



Use of ^{210}Pb and ^{137}Cs in the assessment of recent sedimentation in Patos Lagoon, southern Brazil

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Abstract

In this study, the sedimentation conditions of Lagoa dos Patos, southern Brazil, were analyzed by applying ^{210}Pb and ^{137}Cs geochronological methods on four geological cores. The sedimentation rates showed a decreasing north-to-south pattern, indicating a strong influence of the Guaíba River discharge (the main Patos Lagoon tributary) on the transport of sediments into the interior of the lagoon. Core PT02 (north) had the highest sedimentation rate (of the order of 7.0 mm year^{-1}), while the central and central-southern drilling sites (PT04 and PT07) presented roughly lower values that corresponded to rates of 5.5 and 4.4 mm year^{-1} , respectively. This decreasing trend was reversed at the southernmost site (PT08), which showed a 4.8 mm year^{-1} rate due to the joint influence of the Camaquã River and São Gonçalo Channel discharges, combined with higher flocculation associated with the site's proximity to the estuary. Significant interannual oscillations of the sedimentation rates were observed when the CRS model was applied to the ^{210}Pb data. In general, the rates were higher in periods of higher precipitation, whereas the opposite took place in drier periods. The correlation between these anomalies and El Niño-Southern Oscillation (ENSO) events was identified. During El Niño years, the sedimentation rates increased by 135% in the northern sector (PT02); in the central and central-southern sectors, the rates increased by 164% (PT04) and 170% (PT07), respectively, while there was an increase of 262% to the south of the lagoon as observed at site PT08.

Introduction

Coastal lagoons are relatively shallow water bodies separated from the ocean by sandy and generally alongshore-oriented barriers. They are often sporadically connected to the ocean by

one or more restricted channels that rarely exceed a few meters deep (Kjerfve et al. 1997).

From an evolutionary point of view, these coastal environments are related to eustatic sea-level variations. Some coastal lagoons are associated with ancient valleys flooded by post-glacial transgressions; others are linked to the preservation of ancient barriers; and, in some cases, the lagoons were recently conceived by the alongshore growth of relatively new sandy barriers (Kjerfve and Magill 1989).

Like most coastal environments, these lagoons have developed during the last 7000 years when sea level rise became stable compared with its last transgressive event, thereafter beginning to decrease during the Holocene (Phleger 1981). They are often short-lived relatively to geological time scales due to rapid sedimentation, tectonic activity, or eustatic sea-level changes (Martin and Dominguez 1994).

Most coastal lagoons are maintained only by the protection provided by sandy barriers, with some cases where intense modifications due to human settlements perform this function such as in Chesapeake Bay (Gibbons and Nicholls 2006) and Gold Coast (Cooper and Lemckert 2012). Several human activities such as housing, port activity, agriculture, and power generation are potential threats to the quality of these

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environments because of the consequent changes in sediment production and accumulation.

Therefore, studies on sedimentation rates become relevant for the understanding of element input dynamics, which involves several sources for the coastal environment. Furthermore, the understanding of the interaction between human activities and coastal regions provides support for their management. Thus, this work aims to understand the depositional dynamics of Patos Lagoon by analyzing average rates of recent sedimentation and their interannual variability using both ^{210}Pb and ^{137}Cs geochronological methods.

Study area

Climatology and hydrology

Patos Lagoon is the largest lagoon system in South America and the world's largest choked lagoon (Kjerfve 1986), presenting a surface area of 10,227 km², a NE-SW main axis that is over 180 km long, and an average depth of 5 m. Located in the southern portion of Brazil between 30°–32° S and 50°–52° W, the lagoon is connected to the Atlantic Ocean by a single channel (Fig. 1), where the tide has a small amplitude (Andrade et al. 2018).

The study area consists of a temperate climate with large interannual variability associated to El Niño-Southern Oscillation (ENSO) events. According to the Köppen-Geiger climate classification (presented by Strahler and Strahler 1987), this region is classified as Cfa, which is characterized by a temperate rainy climate consisting of regularly distributed rains throughout the year. The average temperatures of the hottest and coldest months are higher than 22 °C and –3 °C, respectively.

The tributaries of Patos Lagoon (Fig. 1) belong to the Atlantic Basin and drain a total area of more than 200,000 km², divided into two large complexes consisting of several sub-basins.

The largest of these complexes is the Patos Complex (drainage area of 150,432 km²), formed by the Vacacaí, Taquarí, Jacuí, Caí, Sinos, Gravataí, Camaquã, and Guaíba rivers, and creeks. The other one is the Mirim Complex, which is formed by the Mirim Lagoon, the Jaquarão, Taquari, Cebolati, Piratini and Pelotas rivers, the Sarandi Grande, Santa Vitória, Rio Grande and Grande creeks, and by the São Gonçalo Channel. Its drainage area corresponds to 51,194 km² (Vieira and Rangel 1988).

In the northern region, the main tributary is the Guaíba River, which receives freshwater from the Jacuí-Taquarí river system that is responsible for 85% of the total mean freshwater intake into the lagoon interior. In the north of Patos Lagoon, the annual freshwater contribution is equivalent to 2400 m³ s⁻¹. Seasonal variations range from 700 m³ s⁻¹

during the summer (from late December to March) to 3000 m³ s⁻¹ during the spring (from September to early December). In the central region, the main tributary is the Camaquã River, responsible for the remaining 15% of freshwater (Vaz et al. 2006).

In the central area of the estuary, the São Gonçalo Channel (70 km long) connects the Patos to the Mirim Lagoon (area of 3749 km²), forming the Patos-Mirim system (Fig. 1). Although information on the freshwater contribution of this channel to the Patos Lagoon estuary is restricted, estimates indicate an average river discharge of 700 m³ s⁻¹ (Moller and Casting 1999).

