after washing the shelf may induce primary production rates under ideal conditions of up to 3 gCm^2.day^{-1} (Demaster et al., 1996).

As the mixing zone and plume and most of the sediment transport and primary production of the Amazon estuary are set upon the shelf and are limited by the NBC at its outer boundary, we define its prime biome as the ***Amazon Shelf Biome*** (A $\approx 1.1 \times 10^5$ km^2) which is embedded in the Large Marine Ecosystem nr. 17 and also closely follows its physical-ecological premises (LME 17, Ekau and Knoppers, 2003; www. edc.uri.edu/lme). The second Biome is the vast ***Mangrove Forest Biome*** (A $\approx$ 8,900 km^2) bordering the coastline (Kjerfve and Lacerda, 1993).

In addition, it harbours a unique continental background setting. The large drainage basin encompasses 63.88% of the territory of Brazil, 16.14% of Columbia, 15.61% of Bolivia, 2.31% of Ecuador, 1.35% of Guiana, 0.6% of Peru and 0.11% of Venezuela (ANA, 2002). The largest part of its ***Rainforest Biome*** (4.2×10^6 km^2) is set in Brazil and covers the tropical girdle above and below the Equator and, in spite of its large tributaries and their different origin along its course, it presents a well defined unimodal seasonal pattern of river discharge varying by a factor of less than four between years (Nittrouer and Demaster, 1996; Smoak et al., 2006).

2.2. The São Francisco Estuary, NE-Brazil (10° 25' S and 36° 23' W)

The São Francisco River (SFR; A_B = 639,219 km^2, L = 2863 km) source is located in the southeast of Brazil and debouches into the northeastern coast of Brazil (Lat. 10° 25' S and Long. 36° 23' W) into the SW Atlantic Ocean at the border of the states of Sergipe and Alagoas (Figure 2 and Table 2). Its medium-sized estuarine-delta (MED), including the Pleistocene-Holocene plains, river channel and pro-delta (Figure 2) covers an area of approximately 800 km^2 (Dominguez, 1996). The plains harbour several biomes including the ***freshwater wetlands, beach-ridges, sand dunes and mangroves***, as well as its *coastal* ***shelf plume*** which may extend up to 30 km towards the south in summer. The estuarine channel up to the premises of the freshwater end member at the town of Piaçabuçu, 15 km upstream from the mouth, has an area of 19.23 km^2, a mean depth of 3 m and a maximum depth of 12 m at low tide conditions (Medeiros, 2007; Knoppers et al., 2006).

Its hydrographic basin corresponds to the most extensive watershed covering 7% within the Brazilian territory and encompasses seven states, Bahia (47.2%), Minas Gerais (38.2%), Pernambuco (10.6%), Alagoas (2.3%), Sergipe (1.1%), Goias (0.4%) and the Federal District (0.2% of the basin's area). It services a total population of approximately 15×10^6 inhabitants. Due to its length, it traverses several climatic regimes and comprises several physiographic compartments. The climate along the basin varies from tropical humid (i.e. Upper SFR and Lower SFR compartments) to semi-arid (i.e. Middle and Sub-Middle SFR compartments). Precipitation in the Upper SFR and Lower SFR basin sectors is in the order of 1,500 mm.yr^{-1} and only about 350 mm.yr^{-1} in the semi-arid Sub-Middle SFR, (Bernardes, 1951; www.ana.gov.br). The El Niño and La Niña phenomena affect considerably the region, causing marked shifts between droughts and humidity, respectively.

