Nutrient Transport, Cycles, and Fate in Southern Brazil (Southwestern Atlantic Ocean Margin)

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Abstract The southwestern Atlantic Ocean margin along the coasts of southern Brazil, Uruguay, and Argentina includes a wide continental shelf which varies in width from about 150 km off southern Brazil to over 500 km along the Patagonian coast of Argentina. The region between 28° and 40° is one of the most biologically productive areas of the World Ocean, and this productivity, perhaps driven mostly by ocean margin processes, extends out across the South Atlantic. Because of this high production, this ocean margin is the largest CO_2 sink in the South Atlantic and is significant on a global scale. Complex interactions of physical, chemical, and biological processes active in this ocean margin control the transport pathways and production in time and space. An appropriate understanding of this system obviously requires interdisciplinary study and information synthesis. This chapter assesses the state of knowledge on ocean margin processes of the southwestern Atlantic Ocean, presents a summary of the present understanding of physical and biogeochemical processes operating in this region and how they are linked, and identifies major areas of uncertainty. This paper provides background information about nutrients in the southwestern Atlantic Ocean margin. Initially we focus on a synthesis of past work and then consider more recent research on nutrients. The chapter emphasizes recent research which considers new nutrient sources to the ocean margin. At the end, the major scientific uncertainties are pointed out to provide a framework for discussion regarding future international, interdisciplinary research in the region.

Keywords Nutrient transport · Southwestern Atlantic · Nutrient sources · Multidiscipline syntheses

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1 Introduction

The southwestern Atlantic Ocean region between 28° and 40° is an important part of the global ocean system in terms of ocean circulation and production, but it is of greatest significance to the adjacent South American countries of Brazil, Uruguay, and Argentina. A considerable amount of research has been conducted in this region by South American scientists and by collaborations of foreign scientists with local researchers. Much of this work has been part of local national programs, related to fisheries and other coastal environmental issues, as well as regional programs such as PROSUL (Program to Enhance Cooperation in Science and Technology in South America). International cooperative programs include the World Ocean Circulation Experiment (WOCE), other programs sponsored by the Inter-American Institute for Global Change Research, and a number of North American-South American cooperative programs such as the EcoPlata collaboration between Uruguay, Argentina, and Canada; the NICOP-PLATA collaboration between the US Office of Naval Research, Brazil, Uruguay, and Argentina; and the PATEX (PATagonia Experiment) collaboration between GSFC/NASA, Brazil, and Argentina. Additionally, specific investigator-driven research efforts have brought South American researchers from this area together with North American colleagues to address a number of topics which have both regional and global significance.

Continental shelf processes in this region are influenced by the complex interaction of two major current systems, the Brazil and Malvinas currents, which converge in this region and provide a dynamic environment for cross margin transport and coastal circulation. Material transport to the system from the continent is dominated by a major river system and additional surface runoff sources, but atmospheric transport, groundwater inputs, and coastal water advection through permeable sediments may provide additional important inputs. And, of course, upwelling and intrusions of deep water and offshore transport at the continental shelf edge are important additional processes occurring in this region. The southwestern Atlantic Ocean margin (SWAOM) therefore provides an opportunity to study/understand complex biogeochemical processes which are of interest to a wide range of ocean science disciplines.

2 Shelf Waters

Shelf waters in southern Brazil have been broadly characterized in terms of oceanic water masses and surface inputs from land, and despite the considerable number of nutrient measurements performed in the past four decades in this region (Fillmann 1990; Sales Dias 1994; Niencheski and Fillmann 1997; Del Rosso 2000), the chemical processes and the sources of nutrients in SWAOM are still poorly understood. And part of this is because, with few exceptions, only