The rivers that flow into the lagoon exhibit a typical pattern of mid-latitude rivers, with high discharge in the late winter and early spring, followed by low to moderate discharge during the summer and fall. However, there is significant rainfall variability in the Patos Lagoon drainage basin due to large-scale events such as the ENSO. During El-Niño years, the rainfall periods prevail and, according to Moller et al. (1991), discharge peaks of the order from 12,000 to 25,000 m³ s⁻¹ can occur associated with this phenomenon.

Complementary and correlated to the average flows of the main rivers is the residence time of the water inside the lagoon body. This residence time was calculated by Toldo Jr. et al. (2000), resulting in approximately 108 days.

Another important aspect of coastal lagoon hydrodynamics is the wave height and frequency. Toldo Jr. et al. (2006a, 2006b) made wave predictions for eleven sites of Patos Lagoon by using wind measurements from four stations. Since northeastern winds prevail in the summer and spring, the direction of the predominant waves on the lagoon's western side is NE/ENE, with mean significant wave heights ranging from 0.5 to 0.7 m and periods between 2.7 and 3.3 s.

On the eastern side of the lagoon, the prevailing winds are from WNW and WSW. During the winter and fall, the winds drive the highest maximum heights in the lagoon, with values corresponding to 1.6 m and a period of 4.8 s; the significant wave heights are between 0.4 and 0.8 m and the periods between 2.4 and 3.4 s. These parameters play determining roles in the sedimentation of the lagoon interior as demonstrated by Toldo Jr. et al. (2006a, 2006b).

Geological context

The Coastal Plain encompassing the studied area was formed during transgressive-regressive events induced by the Quaternary eustatic sea-level oscillations. As a consequence of these variations, four Lagoon-Barrier depositional systems were formed: from the oldest to the most recent, those systems are called Lagoon-Barrier I, II, III, and IV. Barriers I to III are from the Pleistocene, and barrier IV is from the Holocene. The isolation of the Patos-Mirim Lagoon system initiated with the

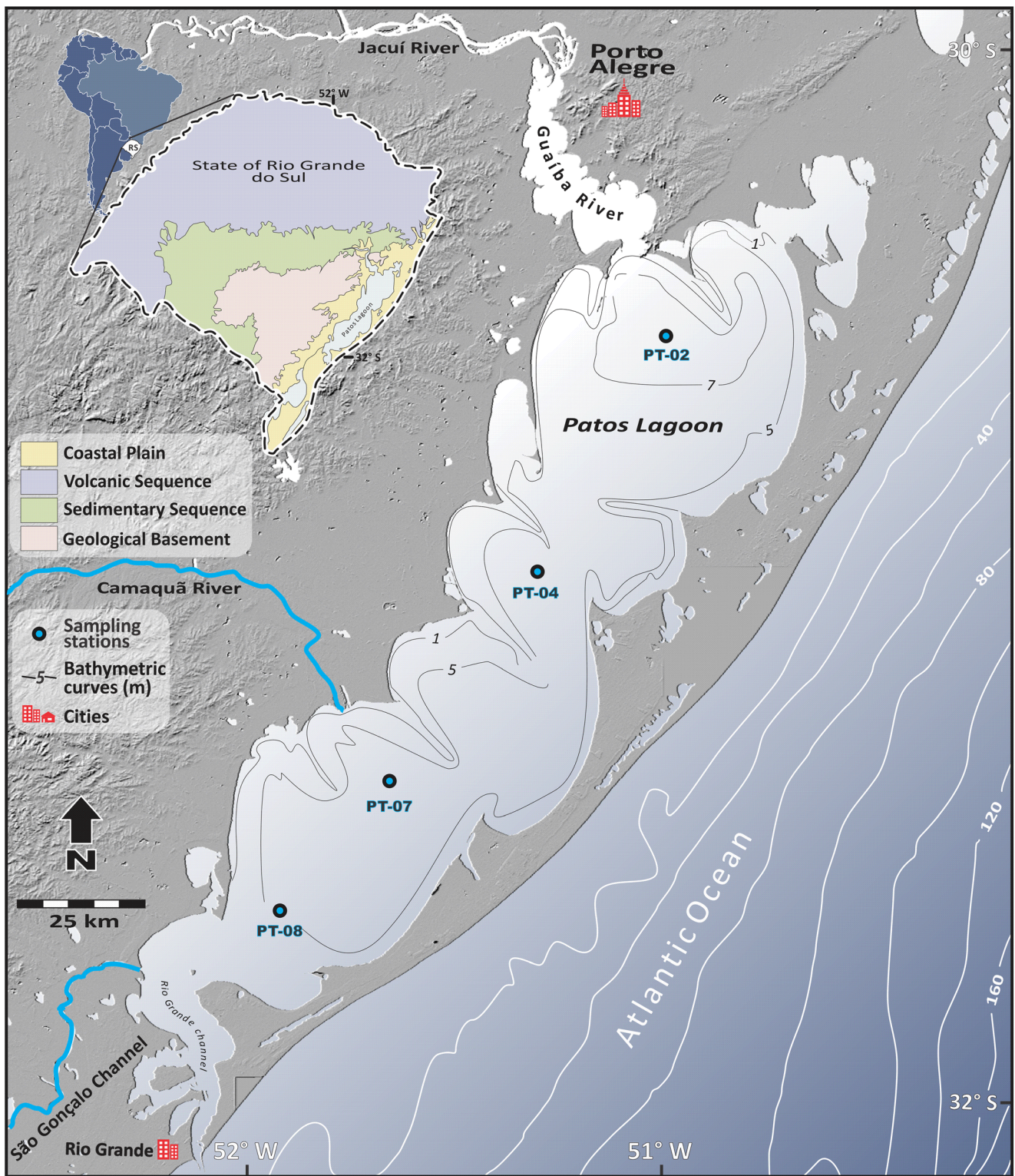


Fig. 1 Map of the study area with the location of the drilling sites. Modified from Baitelli (2012)

formation of Barrier III during the late Pleistocene, approximately 120,000 years ago (Tomazelli et al. 2000).

