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Independent time markers validate ^{210}Pb chronologies for two shallow Argentine lakes in Southern Pampas

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ABSTRACT

We report here the results of detailed ^{210}Pb analysis from two lake sediment cores collected from Lagunas Encadenadas del Oeste (LEO), located in the southern Argentinean Pampas (37°S, 62°W). Non-exponential and non-monotonic $^{210}Pb_{uns}$ depth-profiles in the sedimentary record of these shallow lacustrine systems indicate the interaction of complex processes behind radionuclide fluxes and lake sedimentation. The chronologies and sediment accumulation rates (SAR) for the lake sediment sequences were modeled using different ^{210}Pb-based mathematical models. Since modeled ^{210}Pb ages must be validated against independent stratigraphic markers of known age, two chrono-stratigraphic markers were selected to control the upper and lowermost parts of the ^{210}Pb dated sediments. The younger stratigraphic marker of AD 1980 ± 2 corresponds to an uppermost organic carbon-rich mud accumulated by 1977–78 matching the most noticeable lake highstand occurred during the 20th century, registered on instrumental and paleolimnological records across the Pampean Plains. The oldest stratigraphic marker corresponds to AD 1878 ± 10 matching with a high lake productivity and wet phase related to anomalously intense rainfall and flooding events in southeastern South America for AD 1877–1878. When comparing the resulting ages to the stratigraphic markers, our results show that CRS-model (constant rate of supply) performs better than the other models. Thus, these independent chronostratigraphic markers used along the sedimentary records were critical to validate ^{210}Pb-derived ages and therefore to select the most appropriate model to establish the chronological framework of the recent sediments of the LEO system. The CRS-model appears to be an adequate technique for deriving ages and SAR in the LEO sedimentary record and other Pampean lacustrine systems under strong hydrological variability.

1. Introduction

High-precision dating and accurate chronological models are essential to interpret the record of Late Quaternary environmental changes. Particularly, the success in performing consistent reconstructions based on lake sediments primarily depends upon factors such as the development of reliable age models in order to calibrate the recent multi-proxy record against instrumental data (Jones and Mann, 2004; Moberg et al., 2005; Jones et al., 2009; von Gunten et al., 2012). ^{210}Pb radiochronology is a widely-used technique for dating lake sediments spanning the past 100–150 years (Goldberg, 1963; Krishnaswamy et al., 1971; Robbins, 1978; Appleby, 2001, 2008). ^{210}Pb occurs naturally in the atmosphere from the decay of ^{222}Rn (Goldberg, 1963), where it settles out as dry fallout or is washed out during rainfall events (wet deposition), which constitutes the main source of ^{210}Pb into surface waters

Abbreviations: LEO, Lagunas Encadenadas del Oeste (LEO); CRS, Constant Rate of Supply; CIC, Constant Initial Concentration; CFCS, Constant Flux Constant Sedimentation Rate; SIT, Sediment Isotope Tomography; SAR, Sediment accumulation rates; BASAL-SAR, Basal sediment accumulation rates; SPR, Southwestern of the Pampas Region; SAMS, South American Monsoon-like System; LLJ, Low-Level Jet; TOC, Total organic carbon; ARPI, Annual Regional Precipitation Index.

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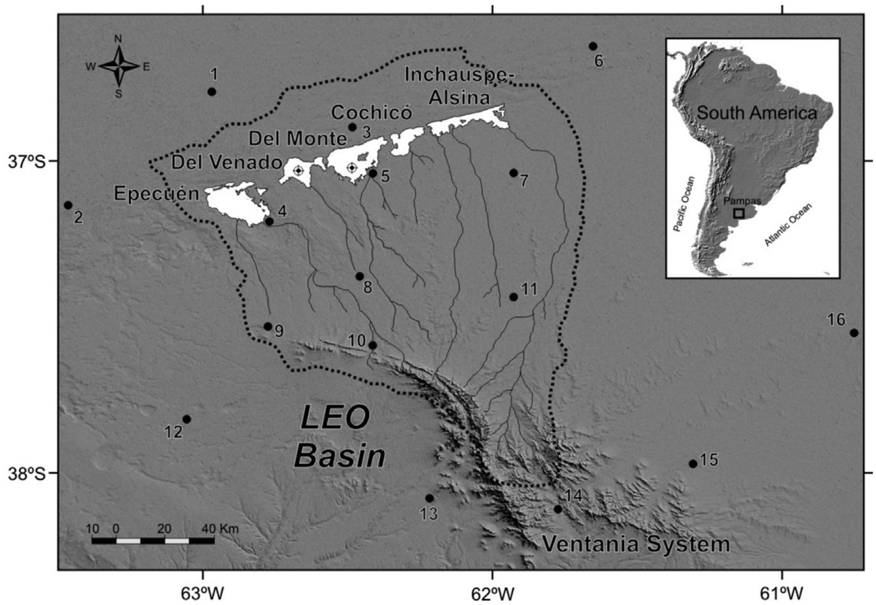

Fig. 1. The location of the Lagunas Encadenadas del Oeste (LEO) basin in the southwestern part of the Argentinean Pampas Region and detailed map of the lakes with their catchment area (thick dotted line), the positions of coring sites (⊕) and the location of the precipitation stations. The names of the stations (indicated by numbers) are listed in Table 1.

(Turekian et al., 1983; Appleby, 2001, 2008). ^{210}Pb is particle reactive, quickly sorbs to settling inorganic particles and organic matter from the water column and deposits to bottom sediments (Nyffeler et al., 1984; Honeyman and Santschi, 1989). The total ^{210}Pb activity in lake sediments is derived from two components: one from the *in situ* radioactive decay of the natural ^{226}Ra (supported ^{210}Pb; $^{210}Pb_{supp}$), and the other, which is derived from the atmospheric deposition (unsupported ^{210}Pb; $^{210}Pb_{uns}$).

Typically, when establishing the geochronology in recent lake sediments, it is common to assume that the $^{210}Pb_{uns}$ fluxes onto the sediment-water interface is homogeneous and constant over time, whereby $^{210}Pb_{uns}$ activity depth-profile should decrease smoothly and exponentially as result of radioactive decay whether the sedimentation is constant (Krishnaswamy et al., 1971; Appleby, 2008). Nevertheless, in some cases, radiometric profiles exhibit significant deviations from the simple $^{210}Pb_{uns}$ concentrations exponential decline. For instance, episodic events (e.g. historical flood, wind, earthquake or volcanic ash layers) can introduce biases resulting in non-exponential and non-monotonic $^{210}Pb_{uns}$ depth-profile (e.g., Whitmore et al., 1996; Arnaud et al., 2002, 2006; Lupo et al., 2006; Chapron et al., 2007; Mulsow et al., 2009). Difficulties arise when the same $^{210}Pb_{uns}$ data can be explained by different mathematical models, which can lead to significant discrepancies among the different results (Abril, 2004; von Gunten et al., 2009). The accuracy of ^{210}Pb-derived dates in these cases is highly dependent on the established assumptions about the supply of $^{210}Pb_{uns}$ to the sediments, and the nature of sedimentation processes, as well as the selected mathematical model. Thus, it is possible to minimize the biases by selecting the proper numerical model (Appleby and Oldfield, 1978; Robbins, 1978; Carroll and Lerche, 2003) while validating the set of ^{210}Pb-derived dates against discrete sedimentary markers with a known age (Smith, 2001; Appleby, 2008).

The Pampean region in central Argentina is a particularly interesting site to study by using the ^{210}Pb-dating methodology. This region is characterized by the development of widespread shallow, closed lacustrine systems (Iriondo, 1989) with a wide range of water composition, salinities and trophic states (Quirós and Drago, 1999; Stutz et al., 2012). Instrumental, historical and paleolimnological studies revealed that Pampean hydrological systems have undergone important water level oscillations, mainly triggered by moisture changes (Cioccale, 1999; Kröhling and Iriondo, 1999; Pasquini et al., 2006; Piovano et al., 2009; García-Rodríguez et al., 2009; Troin et al., 2010; Guerra et al., 2016). Within this geographical and climatic setting, dating sediment cores from these shallow lakes using ^{210}Pb-dating method can be problematic. Sedimentary sequences from different lakes have showed $^{210}Pb_{uns}$ radiometric profiles with notably irregularities at depth (Piovano et al., 2002; Stupar et al., 2014; Guerra et al., 2015), which have generated consequences concerning the quality of the ^{210}Pb dating.