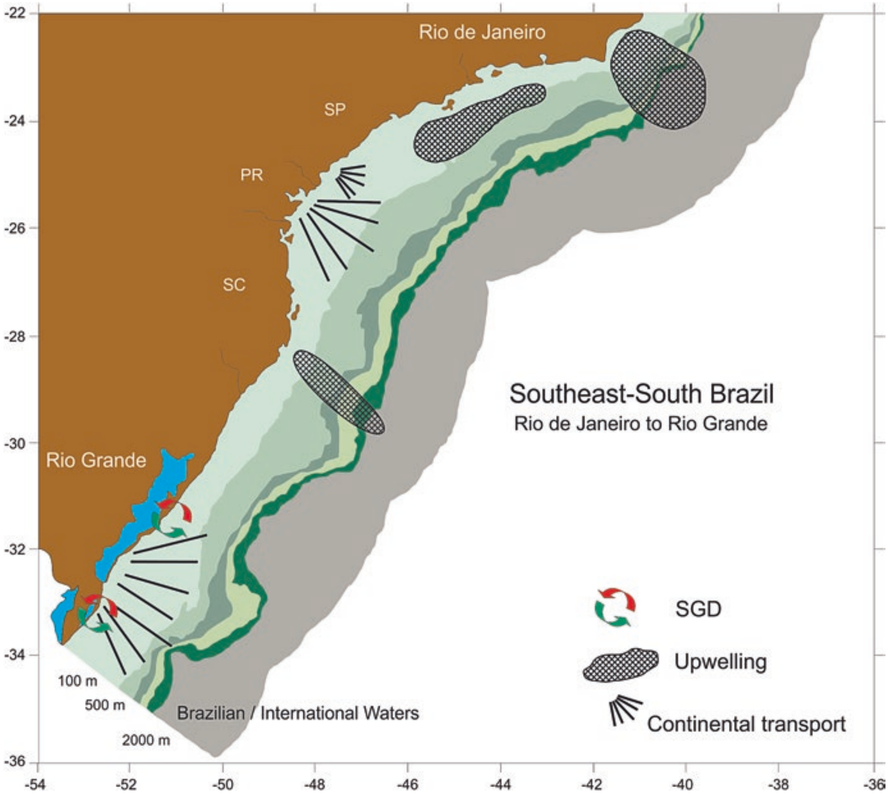

Fig. 1 Terrestrial influences (continental transport symbol) submarine groundwater discharge (SGD symbol) and upwelling (upwelling symbol) along southern Brazil. (Adapted from Braga and Niencheski 2006)

surface shelf waters concentrations have been the focus of studies. This has limited interpretations of the nutrient association with bottom water masses, mixing, and sources of nutrients in a region where the water chemistry is mainly governed by the mixing of waters of the Brazil and Malvinas currents as they collide (the Brazil-Malvinas Confluence Zone).

A review by Niencheski et al. (1999) indicated that the nutrient characteristics of seawater are well known in regions near Rio de Janeiro, Sao Paulo, and Rio Grande do Sul states. But they point out that coastal studies predominate over those further out on the shelf and slope. More recently studies such as ECOPEL, COROAS, CABO FRIO, PRONEX, and SACC GROUP programs have become more interdisciplinary and systematic and temporally sequenced.

Braga and Niencheski (2006) summarized the existing information for the southern Brazilian continental margin. This included the terrestrial influence from rivers and lagoon inputs and oceanic influences as observed by the presence of upwelled South Atlantic central water and subantarctic shelf water (Fig. 1).

Lopes (2004) suggested that the chemical features of the coastal and shelf waters of southernmost Brazil are mainly influenced by the Brazil current (tropical water, TW), the Malvinas current (subantarctic water, SAW), and subtropical water (STW). In addition to these, the outflow of the Río de la Plata and Patos Lagoon contributes jointly to a coastal water (CW) mass. This study was based on four oceanographic cruises as part of the ECOPEL program (from 1987 to 1991) and a cruise associated with the COROAS program (ocean circulation of the west region of the South Atlantic), carried out in April 1993. Lopes observed higher nitrate concentrations on the continental shelf in the autumn. During the spring increased levels of silicate were observed, while during winter, higher concentrations of nitrate and phosphate were observed on the shelf as a result of the intrusion of SAW. During the summer when lowest nutrient levels occur, the influence of TW on continental shelf is evident.

3 Shelf Break Waters

At the shelf break, upwelling of STW occurs during the spring. This water mass contains high nutrient concentrations and supports new production which is manifested in high fish stocks in the region. Observed heterotrophic conditions during this period result in increased consumption of dissolved oxygen.

Most recent nutrient surveys in SWAOM have focused on the continental shelf (i.e., <200 m), and many of these have included near bottom samples. But most attention has been focused on surficial water and their relation to primary production. Less attention has been given to sources on the shelf or at the shelf break. And even when surveys have extended across the slope, little attention has been paid to bottom waters (i.e., likely nutrient sources). Results from older nutrient surveys (Fig. 2) show considerable silicate enrichment along the shelf break. Clearly the slope water is a likely important source of nutrient supply to the shelf and needs further investigation. This is because very little attention has been paid to bottom water nutrient data in the past.