The sediments that constitute the shallow bottom along the west side of the lagoon are poorly selected, and their sizes

range between fine sand and gravel, while on the eastern margin the sands are predominantly thin and are very well selected (Martins et al. 1989). The lagoon bottom sediments have less than 4% of sand and mainly consist of silt and clayey silt in the

northern half of the lagoon, while the southern half is characterized by silty clay. The mud deposited on the lagoon bottom occurs at depths below the base level for wave erosion, which rarely exceeds 4 m deep (Toldo Jr. et al. 2006a, 2006b).

The sediments that enter the coastal lagoon interior originate from the contribution of the Camaquã River and São Gonçalo Channel especially in its southern portion; to a lesser extent, there is an input of marine sediments from the continental shelf through the Rio Grande Bar (Hartmann and Schettini 1991). The rivers that constitute the Camaquã basin flow over the Crystalline Shield (Fig. 1), which is composed of intrusive and metamorphic igneous rocks from the Uruguayan-Southern Brazilian Shield. Those rivers are mostly mature, with reduced erosive activity (according to Villwock et al. 1972).

In addition to these sources, the Southeastern Hydrographic Basin located to the north of the state stands out, which is composed of the Jacuí and Guaíba rivers (Fig. 1). It is the largest basin from the State of Rio Grande do Sul (RS) and the largest sediment source to Patos Lagoon, presenting an average flow of $1483 \text{ m}^3 \text{ s}^{-1}$ (Vaz et al. 2006). This hydrographic network flows through the region composed of the Paleozoic sedimentary and Mesozoic volcanic rocks from the Paraná Basin (Tomazelli et al. 2000), located in the central and northern portions of RS, respectively (Fig. 1).

Indirect estimates of the solid suspended discharge from the Guaíba River, performed by Baisch (1994) and Rigon (2009), suggest an average annual contribution of 1×10^6 and $4 \times 10^6 \text{ t year}^{-1}$ of suspended sediments, respectively. Andrade Neto et al. (2012) estimated the average annual discharge of suspended solids and found it was equivalent to $1,100,000 \text{ t year}^{-1}$.

Material and methods

Four geological survey cores were collected in Patos Lagoon at sites that were representative of the sedimentary dynamics (Fig. 1), so that core PT02—located to the north of the lagoon—is in an area with direct river contribution from the Guaíba River; core PT04 is in an intermediate portion regarding river discharge sources; and cores PT07 and PT08 are located in the south, in the vicinity of the Camaquã River and São Gonçalo Channel, which are main tributaries that flow into the southern sector of Patos Lagoon (Fig. 1).

The sedimentation rate was obtained by gamma spectrometry performed at the Oceanographic Institute from the University of São Paulo (USP). A coaxial hyper-pure germanium detector from the GEM series was used, EG&G ORTEC (25190P) model, with a resolution of 1.9 keV at the ^{60}Co photopeak of 1332.5 keV.

The sedimentation rates were determined by ^{210}Pb activity ($T_{1/2} = 22.26$ years), a natural radionuclide that belongs to the

radioactive decay series of ^{238}U and ^{137}Cs ($T_{1/2} = 30.17$ years), which is an artificial radionuclide produced by the ^{235}U fission.

^{210}Pb is incorporated into the sediment by the ^{226}Ra natural decay and remains in radioactive equilibrium with it, the so-called supported ^{210}Pb (in equilibrium). It is analyzed by the gamma spectrometry of ^{214}Bi , with a photo peak of 609 keV.

In many environments, the element ^{210}Pb is in excess when compared with its precursor ^{226}Ra . This happens due to the natural cycle of the ^{222}Rn emanation through the soil and rocks, and due to its subsequent decay to ^{210}Pb . When absorbed by aerosols, ^{210}Pb returns to the terrestrial and aquatic environments through its fallout. This ^{210}Pb input source in the sediment is in excess relative to ^{226}Ra , which is denominated as “unsupported ^{210}Pb ”, and its concentration decreases with depth in sedimentary deposits. The relationship between these elements provides the basis for the sedimentation rate determination. The ^{210}Pb (unsupported) activity is determined by directly counting its photo peak at 46.5 keV in gamma spectrometry.

The CRS model (Appleby 2001; Lubis 2006) was used for the ^{210}Pb age and sedimentation rate determinations. This model is applied by assuming that the content of ^{210}Pb incorporated in sediments is constant over time, regardless of the changes in the amount of sedimentary input and variations in the ^{210}Pb activity. The model thus makes it possible to estimate interannual differences in sedimentation rates.

The presence of ^{137}Cs in the environment occurs due to the explosion of atomic bombs or accidents in thermonuclear power plants. The remaining radioactive material was incorporated into the air masses from the troposphere (Kathren 1984). In the Southern Hemisphere, the peak of nuclear tests took place between the end of the Second World War and the Cold War, beginning in 1945 and having its peak in 1963 (UNSCEAR, 2000).

These events were the dominant input source of this radionuclide across the troposphere, which corresponds to the process called “fallout.” The calculation of sedimentation rates by the analysis of ^{137}Cs in sedimentary columns is obtained considering the existence of a peak in ^{137}Cs (global fallout in 1963), which is used as a reference for the calculation of the integrated sedimentation rate of the column.

Results

The levels of ^{210}Pb (total), ^{226}Ra , and ^{137}Cs acquired in Patos Lagoon were used to determine the sedimentation rates at each studied site, and the results are shown in Table 1.

