Variability in terrigenous sediment supply offshore of the Rio de la Plata (Uruguay) recording the continental climatic history over the past 1200 years

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Abstract

The continental shelf adjacent to the Río de la Plata (RdlP) exhibits extremely complex hydrographic and ecological characteristics which are of great socio-economic importance. Since the long-term environmental variations related to the atmospheric (wind fields), hydrologic (freshwater plume), and oceanographic (currents and fronts) regimes are little known, the aim of this study is to reconstruct the changes in the terrigenous input into the inner continental shelf during the Late Holocene period (associated with the RdlP sediment discharge) and to unravel the climatic forcing mechanisms behind them. To achieve this, we retrieved a 10-m long sediment core from the RdlP mud depocenter at 57 m water depth (GeoB 13813-4). The radiocarbon age control indicated an extremely high sedimentation rate of 0,8 cm per year, encompassing the past 1200 years (750-2000 AD). We used element ratios (Ti/Ca, Fe/Ca, Ti/Al, Fe/K) as regional proxies for the fluvial input signal, and the variations in relative abundance of salinity-indicative diatom groups (freshwater versus marine-brackish), to assess the variability in terrigenous freshwater and sediment discharges. Ti/Ca, Fe/Ca, Ti/Al, Fe/K and the freshwater diatom group showed the lowest values between 850 and 1300 AD, while the highest values occurred between 1300 and 1850 AD.

The variations in the sedimentary record can be attributed to the Medieval Climatic Anomaly (MCA) and the Little Ice Age (LIA), both of which had a significant impact on rainfall and wind patterns over the region. During the MCA, a northward migration of the Intertropical Convergence Zone (ITCZ), and an associated weakening of the South American Summer Monsoon System (SAMS) and the South Atlantic Convergence Zone (SACZ), could explain the lowest element ratios (indicative of a lower terrigenous input) and a marine-dominated diatom record, both indicative of a reduced RdlP freshwater plume. In contrast during the LIA, the southward migration of the ITCZ, and a strengthening of SAMS and SACZ, may have led to an expansion of the RdlP river plume to the far north, as indicated by higher element ratios and a marked freshwater diatom signal. Furthermore, a possible multi-decadal oscillation probably associated with Atlantic Multidecadal Oscillation (AMO) since 1300 AD, reflects the variability in both the SASM and SACZ systems.

Keywords

Terrigenous sediment supply, element ratios, salinity-indicative diatom groups, historical climatic changes, Intertropical Convergence Zone, South American Summer Monsoon System, South Atlantic Convergence Zone, Río de la Plata, mud depocenter, continental shelf, Uruguay.

1 Introduction

The Río de la Plata (RdlP) estuary is fed by the Paraná and the Uruguay Rivers and drains into the Southwestern Atlantic Ocean (SWAO) forming the second largest estuary system in South America (Bisbal, 1995; Acha et al., 2003). The RdlP is the main source of continental freshwater and sediments entering the SWAO (Piola et al., 2008; Krastel et al., 2011, 2012; Razik et al., 2013; Lantzsch et al., 2014; Nagai et al., 2014). In this sense, the RdlP provides an average annual suspended sediment load of 79.8×10^6 tons yr^{-1} (Depetris et al., 2003). Most of this discharge is directed close to the Uruguayan coast towards the inner continental shelf (Depetris et al., 2003; Gilberto et al., 2004). The RdlP freshwater discharge, leads to a low salinity plume on the inner continental shelf, which can reach northerly areas up to 28°S (Piola et al. 2000). The low-salinity waters on the inner part of the continental shelf extend downwards to a depth of approximately 50 m, while the outer part of the continental shelf (from 50 m to 200 m) is influenced by the Subtropical Confluence, where the warm, salty southward-flowing Brazil Current collides with the cold and less salty northward-flowing Malvinas Current (Piola et al., 2000).

The Paraná River contributes about 73% to the total RdlP freshwater discharge and maximum values are found during austral summer (Depetris and Pasquini, 2007). This precipitation and river discharge pattern is associated with the southward expansion and intensification of the South American Summer Monsoon System (SAMS; Zhou and Lau, 1998; Chiessi et al., 2009). The SAMS is known to be a poleward displacement of the Intertropical Convergence Zone (ITCZ), and it is associated with a wet season that begins in the equatorial Amazon and propagates rapidly eastward and southeastward during austral spring (García and Kayano, 2010). The SAMS is tightly associated with the South Atlantic Convergence Zone (SACZ, Carvalho et al., 2004), which is a main component of the SAMS (Nogués-Paegle et al., 2002; Almeida et al., 2007). The SACZ is an elongated NW-SE band of convective activity that originates in the Amazon Basin, which extends above the northern RdlP drainage basin, and has its southernmost limit in the adjacent SWAO (Carvalho et al., 2004). Thus, the Paraná River discharge is largely determined by the SACZ (Robertson and Mechoso, 2000).