In this paper we examine ^{210}Pb radiometric profiles from two shallow lakes under highly variable hydroclimatic conditions located in the southwestern part of the Pampas Region (SPR) of Argentina. The sedimentary record of the Lagunas Encadenadas del Oeste (37°S, 62°W), provides an opportunity to explore the application of widely know ^{210}Pb dating models. Since ^{210}Pb radiometric profiles notably disagree with the theoretical exponential decay of the ^{210}Pb activity with depth, the focus of this paper was to select the most suitable ^{210}Pb-based mathematical model to develop the chronology and accumulation rates of sediment cores, constrained by independent hydroclimatic data and sedimentary proxies.

2. Geographical and climatic settings

The LEO system is formed by a chain of shallow lakes (from 2 to 8 m deep during high lake water level stages) in the SPR of Argentina (36° 45′–37° 14′S, 61° 47′–62° 59′W; Fig. 1). The LEO catchment area is ~15,600 km^2 and includes five major interlinked lakes along a narrow linear depression from the Laguna Alsina-Inchauspe in the NE to Laguna Cochicó, Laguna del Monte, Laguna del Venado and the terminal and deepest Laguna Epecuén in the SW (Fig. 1). A marked gradient of lake water salinity develops from freshwater conditions at Laguna Alsina-Inchauspe with 0.8 g L^{-1} to hypersaline conditions at Laguna Epecuén with 56.8 g L^{-1} (salinity values corresponding to year 1994). The area is underlain by Miocene and Pleistocene-Holocene sedimentary units (Zárate, 2003) and the geomorphology corresponds to a rising plain toward the south, reaching the highest altitudes at the Ventania System (Fig. 1).

The LEO lies between two main geographical settings (Pampas and northern Patagonia) in a transitional zone between two climatic

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domains: a) the southernmost influence of a subtropical Low-Level Jet (LLJ) associated with the South American Monsoon System (SAMS; Zhou and Lau, 1998; Vera et al., 2006; Garreaud et al., 2009) and, b) the northernmost influence of the Southern Westerlies (Prohaska, 1976; Garreaud et al., 2009). The hydrological sensitivity shown by this system can be mainly ascribed to the variability of LLJ intensity and position, which controls the hydrological variability of most of the Pampean lakes (Piovano et al., 2009; Córdoba et al., 2014). The water vapor transported by LLJ is strengthened to a maximum during austral summer (DJF), which corresponds to the rainy season. During austral winter (JJA), the weakening of LLJ and the northward displacement of the Southern Westerlies produce a noticeable diminution in the regional precipitation. Rainfall exhibits a marked regional and temporal variability in total annual and monthly values. For instance, at the Guaminí Station (see station 5 in Fig. 1; Table 1) the annual average from years 1931–2000 is 746 mm yr^{-1}, ranging from a minimum of 437 mm yr^{-1} (year 1933) to a maximum of 1233 mm yr^{-1} (year 1985). The annual mean temperature is 16 °C with the highest values in January (maximum average = 33.0 °C) and the lowest in July (minimum average = 1.6 °C). The annual mean potential evapotranspiration is 1080 mm yr^{-1}.

gradients. Homogenized monthly rainfall data from 16 stations in the LEO region, covering the period AD 1888–2008 (Table 1; Fig. 1), were selected to construct this index. The analyzed dataset is the longest available record and the highest quality data covering the area (Córdoba, 2012). Stations are located throughout the LEO hydrological basin and in adjacent areas (Fig. 1). Records were obtained from the Version 2 of the Global Historical Climatology Network (GHCN; Vose et al., 1992), Servicio Meteorológico Nacional (SMN), Instituto Nacional de Tecnología Agropecuaria (INTA) and local sources (LS). Monthly precipitation series were converted to standardized monthly precipitation anomalies (anomaly divided by standard deviation) considering the interval AD 1961–2000 as the reference period and subsequently weighted-average to estimate the Annual Regional Precipitation Index (ARPI). The ARPI was smoothed applying a 10-point Low-pass Gaussian filter to analyze the low-frequency pattern in the record.

Daily lake water level records from the LEO system covering the period between AD 1969/1970 to 2005 were provided by Autoridad del Agua in Buenos Aires Province.

Table 1
Meteorological stations used to develop the annual regional precipitation index (ARPI). Data sources: (GHCN) Global Historical Climatology Network Version 2 (Vose et al., 1992); Servicio Meteorológico Nacional (SMN), Instituto Nacional de Tecnología Agropecuaria (INTA), Centro de Investigaciones Biometeorológicas (CIBIOM) and local sources (LS).

Number	Station	Latitude (S)	Longitude (W)	Altitude (m a.s.l.)	Period	Data source
1	Saliquello	36°45′	62°57′	126	1908–2008	CIBIOM-LS
2	Rolón	37°10′	63°24′	123	1921–2007	INTA
3	Cesáreo Naredo	36°51′	62°27′	116	1910–2008	INTA
4	Carhue	37°10′	62°45′	111	1911–2005	CIBIOM-LS
5	Guaminí	37°00′	62°24′	108	1900–2009	GHCN
6	Daireaux	36°36′	61°44′	115	1911–2007	CIBIOM-LS
7	Huanguelen	37°03′	61°56′	159	1918–2008	CIBIOM-LS
8	Espartillar	37°21′	62°26′	214	1894–2009	CIBIOM-LS
9	Puan	37°32′	62°45′	237	1931–2008	LS
10	Pigue	37°36′	62°24′	303	1911–2005	SMN
11	Coronel Suarez	37°27′	61°55′	237	1888–2005	SMN
12	Bordenave	37°50′	63°01′	212	1928–2008	INTA
13	Tornquist	38°06′	62°13′	290	1889–2007	GHCN
14	Sierra de la Ventana	38°08′	61°47′	280	1915–2008	LS
15	Coronel Pringles	37°59′	61°21′	252	1911–2008	CIBIOM-LS
16	Laprida	37°33′	60°48′	211	1911–2008	CIBIOM-LS

The LEO is a highly variable lake system characterized by temporal variability in water salinities and volumes as a result of drastic changes in the regional hydrological balance. Inflows controlling the lakes water balance are mainly ruled by precipitation (69.6%), followed by surface stream contribution (27.8%), and groundwater (2.6%), while the main loss of water is by evaporation (González et al., 1991; Roselli et al., 1991). During wet periods, the lakes develop highstands and the whole system may become interconnected by surface streams as well as by groundwater flows. Conversely, during dry periods, lake volumes are drastically reduced and the lakes may become disconnected.

3. Materials and methods

3.1. Instrumental hydroclimatic data

A regional precipitation climatic index was built to characterize temporal precipitation patterns in order to evaluate the influence of precipitation variability on lake level fluctuations. The regional precipitation climatic index was obtained by using the methodology proposed by Jones and Hulme (1996) for regions under large spatial variations and high precipitation

3.2. Core collection and sampling

A set of undisturbed sedimentary cores was collected from the deepest part of two lakes from the LEO system (Fig. 1) during February 2007 (core GT10-07, Laguna del Monte) and August 2007 (core VT23-07, Laguna del Venado) using a hand corer beeker-type sampler (Eijkelkamp). The sedimentary cores were transported to the laboratory and stored at 4 °C, prior to analyses. Cores were splitted, photographed, macroscopically described (lithology, colour, sedimentary structures, contact types, bedding) and sampled for geochemical (total organic carbon) and radiochemistry analysis (^{210}Pb). For total organic carbon measurements, core GT10-07 was sampled every 0.5–2 cm and at observed lithological changes. Core VT23-07 was sampled continuously every 1 cm. For radiochemistry analysis, both sedimentary records were sampled every 0.5 cm intervals down to 1 cm and every 1 cm down up to 20 cm in depth, and thereafter every 2 cm to the bottom of the core.