The ^{210}Pb results from core PT02 showed that this site had the greatest sediment deposition when compared with the other analyzed sites, presenting an average sedimentation rate of

Table 1 Sampling and gamma spectrometry data from cores PT02, PT04, PT07, and PT08 in Patos Lagoon. *S.R. sedimentation rate

Core	Length (m)	Water depth (m)	*S.R. ²¹⁰ Pb (mm year ⁻¹)	Mass accumulation (g cm ⁻² year ⁻¹)	S.R. ¹³⁷ Cs (mm year ⁻¹)
PT 02	1.35	7.22	7 ± 1.2	0.62 ± 0.11	5.4 ± 1
PT 04	3.79	5.69	5.5 ± 1	0.55 ± 0.1	5 ± 0.1
PT 07	3.55	6.44	4.4 ± 0.8	0.4 ± 0.07	3.8 ± 1
PT 08	0.71	5.12	4.8 ± 0.5	0.65 ± 0.09	5.4 ± 0.1

7 ± 1.2 mm year⁻¹ and a mass accumulation index of 0.62 ± 0.11 g cm⁻² year⁻¹.

¹³⁷Cs presented a maximum activity of 5.48 ± 0.13 Bq kg⁻¹ between 20 and 28 cm deep (Fig. 2), the mean depth interval that corresponded to 1963, thus providing a mean sedimentation rate of the order of 5.4 ± 1 mm year⁻¹. The observed maximum ¹³⁷Cs activity over a range of 8 cm in the sedimentary column may be related to its vertical migration, which is usually associated with the diffusive transport through pore water or pore-water vertical convection in sediments (Ajayi and Raji 2010; Ligeró et al. 2005).

Core PT04 had a ²¹⁰Pb mean sedimentation rate of 5.5 ± 1 mm year⁻¹ and a mass accumulation index of 0.55 ± 0.1 g cm⁻² year⁻¹. ¹³⁷Cs showed a maximum activity of 5.87 ± 0.14 Bq kg⁻¹ at 26 cm deep, resulting in a rate of 5 ± 0.1 mm year⁻¹, therefore showing an excellent correlation between the sedimentation rates computed from the ²¹⁰Pb and ¹³⁷Cs data.

The ²¹⁰Pb results from core PT07 indicate that this site had the lowest sedimentation rate among all assessed drilling sites, presenting a mean rate of 4.4 ± 0.8 mm year⁻¹ and a mass

accumulation index of 0.4 ± 0.07 g cm⁻² year⁻¹. The highest ¹³⁷Cs activity—of the order of 5.64 ± 0.13 Bq kg⁻¹—occurred in the depth range from 20 to 28 cm (Fig. 3), suggesting a mean sedimentation rate of 3.8 ± 0.1 mm year⁻¹ and a ¹³⁷Cs vertical migration very similar to what was observed in core PT02.

Core PT08 represented the southernmost site of Patos Lagoon, where the mean sedimentation rate (according to the ²¹⁰Pb method) and the mass accumulation index were equal to 4.8 ± 0.5 mm year⁻¹ and 0.65 ± 0.09 g cm⁻² year⁻¹, respectively. Similarly to what was observed in the other cores, the PT08 maximum ¹³⁷Cs activity (Fig. 3) occurred at 20 cm deep, which corresponded to 3.92 ± 0.27 Bq kg⁻¹ and resulted in a sedimentation rate of 5.4 ± 0.1 mm year⁻¹.

Discussions

The sedimentation rates obtained with the combined use of the radioisotopes ¹³⁷Cs and ²¹⁰Pb showed a good agreement (Table 1). However, at the PT08 site, the sediment