The RdlP is an extremely dynamic system which exhibits complex hydrodynamic features associated with the climatic pattern that affect the wind and oceanographic systems, as well as the river discharge (Piola et al., 2008). As mentioned above, a natural intra-annual variability exists with a higher river discharge during the summer season (Depetris and Pasquini, 2007). Besides, a northerly wind pattern during summer leads to a southward and offshore displacement of the low-salinity RdlP freshwater plume (Guerrero et al., 1997; Möller et al., 2008; Piola et al., 2008). In contrast during the winter season, existed a lower RdlP discharge, but exists a predominant southerly wind pattern (associated with a northward displacement of the Westerlies). This situation forces a northward displacement of the RdlP plume and thus, considerably diminishes the salinity on the southern Brazilian continental shelf (Guerrero et al., 1997; Camilloni, 2005; Möller et al., 2008; Piola et al., 2008).

The regional climatic system also exhibits an inter-annual and inter-decadal variability, associated with environmental changes (expressed mainly in precipitation patterns) related to the El Niño/La Niña Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), respectively (Depetris and Kempe, 1990; Depetris et al., 2003; Depetris and Pasquini, 2007; Garreaud et al., 2009; Barreiro, 2010). PDO is associated with ENSO as both seem to produce similar climatic effects, though their mechanisms are not yet fully understood (Garreaud et al., 2009). In this sense, it has been suggested that during both the warm El Niño and the positive PDO phases, there is an increasing trend in precipitations over the RdlP drainage basin associated with an intensification of the SAMS, which leads to a higher RdlP river discharge, while the opposite trend was observed for the negative phases (Ciotti et al., 1995; Depetris and Pasquini, 2007; Garreaud et al., 2009; Barreiro, 2010; García-Rodríguez et al., 2014). However, Piola et al (2005) reported strong NE winds during El Niño conditions which compensate the effect of the positive precipitation anomalies, and thus prevent an anomalous northeastward displacement of the RdlP plume. In addition, there is evidence that the interannual variability in the RdlP drainage basin has a stronger influence on the Uruguay River discharge, whilst the decadal variability is most pronounced in the Paraná River supply (Robertson and Mechoso, 2000). Furthermore, Chiessi et al. (2009) published evidence that the Atlantic Multidecadal

Oscillation (AMO) influences SAMS intensity on the multidecadal time scales.

Regarding the Late Holocene period, a significant number of studies has described the climatic history of South America over the last 1500 cal yr BP (calibrated thousands of years before present), i.e., for the Medieval Climatic Anomaly (MCA, 800-1300 AD) and the Little Ice Age (LIA, 1400-1800 AD), (Cioccale, 1999; Iriondo, 1999; Piovano et al., 2009; del Puerto et al., 2011; Vuille et al., 2012; del Puerto et al., 2013; Salvatecci et al., 2014). These climatic changes have affected the precipitation pattern over South America with regional differences. For eastern Uruguay, this means a warmer and more humid pulse during the MCA, while in the LIA, a drier and colder climate was recorded (del Puerto et al., 2013). Piovano et al. (2009) have inferred similar climatic conditions for the northeastern region of Argentina. In contrast, the opposite pattern was reported for southern Chile and Argentina, where a dry period occurred during the MCA, and a wetter pulse governed the LIA (Haberzettl et al., 2005). Furthermore, Vuille et al. (2012) inferred similar conditions for southeastern Brazil as Haberzettl et al. (2005).

Nevertheless, little is known about how the natural climatic variability over South America affects sedimentation, salinity and river discharge on the continental shelf in front of the RdlP, during the Late Holocene period (Burone et al., 2012; Perez et al., in press). The aim of this study therefore, is to determine the variations in the terrigenous sediment input into the ocean over the last 1200 cal yr BP. To determine how the continental influence competed with the marine regime, a 10-m long sediment core was taken from a confined mud depocenter on the inner Uruguayan continental shelf (GeoB 13813-4, Fig. 1). The sedimentary succession of this core was analyzed for major chemical elements (Ca, Ti, Al, Fe, and K) and compared with previously published data of the diatom salinity-indicative groups, i.e. freshwater (F) and marine, marine-brackish (M-B), (Perez et al. in press) in order to assess variations in continental influence.

2 Study Area

The study area is located on the Uruguayan inner continental shelf hosting the RdlP mud depocenter (50 m water depth, Fig. 1a, b). This silty clay depocenter (Martins and Urien, 2004; Lantzsch et al., 2014) is the result of regional paleogeographic evolution and is associated with deposits of fluvial origin (Urien and Ewing, 1974). The depocenter built up inside the RdlP paleo-valley which was incised by the Paleo-Paraná River during lower sea levels (Masello and Menafra, 1998; Martins et al., 2003; Lantzsch et al., 2014; Hanebuth et al., in press). The RdlP paleo-valley depression offers an effective protection against the generally strong hydrodynamic conditions on the shelf, thus favoring the deposition and preservation of these muds (Fig. 1b).

3 Materials and Methods

A 1028-cm long sediment core (GeoB 13813-4) was taken from the RdlP mud depocenter (34°44'13" S, 53°33'16" W) during research cruise M76/3a with the German research vessel “Meteor” in July 2009 (Krastel et al., 2012; Fig. 1a). During this expedition, sub-bottom profiling with the shipboard PARASOUND system (4 kHz) showed an elongated depression on the seafloor corresponding to the RdlP paleo-valley filled with a complex pattern of acoustic facies (Fig. 1b, Krastel et al., 2012; Lantzsch et al., 2014).