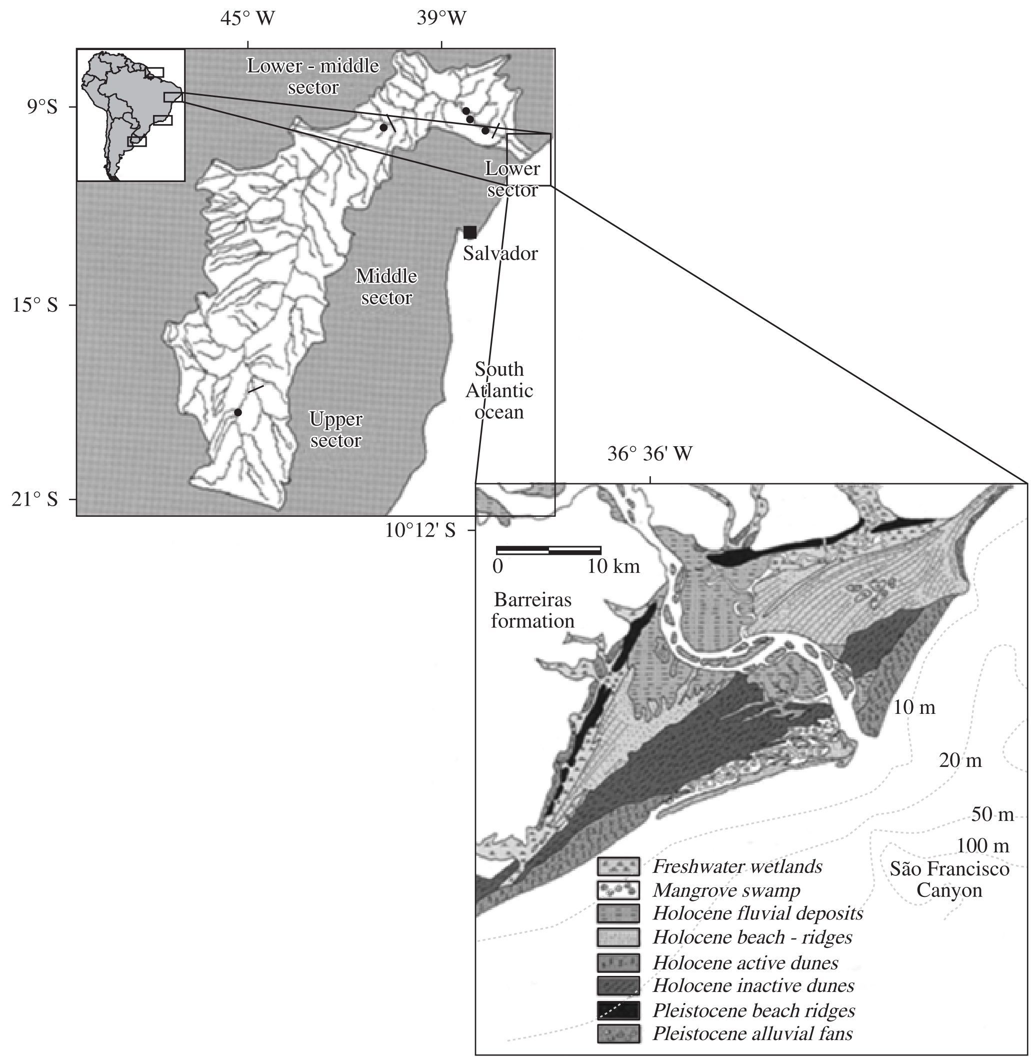

Figure 2. The São Francisco Estuary, NE-Brazil (10° 25' S and 36° 23' W).

The basin harbours 4 main biomes. The Upper SFR contains ***Atlantic Rain Forest***, partly devastated by agriculture and grazing, the Middle SFR ***Cerrado*** (Savannah), the Middle-Lower SFR ***Caatinga*** (scrubland in semi-arid regions) and the Lower SFR and estuary forested patches and mangroves (A = 30 km^2). The total area of dense, open and degraded *caatinga* lands (scrubland) corresponds to 24.6% of the total basin area and harbours a cascade of river dams. The hydrographic basin from the Upper to the Lower compartments is composed of Cretacean (mountain ranges), Tertiary (Formação Barreiras) and Quarternary deltaic formations. The "Tertiary Barreiras Formation" (Formação Barreiras), which consists of tablelands, covers most of the Sub-Middle and Lower SFR. The river flows through several economically important states, cities and industrial centres, and harbours a cascade of eight major dam reservoirs (V > 0.1 km^3) for hydropower, irrigation and water supply purposes set mainly at its middle-lower compartment.

The mean annual flow established from long-term hydrographs since the 30's has been Q_R = 3,150 m^3.s^{-1} and, since the operation of the late Xingó dam in 1994, it diminished to 2,060 m^3.s^{-1}. The near to constant river flow after 1994, dampened the migration of the estuarine mixing zone, now generally set along the river mouth shoals. High wave energy and mesotidal forcing induce intense vertical mixing of the estuarine zone and constant resuspension of particulates affect chemical processes. Other impacts induced by the diminished and more constant river flow, include severe coastal erosion, loss of seasonal inundation and fertilisation of agricultural land along the river's margin and, even, rodent epidemics. The river waters are now oligotrophic and fisheries yields are on the decline. This all is reflected by the low material concentrations and loads. Suspended matter concentrations and annual loads at the freshwater end of the estuary were 70 mg.L^{-1} and 6.9 × 10^{6} t.yr^{-1} in 1970 and 4 mg.L^{-1} and 0.3 × 10^{6} t.yr^{-1} in 2000. The sediment yield today is low with 0.4 t. km^{-2}.yr^{-1}. (Knoppers et al., 2006; Medeiros et al., 2007; Medeiros et al., 2011).

2.3. The Paraíba do Sul Estuary, E-SE-Brazil (21° 37' S and 41° 01' W)

The Paraíba do Sul river (PSR) is 1145 km long and drains an area of 55400 km^{2} (Brasil, 1987). The drainage basin is located between latitudes 20° 26'-23° 38' S, and longitudes 41° 00'-46° 30' W (Figure 3). The source of RPS lies in the state of São Paulo at approximately 1800 m altitude and the estuary lies within a wide coastal plain in the northeastern portion of the state of Rio de Janeiro. The estuary is backed by lowlands and the high relief Atlantic Serra do Mar mountain range, which proliferates more or less parallel to the coast. The river debouches into the sea at Lat. 21° 37' S and Long. 41° 01' W. It integrates several biomes, such as the ***Pelagic-Benthic Estuarine Biome, Mangrove Forest Biome and Coastal Plume Biome***.

River discharge follows a unimodal seasonal pattern similar to rainfall. Discharge attains its maximum in summer, with about 3000 m^{3}.s^{-1}, and a minimum in winter, with about 300 m^{3}.s^{-1}. The average annual discharge of RPS, recorded at Campos city 32 km from the coast has been 886 m^{3}.s^{-1} (Brasil, 1983), but has diminished over the last 10 years by about 30%. The climate regime is governed by the Equatorial Continental air mass in summer and the Tropical Atlantic air mass in winter. In autumn and winter, incursions of the Polar Atlantic air mass result in the frequent