3.3. Radiometric measurements and ^{210}Pb numerical models

Aliquots (about 1 g) of freeze-dried sediments were used to estimate ^{210}Pb total activity (^{210}Po in secular equilibrium) using the isotopic dilution method (Mulsow et al., 1999). ^{209}Po was used

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as a chemical yield and the ^{210}Po and ^{209}Po were spontaneously deposited onto copper discs that were later on measured by alpha spectroscopy (ORTEC-Octete; Geobenthos Laboratory-Universidad Austral de Chile). All samples were counted until reported errors were <5% of the activity of samples. IAEA-300-certified reference material was also analyzed with each set of samples. $^{210}Pb_{supp}$ was calculated from the mean asymptotic activity at depth (the average total ^{210}Pb activity of the lowermost samples in each core assumed to be in equilibrium with ^{226}Ra) and was subtracted from the total ^{210}Pb activity measured at each level to obtain the $^{210}Pb_{uns}$ activities (Sánchez-Cabeza and Ruiz-Fernandez, 2012; Supplementary Tables 1 and 2). Because the appropriate choice of the calculation model is not a-priori known, ^{210}Pb ages and sediment accumulation rates (SAR) were calculated with the CRS, CIC, CFCS and SIT numerical models (Goldberg, 1963; Appleby and Oldfield, 1978; Robbins, 1978; Appleby, 2001, 2008; Carroll and Lerche, 2003). ^{210}Pb chronologies and SAR obtained using different models are shown in Supplementary Tables 3 and 4. CRS, CIC and CFCS models were used to calculate sediment ages and SAR including error propagation following Sánchez-Cabeza and Ruiz-Fernandez (2012), while the software for SIT calculations is documented in Carroll and Lerche (2003; SIT software kindly provided by J. Carroll, Polar Environmental Centre, Norway). The SIT model was applied either using only $^{210}Pb_{uns}$ data (unconstrained SIT) or constrained through chronostratigraphic markers (constrained SIT). Dry bulk density estimations were calculated following Binford (1990) (Supplementary Tables 1 and 2). In order to cover a broad range of potential chronological framework, sediment ages beyond the limit of ^{210}Pb dating were calculated using extrapolated basal sediment accumulation rates (Basal-SAR; see Table 2). Basal SAR refers to the values of the sediment section deposited below 20.0 and 30.0 cm sediment-depth in the Laguna del Monte and Laguna del Venado cores, respectively. Dating results from deeper strata (limit of $^{210}Pb_{uns}$ activity) were excluded from further calculations using the CRS-model due to large uncertainties of respective calculated sediment mass accumulation rates. Diagnostic environmental stratigraphic chronomarkers of know ages were selected to independently verify the resulting ^{210}Pb-based chronologies.

Table 2
Sediment accumulation rates (SAR) calculated using different ^{210}Pb-based mathematical models in core GT10-07 (Laguna del Monte) and core VT23-07 (Laguna del Venado).

Core	SAR (cm yr^{-1})	CRS	CFCR	Unconstrained-SIT	Constrained-SIT
GT10-07	Max SAR	2.25	0.45	1.14	1.16
	Mín SAR	0.31	0.45	0.53	0.51
	Mean SAR	0.91	0.45	0.76	0.77
	Basal SAR[a]	0.49	0.45	0.59	0.55
VT23-07	Max SAR	3.19	0.62	1.34	1.32
	Mín SAR	0.24	0.62	1.03	1.05
	Mean SAR	1.09	0.62	1.15	1.19
	Basal SAR[a]	0.38	0.62	1.13	1.21

[a] Basal-SAR used to calculate sediment ages beyond the limit of ^{210}Pb dating.

3.4. Total organic carbon (TOC) determination

TOC contents were measured using a CNS elemental analyzer (FISONS 1500) at CEREGE (Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, France) following the method proposed by Verardo et al. (1990). Freeze-dried sediment samples were pretreated for carbonates removal by adding 1 M HCl and then washed in deionized water. Each TOC value is an average of two measurements.

4. Results and interpretation

4.1. The last 120 years of hydroclimatic variability at the LEO Basin

The onset of the instrumental record in the study area is around AD 1888 after the most important wet pulse occurred during the 19th century (Aceituno et al., 2009). Available rainfall data from meteorological stations in Argentina (Corrientes, Goya, Córdoba, Buenos Aires and Bahia Blanca, this latter next to LEO basin), reports on the impacts of flooding cities along the Paraná River (Aceituno et al., 2009) and hydrological reconstructions from several Pampean lakes (Piovano et al., 2002; Guerra et al., 2015, 2016) point toward the regional magnitude of this wet event centered around AD 1877–1878. Furthermore, this well-documented flood event of AD 1877–1878 is considered as one of the three largest events in the Paraná River (i.e. Río de la Plata Basin) during the last two centuries (Aceituno et al., 2009).

Lake level fluctuations covering the period comprised between AD 1969 and AD 2005, and the regional precipitation variability pattern for the period AD 1888–2008 is presented in Fig. 2. ARPI values show a positive linear trend over the last 120 years, although the smoothed index values highlight the presence of alternating spells of rising/decreasing precipitation throughout the whole period. Negative anomalies are dominant from the beginning of the instrumental record until the decade of 1970s (Fig. 2d). Negative ARPI values near the year AD 1910 (−0.78 below the mean), correspond to a well-known dry period at the beginning of the 20th century. This dry period included short-term humid spells from AD 1918–1927 and from 1940 to 1949 as noted by the development of positive anomalies values. After the decade of 1970s the ARPI values indicate the onset of a wet spell, which has been the longest wet period instrumentally recorded in central Argentina. Maximum positive anomalies values mostly match El Niño (warm phase of the El Niño-Southern Oscillation – ENSO) events (at AD 1918/19, 1925/26, 1939/40, 1963/64, 1976/77, 1991/92, 1997/98, 2002 and 2004). Conversely, negative anomalies correspond to La Niña (cold phase of the ENSO) events (at AD 1920/21, 1928/29, 1938/39, 1949/50, 1988/89, 1995/96, 1998/99, 2005 and 2007/08) (Fig. 2d). After AD 2005, the index shows a marked drop to negative values corresponding to a hydrological reverse to drier conditions also noticed across the Pampean region (Piovano et al., 2009; Troin et al., 2010).

Historical and instrumental data of water lake-levels and water salinity (Fig. 2a–c) show dramatic changes over the past ~120 years. For instance, a maximum variation in water salinity ranging from 381 g L^{-1} to 37.8 g L^{-1} was reported in Laguna Epecuén – the terminal lake of the system-for the period AD 1886–2007 (Fig. 2c). Other records indicating water salinity variability are also available for the other lakes in the system (22.2 g L^{-1} in AD 1929; 4.0 g L^{-1} in AD 1988 in Laguna del Monte; 8.8 g L^{-1} in AD 1996 in Laguna del Venado). Lowstands and extreme salinities (373.9 g L^{-1} in AD 1903 in Laguna Epecuén), in concordance with negative ARPI anomalies, took place throughout the LEO system during the dominant dry period, which extended from the end of 19th century until the early 1970s (Fig. 2). During this long dry interval, comparatively lower salinities and lake level rises in the LEO system can be ascribed to the wet spell between AD 1918 and 1927 (Fig. 2d). A period characterized by extreme droughts, intense dust storms, cattle mortality, crop failure and rural migration, began during the 1930s, and was popularly known as the *Pampas Dust Bowl* (Viglizzo and Frank, 2006; Tripaldi et al., 2013), an equivalent to the American Dust Bowl in the Northern Hemisphere (Schubert et al., 2004). Conversely, highstands and comparatively lower water salinities (e.g. 37.8 in AD 1987 in Laguna Epecuén) become dominant after the 1970s, and correspond to the most recent precipitation