3.1 Age-depth model and sedimentation rates

Material from bivalve shells collected from six sediment samples, distributed evenly over the core and preserved in life position, were used for radiocarbon dating (^{14}C), (Tab.1). The samples were analyzed using AMS-^{14}C (accelerated mass spectrometry) at the Poznan Radiocarbon Laboratory in Poland. The age depth model was then generated by using the free software Bacon (Blaauw and Christen, 2011, Fig. 2). The raw ^{14}C dates were calibrated using the calibration curve Marine13 (Reimer et al., 2013, cc=2) integrated into this program, and the weighted average ages are expressed in table 1 (Blaauw and Christen, 2011). The standard reservoir age of 405 years was applied during calibration due to a lack of regional data, although intense water mixing in shallow waters might lead to a significantly smaller reservoir age (Reimer et al. 2013).

Bacon software is an approach for developing an age-depth model that uses Bayesian statistics to reconstruct Bayesian accumulation histories for sedimentary deposits. Bacon divides a sediment core into vertical sections (5 cm thick), and estimates the sedimentation rate (years/cm) for each section through millions of Markov Chain Monte Carlo (MCMC) iterations.

3.2 Paleo-environmental proxies

The two methodological approaches combined in this study were chosen according to previous successful applications for inferring continental versus marine influences in the Atlantic Ocean, (Romero et al., 1999; Chiessi et al., 2009; Mahiques et al., 2009; Govin et al., 2012; Burone et al., 2013; Perez et al., in press), as indicated below.

3.2.1 Runoff-indicative element ratios

The relative concentrations (expressed in counts per second, cps) of the major chemical elements used in this study (Ca, Ti, Fe, K, Al) were obtained by an X-ray fluorescent (XRF) sediment core scanner AVAATECH at MARUM, University of Bremen. XRF core scanning is a fast, non-destructive technique, which allows for the detection of a large number of chemical elements (Löwemark et al., 2011). This technique does not measure absolute element concentrations, but relative intensities. As a consequence, the intensities of the elements are influenced by numerous factors such as water content and sediment density, organic matter content, grain size, biogenic contributions, and carbonate dissolution (Weltje and Tjallingii, 2008). For these reasons, it is unwise to use single element intensities, and it is more appropriate to use element ratios to normalize the data (Weltje and Tjallingii, 2008; Francus et al., 2009; Govin et al., 2012). Core GeoB 13813-4 was scanned in 1-cm steps throughout, and the Ti/Ca, Fe/Ca, Fe/K and Ti/Al element ratios were used.

Ti, Fe and Al are elements related to aluminum/silicates, and are associated with clay minerals carried from the continent as weathering products, and through river discharge, they enter into the ocean (Goldberg and Arrhenius, 1958; Jansen et al., 1992; Yarincik et al., 2000). Therefore these elements vary with the terrigenous portion in offshore sediment (Martins et al., 2007; Burone et al., 2013). Most of the K in marine sediments is also associated with terrigenous materials (Goldberg and Arrhenius, 1958), and occurs mainly in fully arid regions where chemical weathering rates are lower (Govin et al., 2009). In contrast, Ca mainly reflects the marine carbonate content in the sediment, and is thus associated with the local marine productivity (Haug et al., 2001; Salazar et al., 2004; Gonzalez-Mora and Sierro, 2007). Al, Ti and K are little affected by biological and redox variations, whilst Fe is sometimes altered by redox processes (Löwrmark et al., 2011; Jansen et al., 1992; Yarincik et al., 2000). Burone et al. (2013) recorded a decreasing seaward gradient in Ti, Fe, Al from surface sediment transect from the inner RdlP off to the shelf. In addition, they observed the opposite trend for Ca.

Numerous studies used major elements in marine sediments to reconstruct climatic history, but the choice of particular element ratios and the interpretation of such proxies vary from site to site (Govin et al., 2012). Ti/Ca and Fe/Ca ratios were widely used to reconstruct the continental versus the marine influence in the SWAO region (Chiessi et al., 2009; Mahiques et al., 2009; Govin et al., 2012; Bender et al., 2013; Burone et al., 2013). On the other hand, Fe/K and Ti/Al ratio was used in South America to reflect the degree of chemical weathering in areas without significant eolian input (Govin et al., 2012), such as the case of the RdlP (Mahowald et al., 2006). As a consequence of the mentioned above, we used element ratios (Ti/Ca, Fe/Ca, Ti/Al, Fe/K) as regional proxies for the fluvial input signal on the inner Uruguayan continental shelf.

3.2.2 Salinity-indicative diatom groups

Samples for diatom analyses were first chemically treated (with the aim of cleaning the material from carbonates, organic matter and clay particles) as explain in Perez et al. (in press). Diatom samples were first treated with $Na_2P_2O_7$ to deflocculate the sediment and eliminate clay particles. The samples were then treated with a 35 % HCl to remove inorganic carbonate material. Finally, the samples were boiled in 30 % H_2O_2 for two hours to eliminate organic matter (Metzeltin and García-Rodríguez, 2003). Between each treatment, samples were rinsed at least four times with distilled water. Permanent sediment slides were mounted using the Entellan® mounting medium. A minimum of 400 valves was counted on each slide with a light microscope at 1250 x magnification. The diatoms were then identified and counted at 10 cm depth intervals throughout the sediment core and in 1 cm steps within the uppermost 100 cm. Diatom species were identified and separated into two groups according to their ecological salinity preference, i.e., in groups indicating freshwater (F) and marine/marine-brackish (M-B) conditions, according to Frenguelli (1941, 1945), Müller-Melchers (1945, 1953, 1959), Hasle and Syversten (1996), Witkowski et al. (2000), Metzeltin and García-Rodriguez (2003), Metzeltin et al. (2005), Hassan et al. 2010, Sar et al. (2010) and other standard diatom literature (Perez et al., in press).