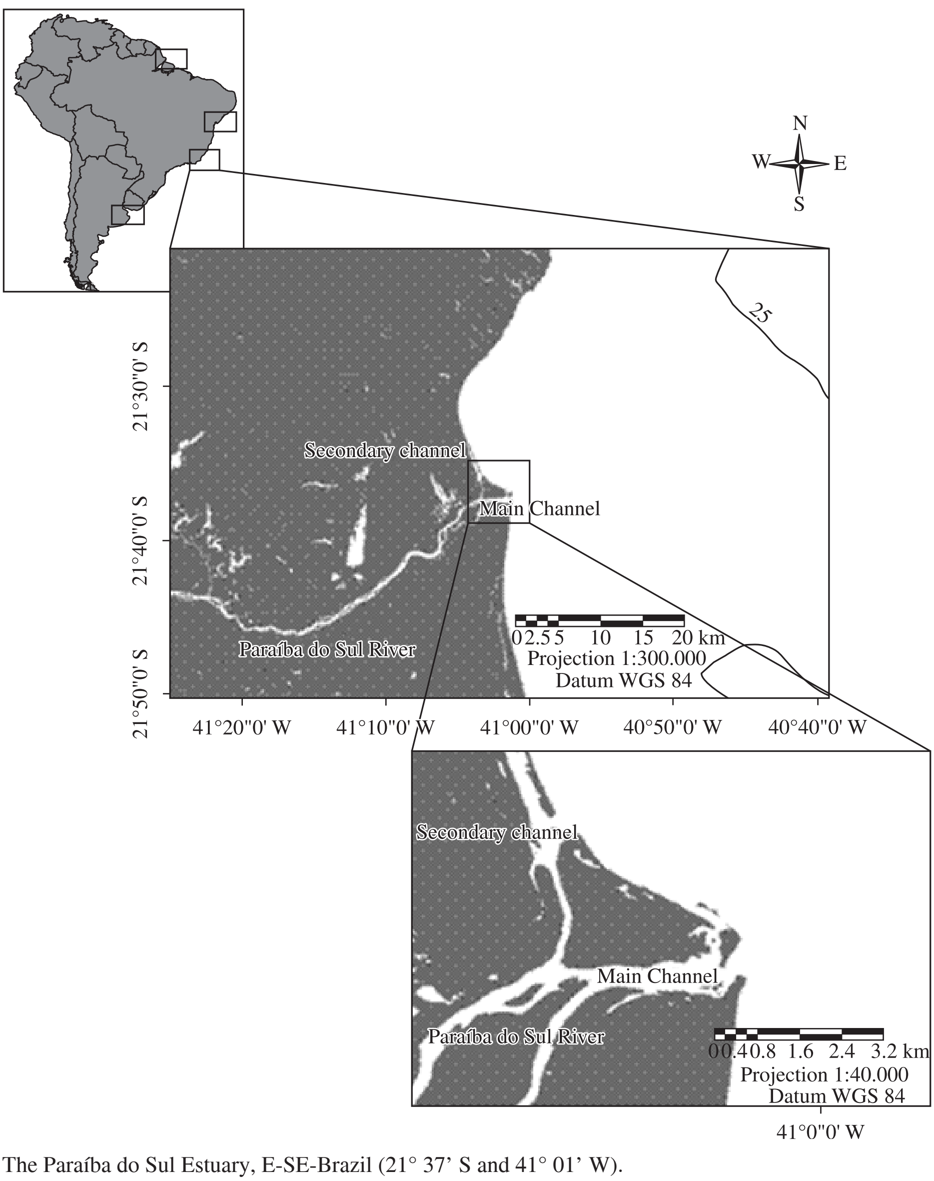

Figure 3. The Paraíba do Sul Estuary, E-SE-Brazil (21° 37' S and 41° 01' W).

passage of SE weather fronts and highest wave energy at the coast. The climate in the upper and middle reaches of RPS is Köppen type Cwa and in the lower reaches Aw, with highest rainfall in austral summer between the months of October and March throughout. Annual rainfall in the upper reaches ranges between 1500 to 1800 mm, in the middle between 1100 and 1500 mm, and at the coastal plain between 900 and 1100 (FIDERJ, 1978).

The construction of dams along its course has slightly dampened the seasonal amplitude and suspended matter discharge to the coast. Estimates of material loads and fluxes from RPS to the coast are scant. The average annual load estimated during an austral annual cycle in 1994/1995 was 0.6×10^6 $t.yr^{-1}$ for Total Suspended Solids, 0.08×10^6 $t.yr^{-1}$ for total carbon, 0.02×10^6 $t.yr^{-1}$ for total nitrogen and 0.001×10^6 $t.yr^{-1}$ for total phosphorous. The TSS yield was low with 11 $t.km^{-2}.yr^{-1}$ (Carneiro, 1998).

The coast is characterised by high wave energy from the Southeast and micro-tides with a maximum range of 1.3 m. Apart from wave energy and tidal range, sea-level history played a particular role in the formation of the RPS coastal plain and other coastal regions of eastern and southeastern Brazil (Martin et al.,1996). The coastal plain of RPS is characterised by a sequence of sandy beach ridge terraces (Figure 3), established during the Late Quaternary. Sand barriers and also coastal lagoons in the region attained peak expansion during two major sea-level high stands. The first occurred at about 123,000 yr BP during the last Pleistocene interglacial stage with a relative sea-level at 8 ± 2 m above the present level. The second occurred during the Holocene at about 5,100 yr B.P, with a sea-level high stand at 4.8 ± 0.5 m. Thereafter, sea-level dropped with several oscillations up to the present day, but experienced several oscillations. Longshore transport of sediments under normal conditions with incidence of wave fronts from the Southeast occurs from south to north. Under "El Niño" conditions the direction of wave fronts is from the northeast and littoral sand transport reverses from north to south (Martin et al., 1996). In general, the coastal plain is characterised by Quaternary hydromorphic Podzols and quartz.

The Paraíba do Sul is an example of highly impacted system along its river course, with still a lack of information on the impact consequences upon its delta region. The Paraíba do Sul River fulfils manifold economic services to the inhabitants (Urban Pop. $\approx 5 \times 10^6$; Rural Pop. $\approx 0,8 \times 10^6$ (ANA, 2002) of the States of São Paulo, Minas Gerais and Rio de Janeiro, Brazil. It receives industrial, agricultural and domestic effluents, furnishes potable water for most of the cities along its course, including the city of Rio de Janeiro, generates energy from hydroelectric power dams, and maintains substantial local fishery in its coastal waters. Most of the human activities affecting the system developed in an arbitrary fashion, but concerted actions by governmental and private agencies are focused on reverting perturbations. Most of the environmental studies in the Paraíba do Sul system have focused on the mid – to upper reaches of the drainage basin, subject to greatest human impact.