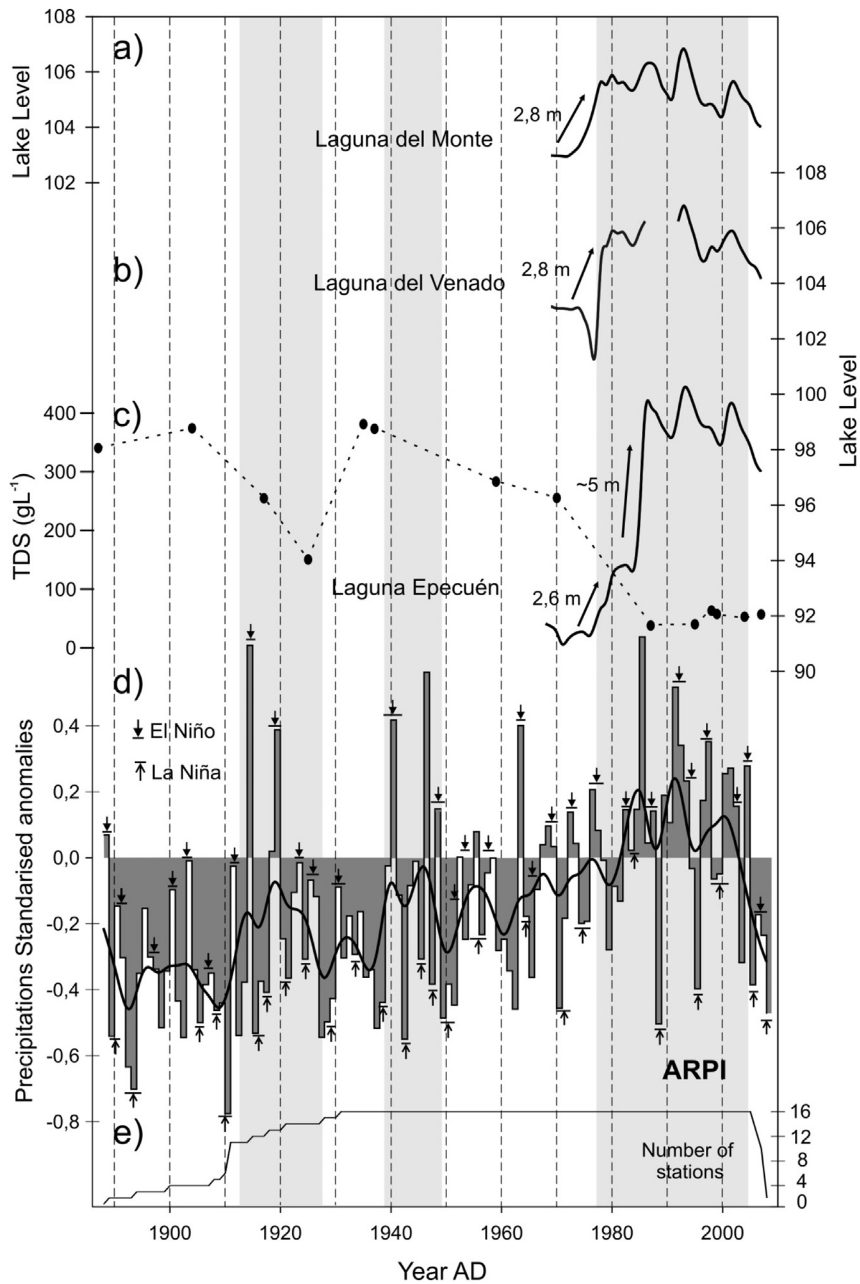

Fig. 2. A comparison between water-lake level fluctuations in the LEO system and the Annual Precipitation Index. (a) Water level record at Laguna del Monte. b) Water level record at Laguna del Venado. (c) Water level record and water salinity expressed as Total Dissolved Solids (TDS) concentration at Laguna Epecuén. (d) Annual Regional Precipitation Index (ARPI) for the period 1888–2008. Homogenized monthly precipitation series were converted to standardized anomalies with respect to the 1961–2000 reference period and subsequently weighted average to create this regional index. Least squares linear trend (straight line) and smoothed (applying a 10-year Low-pass Gaussian filter) are shown to highlight the trend and the low-frequency patterns in the index. (e) Number of stations contributing to the regionally-averaged precipitation index in any given year. The shaded bars indicate short wet spells between 1918 and 1927, 1940–1949, and the most recent wet period from 1977/1978 to 2005.

increase (Fig. 2c). A synchronic and widespread rise in lake levels took place after AD 1972/73, with the exception of Laguna del Venado which shows a sharp water drop in water lake-level between AD 1974 and 1977 as consequence of lake water regulations (Fig. 2a–c). From AD 1972–1981, lake-water levels increased dramatically (Δ lake level: +2.6 m in Laguna Epecuén; Δ lake level: +2.8 m in Laguna del Venado and Laguna del Monte), to an unprecedented magnitude, not observed during the previous 120 years of analyzed hydrological variability. During the last humid phase, the lakes coalesced and began spilling into the terminal Laguna Epecuén. From AD 1984–1986, Laguna Epecuén received large spillages, showing a second abrupt jump (Δ lake level: +5.6 m; Fig. 2c). The instrumental record of the LEO system indicates synchronic water level fluctuations throughout the wet period while a pronounced lake level drop started after year AD 2003.

In addition to the similar fluctuation pattern seen across a large number of lakes in the Pampean Plains (Piovano et al., 2009, 2014; Guerra et al., 2015), the close relationship between lake level variability and precipitation (Fig. 2a–d) points towards the regional magnitude of the hydroclimatic change which started during the 1970s in southeastern South America. Faced with changes in precipitation across the basin, the lakes' shallow depths (2–8 m) and small water volumes show a shortened response time. Lake level records show a strong positive correlation with the smoothed ARPI (average $r = 0.55$, range 0.51–0.62, $p < 0.01$) highlighting that precipitation change is the main forcing behind lake level variability.

4.2. *The sedimentary records of Laguna del Venado and Laguna del Monte*

Distinct lithofacies were defined in the recent pelagic sedimentary records (cores GT10-07 and VT23-07; Figs. 3 and 4) based on color, particle size, contact types, sedimentary structures and TOC content. Overall, the cores are mostly composed of massive and massive to vaguely laminated, black and greyish silts.

TOC percentages are presented in Figs. 3a and 4a. Core GT10-07 shows important variations in TOC ranging from 1.4 to 8.5% with an average value of 3.9%. TOC values in core VT23-07 range from 1.3 to 7.2% with an average value of 3.9%. The vertical variation of TOC shows a similar pattern in the analyzed cores. Comparatively lower values (between 1.3% and 3.7%) characterize the lowermost portion up to a level of 19.5 cm in GT10-07 and level 29.0 cm in VT23-07, where an abrupt increase occurred (between 4.6% and 8.5%).

Previous studies evidenced that the sedimentary records of the Pampean lakes present a significant correlation between sedimentary facies and lake-level fluctuations (Piovano et al., 2002, 2004, 2009; Córdoba, 2012; Guerra et al., 2015; Coianiz et al., 2015). In this sense, Piovano et al. (2009) and Guerra et al. (2015) described the strong relationship between precipitation/evaporation (P/E) ratio and organic matter content in Laguna Mar Chiquita and Laguna Melincué sediments, respectively. Changes in water salinity during lake-level fluctuations control both the amount of primary producers and the precipitation of authigenic minerals. This is recorded as distinctive organic-rich or evaporite-rich/organic-poor lacustrine facies at highstands and lowstands respectively. Therefore, sedimentary organic matter content, expressed as TOC, can be used as a proxy to reconstruct the primary productivity and lake water salinity controlled by hydroclimatic variability (Piovano et al., 2002, 2004; da Silva et al., 2008; Córdoba, 2012; Coianiz et al., 2015). High lake levels and

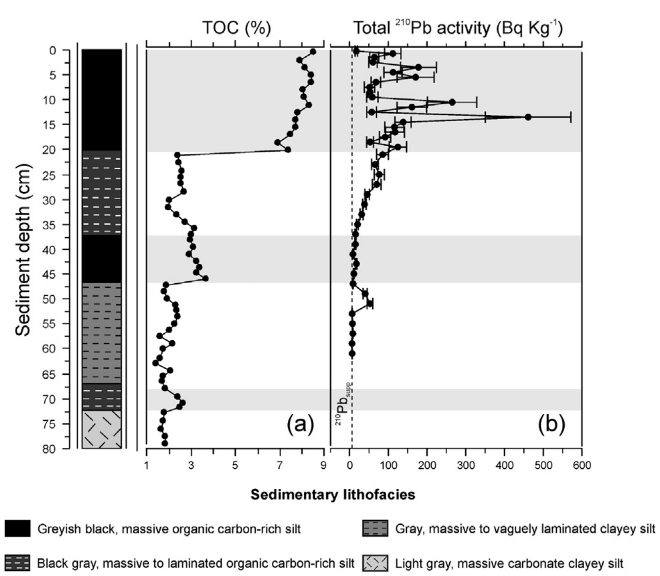

Fig. 3. Lithofacies and vertical profiles of (a) Total Organic Carbon (TOC) and (b) Total ^{210}Pb activity versus depth in Laguna del Monte sedimentary core (Core GT10-07).

