1 **Late Holocene environmental changes as recorded in the sediments of high Andean Laguna**

2 **Chepical, Central Chile (32°S; 3050 m a.s.l.)**

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29 **Abstract**

30 We present a reconstruction of environmental changes from sediments of high-altitude Laguna

31 Chepical in the subtropical Andes of Central Chile (32°16'S; 70°30'W, 3050 m a.s.l.) for the past

32 3100 years. Based on fossil pollen, microscopic charcoal and diatoms, we inferred changes in

33 moisture (related to precipitation) and ice-cover/ice-free season (related to summer temperature) at

34 decadal to millennial scales. Sustained wetter and colder summer temperatures than today

35 prevailed between BC 1100 and ca. AD 1. Afterward, decreasing pollen accumulation rates and

36 increased fire activity suggest drier conditions and possibly enhanced seasonality and/or inter-

37 annual climate variability. Frequent changes between cold and warm summers were observed,

38 particularly for the last 1000 years. About AD 1250 (during the Medieval Climate Anomaly), wet

39 years and early break up of ice-cover occurred in central Chile, which is today typical for El Niño-

40 like mean conditions. Conversely, and with the exception of a few wet pulses, a generally dry period

41 with extended ice-cover (cool summers) was observed between AD 1400 and AD 1850 (Little Ice

42 Age). This can be interpreted as a trend towards more La Niña-like mean conditions. Recent

43 warming and human disturbances during the last 100 yrs have prompted changes in diatom and

44 plant communities that are unprecedented in the late Holocene. First, planktonic diatoms increased

45 as a result of hydraulic interventions in the lake during the late 19th c., and secondly, the Andean

46 vegetation shifted upward as result of recent warming, and the frequency of arboreal taxa was

47 significantly reduced. At the same time peaks of fire activity were observed.

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1. Introduction

Mountain ecosystems are characterized by steep gradients in precipitation, temperature and other environmental variables. Thus, plant communities in mountain habitats are potentially very vulnerable to climatic changes (Arroyo et al., 1993; Beniston, 2003; Diaz et al., 2003; Fagre et al., 2003). The Andean Cordillera and the foothills of Central Chile (30°-35°S) are among those areas in the world that experience particularly strong desertification as a consequence of ongoing climatic change (Carrasco et al., 2005; Fuenzalida et al., 2006; Rosenblüth et al., 1997; Trenberth et al., 2007). Studies of global warming scenarios for the subtropical Andes project a substantial decline of precipitation (-30%) for the 21st century and an increase in temperature (+3-4°C). Moreover, a concomitant decline in the snowpack and changes in the snowmelt and stream flow regimes are expected (Carrasco et al., 2005; Fuenzalida et al., 2006; Vicuña et al., 2011), which will negatively impact water storage for the surrounding foothills during the dry summer season. Andean biota will be affected and may be displaced because of a reduction of habitat (Arroyo et al., 1993; Pliscoff et al., 2012). At the same time, socioeconomic activities (e.g. hydropower generation, agriculture, domestic water consumption) will also be impacted by the lower water availability. This is a serious problem, because the demand for water is high and rapidly increasing in this area: indeed, this is the area with the highest population of Chile (13 million; 73% of population) and with water demand for boosting industrial agriculture and mining (AGRIMED, 2008; CEPAL, 2012). This makes central Chile, and in particular the semiarid Andes, extremely vulnerable to climate change. Understanding natural climatic variability is, therefore, crucial to reduce uncertainties in future scenarios.

Central Chile also is a key area to study the interaction between the Southern Westerly Wind Belt (SWWB) and the Southeast Pacific Subtropical Anticyclone (SEPSA) (Jenny et al., 2002). Moreover, extreme climatic variability in this area is associated with large-scale ocean-atmosphere phenomena, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (Montecinos and Aceituno, 2003; Quintana and Aceituno, 2012). The warm phase of the Southern Oscillation (El Niño) is typically associated with a weakened SEPSA and enhanced blocking in the Amundsen–Bellingshausen seas in Antarctica (southeast Pacific), which produces increased storminess, above average precipitation and snowpack formation in central Chile, whereas

87 generally opposite conditions occur during La Niña cold phases (Masiokas et al., 2006; Montecinos

88 and Aceituno, 2003; Rutllant and Fuenzalida, 1991). Particularly because SEPSA is modulated by

89 the Southern Oscillation, there is a strongly negative correlation between the Southern Oscillation

90 Index and winter rainfall over the region (Fig. 1a). During negative SOI phases, high rainfall is

91 expected and vice versa (Quintana and Aceituno, 2012). Surface air temperatures are generally

92 warmer during warm ENSO phases, particularly in fall and winter (Garreaud, 2009).