The mid and upper reaches of the Paraíba do Sul river receives a variety of metallic pollutants from metallurgic industries and also urban wastes, particularly Zn, Pb, Cu and Cr (Malm et al., 1989). The mid and lower RPS sections have also been affected by considerable inputs of Hg (Lacerda et al., 1993). Until 1980, it was widely introduced through usage of the now banned fungicides in sugarcane plantations and from the early 1980's onwards, from gold mining via the amalgamation process which separates gold particles from the river sediments (Lacerda et al., 1993). The latter contributed approximately 150 kg of mercury per year to the river.

Average annual concentrations for 1994-1995 of heavy metals in particulates (SPM = 35 ± 45 $mg.L^{-1}$, n = 15) close to the river mouth were 75 ± 41 $\mu g.g^{-1}$ for Cu, 81 ± 42 $\mu g.g^{-1}$ for Cr, 297 ± 197 $\mu g.g^{-1}$ for Zn, 2.386 ± 1.043 $\mu g.g^{-1}$ for Mn and 69.43 ± 14.78 $mg.g^{-1}$ for Fe (Carvalho et al., 1998). The slightly higher Fe and Mn values than the global average are due to the naturally enriched Fe and Mn top soils governing the watershed. Polyaromatic Hydrocarbon concentrations of suspended matter are low within the range of 1 to 10 $\mu g.L^{-1}$, total fluxes measured on 5 occasions close to the river mouth varied between 116 to 442 kgPAH's.day^{-1} (Carneiro, 1998).

2.4. The Rio de La Plata Estuary (34° 00'-36° 10' S and 55° 00'-58° 10' W)

The Rio de La Plata Estuary is located on the Atlantic coast of southeastern South America between 34° 00'-36° 10' S and 55° 00'-58° 10' W (Figure 4). It corresponds to a large 38,800 km^2 and 320 km long funnel-shaped estuary expanding more or less exponentially with a variable width from 35 km at its head, the upper tidal river portion of the Paraná delta front, to 230 km at its lower ocean margin premises. Depths from the upper to the lower portions vary from 2 to 18 m, respectively. The northern coastline along Uruguay is 416 km long and the southern one of Argentina is 393 km (Figure 4). The system is in fact composed of two physiographical sections, one being the narrower and shallower (Z_m = 2 to 8 m) section of the upper and middle estuary set between the Paraná delta front to the virtual transverse between the cities of Montivideo (Uruguay) and Punta Piedras (Argentina) and the other being the larger, wider and deeper (Z_m = 8 to 18 m) lower estuarine shaped embayment delimited in transverse between Punta Del Leste (Uruguay) and San Antonio Cape (Argentina). The lower sector covers 18 to 22,000 km^2 of the total system, depending on the extent of river outflow and extent of salinity intrusion from tidal and wind forcing (Piccolo and Perillo, 1999; Laborde and Nagy, 1999). The shelf front at the closely set 100 to 200 m isobaths is approximately 170 km offshore. The La Plata System contains essentially 2 biomes: the ***Turbid Estuarine Biome and the La Plata Shelf Plume Biome*** which extends northwards towards the Brazilian

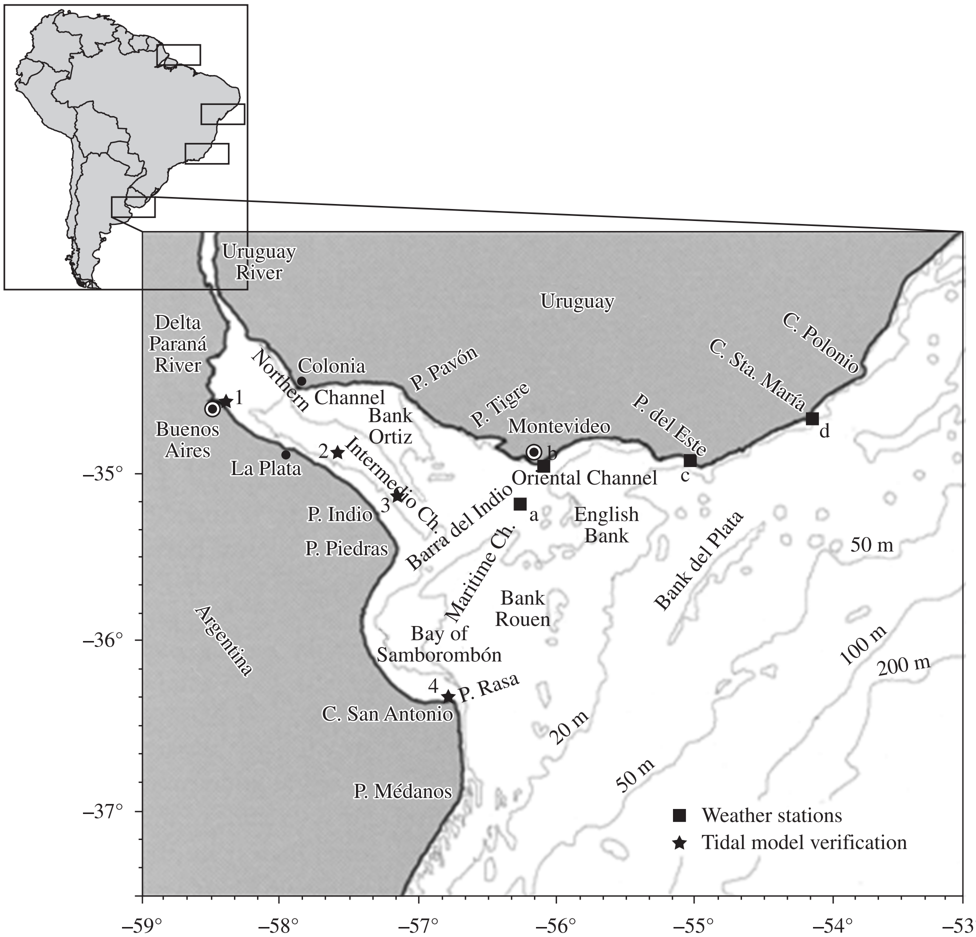

Figure 4. The Rio de La Plata Estuary (34° 00'-36° 10' S and 55° 00'-58° 10' W).

coast and intercepts the freshwater input from the Patos lagoon System.