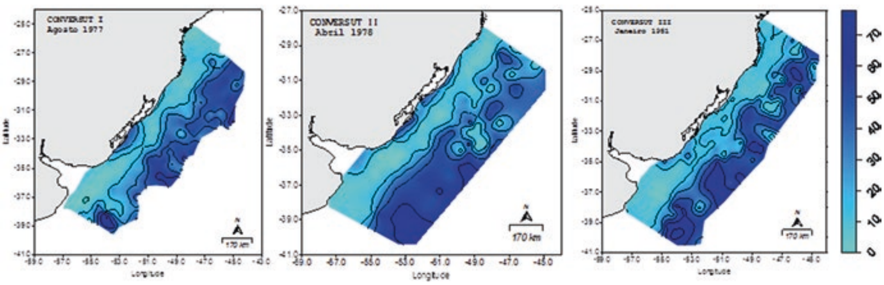

Fig. 2 Silicate concentrations in bottom waters (μM). Data from CONVERSUT program by Brazilian Navy – 1977; 1978 & 1981

4 Coastal Waters

A clear dependence of chemical conditions on oceanographic processes, which create fronts and shelf break upwelling, is evident in the distribution of nutrients on the shelf. Nutrient levels in coastal water (CW), however, are driven by freshwater discharge – from Río de la Plata and Patos Lagoon and the coastal wind stress, all of which depend on weather condition. Because of this, the CW nutrient level also responds to "El Niño" events. But generally, surface inputs such as that of Patos Lagoon outflow have seasonal influences over the local continental shelf. The Patos Lagoon exports dissolved inorganic nitrogen during autumn/winter periods, induced by NE winds.

Braga et al. (2008) (South Atlantic Climate Change Consortium – SACC) presented nutrient distributions over a larger area at continental shelf from 27° 05' S (Brazil) to 39° 31' S (Argentina) during winter 2003 and summer 2004. The relation between nutrient levels and salinity indicates the influences of freshwater discharge over the coastal region and in the front of the Río de la Plata estuary. The low values of salinity associated with high nutrient concentrations clearly suggests the influence of terrestrial inputs, both in summer and in winter, with a larger northward penetration in winter.

Although considerable information exists on nutrient dynamics for the SWAOM, summarized above, scientists in the region view the high-productivity periods in the coastal and shelf waters, as dominantly controlled by river outflow as the major source. Instead, atmospheric transport and submarine groundwater discharge (SGD) of nutrients have only been considered recently.

5 Influence of SGD on Nutrients

During the 1990s research on the variations and interrelation of nutrients in the estuarine region of Patos Lagoon was initiated. The initial aim was to assess the processes occurring within the lagoon (0–30 salinity region) and the role of biological processes (i.e., uptake and remineralization) in the transport and fate of nutrients. In situ benthic flux chamber experiments indicated that remineralization within the sediments dominates the recycling of organic matter and nutrients within the lagoon (Niencheski and Jahnke 2002). But overall, nutrient budgets suggested that the lagoon was a net nutrient trap. From studies of trace metals (Windom et al. 2006), however, it was clear that other processes, specifically surface water-groundwater exchange, may be important to nutrient cycling and transport.

The southern portion of the Brazilian coast is dominated by coastal lagoons formed by sandy barrier spits with small inlets. This coastal configuration is a barrier to the surface flow of freshwater to the sea and accounts for the long water residence time which enhances the lagoon nutrient trapping ability. Significant amount of freshwater from the lagoon has been demonstrated to flow through the permeable

Fig. 3 Schematic representation of SGD on southern Brazil

sands, beneath the barrier spits, where it mixes with seawater (see Figs. 3 and 4; Moore 2008 ; Niencheski et al. 2007, 2010; Niencheski and Windom 2014; Niencheski et al. 2014).

Studies based on nutrient levels in wells from the barrier spit which separates Patos Lagoon from the South Atlantic shelf, along with estimates of SGD, suggest that the following processes are active: products of remineralization of organic detritus accumulated in lagoon sediments are advected through permeable sediments to the oceans, dissolution of biogenic solids and/or solid silicates mobilizes silicate, and phosphate is mobilized from phosphate-rich sediment layers. The resulting SGD has a significantly different composition than that of typical surface water sources. It was pointed out that these processes are not only important to the transport, cycling, and fate of nutrients within the coastal region of southern Brazil but perhaps to coastal areas in general. Niencheski et al. (2007) show that SGD may provide an important flux of nutrients to coastal ocean regions characterized by permeable sediments such as barriers of coastal lagoons. They also suggest that the subterranean transport pathway may be important in explaining the nutrient budgets of coastal lagoons. The authors present a conceptual model of nutrient fluxes in the coastal surface water-groundwater system (Fig. 5). They calculated the nutrient fluxes in the fresh groundwater (the freshwater moving toward the ocean), and these fluxes were compared to those associated with surface freshwater inputs to Patos