Romero et al. (1999) determined variations in the continental water discharge by using freshwater diatoms (especially from the genus *Aulacoseira*) along a sediment surface transect from the eastern South Atlantic coast to the open ocean. The same approach was also used in this study to evaluate the freshwater influx on the inner continental shelf.

4 Results

4.1 Age-depth model and sedimentation rates

The core's base was dated to 1200 cal yr BP (750 AD), while a sample at 255 cm was dated to 230 cal yr BP (1700 AD, Table 1). The sedimentation rate varied between 0.68 and 1.0 cm yr^{-1}, with a mean sedimentation rate of 0.8 cm yr^{-1}. Minimum values were observed in the top section (i.e., at 200 to 350 cm) and in the bottom section (i.e., at 705 to 967 cm), while the highest values were observed in the middle of the core (at 500 to 705 cm).

4.2 Paleo-environmental proxies

4.2.1 Runoff-indicative element ratios

All the element ratios (Ti/Al, Fe/K, Ti/Ca and Fe/Ca) showed similar profiles (Fig. 3). The lowest values were recorded between 850-1300 AD (coinciding with the MCA), and remained stable during this interval of time. In contrast, high values were recorded from 1300 to 1850 AD (associated with the LIA) and showed a high variability with a number of sharp maxima. In that sense, for the Ti/Al and Fe/K ratios we recorded, a succession of peaks and lows approximately every 100 years (from 1300 to 1500 AD) and every 50 years (1500 AD up to the present), (Fig. 3). Moreover during the last century, all element ratios showed a rapid increase toward the highest measured values, most pronounced over the last 50 years (Fig. 3).

4.2.2 Salinity-indicative diatom groups

Regarding the salinity-indicative diatom groups as shown in Perez et al. (in press), the profile of Group F seems to generally run parallel to those of the four element ratios with lower percentages around 20 % during the MCA times, and higher up to 60 %, rising and more variable values during the LIA period (Fig. 3). An exception is observed for the last 50 yr BP where the percentages declined rapidly towards the former values counted for the MCA time interval. In contrast, the Group M-B ranged from 30 to 80 % generally describing the expected opposite trend compared to the F group (Fig. 3). Over the last 100 yr BP (1900 AD up to the present), an increasing rapid trend coincides with the highest values shown for the element ratios (Fig. 3).

5 Interpretation and Discussion

5.1 Age-depth model and sedimentation rates

The RdlP mud depocenter shows an exceptionally high sedimentation rate (0.8 cm yr^{-1} on average) compared with other records from the southern Brazilian continental shelf (Mahiques et al., 2009; Chiessi et al., 2014). This high sedimentation rate is consequence of the enormous amount of sediment transported by the Paraná and Uruguay Rivers into the RdlP watershed and further onto the Uruguayan shelf (Lantzsch et al., 2014). In addition, an amplification of the sedimentation rate could be a consequence of the fact that the RdlP paleo-valley depression offers protection against strong hydrodynamic conditions on the shelf, favoring the deposition of sediments (Lantzsch et al., 2014; Hanebuth et al., in press). The beginning of sedimentation is possibly associated with the establishment of humidity conditions in the Late Holocene which have resulted in an increasing RdlP River discharge, as well as a significant sedimentation of terrigenous material over the RdlP paleo-valley (Urien et al., 1980; Iriondo, 1999; Mahiques et al., 2009; Lantzsch et al., 2014).

5.2 Paleo-environmental proxy records

The proxy data used in this study are correlated positively with each other (excluding the last century), and reveal the direct influence of the RdlP as a source of terrigenous sediments within the inner Uruguayan continental shelf.

The element ratios Ti/Ca and Fe/ Ca indicates, as do other geochemical and biological proxies (Perez et al., in press), a mixed fluvio-marine signal on the inner Uruguayan continental shelf, spanning over the last 1200 years. Ti and Fe are supplied from the RdlP watershed (Depetris et al., 2003), whilst Ca is an element associated with calcareous organisms such as small mollusks, forams and coccolithophorides in the ocean, and therefore it is related to the marine-biogenic productivity of the continental shelf (Depetris and Pasquini, 2007; Govin et al., 2012; Razik et al., 2013). Thus the variability in these element ratios indicates different degrees of continental influence in the study area during the Late Holocene.

The results of the proxies integral analysis have been linked to general climatic changes that have occurred on a regional to global scale (Fig.3), and allow us to infer three major time intervals, i.e., the MCA, the LIA and the current warm period (Mann et al. 2009), all of which were characterized by changing continental versus marine influences in the study area.