The Rio de la Plata corresponds to the second largest drainage system of South America with a total area of 3.17×10^6 km^2 (Tossini, 1959). It is formed by the Paraná-Paraguay and Uruguay rivers with boundary coordinates between 14° 05'-37° 37' S and 67° 00'-43° 35' W. The Upper and Lower Paraná ($A_B = 1.68 \times 10^6$ km^2; L = 4000 km), Paraguay ($A_B = 1.1 \times 10^6$ km^2), Uruguay ($A_B = 0.35 \times 10^6$ km^2) and smaller Rio de la Plata ($A_B = 0.037 \times 10^6$ km^2) rivers, cover parts of the countries of Brazil, Argentina, Uruguay, Paraguay, Bolivia and Peru. The average flow Q_R has been estimated at 22,505 m^3.s^{-1}, with minimum and maximum values of 10,800 and 30,6000 m^3.s^{-1}, respectively. It is considered the third largest river flow from South America (Laborde and Nagy, 1999). Since the Fifties' up to the mid-Nineties', however, many reports indicate that river discharge has been on the increase with a linear trend expansion of normal and maximum values. The Paraná and Uruguay increased their flow rate by approximately 20%. This has been attributed to several features, such as deforestation/reduction of water retention capacity in the upper basins, the development of an excessive hydrological period, and the "El Niño" phenomenon, particularly, of 1982/1983 (Depetris and Kempe, 1993; Depetris, 1996, 2007; Milliman et al., 2008).

3. Results and Discussion

The Brazilian coastal zone spread from 4° N to 34° S of latitude and because of its long extension the interface zone from continent to ocean include a high diversity of climatic and geographic regions with differences in hydrologic, geology, geomorphologic and oceanographic characteristics. First of all, geographic criteria distinguishes at least four main sectors along the Brazilian coast, the North (4° N and 3° S), Northeast (3°-13° S), East (13°-22° S) and South (22°-34° S) (Guerra, 1962) (Figure 5 and Table 1). The coastal zone from the North, Northeast and East regions are governed by humid tropical weather (Köppen Af type); while the southern region is governed by warm tropical weather (Caf) and part of the Northeast region, mainly in the continental basin area, by a dry (semi-arid) tropical weather (Bsw). Independent of the extended quaternary shelf of the Amazon (North region)

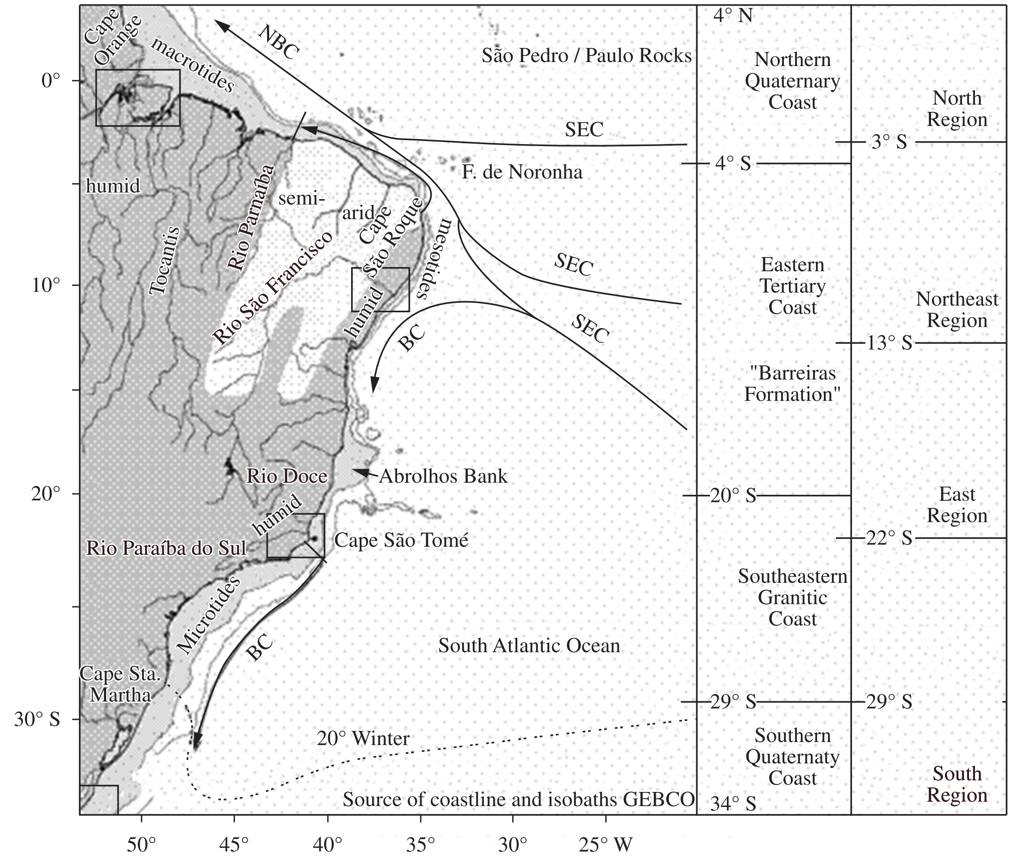

Figure 5. Brazilian coastal classification (From Ekau and Knoppers, 1999).