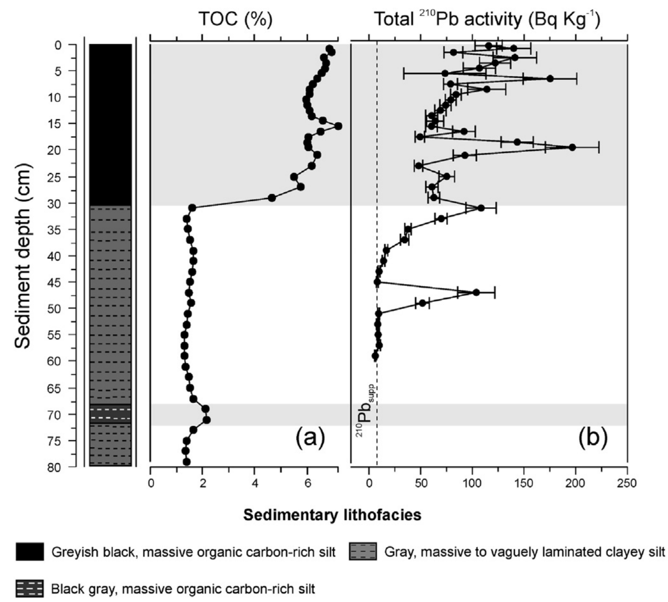

Fig. 4. Lithofacies and vertical profiles of (a) Total Organic Carbon (TOC) and (b) Total ^{210}Pb activity versus depth in Laguna del Venado sedimentary core (Core VT23-07).

low salinities are recorded by high TOC sediments contents as the result of an enhanced primary productivity during wet spells. Overall, the Pampean sedimentary cores comprise an uppermost carbon-rich mud facies which accumulated during the most recent highstands that serves as a prominent chronostratigraphic marker (T1) for core-to-core correlation. Both Laguna Mar Chiquita and Laguna Melincué ^{210}Pb-based chronology support the general scheme that the uppermost organic-rich facies has accumulated since AD 1977/1978 during the last highstands (Piovano et al., 2002, 2004; Guerra et al., 2015; Coianiz et al., 2015). Consistent with the sedimentary records from saline Pampean lakes, all retrieved cores along the LEO system exhibit an uppermost organic carbon-rich lithofacies (Figs. 3a and 4a), which correspond to the record of the last highstands triggered by increased regional precipitation after AD 1977/1978 (see Fig. 2). This lithofacies is clearly distinguishable in comparison to the underlying lithofacies displaying a sharp shift in the sediment properties and lake dynamic.

In addition, high TOC values at the interval 68–72 cm in core GT10-07 and 67–72.5 cm in core VT23-07 (Figs. 3a and 4a, respectively) can be ascribed to the record of a highstand triggered by wet conditions centered around AD 1877–1878 (Aceituno et al., 2009). This wet episode is well-documented both in the historical, instrumental and paleolimnological records across the Pampean plains during the second half of the 19th century (e.g., Piovano et al., 2002; Aceituno et al., 2009; Córdoba, 2012; Guerra et al., 2015; Coianiz et al., 2015), suggesting its value as an second prominent chronostratigraphic marker (T2) in the Pampean paleolimnological records.

The ubiquitous top and bottom organic carbon-rich lithofacies, present in all of the retrieved cores, allow using them as stratigraphic age-markers to correlate cores and validate ^{210}Pb-derived ages in the LEO system.

4.3. *^{210}Pb activities and inventory*

Total ^{210}Pb activity profiles measured in the sediment together with $^{210}Pb_{supp}$ specific activity calculated from the mean asymptotic activity in the lowermost cores are shown in Fig. 5 and

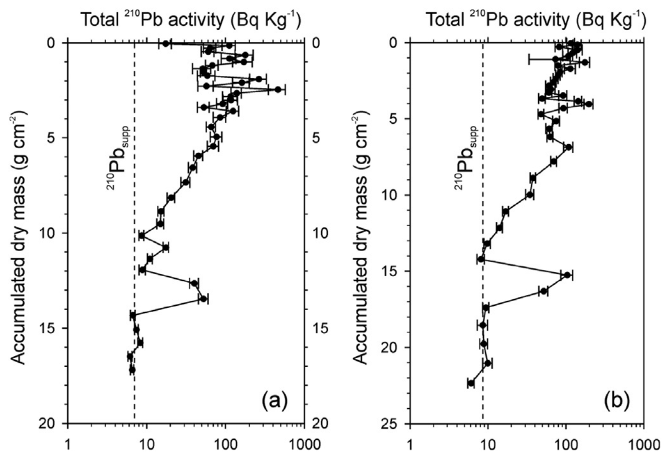

Fig. 5. Total and unsupported ^{210}Pb activity versus accumulated dry mass from cores (a) GT10-07 (Laguna del Monte) and (b) VT23-07 (Laguna del Venado).

Supplementary Tables 1 and 2. There is a general trend in decreasing total ^{210}Pb activity expected due to the decay of the $^{210}Pb_{uns}$. However, $^{10}Pb_{uns}$ activities decline in both cores with depth and deviate significantly from the theoretical exponential distribution, showing multiple peaks throughout the core-depths (Fig. 5). Conversely, in the deepest part of the cores the lowest and most constant concentrations occurred suggesting probably a rather constant sediment accumulation rate throughout these portions of the cores. $^{210}Pb_{supp}$ activity concentration was 7.0 Bq kg^{-1} at accumulated dry masses between 14.3 and 17.2 g cm^{-2} (~53 and 61 cm) in Laguna del Monte sediments (core GT10-07) and 8.6 Bq kg^{-1} at accumulated dry masses between 17.4 and 22.3 g cm^{-2} (~51 and 59 cm) in Laguna del Venado (core VT23-07). $^{210}Pb_{uns}$ activity ranges from 454 Bq kg^{-1} to 1.6 Bq kg^{-1} in core GT10-07 (average = 77.6 Bq kg^{-1}), while in core VT23-07 values range from 188.1 Bq kg^{-1} to 1.2 Bq kg^{-1} (average = 74.9 Bq kg^{-1}). The $^{210}Pb_{uns}$ inventory in the cores was estimated to be 7207.2 Bq m^{-2} in Laguna del Monte and 8639.8 Bq m^{-2} in Laguna del Venado (Supplementary Tables 1 and 2), which corresponds to a mean $^{210}Pb_{uns}$ supply rate of about 224.7 ± 9.1 Bq m^{-2} yr^{-1} and 269.4 ± 10.1 Bq m^{-2} yr^{-1}, respectively. $^{210}Pb_{uns}$ fluxes were determined from the specific activity profiles, obtained from core inventories according to Sánchez-Cabeza and Ruiz-Fernandez (2012). It is important to consider that determinations of atmospheric $^{210}Pb_{uns}$ flux were not performed in the Pampean region of Argentina yet. The $^{210}Pb_{uns}$ sediment inventories and fluxes in the LEO system are comparable with the values found in other Pampean and northern Patagonia lakes. The estimated $^{210}Pb_{uns}$ inventory and flux in Laguna Melincué were 12,479 Bq m^{-2} and 389 ± 16 Bq m^{-2} yr^{-1}, respectively (L. Guerra, pers. comm.). While the difference in latitude between both Pampean lacustrine systems is not large, the annual rainfall in the LEO basin is lower than the Laguna Melincué. This may explain the comparatively low values found in the study area. Conversely, atmospheric $^{210}Pb_{uns}$ flux over northern Patagonian lakes located near or along the Andean mountains range, under the influence of westerly winds (limited rainfall regimen), was found to vary between 4 and 48 Bq m^{-2} (Ribeiro Guevara et al., 2003). The ^{210}Pb fluxes measured from Pampean lake core inventories showed very high values when compared with northern Patagonia region, suggesting that the regional conditions probably associated with the South American Monsoon System dynamics could determine the high atmospheric ^{210}Pb flux values observed. The $^{210}Pb_{uns}$ fluxes observed in Pampean lakes are higher than mean atmospheric ^{210}Pb global flux in continental lands, which was estimated to be about 74 Bq m^{-2} yr^{-1}, varying from 19 to 148 Bq m^{-2} yr^{-1} in Australia and New Zealand up to 222–481 Bq m^{-2} yr^{-1} in Japan (Ribeiro Guevara et al., 2003).