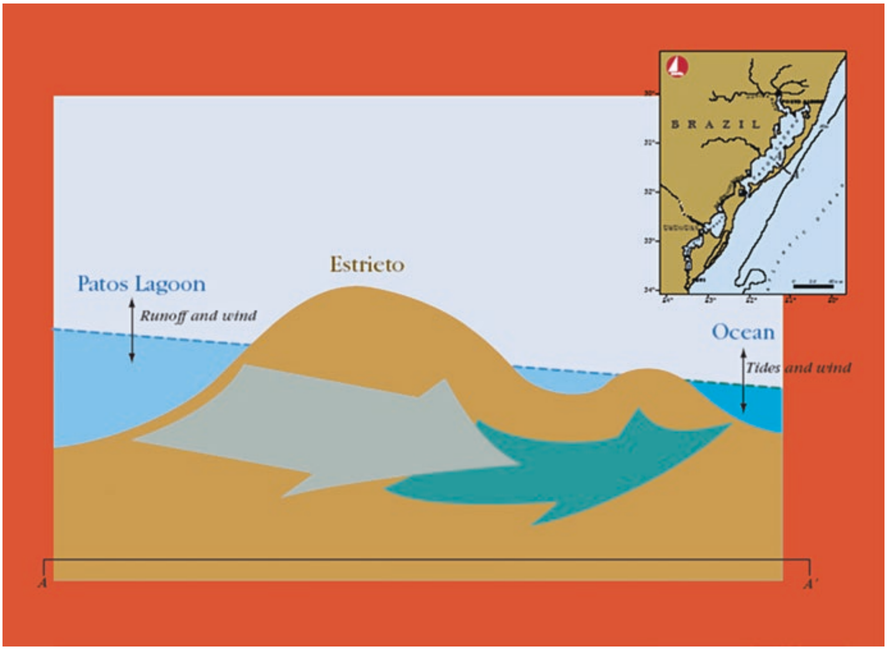

Fig. 4 Schematic representation of groundwater flux in a cross section of Patos Lagoon barrier

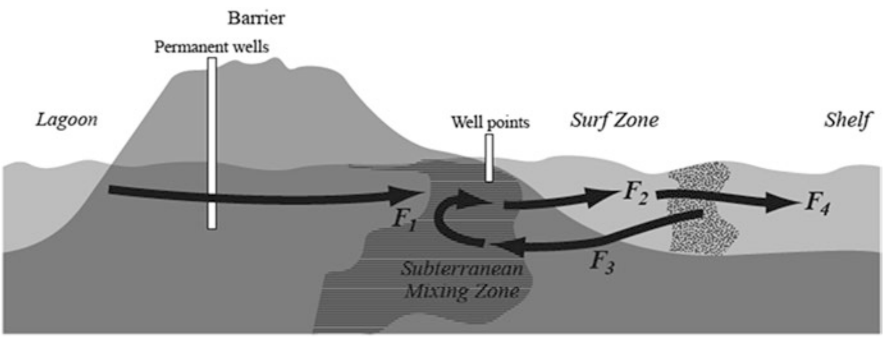

Fig. 5 Conceptual model of nutrient flux in coastal surface water – groundwater systems F1 flux in fresh groundwater, F2 flux associated with SGD, F3 recirculated seawater, F4 transport to the inner shelf, F5 transport offshore

Lagoon. Nitrate is the only nutrient species for which the groundwater flux is considerably less than the surface freshwater flux to Patos Lagoon, but this appears to be compensated by the ammonium flux so that the total nitrogen fluxes are similar (Table 1). Under the assumption that nitrogen limits production in the nearshore or surf zone region, the production supported by the SGD can be calculated. Using this data, the authors estimated that the N flux can support a production rate of about 8 g C m^2 day^{-1} or ca. 3000 g C m^2 $year^{-1}$.