93 Continuous paleoclimate archives from this area contain information that can be used for

94 comprehensive regional, continental and hemispherical assessments of climate variability during

95 the late Holocene (Neukom et al., 2014; Neukom et al., 2010; Neukom et al., 2011; PAGES-2k-

96 Consortium, 2013). In a recent study, de Jong et al. (2013) presented a high-resolution (sub-

97 decadal) record of warm season temperature from Laguna Chepical, which provided, in

98 combination with information from nearby low elevation (350 m a.s.l.) Laguna Aculeo (von Gunten

99 et al., 2009), insight into the similarities and dissimilarities of temperature variability at high and low

100 elevation sites.

101 Here we present the results of pollen and diatom analyses from Laguna Chepical. In this

102 investigation we explore whether biological proxies contain information about past precipitation and

103 moisture regimes to complement the existing reconstructions of summer temperature. Moreover, we

104 were interested in whether and how anthropogenic activities may have influenced this remote high

105 Andean site.

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107 **2. Study area**

108 Laguna Chepical (32°16'S; 70°30'W, 3050 m a.s.l.) is a high Andean, oligotrophic endorheic cold-

109 monomictic freshwater lake located on the western slope of the Andes in Central Chile (Fig. 1b).

110 The geologic bedrock of the lake catchment is composed of volcanic basaltic, andesitic and dacitic

111 rocks of Middle to Late Miocene age (Munizaga and Vicente, 1982). According to de Jong et al.

112 (2013), the lake sediments consist of diatomaceous organic silt (C_{org} 8–20 %). The top part of the

113 sediment core shows a dark brown laminated facies, which was interrupted at 20 cm by a 1-cm

114 thick homogeneous light brown layer. This layer is associated with the construction of an earth dam

115 in AD 1885 (de Jong et al., 2013). Between 21 cm and 58 cm sediment depth, the sediments are

116 composed of dark brown diatomaceous silt, and, below 58 cm, the color shifts to grey.

117 The surface of the lake covers an area of 0.65 km^2, and the maximum depth is 12.9 m. The lake is

118 ice-covered for ca. 9 months during austral winter and spring, i.e. April to December (de Jong et al.,

119 2013). The water level has been stabilized by an earth dam built in AD 1885.

120 The local climate is classified as subtropical semiarid dry summer and cold winter climate (BSk

121 Köppen classification). The average winter temperature is -4°C (July), and average summer

122 temperature (February) is 8°C (Fig. 1b, El Soldado meteorological station, AD 2001-2005, 32°S,

123 70°19'W, 3290 m a.s.l.). About 90% of the precipitation falls in the austral autumn-winter season

124 from April to September (Falvey and Garreaud, 2007), mostly as snow. Cold season precipitation

125 originates from frontal systems carrying moisture from the Pacific Ocean to the Andes. These

126 systems are associated with the northern border of the SWWB and lead to strong orographic rainfall

127 gradients between the foothills and the high mountains (Falvey and Garreaud, 2007). Rainfall

128 during summer is less frequent and related to convective storms originating from the east of the

129 Andes (Garreaud and Rutlland, 1997). A nearby weather station (Fig. 1b, La Mostaza

130 meteorological station located to 20 km downstream, 32°25'S, 70°40'W, 1200 m a.s.l.) measured

131 total annual precipitation of ca. 320 mm (AD 1980-2010).