The oldest recorded period, from 800 to 1300 AD, is closely associated with the MCA (reported as a positive temperature anomaly in the northern hemisphere, Bradley et al., 2008; Mann et al., 2009). During this period, a strong and steady influence of marine conditions governed the inner Uruguayan continental shelf (inferred by low values of Ti/Ca and Fe/Ca, and a dominance of the M-B diatom salinity group), probably as a result of a weakened RdlP water and terrigenous sediment discharge. This situation led to a major and more constant sedimentation of marine particulate carbon during the MCA (Perez et al., in press). In addition, the low Fe/K values registered during the MCA would suggest conditions of reduced RdlP river discharge and dry conditions over the drainage basin (Vuille et al., 2012). Climatically drier conditions appear to decrease chemical weathering in the Fe-rich RdlP drainage basin, thus depleting the Fe content in the offshore depocenters in relation to K, which is associated with drier conditions (Depetris et al., 2003; Depetris and Pasquini et al., 2007).

Our findings, combined with those reported in other studies, suggest that a northward displacement of the ITCZ and a weakened SAMS could have taken place during the MCA (Bird et al., 2011a; Bird et al., 2011b; Vuille et al., 2012; Apaéstegui et al., 2014; Salvatecci et al., 2014). Though the continental SAMS exhibits spatial-temporal characteristics that differ from the ITCZ, the latitudinal position of the ITCZ is closely related to changes in the SAMS intensity, and both climatic elements also respond to temperature anomalies in the northern hemisphere (Stríkis et al., 2011; Vuille et al., 2012). In this sense, positive/negative northern hemisphere temperature anomalies are linked to the north/south directional migration of the ITCZ thus diminishing/increasing SAMS activity (Broccoli et al., 2006; Bird et al., 2011b; Stríkis et al., 2011; Vuille et al., 2012). Hence, the positive temperature anomalies in the northern hemisphere during the MCA (Mann et al., 2009; probably associated with a positive phase of the AMO), probably led to reduced SAMS and SACZ intensity, in addition to a northward displacement of the ITCZ (Chiessi et al., 2009; Stríkis et al., 2011; Vuille et al., 2012). Such atmospheric conditions during the MCA led to a significant decrease in rainfall over the RdlP watershed (mainly in the catchment area of its main tributary, the Paraná River;

Robertson and Mechoso, 2000). As a consequence of this, we inferred a reduction in both freshwater and sediment input, in conjunction with an increase in salinity (Perez et al., in press) on the Uruguayan continental shelf. The decrease in SACZ activity during the MCA could also help explain the more humid conditions inferred for Uruguay during this episode (del Puerto et al., 2013). This is associated with an increase in precipitation over the Uruguay River drainage basins due to a reduced SACZ intensity as discuss below (Robertson and Mechoso, 2000).

The following period, from 1300 to 1850 AD, coincided with the LIA as reported for the northern hemisphere (Bradley et al., 2003; Mann et al., 2009). This period is characterized by higher values of Ti/Al, Fe/K, Ti/Ca and Fe/Ca than those recorded during the preceding period. Therefore, we recorded a higher content of terrigenous material rich in Ti and Fe from the RdlP watershed (Depetris et al., 2003; Depetris and Pasquini, 2007) which is associated with a higher river discharge during the LIA (Fig. 4). Furthermore, a dominance of F diatoms (Fig. 3) was detected. The F diatom group was mainly dominated by *Aulacoseira* spp., especially *A. granulata* (Perez et al., in press), which is the most common diatom genus from the Paraná River and the inner RdlP (Gomez and Bauer, 2002; Licursi et al., 2006; Devercelli et al., 2014). Moreover, Massaferro et al. (2014) observed that the F diatom group recorded in the uppermost 55 cm of the sediment core GeoB 13813-4 was associated with the positive anomalies of the Paraná River discharges. Thus, all the proxies indicate wetter conditions over the RdlP drainage basin, and consequently, a major freshwater supply from the RdlP to the inner Uruguayan shelf during the LIA. Accordingly, we observed the highest rates of terrigenous deposition during this episode.

The LIA, characterized by cold conditions over the northern hemisphere, was then related to a southward displacement of the ITCZ and a strengthening of SAMS and SACZ (Bird et al., 2011b; Vuille et al., 2012). This leads to both a reduction in rainfall rates over northern South America, Central America and Mexico (Haug et al., 2001; Vazques-Castro et al., 2008), and elevated rainfall rates in the Andes (Sifeddine et al., 2008; Bird et al., 2011a; Bird et al., 2011b; Vuille et al., 2012; Apaéstegui et al., 2014; Salvatecci et al., 2014), and over SESA (Meyer and Wagner, 2009; Vuille et al., 2012). The intensification and northward displacement of the Southern Westerlies during the LIA was also registered (Moy et al., 2009; Koffman et al., 2014). This, in conjunction with a higher river discharge, would have also caused an anomalous northward shift of the RdlP river plume. Such atmospheric conditions during the LIA have led to a significant increase in rainfall over the RdlP watershed. Therefore, the outcome was a higher influence of the RdlP river plume within the inner Uruguayan continental shelf as recorded in this study.

The succession of maximum and minimum peaks in the element ratios from 1300 AD to present (every 50 to 100 years), suggests an influence of the AMO on RdlP river discharge related to changes in SAMS and SACZ intensity (Chiessi et al., 2009; Stríkis et al., 2011). The AMO significantly affects the SAMS at multi-decadal time scales, leading to a reduced SAMS intensity when the AMO is in its positive phase, and the ITCZ retreats northward, leading to a decrease in RdlP river discharge (Chiessi et al., 2009; Strikis et al., 2011; Bird et al., 2011b). In addition, Chiessi et al. (2009) proposed that sea surface temperature and atmospheric circulation anomalies triggered by the AMO would control the variability in SAMS and SACZ intensity.