Table 1 Estimated nutrient fluxes to the coast, F_1, in fresh groundwater compared to surface freshwater nutrient inputs to Patos Lagoon (10^6 mol day^{-1})

	F_1	Freshwater nutrient flux to Patos Lagoon (Niencheski and Windom 1994)
Silicate	23.2	13.1
Phosphate	0.25	0.05
Ammonium	1.15	0.25
Nitrite	0.002	0.01
Nitrate	0.086	0.98
Total nitrogen	1.25	1.24

The Southern Brazil and Uruguayan coast is dominated by several coastal lagoons. Of these the Patos and Mirim/Mangueira lagoons are the most well known. This coastal system certainly provides local hydraulic gradients resulting in groundwater flow toward the South Atlantic along ca. 1500 km length of their coastline, as exhibited by water levels in wells placed in the sandy barrier that respond to changing water level in the lagoons. Niencheski et al. (2007), however, show that groundwater transport and seawater cycling through permeable coastal/shelf sediments and SGD along the coast of southern Brazil are more complex than was originally hypothesized (Figs. 3 and 4). Instead of SGD being driven simply by a surficial aquifer which links the lagoon to the ocean, an additional aquifer system(s) underlies this region and may support SGD over a wider region of the shelf. We can speculate that Guarani aquifer or another important regional aquifer may have an even greater geographic influence and may, in fact, provide for nutrient input in SGD on the shelf.

The isotopic composition (d18O, d2H) of groundwater, lagoon water, and seawater collected in a coastal lagoon system in southern Brazil as a tool to define groundwater sources within a permeable barrier that separates the Mirim/Mangueira lagoons from the ocean was described by Schmidt et al. (2011). The isotopic signature of the barrier groundwater differs both from the isotopic composition of lagoon water and seawater. The groundwater is significantly lighter, indicating that the major recharge source to the barrier is precipitation, rather than lagoon water. In the southern and central part of the barrier, no interaction of groundwater with lagoon water was observed. In the northern part, however, lagoon water intrusion into the barrier was identified. This effect is apparently caused by different vegetation types on the barrier influencing subsurface hydrological processes. The central and the southern areas are characterized by natural dune vegetation (high infiltration, low evapotranspiration rates) whereas the northern part is covered by extensive pine tree plantations (low infiltration, high evapotranspiration rates). The presence of pine trees may enhance lagoon and seawater intrusion into the shallow aquifer and decrease fresh submarine groundwater discharge.

Chemistry of southern Brazilian continental shelf (SBCS) waters, between 28.5°S and 34°S, was evaluated in relation to the mixing of thermohaline-defined water masses and concomitant water column processes by Niencheski and Windom. (2014). Data on inorganic nutrient and trace metal (Ba, Cd, Co, Cu, Fe, Mn, U, V, and Zn) concentrations and radium isotopic activities from previous reports and recent analyses were presented and discussed by Niencheski et al. (2014) with the aim of providing a state of knowledge on processes governing their sources, distribution, transport, and fate on the SBS. Nutrient concentrations/distributions on the shelf are controlled mainly by tropical water/subtropical shelf water, seasonally modified as a result of summer upwelling in the northern shelf region, and by Río de la Plata plume water, which is seasonally modified by discharges of submarine groundwater (SGD) and the Patos Lagoon and by the greater northern penetration of the Rio de la Plata plume during winter. ^{226}Ra activity varies little across the shelf. ^{228}Radium, associated dominantly with SGD, decreases conservatively, with respect to salinity, across shelf transects, converging on a typical ocean end-member activity. The low salinity end-member activity, however, depends on the location of the shelf transect controlled by the variability of coastal SGD. Because SGD is so important to the coastal shelf region, ^{228}Ra activity appears to provide a better tracer of water mass interactions than thermohaline characteristics. Using metal-^{228}Ra relationships, sources, transport, and fate of trace metals are better constrained enabling the following conclusion: the major source of dissolved Co, Mn, and Fe to the shelf is SGD, along the coastal Holocene barrier system, followed by removal as coastal water mixes across the shelf. Cu and Si concentrations are explained as conservative mixtures of three end-members: SGD, surface freshwater discharge, and oceanic. Cd and Zn are largely explained similarly. Vanadium is enriched in coastal waters during the summer presumably due to seasonal remobilization from sediments but exhibits conservative mixing behavior across the shelf. Barium behavior is the most unexpected and is speculated to be the result of biochemical removal in highly productive coastal waters followed by release from decaying phytoplankton detritus as it is advected across the shelf.

6 Potential Nutrient Sources on the Shelf

Silicate is relatively enriched in terrestrial runoff and typically shows a conservative mixing behavior when freshwater mixes with seawater. To determine the sources of nutrient inputs along the coast during different seasons, silicate variations along S-N transect from Chuí (zero km) to Conceição (270 km) (Fig. 6) provide insights.

Data collected along this transect for silicate (Fig. 7) shows that for any time of the year, concentrations near the Albardão region are always high; in some instances, such as spring, they are even higher than the concentrations observed at stations located near the mouth of Patos Lagoon and Chuí (where the input of the Plata should have greatest influence). These results suggest that silicate sources other than the traditional ones (La Plata River and Patos Lagoon) may be responsible for the high silicate concentration which occurs near Albardão.