132 In the Andes of north-central Chile, the flora is arranged in vegetation belts according to the

133 altitudinal gradients of temperature, precipitation and topography. As the vegetation above ~2500 m

134 a.s.l. is covered with snow in austral winter, growth, flowering and fruiting occur between

135 approximately late October to May (Arroyo et al., 1981). According to Cavieres et al. (2000), Muñoz

136 et al., (2000) and Luebert and Gajardo (2004) the vegetation belts in the area are structured as

137 follows (Fig. 1c):

138 The pre-Andean belt (1500-2000 m a.s.l.) is characterized by shrubs and trees. The most important

139 species are *Schinus polygamus*, *Colliguaja odorifera*, *C. integerrima*, *Trevoa quinquinervia* and

140 *Adesmia confusa*. Between 1900 and 2100 m, the treeline is composed of montane sclerophyllous

141 woodlands that contain tree species such as *Quillaja saponaria*, *Schinus montanus* and *Kageneckia*

142 *angustifolia*. This belt has a vegetation cover of *ca*. 30-60 % with considerable anthropogenic

143 disturbance.

144 The sub-Andean belt (2000-2500 m a.s.l.) is characterized by shrubs and perennial herbs. Common

145 taxa are *Ephedra chilensis*, *Chuquiraga oppositifolia, Mulinum spinosum, Tetraglochina latum,*

146 *Nardophyllum lanatum* and *Viviania marifolia*. This belt has a vegetation cover of ca. 40-50%.

147 The lower Andean belt (2500-3100 m a.s.l.) is dominated by perennial herbs and cushion plants.

148 Dominant species are *Laretia acaulis*, *Berberis empetrifolia*, *Senecio donianus*, *Haplopappus*

149 *scrobiculatus* and *Nassauvia uniflora.* The vegetation cover is around 20-30%.

150 The higher Andean belt (above 3100 m a.s.l.) is characterized by perennial herbs and secondly

151 cushion plants. *Azorella madreporica*, *Nassauvia pyramidalis, Stipa chrysophylla, Hordeum*

152 *comosum, Adesmia aegiceras, Perezia carthamoides* are present. This belt has a vegetation cover

153 of ca. 10-30%.

154 Laguna Chepical is located in the lower Andean belt, with some sub-Andean elements. The main

155 species around the lake are *Chuquiraga oppostifolia, Berberis empetrifolia, Haplopappus*

156 *scrobiculatus, Mutisia sinuata* and *Nassauvia uniflora.*

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158 **3. Methods**

159 **3.1. Field sampling and chronology**

160 During summer 2006 we obtained four sediment cores from the center of the lake with an UWITEC

161 gravity corer at a water depth of 12.3 m. We used the age-depth model established by de Jong et

162 al. (2013), which was developed from ^{226}Ra, ^{210}Pb and ^{137}Cs activity profiles and five ^{14}C AMS dates

163 on the sediment core CHEP06/03 (Fig. 2). In the present study we used sediment subsamples from

164 the parallel core (CHEP06/04) for pollen and diatom analysis, which was visually correlated with

165 CHEP06/03. The ^{14}C AMS dates were calibrated to calendar ages using the ShCal04 curve for the

166 Southern Hemisphere (McCormac et al., 2004). Further details on the age-depth model are

167 available in de Jong et al. (2013).

168 **3.2. Proxy analysis**

169 The 86-cm-long core CHEP06/04 was sampled at 0.5 cm intervals. Generally, pollen analysis was

170 carried out every 2 cm. For the section between 20 and 30 cm sediment depth pollen was counted

171 contiguously every 0.5 cm to account for the low sediment accumulation rates. Diatom samples

172 were analyzed at 0.5 cm intervals in the uppermost 16 cm, and at 1-cm discrete intervals further

173 downcore.