Fig. 2 ¹³⁷Cs activity in cores PT02 and PT04

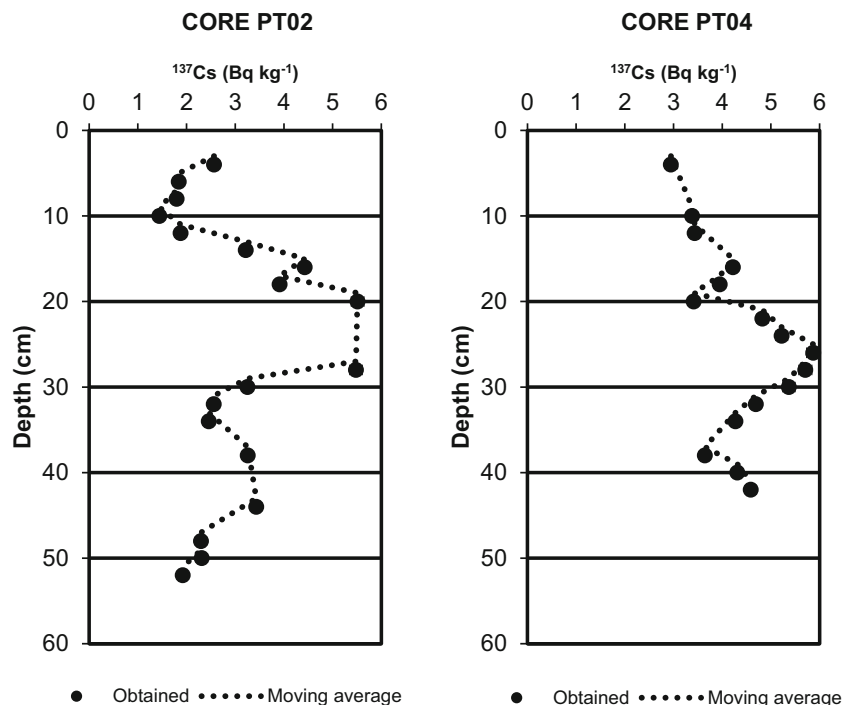
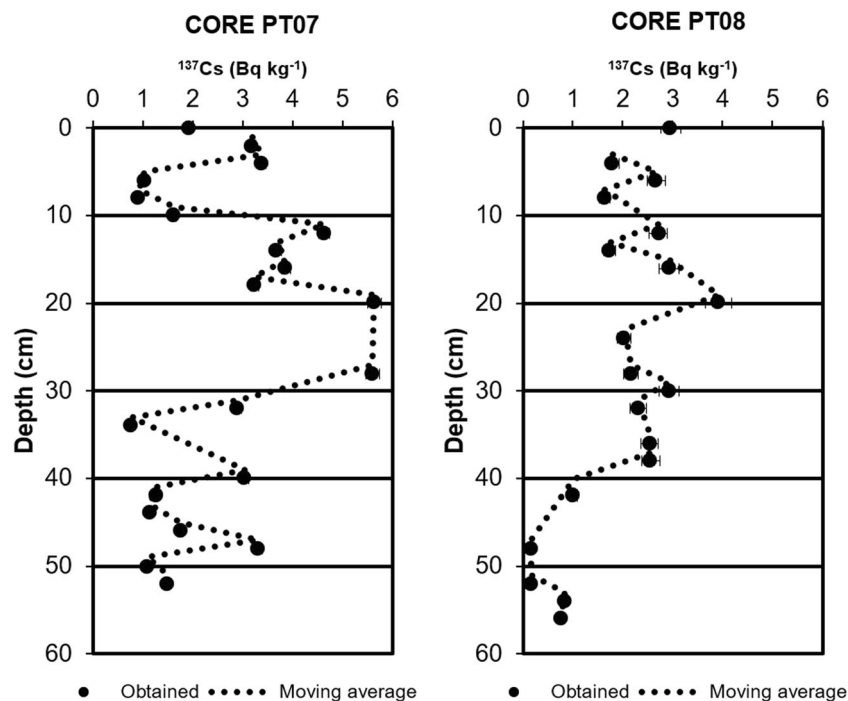


Fig. 3 ^{137}Cs activity in cores PT07 and PT08



accumulation rate determined from ^{137}Cs —even though similar to the other sites analyzed through this method—was almost 15% higher than the rate determined from ^{210}Pb . A possible explanation for this result is the loss of surface and ^{210}Pb -associated sediments through the natural erosion induced by bottom remobilization before 1963, the year corresponding to the maximum ^{137}Cs fallout. On the other hand, core PT02 presented a ^{210}Pb sedimentation rate about 30% higher than the one obtained from ^{137}Cs , but within the presented margin of error for both radionuclides. This core probably expresses the condition of ^{137}Cs vertical migration (Fig. 2), consequently reducing the rates measured through this method.

Furthermore, the ^{210}Pb data indicated that the mean sedimentation rate of $7 \pm 1.2 \text{ mm year}^{-1}$ (obtained from core PT02) was the highest among all analyzed sites, explained by the proximity of this drilling site to the Guaíba River, the main tributary of Patos Lagoon. According to Vaz et al. (2006), the Guaíba River basin contributes around 60% to the mean annual discharge of Patos Lagoon. In addition to it, the larger depth of this area reduces the wave-driven turbulence on the bottom, favoring sedimentation (Table 1).

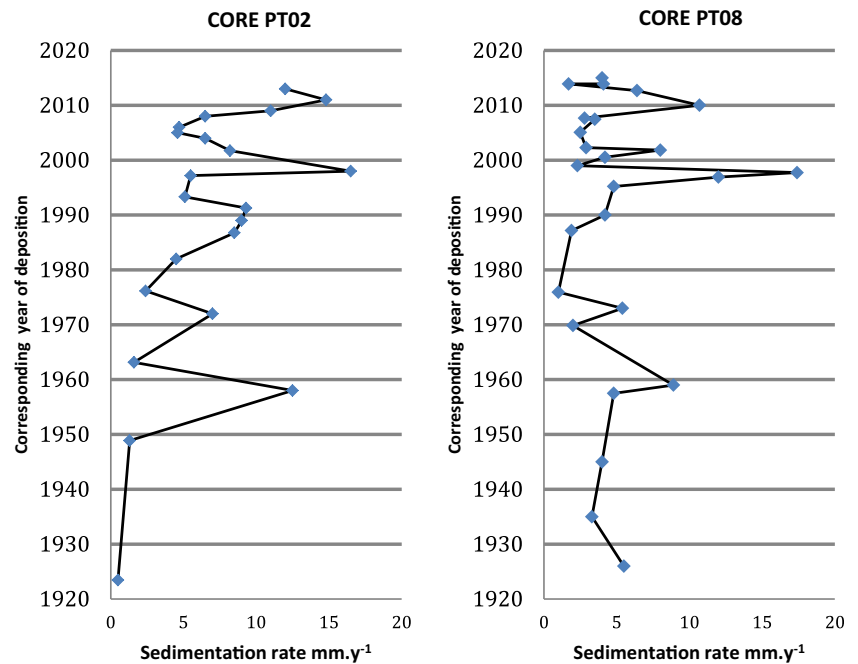
In a study developed by Tavora et al. (2019), it was found that the suspended solid concentrations were higher in the northern part of the lagoon, and decreased towards the south. When comparing the main drivers of the lagoon circulation (wind and the Guaíba River discharge), the maximum sediment inputs occurred after peaks of river discharge combined with strong northeasterly (NE) winds, suggesting that the freshwater inflow and the wind in certain directions are the main sediment transport mechanisms in Patos Lagoon.

On the other hand, core PT04 presented an average sedimentation rate of $5.1 \pm 1 \text{ mm year}^{-1}$, which is lower than what was found in the northern portion. This depositional behavior may be mainly explained by its larger distance from the Guaíba River mouth in addition to the absence of direct drainage at this lagoon site.