The map of silicate contours shown in Fig. 8 suggests two areas of high concentrations. But gradients associated with them show no obvious link to the Plata River or Patos Lagoon outlet. Campos et al. (2009) recently reported on the discovery of

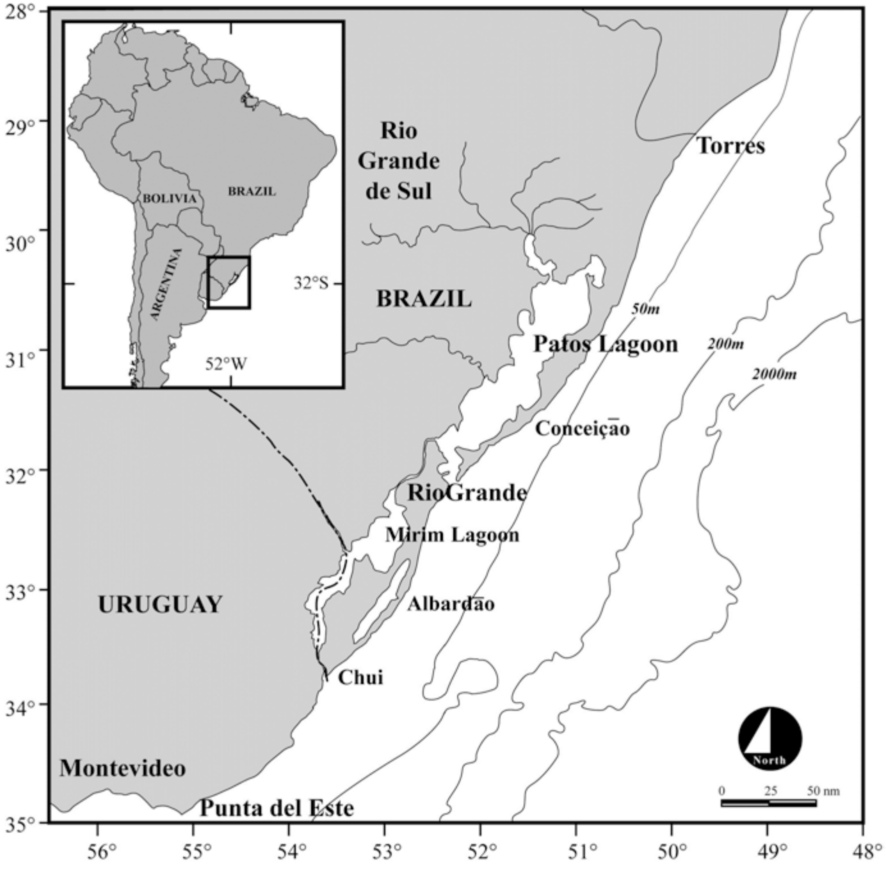

Fig. 6 Southern Brazil and Uruguayan coast

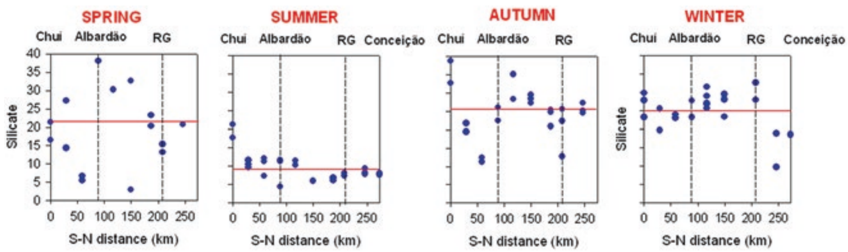

Fig. 7 Distribution of silicate concentrations as µM (down to a 10-m depth) along the coast, from Chuí to Conceição. Adaptado de Attisano et al. (2013)

the Albardão paleochannel which occurs about 35 kms offshore of southern Brazil and Uruguay. It begins near Punta del Este and extends, to approximately 50 km northeast along the coast. This feature reprints an ancient Plata River drainage