An increase in SACZ intensity during the LIA and its decrease during the MCA, inferred in this study, explain the contrasting spatial/temporal climatic conditions recorded in the two regions in the RdlP drainage basin (Vuille et al., 2012; del Puerto et al., 2013). SACZ intensity is associated with increased river runoff in the northern region of the RdlP catchment area (Paraná River) and a decreased runoff in the southern area (Uruguay River; Robertson and Mechoso, 2000). The north/south river runoff contrast, in response to an intensified/weakened SACZ appear to transport less/more moisture over the Uruguay River basin, thus leading to an increase/decrease in precipitation during MCA/LIA over Uruguay (del Puerto et al., 2013).

Finally, the latest period started around 1850 AD, and is characterized by a sharp global increase in temperature due to significant human impact (Crutzen, 2006; Halpern et al., 2008; Hoegh-Guldberg and Bruno, 2010; Mauelshagen, 2014). Our sediment record for the last century indicates a high river discharge as the highest element ratios were recorded, whilst the diatom record shows a dominance of the M-B species, typical for marine-estuarine conditions. We make the assumption that such a unique incongruence, compared with a optimal positive correlation for the preceding time intervals, is not only a consequence of the regional anthropogenic impact (Depetris and Pasquini, 2007; Bonachea et al., 2010, García-Rodríguez et al., 2010), as already reported by Perez et al., (in press), but it is also related to natural changes associated with an increasing Paraná river runoff after 1970 (Marrero et al., 2015).

6 Conclusions

The observed changes in the presented proxy records indicate variations in both the continental runoff and the marine influence, related to regional climatic variability. Therefore, we put forward the suggestion that global atmospheric changes (latitudinal shifts of the ITCZ, related to changes in SAMS and SACZ intensity) have made an impact on the hydrodynamics and consequently, on the local sedimentation regime, on the inner Uruguayan continental shelf over the past 1200 cal yr BP (750-2000 AD).

During the MCA (800-1300 AD) a northward shift of the ITCZ and a reduction in SAMS and SACZ activities would have caused a decrease in the rainfall rate over the RdlP drainage basin, resulting in more estuarine-marine conditions predominating over a freshwater plume signal. During the LIA (1400-1800 AD) in contrast, a southward shift of the ITCZ and a strengthening in SAMS and SACZ activities led to an increased precipitation over the RdlP drainage basin, reflected by stronger terrigenous influences in terms of freshwater supply on the inner Uruguayan shelf. Furthermore, a possible multi-decadal oscillation probably associated with AMO since 1300 AD, reflects the variability in both the SASM and SACZ systems.

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Table 1. Radiocarbon dates as obtained from the Bacon modeling.

Lab # (Poz-)	Depth in core (cm)	Raw ^{14}C age (yr BP)	Bacon weighted average age (cal yr BP)	Bacon weighted average age (cal yr AD)	Sedimentation rate (cm yr^{-1})
35198	255	640± 30	230	1688	0.72
47935	305	775± 35	371	1494	0.68
42428	447	1000± 40	552	1293	0.78
35199	560	1090± 30	665	1167	1.00
47937	705	1220± 40	830	994	0.88
42429	964	1600± 30	1197	753	0.70