174 For pollen analysis 1 ml of sample material was used following conventional procedures (Faegri and

175 Iversen, 1989). This included acetolysis and hydrofluoric acid treatment. Two *Lycopodium* tablets

176 (Stockmarr, 1971) were added to each sample to measure pollen concentrations and calculate

177 pollen accumulation rates (PAR). Pollen samples were concentrated, ultrasounded, and mounted

178 on slides using glycerin. Pollen identification was made with reference to the palynological literature

179 (Heusser, 1971; Markgraf and D'Antoni, 1978; Wingenroth and Heusser, 1984) and a modern

180 pollen reference collection. An average of 320 pollen grains of local terrestrial taxa was counted per

181 sample. Additionally, microscopic charcoal particles (10-120 µm size range) were counted on the

182 pollen slides. Microscopic charcoal concentrations were computed using the *Lycopodium* tracers,

183 and microscopic charcoal accumulation rates (mCHAR) were calculated. The microscopic charcoal

184 record permits an inference of extra-local or regional fire activity (Whitlock and Larsen, 2001) at

185 lower altitude, where, in contrast to the high elevation site of Laguna Chepical, the climatic

186 conditions and lowland plant associations allow the ignition and spread of wildfires.

187 For diatom analysis ca. 0.1 g of dry sediment was processed using standard techniques (Battarbee,

188 1986), including removal of organic matter and carbonates, washing and centrifugation. The

189 samples were mounted onto glass slides with Naphrax® (refractive index= 1.74). An average of 420

190 diatom valves were identified to the lowest taxonomic level possible. Systematic and ecological

191 interpretations are based on regional (Díaz and Maidana, 2005; Parra and Bicudo, 1996; Rivera et

192 al., 1982) and international literature (Bellinger and Sigee, 2010; Round et al., 1992; Stoermer and

193   Smol, 1999). Nomenclature follows the most recent changes in the literature and the algae base

194   (http://www.algaebase.org/).

195   Pollen and diatom assemblages were plotted with Tilia Software 1.7.16. Stratigraphically

196   constrained cluster analysis was performed with CONISS (Grimm, 1987) in order to define pollen

197   and diatom zones. Only taxa with occurrence >2% were included in the analysis. In the pollen

198   diagram only the main local terrestrial taxa were included. Additionally, the Poaceae percentage

199   record was annually interpolated in R (R core Team, 2015) using the Rioja package (Juggins,

200   2014). Then a running correlation analysis between annually interpolated Poaceae and a Southern

201   Oscillation Index reconstruction (Yan et al., 2011) (AD 50-1950) was carried out using the R gtools

202   package (Warnes et al., 2015), with an arbitrary window width of 500 years in order to capture multi-

203   centennial correlation patterns.

204

205   **4. Results**

206   **4.1. Changes in pollen assemblages**

207   We identified five pollen zones in the sediment core (Fig. 3):

208   **CHEP-P1 (BC 1100 – BC 720):** This zone is dominated by perennial herbs and shrubs of the lower

209   Andean and sub-Andean belts, i.e. Poaceae (15-35%) and *Ephedra* (up to 15%). This assemblage

210   also includes Chenopodiaceae (7-9%), Euphorbiaceae (5-8%), and the Asteroideae-subfamily.

211   Around BC 1000 a peak of Montiaceae reaches 28%. The PAR values are moderately high and

212   mCHAR are moderately low during this time (compared with the pattern observed between BC

213   1000 and AD 1800).

214   **CHEP-P2 (BC 720 – AD 680):** The increase of Poaceae to 40-60% indicates the dominance of

215   perennial herbs of the lower Andean belt at Laguna Chepical. After AD 550, *Arenaria/Stellaria*

216   increases up to 9%. This assemblage is accompanied by Chenopodiaceae (7-9%), Asteroideae-

217   subfamily (5-8%), *Ephedra* (declines to 5%) and Euphorbiaceae (3-7%). The PAR increases

218   slightly, but declines around AD 1 while mCHAR increases after AD 1.