Although unusual non-exponential and non-monotonic ^{210}Pb vertical profiles patterns observed in both cores would preclude the direct use of any ^{210}Pb classical mathematical models to derive ages (i.e., CIC, CFCS; Appleby, 2008; von Gunten et al., 2009; Sánchez-Cabeza and Ruiz-Fernandez, 2012), we discuss and evaluate the confidence of the application of each model. Thus, marked irregularities observed in the $^{210}Pb_{uns}$ vertical profiles (Fig. 5) constituted a unique challenge to identify the most suitable ^{210}Pb model to be applied for dating lake sediments accumulated under contrasting hydroclimate conditions.

4.4. ^{210}Pb dating model selection and chronologies

^{210}Pb ages were calculated with the CRS, CIC, CFCS and SIT (constrained and unconstrained) ^{210}Pb numerical models (Figs. 6 and 7; Supplementary Tables 3 and 4). A summary of sediment accumulation rates derived from the different numerical models is presented in Table 2. Extrapolated ages below the limit of ^{210}Pb dating were calculated using Basal SAR as background values (Table 2; Figs. 6 and 7). In order to check the validity of each model, the derived and extrapolated ages were compared with the discrete chronostratigraphic markers T1 and T2 (Figs. 6 and 7), allow to constrain the upper and lowermost parts of the resulting ^{210}Pb age models. The T1 and T2 markers were defined as TOC increases and lithology changes corresponding to striking regional wet pulses registered across the Pampean Plains and recognized in Laguna Mar Chiquita and Laguna Melincué (Piovano et al., 2002, 2004, 2014; Coianiz et al., 2015; Guerra et al., 2015). As noted above, the uppermost TOC increase in cores GT10-07 (level 19.5 cm; Fig. 6) and VT23-07 (level 29.0 cm; Fig. 7) linked to the record of the lake water-level jump (i.e. Δ lake level: +2.8 m in Laguna del Monte and Laguna del Venado, Fig. 2) experienced by all lakes after AD 1978–1979. The TOC shift recorded at the onset of these lithofacies (Figs. 3a and 4a) highlights the new limnological condition after the abrupt lake-water rise and salinity drop which began in AD 1978–1979 and was fully established around AD 1980 (Fig. 2). Therefore, the base of the uppermost organic-rich sediments can be defined as a chronostratigraphic marker (T1) with an approximate age of AD 1980 and an uncertainty range of ±2 years. The uncertainty was estimated on the basis of the short response time of the LEO system reflected by the instrumental data of precipitation and lake-water level altitude (Fig. 2). The abrupt TOC increase observed in both cores confirms the rapid response that is usually observed in lake systems that face changing environmental conditions (Eugster and Kelts, 1983; Valero-Garcés and Kelts, 1995; Valero-Garcés et al., 1999).

Downcore, a second time-marker (T2) matching high TOC values at levels 68–72 cm in core GT10-07 and 67–72.5 cm in core VT23-07 (Figs. 6 and 7, respectively). This organic-rich interval, present in all retrieved cores, is ascribed to a well-developed highstand triggered by the regional wet pulse occurred around AD 1877–1878 (Aceituno et al., 2009). As mentioned above, the impacts of this wet phase is recorded in the historical and sedimentary records of Pampean lakes (Piovano et al., 2002) and on the lowland areas along the rivers Parana, Uruguay and Paraguay (Aceituno et al., 2009). Therefore, the T2 midpoint age is estimated to be AD 1878 ± 10 yrs corresponding to the midpoint age of instrumental record of the wet spell.

The comparison among the chronologies derived from ^{210}Pb mathematical models and their relationship with the independent time-markers were analyzed for each individual lake.

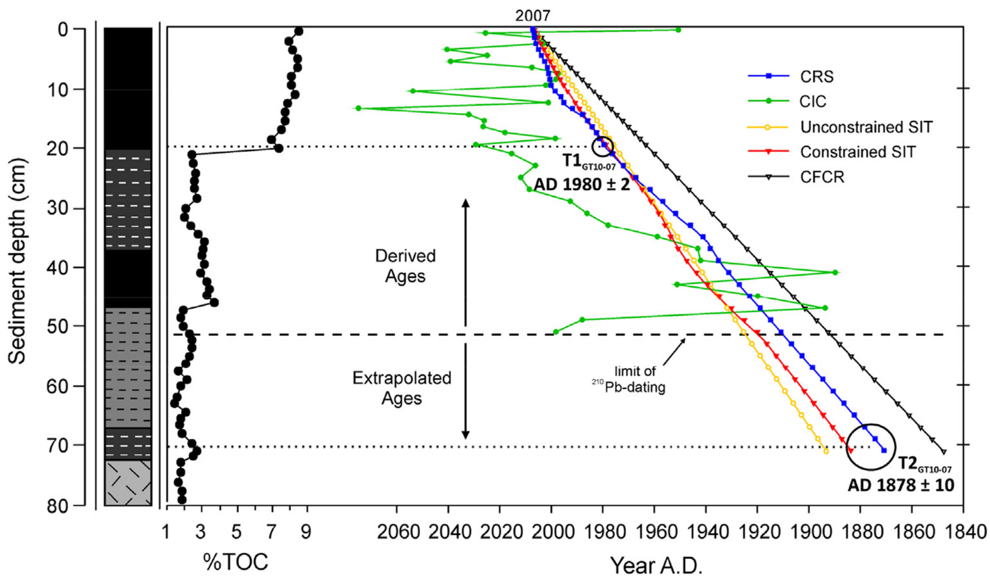

Fig. 6. Laguna del Monte ^{210}Pb chronology: Depth-age profiles obtained using CRS, CIC, CFCS, constrained SIT and unconstrained SIT models. Time markers ($T1_{GT10-07}$: AD 1980.0 ± 2; $T2_{GT10-07}$: AD 1878.0 ± 10) are defined based on the TOC (see text for explanation). The CRS model gives the most plausible dates when compared with $T1_{GT10-07}$ and $T2_{GT10-07}$. For better display, age uncertainty bars are not shown.

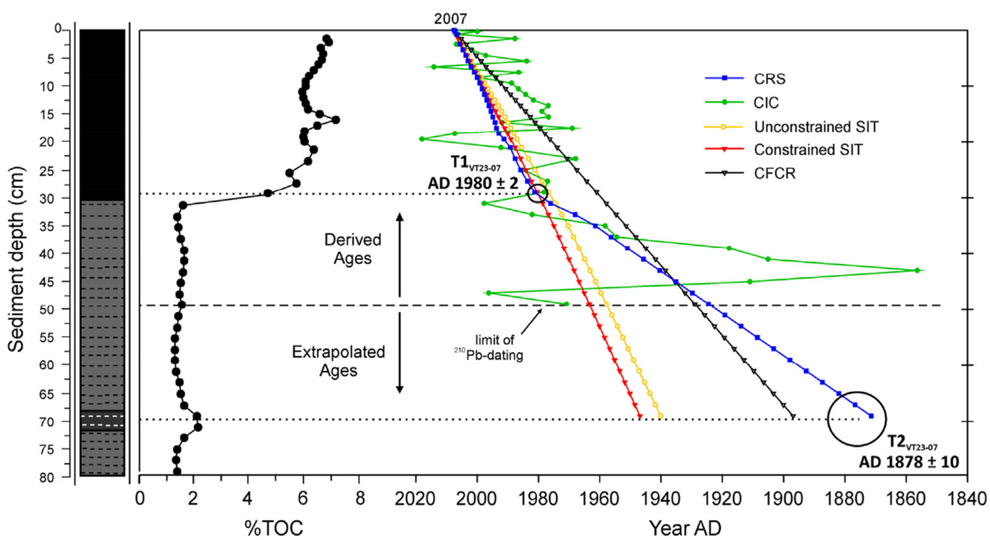

Fig. 7. Laguna del Venado ^{210}Pb chronology: Depth-age profiles obtained using CRS, CIC, CFCS, constrained SIT and unconstrained SIT models. Time markers ($T1_{VT23-07}$: AD 1980 ± 2; $T2_{VT23-07}$: AD 1878 ± 10) are defined based on the TOC (see text for explanation). The CRS model gives the most plausible dates when compared with $T1_{VT23-07}$ and $T2_{VT23-07}$. For better display, age uncertainty bars are not shown.