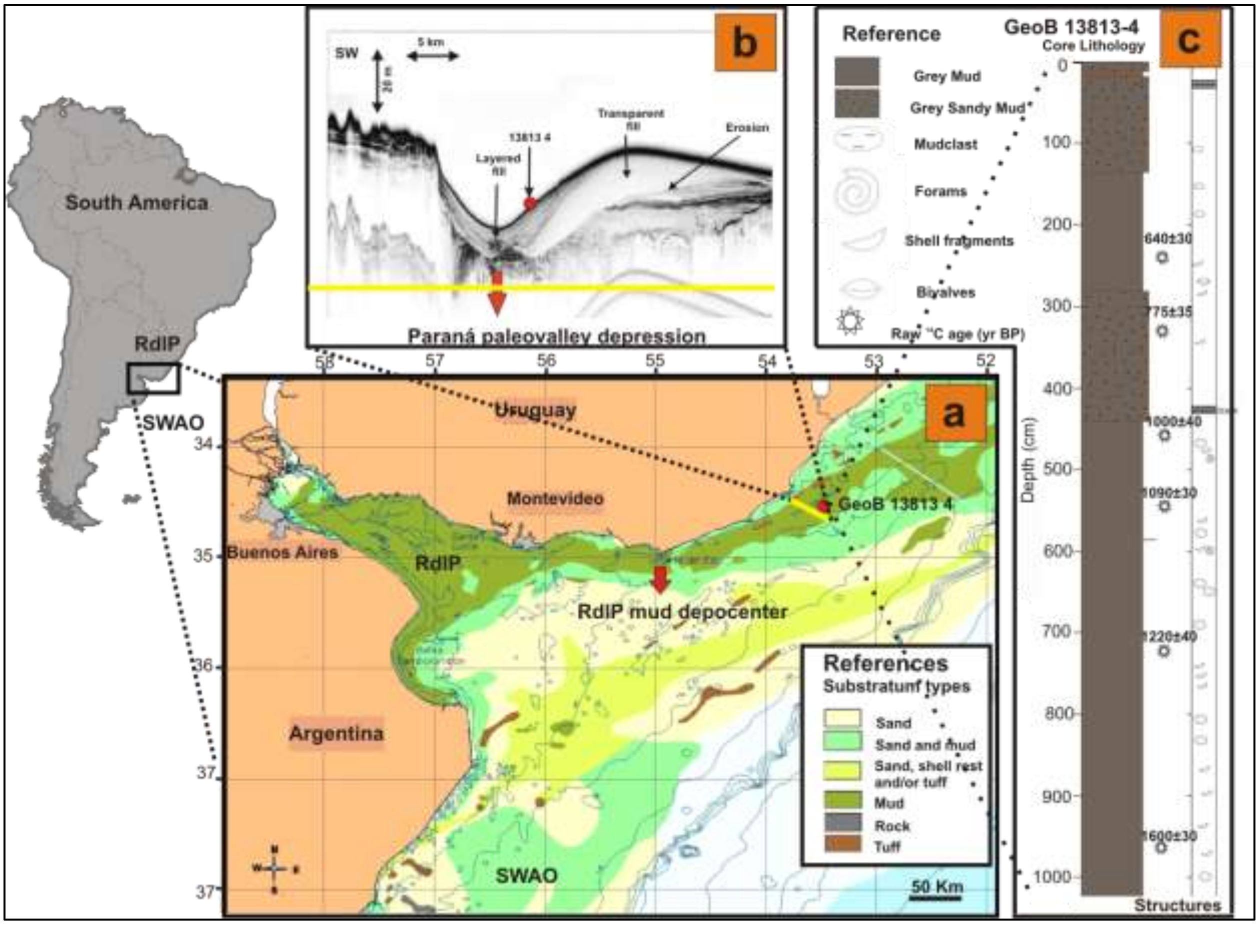

Fig.1. (a) Study area: The red circle indicates the location of Core GeoB 13813-4 retrieved from the inner-shelf mud depocenter off the Uruguayan coast (modified from Freplata, 2004). **(b)** Rio de la Plata (RdlP) mud depocenter (PARASOUND sub-bottom profile), which represents the RdlP paleo-valley and its sedimentary multi-story filling succession. (**c)** GeoB 13813-4 core lithology. (1b and 1c modified from Krastel et al., 2012 and Lantzsch et al., 2014). Stars on the right of the sediment core indicate 14C-dated intervals.

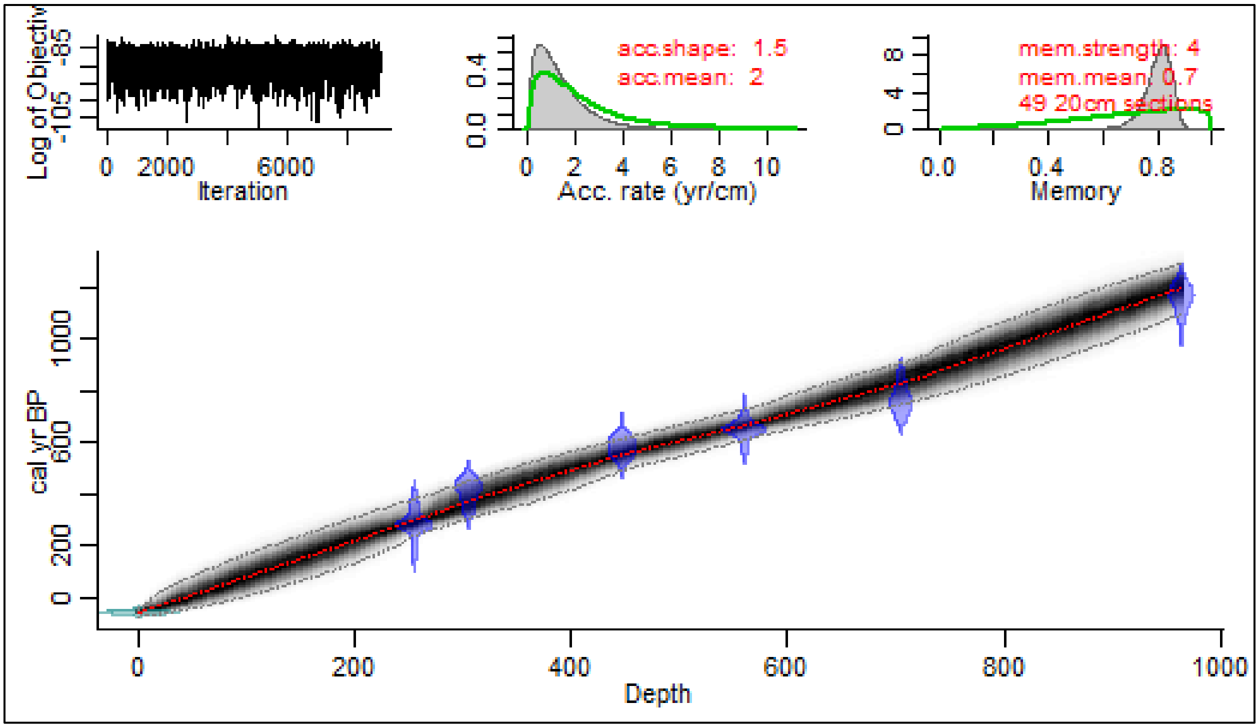

Fig. 2. The age-depth model for core GeoB 13813-4 using the program Bacon. Upper panels depict the Markov Chain Monte Carlo (MCMC) iterations (left), the prior (green curves) and posterior (grey histograms) distributions for the sedimentation rate (middle panel) and memory (right panel). The bottom panel shows the calibrated ^{14}C dates (transparent blue), extraction year of the core (-59 yr BP, 2009 AD, transparent blue light) and the age-depth model (grey stippled lines indicate the 95 % confidence intervals; the red curve shows the 'best' fit based on the weighted mean age for each depth).