The analysis of core PT07, although situated in a site influenced by the Camaquã River, showed that this lagoon's location had the lowest deposition rate among all studied sites, presenting an average rate of 4.4 mm year^{-1} (Fig. 1). An explanation for this finding lies in the different hydrodynamic characteristics between the PT04 site and the northern portion of the lagoon, which is directly influenced by the Jacuí-Guaíba River basin. The Camaquã River presents an average discharge of $307 \text{ m}^3 \text{ s}^{-1}$, considerably lower than the Guaíba River average flow, which corresponds to $1493 \text{ m}^3 \text{ s}^{-1}$ (Torres 2000). Moreover, the Camaquã River basin has less agricultural activity, thus reducing the production and deposition of sediments that are unloaded into the lagoon bottom.

The southernmost portion of Patos Lagoon was analyzed through core PT08, which had a mean sedimentation rate of $4.8 \pm 0.5 \text{ mm year}^{-1}$, a slightly higher rate than the one found for core PT07, also located in the south. This is probably due to the convergence of the Camaquã River remaining sediments, which in case did not settle near PT07 and followed the lagoon's flow towards its mouth, thus later depositing in the PT08 region. In addition to this possibility, the combined effect of the São Gonçalo Channel sediment input and higher flocculation (induced by the saline intrusion near the estuary) favors the sedimentation to the south.

Fig. 4 Variation of the sedimentation rates from the last decades obtained from the application of the ^{210}Pb method (CRS model) on cores PT02 (near the Guaíba River mouth) and PT08 (near the mouths of the Camaquã River and São Gonçalo Channel)



Findings related to sedimentation rates in other studies carried out in coastal lagoons in southern Brazil show similarities to the rates found in Patos Lagoon. In general, they indicate that the sediment deposition nature in these water bodies presents an order of magnitude of a few millimeters per year.

Dillenburg and Burnett (1995) obtained rates between 4.2 and 4.4 mm year^{-1} for the Tramandaí Lagoon, located near Patos Lagoon. Ivanoff et al. (2017), in a study carried out in the Itapeva Lagoon, which is connected to the Tramandaí Lagoon by fluvial channels, found sedimentation rates ranging from 2.4 to 3.2 mm year^{-1} . Both mentioned studies used the ^{210}Pb method.

The sedimentation rates calculated by Martins et al. (1989) using ^{210}Pb had values between 3.5 and 8.3 mm year^{-1} for the Patos Lagoon. In a more recent study conducted by Niencheski et al. (2014) in the Patos Lagoon estuary, a local sedimentation rate varying from 3.0 to 3.4 mm year^{-1} was estimated, which is close to the rates presented in this study.

Furthermore, the chronology derived from the application of the CRS model (Appleby 2001; Lubis 2006) to the ^{210}Pb data from this study allowed the detection of events with exceptionally high deposition rates over the last decades, mainly found in the northern and southern sectors (Figs. 4 and 7).

Data from cores PT02—located near the Guaíba River mouth—and PT08—located in an area with influence from the São Gonçalo Channel and Camaquã River (Fig. 1)—show that the sedimentation rates at these sites were highly variable (Fig. 4). This variability suggests a combined effect of the increased sediment supply from rivers during periods of higher precipitation, and the associated water level increase, consequently causing an enlargement of the internal accommodation space. This situation alternately takes place with

periods of lower precipitation and river discharge, thus causing a water level decrease that, associated with greater wave-driven turbulence on the bottom, would induce a reduction in the sedimentation rates.

Moreover, the analysis of Figs. 4 and 5 revealed that, in cores PT02 and PT08, which were located in areas directly influenced by river discharges, the time intervals of 1957–1958, 1997–

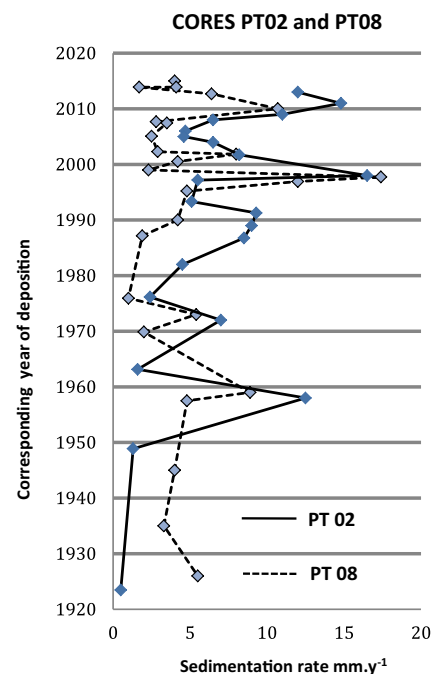


Fig. 5 Comparison between the sedimentation rates from the last decades obtained from the application of the ^{210}Pb method on cores PT02 and PT08, which were located near river mouths

1998, and 2009–2010 had significantly higher sedimentation rates in comparison to the their corresponding site average value.

In percentage terms, it can be observed between 1957 and 1958 that the rates reached $12.5 \text{ mm year}^{-1}$ in core PT02 and 8.9 mm year^{-1} in PT08, representing an increase of 78 and 85% in the average rates, respectively. Between 1997 and 1998, an even greater increase was observed, with sedimentation values jumping to 16.5 and $17.4 \text{ mm year}^{-1}$ in cores PT02 and PT08, respectively, representing extreme increments of 135 and 262% in the sedimentation rates, respectively. A similar increase between 2009 and 2010 was also evident, although to a lesser extent.