4.4.1. Laguna del Monte (core GT10-07)

Time markers $T1_{GT10-07}$ (AD 1980 ± 2) and $T2_{GT10-07}$ (1878 ± 10) in core GT10-07 were established at levels 19.5 cm and at 69.0 cm respectively (Fig. 6).

Resulting ages and uncertainties from the use of different mathematical models are presented in Fig. 6 and Supplementary Table 3. CIC-model derived ages are incoherent due to the presence of multiple large age inversions throughout the core (e.g., AD 2054 at level 10.5 cm). Ages obtained through CFCS and unconstrained SIT models are comparatively older (AD 1963.4 and 1963.6 $^{+19.1}/_{-2.8}$, respectively) than the age corresponding to the $T1_{VT23-07}$ age-marker. Ages estimated by CRS and constrained SIT models (AD 1979.6 ± 1.5 and 1978.8 $^{+2.4}/_{-0.4}$, respectively) are very close to the age corresponding to $T1_{GT10-07}$.

Along the lowermost portion of the core, both the CFCS-model and unconstrained SIT-model predicts inconsistent extrapolated ages according with the age marker $T2_{VT23-07}$ (AD 1852.2 and AD 1855.8, respectively). Consistent with the estimated age of $T2_{GT10-07}$ marker, the CRS and constrained SIT model assign an extrapolated age of AD 1874.2 and AD 1887.2, respectively. Although, constrained SIT-model derived ages are almost identical to those calculated by the CRS-model is important to highlight that CRS-model show a better agreement with both $T1_{GT10-07}$ and $T2_{GT10-07}$ markers. Only the constrained SIT model apparently yield a satisfying chronology when is forced by a chronological marker.

To summarize, CIC, CFCS and unconstrained SIT (constrained SIT) models derived-chronologies show in general inconsistencies and uncertainties and therefore they cannot be used for developing ^{210}Pb ages in the Laguna del Monte sedimentary record, being the CRS model derived ages the most coincident with the time markers. A detailed summary of ^{210}Pb dating results using CRS model, and

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calculations according to Sánchez-Cabeza and Ruiz-Fernandez (2012) are presented in Supplementary Table 3.

The estimated SAR derived from the CRS (Supplementary Table 3) ranging from 0.31 to 2.25 cm yr^{-1} (mean 0.91 cm yr^{-1}; Table 2). The last lacustrine highstands (post-1980) yields SAR of 0.31 and 2.25 cm $year^{-1}$ (average value 1.11 cm $year^{-1}$), while SAR during lowstands (pre-1980) are 0.34 and 0.95 cm $year^{-1}$ (average value 0.49 cm $year^{-1}$).

4.4.2. Laguna del Venado (core VT23-07)

Time markers $T1_{VT23\text{-}07}$ (AD 1980 ± 2) and $T2_{VT23\text{-}07}$ (AD 1878 ± 10) were established in the core VT23-07 at levels 29.0 and 69.0 cm respectively (Fig. 7). According to the different models, the resulting age-depth profiles show a significant discrepancy (Fig. 7; Supplementary Table 4). The CIC model results show age inversions along the age-depth profile and therefore, derived ages must be rejected. The CFCS-model yields inconsistent ages at levels 19.5 cm and 69.0 cm (AD 1961.0 and 1896.9, respectively) than those defined by $T1_{VT23\text{-}07}$ and $T2_{VT23\text{-}07}$ time markers. The unconstrained SIT-model predicts older ages than indicated by the age marker $T1_{VT23\text{-}07}$ (AD 1976.7 $^{+7.6}/_{-1.1}$). Ages obtained through constrained SIT and CRS models are consistent (AD 1980.4 $^{+3.2}/_{-0.5}$ and 1981.3 ± 1.5, respectively) with the age corresponding to the $T1_{VT23\text{-}07}$ age-marker.

The unconstrained SIT (constrained SIT) model assigns an extrapolated age of AD 1940.1 (AD 1946.9) showing incoherency with the estimated age of $T2_{VT23\text{-}07}$ marker while the CRS-model assigns an extrapolated age of AD 1871.4. The general discrepancy between CIC, CFCS, unconstrained SIT and constrained SIT models derived ages in comparison with time markers $T1_{VT23\text{-}07}$ and $T2_{VT23\text{-}07}$ indicate that these models do not yield reliable chronologies. Therefore, the CRS-model dates exhibit a better agreement with the age markers than the other models. ^{210}Pb dating results using CRS model for Laguna del Venado are given in Supplementary Table 4.

For this lake, estimated SAR varied between 0.24 and 3.19 cm yr^{-1} (average value 1.09 cm yr^{-1}; Table 2). The vertical variation of SAR shows a similar pattern such as in the Laguna del Monte. Comparatively lower SAR values (between 0.24 and 0.54 cm yr^{-1}; mean 0.38 cm $year^{-1}$) characterize the lowermost portion up to a level of 29.0 cm (pre-1980), where an important increase occurred (between 0.58 and 3.19 cm yr^{-1}; mean 1.23 cm $year^{-1}$). The estimated SAR are consistent with those reported by Piovano et al. (2002) and Guerra et al. (2015) for other shallow lakes throughout central Argentina for the same temporal period.

5. Discussion

Unusual non-exponential and non-monotonic $^{210}Pb_{uns}$ vertical profiles in the LEO cores indicate the existence of complex processes which control radionuclide fluxes to the sediments and lake sedimentation. The noticeable departures from the ideal decay profile of $^{210}Pb_{uns}$ activity along the analyzed cores and the inconsistency in ages derived from ^{210}Pb numerical models indicate that initial conditions, intrinsic for each numerical model, have not been satisfied in the analyzed environments (i.e., constant flux of ^{210}Pb and/or constant sedimentation rates). Instrumental data indicate a noteworthy hydroclimatic variability throughout the 20th century in the SPR (Fig. 2). These results pinpoint the close relationship that exists between the regional hydrologic balance associated to the interannual variability of precipitation (e.g., from 437 mm yr^{-1} during a dry spell to 1233 mm yr^{-1} during a wet spell), and fluctuating patterns of SAR along the sediment-depths. The results show that SAR has changed according to these variations in the lake-levels mainly during the recent decades. During the period covering the early 1980s to the 1990s, SAR shows a significantly increased and strong variability, which may be in relation to environmental changes that happened after 1980 during the onset of the last highstand. In the lowermost layers of the cores, SAR display rather constant values, and are likely to indicate comparatively constant sedimentation conditions during low-stand lake scenarios with low fluvial input.