(Figure 5), 79% of the Brazilian coast is characterised by a narrow coastal fringe, presenting with frequency low kilometres of extension. Most of the continent upstream and from the Northeast and East regions are characterised by Tertiary Barrier Formation. The other coastal plains occur along the Southeastern Granitic and Southern Quaternary Coasts (≈22° S) (Figure 5) (Ekau and Knoppers, 2003).

The boundaries of the main drainage basins included in the coastal zone practically correspond to the geographic regions. The main basins defined by the National Brazilian Water Agency (ANA) for the North regions are the Amazon and Tocantins; for the Northeast region, the Parnaiba, São Francisco and Occidental and Oriental Atlantic Northeast; and for the East and South regions the Atlantic East, Southeast and South.

The numerical information from the interface characteristics inside the different Brazilian shelves regions are shown in Table 1. The higher regional diversity of the typical characteristics of the coastal zone is clear, compared with the more extensive domain of the oceanic current and the productivity of the Large Marine Ecosystem (LME). The geomorphologic features of the regional shelves variability seem to follow the geographic classification. Table 1 describes the typology of the Brazilian coast and shelf.

The Brazil current, which corresponds to the western boundary current of the tropical/subtropical South Atlantic Gyre, was considered to have low productivity and a single Large Marine Ecosystem divided in geographical regions (Figure 5 and Table 1). A review of its physical, chemical and biological features revealed that the BC current was by far more complex than earlier thought. It originates from a branch of the oligotrophic South Equatorial (SEC) at around 12-15° S along the northeastern–eastern Brazilian ocean margin, meanders southward over more than 3000 km until the Brazil-Malvinas confluence (South Atlantic Convergence Zone – SACZ) at around 35-40° S. Along its pathway, it is laterally enriched by SEC waters and influenced by changes in shelf topography, land runoff, upwelling process, primary production and composition of its shelf sediments. Consequently the former single BC-LME has recently been redefined into one oligotrophic of the Northeast – East Brazil shelves and the other the more productive Southeast-South Brazil shelves region. At the extremes, there are the NBC that meet the Amazon plume and the SACZ influenced by the La Plata river dispersal system.

Due to the large extension and the variability of regional characteristics, the Brazilian coast presents a vast diversity of ecosystem and associated habitats (Table 1). Riverine

Table 1. Typology of the Brazilian coast and shelf, modified from Ekau and Knoppers (1999) and Marone et al (2010).

Characteristics	North (4°N-3°S)	Northeast (3°S-13°S)	East (13°S-22°S)	South (22°S-34°S)
	Continental Features[1]			
Coordinates	(0.5°S-47.5°W to 3.0°S – 41.5°W)	(10.5°S-36.5°W)	(19.5°S-39.8°W to 22°S-41°W)	(28.5°S-48.8°W to 33.7°S-53.4°W)
Basin area (106 km^2)	0.561[a]	0.950b	0.465c	0.244[d]
Water runoff (mm.yr^{-1})	173[a]	32b	169c	662[d]
		(11)	(13)	(5)
Climate[2] (köppen type)	Tropical-Humid	Tropical-Humid	Tropical-Humid	Humid-Warm
	Af	As	Aw	Caf
River discharge (m^3.s^{-1})	3,084[a]	964[b]	2,498[c]	5,125[d,e]
Coastline[3] (km)	730	1,825	1,324	2,507
River discharge / coastline6 (m^3.s^{-1}.km^{-1})	4,22[a]	0,53[b]	1,89[c]	2,04[d,e]
	Coastal Features[1]			
Ecosystems[4,5,6]	Large mangroves., estuaries, mud flats	River delta	River deltas, coastal upwelling	Lagoons, estuaries
Mangrove area[3](km^2)	6,120	20	179	None
Tides[7]	Macrotides	Mesotides	Microtides	Microtides
	Shelf Features[1]			
Shelf width[8](km)	80-180	15-30	45-90	10-170
Shelf area[8](km^2)	115,000	1,075	20,880	122,443
Oceanic currents[8]	NBC	SEC/BC/TW	BC/SACW	BC/SACW/SACZ
Chlorophyll-*a*[9,10,11,12] (mg.m^{-3})	0.2-0.6	0.2-1.5	0.3-1.7	0.2-3.0
Primary production[13,9,10,12] (gC.m^{-2}.d^{-1})	0.3-0.8	0.02-0.5	0.3-1.1	0.3-2.9
Total suspended solids[14] (g.m^{-3})	0.3-1.0	0.5-5.0	0.3-1.0	1.0-10.0

[1]Geographical regions, continental, coastal and shelf features according to Guerra (1962) and Marone et al. (2010); Others sources: [2]Nimer (1972); [3]Kjerfve and Lacerda (1993); [4]Knoppers and Kjerfve (1999); [5]Knoppers e al. (2006); [6]Souza and Knoppers (2003); [7]Brasil (2002); [8]Castro and Miranda (1998) and Castro et al. (2006); [9]Gaeta et al. (1999) and Gaeta and Brandini (2006); [10]Brandini et al. (1997); [11]Medeiros et al. (1999); [12]Teixeira and Gaeta (1991); [13]Knoppers and Pollehne (1991); [14]Milliman (1975). Brackets refer to the number of rivers analysed for each region according to Marone et al. (2010). Oceanic current abbreviations as following NBC: North Brazilian Current, SEC: South Equatorial Current, BC: Brazil Current, TW: Tropical Waters, SACW: South Atlantic Central Waters and SACZ: South Atlantic Convergence Zone. [a,b,c,d] Basin area, water runoff and river discharge without Amazon River (AM), São Francisco River (SFR), Paraiba do Sul River (PSR) and Parana River (PR) and [e]includes Guaiba River (GR).

estuaries from meso to large scale, including the Amazon, with one of the largest mangrove areas of the world and an extended mud plain in the inside shelf, are typical of the Northern region. Dunes, coastal plain estuaries presenting mangroves, deltaic estuaries of meso-scale rivers and also some fringe and barriers corals reefs are spread among the Northeast and East coastal zone. The coastal plain along the Southeastern granitic and Southern Quaternary coasts consist of medium rivers estuaries, estuarine bays and mainly coastal lagoons. Coastal upwelling events occur more intensively in the East and Southeastern-South regions, with the main focus in Cabo Frio (RJ) and Cabo de Santa Marta (SC).