219 **CHEP-P3 (AD 680-1850):** This zone is characterized by the fluctuating and decreasing trend of

220 Poaceae and an increase of lower altitude taxa. First, between AD 800 and AD 1400, Poaceae

221 decrease to ~30-45% whereas cold-tolerant taxa (*Azorella/Laretia*, Nassauvieae-tribe) and Sub-

222 Andean taxa (*Ephedra*) increase. Pre-Andean elements, such as Chenopodiaceae, Euphorbiaceae,

223 and arboreal taxa decline or fluctuate between 800 and 1100 AD. After AD 1400, Poaceae fluctuate

224 strongly (minimum values around AD 1545, maxima around AD 1670). An opposite trend is

225 observed in *Azorella/Laretia*, Nassauvieae-tribe, pre-Andean taxa (Chenopodiaceae, *Baccharis*-

226 type and arboreal taxa) and the Astereaceae group from the lower Andean and Sub-Andean belts

227 (Mutisieae-tribe). Montiaceae (*Caladrinia*-type) show a short peak between AD 1470 and 1550,

228 which is concomitant with a decrease in Poaceae. The PAR values remain low; the mCHARs

229 decrease and reach minimum values between AD 1400 and 1800.

230 **CHEP-P4 (AD 1850 - 1960):** In this zone Poaceae reach 30%. Additionally, the lower Andean taxa,

231 such as the Asteroideae subfamily, are dominant (15%). Sub-Andean (*Ephedra*), pre-Andean

232 (Euphorbiaceae and Chenopodiaceae) and azonal associations (13%) show a decline, whereas

233 taxa, such as *Plantago* and Urticaceae, emerge and increase during this period. The PARs and

234 mCHARs show a significant increase.

235 **CHEP-P5 (AD 1960 - 2006):** Poaceae diminish to 15%. Other dominant taxa are *Arenaria/Stellaria*

236 (20%), Chenopodiaceae (15%), and Asteroideae-subfamily (10%), accompanied by taxa from lower

237 altitudes (Euphorbiaceae, *Baccharis*-type, *Mulinum,* Brassicaceae, Urticaceae and *Plantago*). Also

238 arboreal taxa from low elevations decline after AD 1980. The highest PAR and mCHAR values are

239 found during this period.

240

241 **4.2. Changes in diatom assemblages**

242 The relative abundance profiles of the 23 most abundant diatom species (>5%) are summarized in

243 Fig. 4. Five zones are distinguished. This profile enables the inference of the following changes:

244 **CHEP-D1 (BC 1100 – BC 50):** This zone is characterized by high abundances of tychoplanktonic

245 species, such as *Staurosira construens* (80%) and *Staurosirella pinnata* (5-30%), and as a

246 secondary taxon *Cymbella crassistigmata* (<11%). *S. pinnata* diminished between BC 440 and 210

247 but recovered afterwards. A relative increase in the diversity of benthic and epiphytic taxa is

248 observed toward the top of this zone (e.g. *Amphora veneta*, *Gomphonema* spp. and *Cymbella*

249 *crassistigmata*). All of these species are classified as benthic, epiphytic and eutraphentic (nutrient-

250 rich) taxa.

251 **CHEP-D2 (BC 50 - AD 870):** Strong fluctuations in almost all diatoms species are observed in this

252 zone. *S. construens* shows a decrease to 5% at the base of the zone, recovers and, subsequently,

253 oscillates between 40-70%. An increase is also observed in the abundance of the eutraphentic and

254 epiphytic taxa, such as *C. crassistigamata (aff. cistula)* (13%), as well as fluctuating values of

255 benthic taxa, like *Amphora veneta.* In addition, this zone is characterized by short peaks of

256 *Craticula cuspidata* around 50 BC and AD 200.

257 **CHEP-D3 (AD 870 – 1900):** This zone is dominated by *S. construens* which fluctuates between 15

258 and 55%. Percent values of *C. crassistigmata* fluctuate and increase incrementally to 42%. The

259 values of *Epithemia adnata* (4 to 14%) and *Fragilaria* spp (up to 18%) also increase. *A. veneta*

260 shows a decreasing trend (10 to 1%).

261 **CHEP-D4 (AD 1900 – 1977):** In this zone, *S. construens* (30-50%) is dominant, but an increase in

262 abundance of *C. crassistigmata* (15-40%) also occurs. *A. veneta* increases towards the top of the

263 zone. *E. adnata* decreases from 24% to ~10%.

264 **CHEP-D5 (AD 1977 – 2006):** This zone shows an increase in the planktonic forms, such as

265 *Discostella stelligera*, which reaches 20%. During this zone, *S. construens* increases from 25 to

266 30% towards the present. *C. crassistigmata* and *E. adnata* fluctuate around ~20% and 8%,

267 respectively. *A. veneta* diminishes to ~1%.