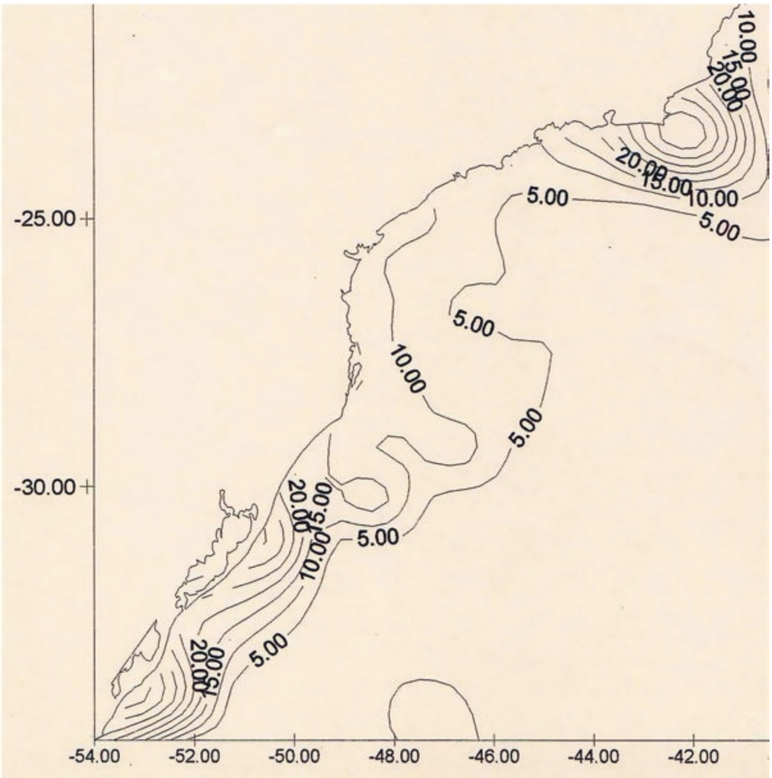

Fig. 8 Surface silicate distribution (autumn) (μM)

channel. SGD controlled by this feature may explain the southernmost area of silicate enrichment.

Although considerable research has been carried out on the southwestern Atlantic Ocean margin, there has been little integration of results across disciplines, and the few recent summaries of research that have been published do not take into account more recent scientific findings in the region. An exception to this was a special issue of *Continental Shelf Research* which was prepared in 2008, to focus on the results of the NICOP-PLATA research on continental shelf oceanography in the region of the Rio de la Plata and Patos Lagoon outflows (Campos et al. 2008).

In 2010, Federal University of Rio Grande (FURG) started the National Institutes of Science and Technology-*Integrated Oceanography and Multiple Uses of the Continental Shelf and the Adjacent Ocean* (Integrated Center of Oceanography – ICO). The main goal of this institute is to understand, quantify, and monitor the changes in the South Atlantic circulation due to changes in the atmospheric circulation and the consequent impacts on coastal processes and on the regional climate. The observational part of this project is conducted in four interlinked components:

(A) Large-scale sub-project, intended to investigate possible changes in the basin-scale South Atlantic circulation due to global climate change and their consequences to the Brazilian continental shelf
(B) A continental edge observational experiment, intended to identify and monitor changes in ocean-atmosphere variables in the Southwest Atlantic and its consequences to the biological pump
(C) A regional-scale component, focused on impacts of the large scale on the shelf and shelf break
(D) A multidisciplinary study intended to investigate the relationships of marine microorganisms and climate changes along the Brazilian coastal waters

7 Major Scientific Uncertainties

The multidisciplinary studies in this region will not only benefit regional researchers in planning future efforts but will also serve the wider marine research community by providing a better overview of the state of knowledge of this important ocean region. But more needs to be done across a wider scope of processes and disciplines. Based on our knowledge, the major uncertainties/issues are pointed out to provide a framework for discussion regarding future international, interdisciplinary research in the region:

- The relative importance of the contributors of surface sources (Rio de la Plata and Patos Lagoon) and groundwater sources of nutrients, in time and space, needs to be understood better.
  - A more detailed geographic distribution of SGD is needed to assess heterogeneity.
- Are there additional SGD nutrient sources on shelf due to larger groundwater systems?
- Understanding the role of slope waters and nutrient sources
- Processes at shelf break on nutrient input to the shelf.

Finally, this paper has a key role to initiate the pursuit of cooperative research projects/programs in the region that articulate with more global research agendas and regional-national collaborations.