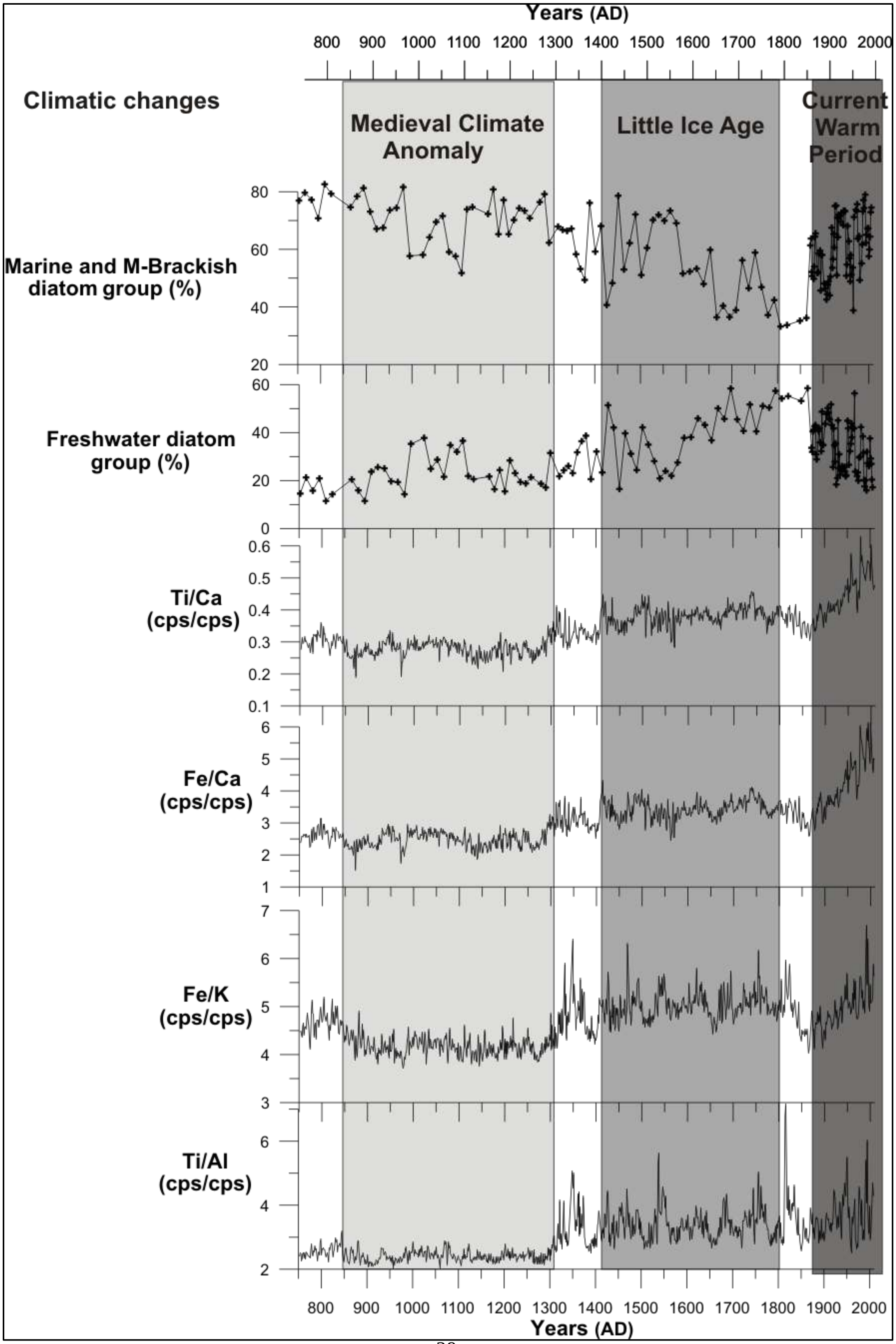
Years (AD)
800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000
Climatic changes
Medieval Climate Anomaly
Little Ice Age
Current Warm Period
Marine and M-Brackish diatom group (%)
80
60
40
20
Freshwater diatom group (%)
60
40
20
0
Ti/Ca (cps/cps)
0.6
0.5
0.4
0.3
0.2
0.1
Fe/Ca (cps/cps)
6
5
4
3
2
1
Fe/K (cps/cps)
7
6
5
4
3
Ti/Al (cps/cps)
6
4
2
800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000
Years (AD)

Fig. 3. Centennial variation of Ti/Al, Fe/K, Ti/Ca, Fe/Ca ratios, and the freshwater and marine, marine-brackish salinity-indicative diatom groups from the sediment core GeoB 13813-4 (from bottom to top, respectively), during the last 1200 yr BP (750-2000 cal yr AD). The major climatic changes during this period of time were the Medieval Climatic Anomaly and the Little Ice Age.