Estuaries are considered to be among the most productive coastal ecosystems. Even being prone to different regional typology settings and mesoscale physical processes, estuary characteristics drive the sustenance of primary production and the material export yields to the ocean (Walsh et al., 1988). The region of the mixture zone of freshwater with marine water masses attends the intensive processing of both riverine and marine materials. The hydrological process and geomorphologic characteristics of the estuarine region will be essential to determine the trophic net system and materials transfer from the continent to the ocean. Different estuarine typologies were shaped during the time as a result of the interaction among physical energy from waves, tides, rivers discharges and coastal currents movements. From a geological standpoint, the estuaries are young systems evolved during the Holocene 6 thousand years ago as a function of sea level progression and regression episodes that determined the coastal sculpture. As a result a hydrological and geomorphologic classification, the following categories should be attributed to the south Atlantic Estuaries: deltas, estuarine deltas, floodplain estuaries and estuarine lagoons. A typical feature of the Brazilian coast is the estuarine-bay which could be included in the floodplain estuary category but could also be of tectonic origin.

Delta regions are characterised by sedimentary deposits and a mixture zone situated outside of the river mouth over the inside shelf. Sediment exports from the continent to the ocean occur throughout the year independently from the seasonal river discharge variability. However, deltaic estuaries are characterised by large sedimentary deposits and by an estuarine mixture zone situated on both sides of the river mouth. The Amazon, São Francisco (SE/AL-Brazil) and Paraíba do Sul (RJ-Brazil) rivers belong for this category. All those estuaries present mangrove and a higher amount of phytoplankton primary productivity taking place in the coastal plumes. The Amazon river estuary is submitted to a macrotide and lower wave influence, the São Francisco river estuary is controlled by mesotide and high influence from wave energy and the Paraíba do Sul river estuary is submitted to a microtide and high energy from waves.

The most important ecosystem included in the coastal zone is the Atlantic Forest with only 6% of the original forest remaining, which is still subject to many impacts such as damming, urbanization, agriculture, industries and mining. As a consequence of all those impacts, changes are observed in water supply and materials transfer from the continent to the coast. The dams trap and transform the sediments in their reservoirs, deforestation causes erosion and increases fluvial sediments transport and many other impacts have also caused the introduction of effluents with a series of organic and inorganic compounds of natural and artificial source.

Most Brazilian rivers that get to the Atlantic coast present multiple environmental impacts in their drainage basin. An actual problem is how to look for natural levels to use as a reference to understanding the causes and effects of those human environmental impacts. This task can only be reached through a detailed study of preterit data related with the actual conditions. Although the Brazilian water agency (ANA) reports a good amount of data about water discharge and sediment yields, there is still a huge lack of information about the input of organic and inorganic compounds that can be used to evaluate the river fertilisation potential to support the primary production and also assess the potential of human contamination in the coastal zone. Henceforth, the following information is restricted to water and sediment supply to the coast.

Table 2 presents flows and yields of water (runoff and input for the drainage of the basin area) and sediment yield in the Amazon, São Francisco, Paraíba do Sul and Paraná drainage basin regions. The water supply in the northern region is about 4700 $km^3.yr^{-1}$ which is equivalent to a performance of 870 $mm.yr^{-1}$ (water supply in relation to the drainage basin area). Despite this region presenting an extended area of a huge mangrove cover and a macrotide regime, the Amazon basin feature predominates with 90% of the continental water supply. From the North to Northeast shelf, the transition from the tropical humid

Table 2. Discharge and runoff of water and sediment load and yield of the Amazon, São Francisco, Paraíba do Sul and Paraná (La Plata) drainage basins. Water and sediment yields calculated from: ANA (2002); Eletrobras (1998); Eletrobras (1992); Souza (2002); Carvalho et al.(2002).

Drainage basin region	Drainage basin (km^2)	Water Discharge and Runoff		Sediment yield	
		($km^3.yr^{-1}$)	($mm.yr^{-1}$)	(10^6 $t.yr^{-1}$)	($t/km^2.yr^{-1}$)
Amazonas	6,930,000	6,591	951	1200	173
São Francisco	634,000	65	102	0.8	1.2
Paraíba do Sul	55,400	28	505	4.2	76
Parana (La Plata)	3,170,000	710	224	92	29

climate to semi-arid is the main characteristic responsible for the continental water supply reduction and also for the absence of coastal ecosystems diversity. In the south zone of this Northeast region, the tropical humid climate from the coast contributes with a runoff of 12 $km^3.yr^{-1}$ with a specific water supply of 129 $mm.yr^{-1}$ (Knoppers et al., 2009). The Northeast to East region of the Brazilian coast is delimited at the São Francisco River mouth. Over the last decades this basin has experienced one of the most significant impacts from the construction of a dam cascade and associated reservoirs. After the construction of the late Xingó dam (1994), 180 km from the coast the impacts from this damming system resulted in a reduction of approximately 30% of the water discharge and a significant loss of the seasonal discharge cycle. Nowadays the water supply from São Francisco basin to the coast is 60 $km^3.yr^{-1}$ (97 $mm.yr^{-1}$). From the east to south coastal region, the water supply increases gradually as a function of the climatic transition, specially from the inner continental region that changes from the north semi-arid to tropical humid from the south. The water supply from approximately 35 rivers with meso and small scales from the Atlantic East drainage basins (including Paraíba do Sul River) is 133 $km^3.yr^{-1}$ (242 $mm.yr^{-1}$). In this sector, the transition from the dry north influence to a southern, more humid one in conjunction with the coastal ecosystems, attains the value of 65 $km^3.yr^{-1}$ (440 $mm.yr^{-1}$) for the region of the Paraíba do Sul River. On the south Atlantic coast shelf, the water supply from all Southeast and South basins contributes with 146 $km^3.yr^{-1}$ (602 $mm.yr^{-1}$). The dominant features from this sector are the "Serra do Mar" mountain range from Rio de Janeiro to Parana, the coastal lagoons situated in the Rio Grande do Sul coastal plain and the La Plata river estuary that contributes with more than 50% supply to the south Atlantic shelf.