References

Attisano KK, Santos IR, Andrade et al. (2013) Submarine groundwater discharge revealed by radium isotopes (Ra–223 and Ra–224) near a paleochannel on the southern Brazilian continental shelf. Braz J Oceanogr 61(3):195–200

Braga ES and Niencheski LFH (2006) Composição das massas de água e seus potenciais produtivos na área entre o Cabo de São Tomé (RJ) e o Chuí (RS). In: O ambiente oceanográfico da plataforma continental e do talude na região sudeste–sul do Brasil. Organizadores Rossi–Wongtschowski, Carmen Lúcia Del Bianco & Madureira Lauro Saint–Pastour, EDUSP, p 161–218

Braga ES, Chiozzini VC, Berbel GBB et al. (2008) Nutrient distributions over the Southwestern South Atlantic continental shelf from Mar del Plata (Argentina) to Itajaí (Brazil): Winter–summer aspects. In: Campos, E.J.D., Piola, AR and RP Matano (Eds.) Synoptic characterization of the Southeastern South American Continental shelf: The NICOP/Plata Experiment. Cont Shelf Res 28(13): 1649–1661

Campos EJD, Piola AR, Matano RP (eds) (2008) Synoptic characterization of the Southeastern South American continental shelf: the NICOP/Plata experiment. Cont Shelf Res 28(13):1551–1692

Campos P, Weigert SC, Madureira LSP (2009) Prospecção hidroacústica do fundo na região do Paleocanal do Albardão – RS – Brasil. Atlântica, Rio Grande. https://doi.org/10.5088/atl.2009.31.1.5

Del Rosso C (2000) Contribuição aos estudos hidroquímicos da plataforma continental sul–sudeste do Brasil. Undergraduate thesis. Oceanologia, FURG. Brazil

Fillmann G (1990) Caracterização química das massas de água da plataforma continental do sul do Brasil. M.Sc. thesis, FURG. 134 p (Brazil)

Lopes MF (2004) Hidroquímica da plataforma sul do Brasil: caracterização e variabilidade sazonal. M.Sc. thesis, FURG (Brazil)

Moore WS (2008) Submarine groundwater discharge. state of knowledge on Southwestern Atlantic ocean margin processes – workshop (SWAOM). Montevideo, November 16–22, 2008. (http://www.skio.usg.edu/meetings/uruguay2008.html)

Niencheski LF and Fillmann G (1997) Chemical characteristics. In: Seeliger U, Odebrecht C, Castello, J.P. (eds.) Ecology of subtropical convergence regions – The coast and sea in the warm–temperate southwestern Atlantic. Chapter: Coastal and marine environments and their biota. Springer, New York, p 96–98

Niencheski LF, Jahnke RA (2002) Benthic respiration and inorganic nutrient release across the sediment water Interface in the estuarine region of Patos Lagoon (Brazil). Aquat Geochem 8:135–152

Niencheski LF, Windom HL (1994) Nutrient flux and budget in Patos Lagoon Estuary. The Science of the Total Environment. 149 (1-2): 53–60

Niencheski LF, Windom HL, Moore WS Brandes J (2010) Nutrient subterranean fluxes to coastal zone of Southern Brazil. American Geophysical Union (AGU). The Meeting of the Americas. Foz do Iguaçu. August 8-12, 2010. Oral presentation at Session H34A

Niencheski LF, Windom H (2014) Chemistry of a surficial aquifer of a large coastal lagoon barrier and its relation to adjacent surface waters of Brazil. J Coast Res. https://doi.org/10.2112/jcoastres–d–13–00175.1

Niencheski LF, Baumgarten MG, Roso et al. (1999) Oceanografia Química – Levantamento Bibliográfico e Identificação do Estado Atual do Conhecimento. Avaliação do Potencial Sustentável de Recursos Vivos na Zona Econômica Exclusiva – REVIZEE. Patrocínio do Ministério do Meio Ambiente, dos Recursos Hídricos e da Amazônia Legal (MMA), Comissão Interministerial para os Recursos do Mar (CIRM), Fundação de Estudos do Mar (FEMAR), p 171 ISBN 85–85966–12–2

Niencheski LF, Windom HL, Moore W et al (2007) Submarine groundwater discharge of nutrients to the ocean along a coastal lagoon barrier, southern Brazil. Mar Chem 106(3–4):546–561

Niencheski LF, Windom HL, Moore WS (2014) Controls on water column chemistry of the southern Brazilian continental shelf. Cont Shelf Res 88:126–139

Sales Dias LM (1994) Caracterização química das águas da plataforma continental sul do Brasil – Verão de 1990 e Outono de 1991. Undergraduate thesis. Oceanologia, FURG, p 55

Schmidt A, Santos IR, Burnett WC et al (2011) Groundwater sources in a permeable coastal barrier: evidence from stable isotopes. J Hydrol 406:66–72

Windom HL, Moore W, Niencheski LF et al (2006) Submarine groundwater discharge: a large, previously unrecognized source of dissolved iron to the South Atlantic Ocean. Mar Chem 102(3–4):252–266