The periods in which the sedimentation rates increased were directly correlated to natural climatic fluctuations since then the southern Brazil was influenced by El Niño (according to the Climate Prediction Center—CPC—from the National Weather Service; NOAA 2017). ENSO events are relatively discrete weather patterns that occur at time intervals from 3 to 7 years. This phenomenon is a result of the warming of the Pacific basin associated with the weakening of the trade

winds. El Niño episodes cause above-average rainfall in southern Brazil (Fig. 6), Uruguay, and northeastern Argentina (Grimm et al. 1998; Philander 1990; Ropelewski and Halpert 1987, 1989).

This phenomenon directly affects the flow of the main rivers from southern Brazil. Other rivers from the south of the continent also experience the influence of ENSO events as confirmed by studies conducted in the Negro and Paraguai rivers (Robertson and Mechoso 1998) as well in the Uruguay River (Krepper et al. 2003). This climatic oscillation is a contributor to the sedimentary load input into the rivers of the southern region, including those that discharge into the Patos Lagoon. In the southern portion of Patos Lagoon near its estuary, Marques et al. (2010) showed a direct relationship between the river discharge and the suspended solid input. The authors used numerical simulations to compare the suspended solid transport towards the Atlantic Ocean during a strong El-Niño event (1998) and a neutral year (1999), thus confirming the increased flow during climate anomalies.

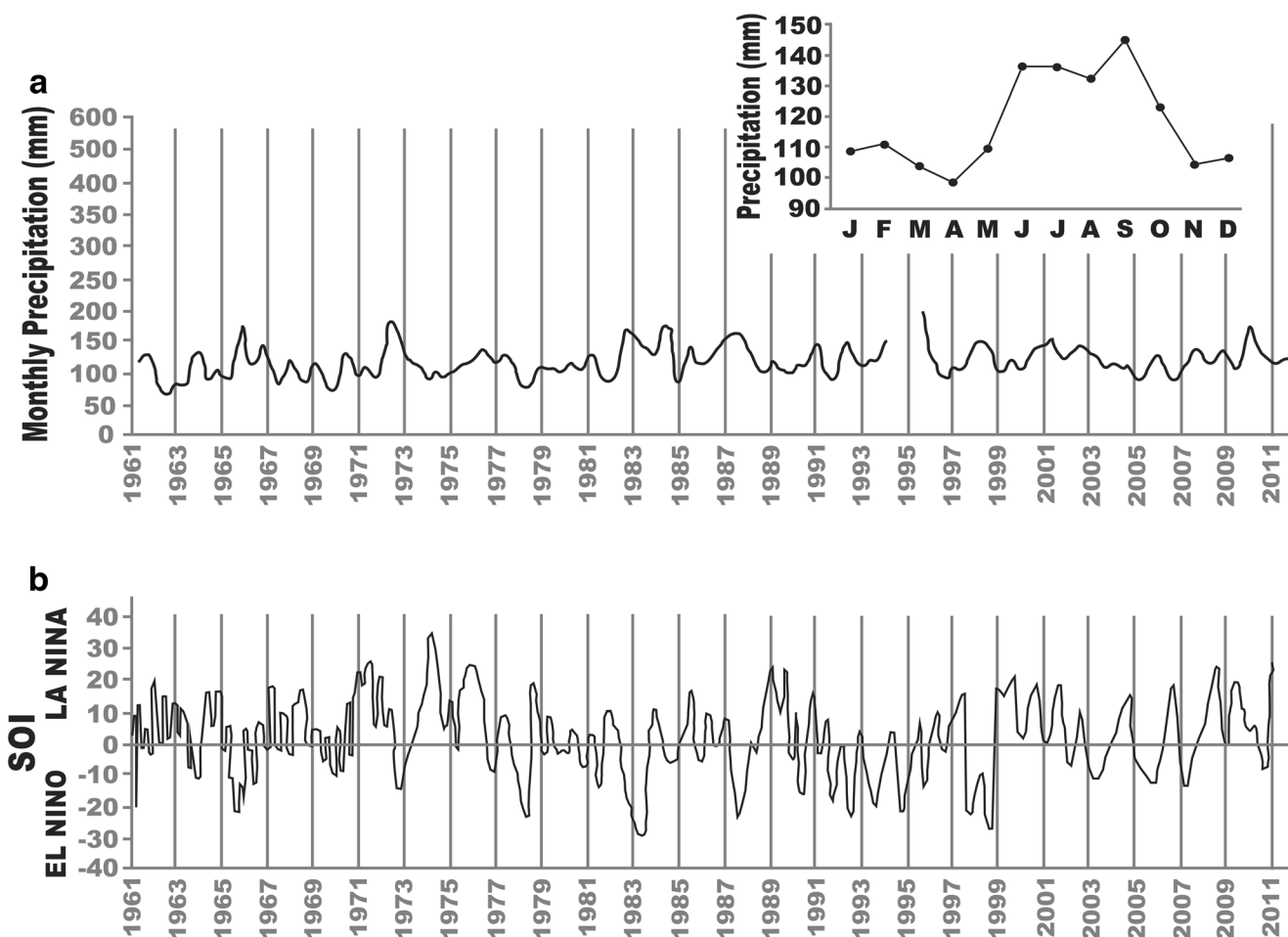
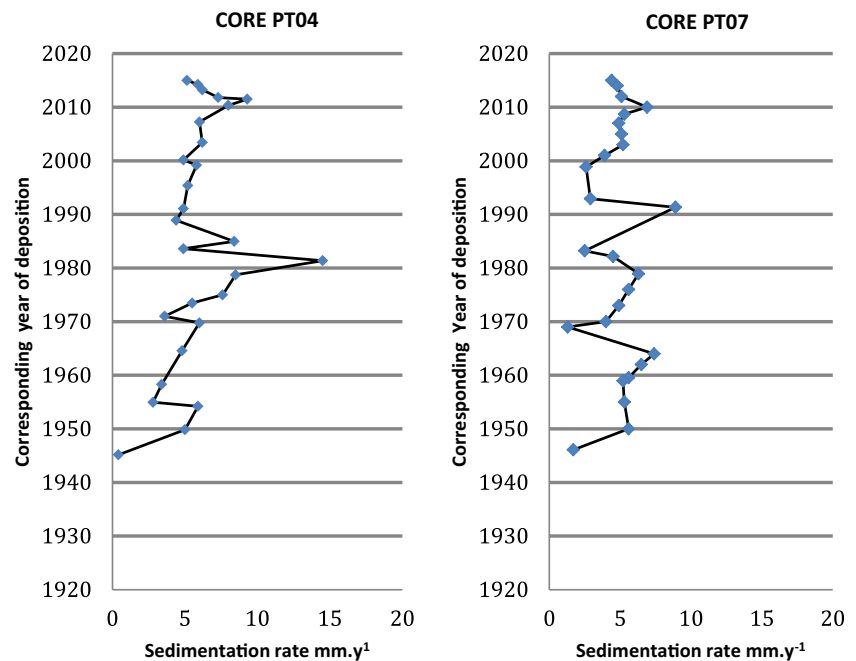