Sediment supply data from the south Atlantic basin are relatively scarce. Most of the studies have been done by energy companies focussing on the assessment of reservoir sediment supplies, but have neglected the important role that the sediments have upon coastal zone fertilization. Estimates along the coast show a range of sediment supply from 1.2 $t.km^{-2}.yr^{-1}$ from the São Francisco River submitted to a semi-arid climate and a series of reservoirs to 1200 $t.km^{-2}.yr^{-1}$ for the Amazon River. With the exception of the continental north shelf where the sediment supply from the Amazon River is extremely elevated, there is no evidence that the actual suspended sediment supply significantly modifies the biogeochemistry of the other sectors from the south Atlantic continental shelf.

The rivers from the Northeast and East regions are marked by a typically unimodal seasonal flux pattern, but different in amplitude. As the climate indicates, the rivers from the Northeast are subject to accentuated seasonal variability with elevated input and flood pulses during the rainy season and low to negligent fluxes during the dry season. Small-scale rivers usually present typical torrential behaviour. In the humid eastern region, the unimodal seasonal cycle is depressed with a more constant input supply. Unfortunately, the missing historical data of nutrients and organic compounds for all basins does not allow us to give a better description.

The freshwater input magnitude is the only possible estimate to give us the potential fertilizer from the continental supply over the continental shelf. Recently, some studies show that the material supply from rivers along the Northeast and East coast are diluted from superficial tropical waters of oceanic currents and that the estuarine plume dispersion is restricted to a narrow coastal belt.

4. Conclusions

The magnitude and pulsation of the freshwater discharge should thus be regarded as the sole likely proxy to obtain some idea of the potential river fertilization of the waters from the coast and continental platform. Furthermore, whatever scenarios obtained from the Marengo et al. (2009a) model, considering the coupling of the different spatial compartments (i.e. multiple biomes) of the watersheds, will only address the impact upon the hydrological balance of the estuaries and extent of plume dispersal patterns over the shelf. Other external physical energy forcing functions, like sea level rise, changes in the wind-wave regime, coastal currents, and pulsation of the oceanic boundary currents, will have to be taken into account:

1) DIC and overall Carbon and land-sea transport concomitant of all carbon species. Most transport estimates are based on suspended matter, POC and dissolved inorganic nutrients. The same holds for Nitrogen, Phosphorous and Silica: most studies have focussed on the dissolved inorganic fractions (i.e nutrients) and neglected the dissolved and particulate organic fractions which, once introduced into the system, are to be considered as a potential contribution to the new nutrient pool after their decomposition and remineralisation within the system compartments along the land-ocean continuum.
2) The Silica budget, cycling and fate, including DSi, BSi and also LSI speciation, in estuarine-coastal waters and its alterations of riverine transport due to human impacts and relations to weathering and climatic gradients have, apart from some sporadic publications, been entirely neglected. Its role upon the phytoplankton based food webs in estuarine-coastal systems dominated by diatoms has to be elucidated.
3) Several aspects of the nitrogen budget, origin and fate and also riverine loading of its diverse species (DIN, DON, PON) still have to be addressed. Processes like denitrification with the potential loss of nitrogen as N_2 and the coupling or de-coupling with nitrogen-fixation in organic-rich and more enclosed estuaries are, apart from some exceptions, lacking in information.
4) Links coupling the origin, nature (composition) and fate of materials transported across the land-

ocean interface generated by the continental biomes with differences in climate, vegetation, soil composition, including mineralogy, and also habitat fragmentation, have as yet to be established. However, all of the major biomes, including the Amazon with deforestation, burning, agricultural expansion and construction of dams, are either prone to multiple or single human impacts, some of which are more severe or at its onset.

5) Multiple or single human impacts like dams and their reservoirs, agriculture, urbanisation and industrialisation may act in concert or one may dominate some river basins. A classical example of a dam dominated system (major single impact) is the São Francisco river system (E-NE) and examples with multiple impacts are the Jaguaribe (NE), Paraíba do Sul (SE) and Guaiba (S) river systems.
6) Up to what extent human impacts superimpose or alter the system to such an extent that no clear signals with proxies of climate change, especially precipitation/run-off and temperature, can be detected, remains the major challenge for the the land-sea interface biomes.
7) Eutrophication is a worldwide problem and also affects manifold systems, mainly estuaries and estuarine-bays set within the vast Brazilian coast. Hypoxia and its future potential of development are more restricted to these system types as both the western boundary currents originating from the highly oligotrophic South Equatorial Current, like the Brazil Current which meanders from North to South and the North Brazil Current, which flows from Northeast to the North, (i.e Amazon) proliferate directly close to the coast and efficiently dilute continental borne materials along the shelf. The geomorphological configuration of the shelf lacks clear depositional basins of land-borne materials.
8) Shelf edge upwelling dominates de southeast and south shelf sectors but deposition of produced materials occurs largely at the edge and slope and is also exported offshore by eddy formations.

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