The systematic comparison of numerical models as well as the step-wise cross-validation with well known independent stratigraphic markers was fundamental to evaluate and select the most suitable numerical model. In this sense, constant ^{210}Pb flux and sedimentation rates over time assumed by CFCS-model (Robbins, 1978; Appleby, 2001, 2008) are not realistic conditions when developing age-depth chronologies in these shallow lakes under the influence of a highly variable hydrological balance, such as in the SPR. Errors were already reported when the CFCS-model was applied in systems under non-steady-state conditions (Liu et al., 1991; Carroll et al., 1999; Sánchez-Cabeza and Ruiz-Fernandez, 2012). On the other hand, the SIT model offers the advantage that no *a-priori* assumptions need to be considered and further, that it can be applied in systems which display variable SAR, and changeable fluxes and variables initial concentrations of $^{210}Pb_{uns}$ trough time (Carroll et al., 1995; Carroll and Lerche, 2003; Abril, 2015). It is worth, however, noting some limitations of the method (Abril, 2015). While tests with synthetic data have shown that the SIT model is a reliable alternative to the CRS and CIC models (Carroll et al., 1995; Carroll and Lerche, 2003), derived and mostly extrapolated ages in the LEO sedimentary records were inconsistent. Unconstrained-SIT model yielded incoherent ages related to stratigraphic markers. Although, constrained SIT model gives a coherent chronology along the uppermost sediments in Laguna del Venado and Laguna del Monte, age discrepancies are found along the bottom sediments in both cores. CIC and CRS models, which assume a constant input of $^{210}Pb_{uns}$ to the sediment-water interface, can yield erroneous results when variations in the $^{210}Pb_{uns}$ activity profiles are highly non-monotonic (Appleby, 2008; von Gunten et al., 2009). Both models give the same results at sites with relatively constant sedimentation rate. In particular, the CIC-model failed completely since it gives non-realistic ages with multiple large time inversions when it is applied to develop the age-model in the LEO sedimentary record, suggesting episodes of variable sedimentation rates (Figs. 6 and 7). This model must be restricted to the cases when the primary delivery pathway of $^{210}Pb_{uns}$ to sediments is through the erosive influx of $^{210}Pb_{uns}$ from lake catchment, satisfying the assumption that a sedimentation increase controls a proportional increase of $^{210}Pb_{uns}$ flux and vice versa (Blais et al., 1998).

^{210}Pb dates calculated using the CRS-model are in good agreement with the two well known chrono-stratigraphic markers. The assumption of a constant flux of $^{210}Pb_{uns}$ into the sediments and a non-steady sedimentation rate considered by the CRS-model (Appleby and Oldfield, 1978; Robbins, 1978) indicate that this model can be applied assuming that $^{210}Pb_{uns}$ flux is independent of sedimentation rates (Blais et al., 1995, 1998; Appleby, 2008). Therefore in this model, an increase in sedimentation rate is assumed to dilute the $^{210}Pb_{uns}$ concentration, and decreases in $^{210}Pb_{uns}$ activity are attributable to increases in the sediment flux to the bottom sediment. As mentioned above, in view of the dramatic environmental change that has taken place since AD 1977–78, rates of sediment accumulation have varied significantly in these shallow lakes during this period. Both cores show clear evidence for increased sediment accumulation rates in the last ~40 years coinciding with a raise of the regional precipitation. Evidence for this phenomenon arises clearly when inflections in the ln $^{210}Pb_{uns}$ vs. cumulative dry mass activity curves show departures from linearity especially at the top of the profiles (Fig. 5; Blais et al., 1998).

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Therefore the non-monotonic $^{210}Pb_{uns}$ profiles in the lakes may be the result of varying sedimentation rates with different histories of deposition before and after AD 1980. Particularly, the CRS model gives consistent chronologies along the uppermost sediments in both cores, suggest that the supply of $^{210}Pb_{uns}$ to the sediments has remained relative constant over this time interval. Thus, the $^{210}Pb_{uns}$ profiles can be simply explained by variable sedimentation rates and relatively constant supply of $^{210}Pb_{uns}$ to the sediments during this time period. Nevertheless, the CRS model overestimates ages (much older than expected) along the lowermost portions of the radiometric profiles (level ~40–50 cm in both cores). This fact can be attributed to changes in radionuclide activities near the bottom of sediment cores which are translated into large (and uncertainties) values in the CRS-model equation toward older sediments (Carroll and Lerche, 2003; von Gunten et al., 2009). These inconsistent ages at the bottom radiometric profiles were reported previously and expected as a result of applying the CRS model (e.g. McCall et al., 1984; Carroll and Lerche, 2003; von Gunten et al., 2009; MacKenzie et al., 2011). Therefore, to extend the CRS chronology below the limit of ^{210}Pb dating but above all the interval with high age-uncertainties, Basal-SAR values (estimated between ~20 and 38 cm in core GT10-07 and ~30–40 cm in core VT23-07; Table 2) were used to avoid the effect of large uncertainties along the lowermost portions of the cores. Such extrapolations are likely to yield accurate dates at sites where sediment accumulation rates have not changed significantly (O'Reilly et al., 2011; Hermanns and Biester, 2013). Since, as discussed above, this appeared to be the case for the analyzed cores, the CRS chronologies were extrapolated to deeper sections of the cores assuming constant rates, to depths corresponding to the late 19th century. There are numerous examples in the literature in which extrapolations of ^{210}Pb chronologies using average SAR have been successfully carried out to reconstruct recent environmental and climate changes recorded in lacustrine sediments from European and South American lakes (e.g., Appleby, 2000; O'Reilly et al., 2011; Hermanns and Biester, 2013). In both sediment cores, the CRS extrapolated ages were consistent according to the second stratigraphic marker.

The use of stratigraphic time markers in the sedimentary record of the LEO system (top and bottom sediments) seems to be critical both to cross check the reliability of the CRS model for derived ages and to highlight inconsistent results when using CFCS, CIC and SIT numerical models. The fact that the stratigraphic markers in two cores from different lakes (i.e., Lagunas del Venado and Laguna del Monte) show equivalent ^{210}Pb-based ages, strengthens the reliability of the selected age models. Even more, these ages are in agreement with other ^{210}Pb-derived ages and stratigraphic-markers (organic-rich intervals) recognized in other paleolimnological records across the Pampean plains (Piovano et al., 2002, 2009; Coianiz et al., 2015; Guerra et al., 2015). Our results suggest that extrapolated ages below the limit of ^{210}Pb dating are relatively safe to provide reliable chronologies in the LEO sediment cores since the late 19th century to the first half of the 20th century.

Results show that the CRS-model yields the most coherent age-depth chronologies in the analyzed cores. This model appears to be an adequate technique for deriving ages and SAR in the LEO sedimentary record and other Pampean lacustrine systems under strong hydrological variability.

6. Summary and conclusions

In this study our aim has been to determine the most suitable ^{210}Pb-based numerical model to be used for assign dates and sediment accumulation rates of lake sediments accumulated under highly variable hydrological settings in the southern Argentinean Pampas. Our systematic comparison of widely used ^{210}Pb-based models (CRS, CIC, CFCS and SIT) in two different Pampean lakes shows that the CRS-model yields the best results compared with two independent chronostratigraphic markers of known age. These well known regional markers were selected to control and validate the upper and lowermost parts of the ^{210}Pb-dated sediments. The younger stratigraphic marker T1 of AD 1980 ± 2 corresponds to an uppermost organic carbon-rich mud accumulated by 1977–78 matching the most noticeable lake highstand occurred during the 20th century, registered on instrumental and paleolimnological records across the Pampean Plains. The oldest stratigraphic marker T2 corresponds to AD 1878 ± 10 matching with high lake productivity and wet phase related to anomalously intense rainfall and flooding events in southeastern South America for AD 1877–1878. The ubiquity of the independent chronostratigraphic markers, corresponding to organic-rich intervals recognized in other paleolimnological records across the Pampean plains, reinforce their regional value as time-markers useful to validate chronologies.

The important increase of organic matter and sedimentation rates detected in both cores after 1980 are shown to coincide with increased regional precipitation over the last forty years in the Pampean region. Varying SAR and sediment composition with different histories of deposition before and after AD 1980 can account for the observed non-monotonic $^{210}Pb_{uns}$ profiles.

The development of accurate ^{210}Pb chronological models for shallow lakes in the Pampean region is essential to calibrate proxy records for reconstructing and analyzing environmental changes during the Anthropocene and previous centuries within a larger time-window along the late Holocene. This fact is especially important in South America, where the length of the instrumental record does not allow for an analysis of the low frequency hydroclimatic variability during times with low anthropic influences.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2016.07.003.

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