Fig. 6 **a** Time series of the monthly precipitation in the city of Porto Alegre (South of Brazil) for the period between 1961 and 2011. **b** Southern Oscillation Index (SOI) for the same period, demonstrating

the tendency of precipitation increase and decrease during El-Niño (negative SOI) and La-Niña (positive SOI) years, respectively. Modified from Pasquini et al. 2012

Fig. 7 Variation of the sedimentation rates from the last decades obtained from the application of the ^{210}Pb method on cores PT04 and PT07



In order to analyze the influence of extreme events on the transport of sediments to the Patos Lagoon interior, Jung (2017) studied the average sediment export during two significant El-Niño events (1998 and 2002). The results showed an average discharge (considering the main tributaries) of approximately $3900 \text{ m}^3 \text{ year}^{-1}$, which corresponds to 167% of the historical average in relation to the periods without the El-Niño influence. The extreme flows found in an El-Niño condition indicated that the Guaíba River exported near 27 times more suspended sediments at its maximum flows than its average rate. The Camaquã River, on the other hand, increased its export rate during this event by up to 30 times, while the São Gonçalo Channel had an increase of up to six times compared to its average rates.

On the other hand, cores PT04 and PT07 showed less variable sedimentation rates over time, probably due to low river discharge. However, from the end of the 1970s to the beginning of the 1980s, the core PT04 region showed a remarkable increase in sedimentation, reaching a maximum rate of $14.5 \text{ mm year}^{-1}$, which represents an increase of 164% when compared with its average value. During this relatively long period of sedimentary accretion, the area may have been directly influenced by the El-Niño event that took place between 1982 and 1983.

In addition, the rise in the accumulation rates in core PT04 from 1978 to 1984 is consistent with the peaks of higher sedimentation detected for the same period in core PT02, demonstrating the influence of the Guaíba River in this area to some extent, albeit on a smaller scale (Fig. 7).

A similar behavior also occurred in core PT07, where the variability of the deposition peaks showed relatively harmonic fluctuations except in 1991. During this year, southern Brazil experienced again a strong El-Niño event (NOAA 2017), and

thus the sedimentation rate increased in approximately 170%, reaching $11.9 \text{ mm year}^{-1}$. This increase was also found in cores PT02 and PT04.

Additionally, it is important to highlight that the period of maximum precipitation in the southern region of Brazil occurs during the austral winter and spring (Fig. 6), precisely during the periods when the land is being prepared for planting the main agricultural crops in the basins that flow in to Patos Lagoon. As examples, the land preparation for corn and soybean planting is performed between August and September, and from October to December, respectively.

In recent years, an advance of soybean crops over grazing areas has been observed, thus encompassing the drainage basins of the Jacuí, Guaíba, and Camaquã rivers, and the Plateau and Central Depression regions, also reaching the southern portion of the state. It is estimated that, between 2012 and 2013, the soybean planted area has increased over 470,241 ha previously used for cattle grazing (FARSUL 2013). Only considering the cities from the southern region of RS, the increase in the soybean planted area was 48% between 2010 and 2013 (EMATER-RS/ASCAR 2014). In future terms, intensive land use should favor extreme sedimentation events due to its increased exposure. In addition to that, higher precipitation mainly during El-Niño years would contribute to greater sedimentary load flowing into the coastal lagoon.

Conclusions

The use of ^{210}Pb demonstrated that the sedimentation rates along the lagoon bottom were decreasing in a north-to-south

direction. Higher sedimentation rates were found in the northern cores (PT02, 7 mm year⁻¹; PT04, 5.5 mm year⁻¹) relative to the southern positions (PT07, 4.4 mm year⁻¹; PT08, 4.8 mm year⁻¹). These results suggest that most of the sediments transported by the Guaíba River are deposited to the north of Patos Lagoon.

The results obtained from the ¹³⁷Cs data had sedimentation rates very close to those acquired from the ²¹⁰Pb data, thus showing that ¹³⁷Cs is a good independent tracer to validate ²¹⁰Pb sedimentation rates.

The CRS model applied to the ²¹⁰Pb data demonstrated that the El-Niño climatic event was closely linked to periods of higher sedimentary deposition. Cores PT02 and PT08, directly influenced by river discharge, were more sensitive to the sedimentation increase in higher precipitation periods, while the more central positions of the lagoon presented a more stable sedimentation.

The increase in intensive land use by agricultural activity in southern Brazil is a factor that will tend to favor periods of extreme sedimentation due to higher soil exposure during planting periods, contributing to erosive processes.

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