268

269 **5. Interpretation and discussion**

270 **5.1. Interpretation of the fossil pollen and diatom records**

271   Based on the current distribution of vegetation belts, the pollen assemblage fluctuations allow an

272   inference of vertical shifts of the Andean plant communities (Fig. 1c). The growth of Andean plants

273   depends on soil moisture during the dry season, which stems mostly from melting snow that

274   accumulated during wintertime (Arroyo et al., 1981). In particular, the frequency of grasses in the

275   arid and semiarid Andes has been interpreted in terms of changes in effective moisture (Latorre et

276   al., 2002; Liu et al., 2005). Moreover, the lack of soil moisture could lead to low plant cover and

277   therefore, low pollen production (and low pollen accumulation rates). Although snow accumulation

278   depends on autumn-winter rainfall (90% of annual input), here, moisture-related changes in the

279   pollen assemblage, especially Poaceae taxa, are interpreted in terms of moisture availability and/or

280   total precipitation. On the other hand, temperature is also an important abiotic factor limiting growth

281   of some taxa (Arroyo et al., 1981). Thus, the cold-resistant taxa of high altitude regions (eg.

282   Apiaceae, Nassauvieae-tribe) and the cold-vulnerable taxa of lower altitudes allow us to infer

283   changes in temperature. Cold-vulnerable taxa include trees, shrubs, such as *Ephedra*, which is

284   sensitive to freezing and snow cover, and annual herbs, such as Chenopodiaceae) (eg. Cavieres et

285   al., 2000; Squeo et al., 1996).

286   In alpine freshwater environments high abundances of *Fragilaria* taxa (represented in Laguna

287   Chepical by tychoplanktonic species, Fig. 5c) and low frequencies of planktonic taxa occur when

288   the growing season is shorter due to longer periods of ice-cover (Hassan et al., 2013; Lotter and

289   Bigler, 2000). This favors the generalist species, such as *Staurosira construens* and *Staurosirella*

290   *pinnata* (Douglas and Smol, 2010; Lotter et al, 2010). With warming (and early break-up of ice-

291   cover) and a longer growing season, mosses and aquatic plants can expand, allowing epiphytic

292   taxa to proliferate and more diverse attached diatom communities to develop (Douglas and Smol,

293   2010). In Laguna Chepical, changes in the length of ice-cover are mostly controlled by late spring

294   and summer air temperatures (de Jong et al., 2013). As a consequence, changes in the abundance

295   of epiphytic and benthic diatoms relative to tychoplanktonic taxa should also reflect summer

296   temperature variability via its influence on the length of the open-water season.

297

298   5.2. Environmental history at Laguna Chepical inferred from pollen and diatom assemblages

299   Because the pollen and the diatom zonations are not exactly the same, the interpretation is made

300   considering the major changes in moisture and temperature patterns inferred from both proxies.

301   5.2.1. BC 1100 - AD 1

302   Lower Andean taxa are dominant (Fig. 5a). Relatively low PAR values (Fig. 5b) for a very short

303   interval around BC 1100 suggest a mountain environment with relatively scarce vegetation cover at

304   the initial phase of the record. The low charcoal influx (Fig. 5b) indicates low fire activity at lower

305   altitude areas. A peak in Montiaceae around BC 1000 suggests stony and bare wet soils (Teillier et

306   al., 2011; Wingenroth and Heusser, 1984) probably related to unstable substrates during an

307   isolated dry spell. After about BC 720, the increase of Poaceae percentages (~30% to~50%),

308   relatively high PARs and the decrease of *Ephedra* suggest a downward shift of the vegetation belts

309   and an increase in vegetation cover (relative to BC ~1100) associated with increased moisture.

310   These humid conditions persisted until ca 1 AD.

311   The diatom record shows an abundance of *Staurosira construen*s (Fig. 4), low abundances of

312   epiphytic and benthic taxa, and the almost total absence of planktonic taxa (Fig. 5c). Together

313   these patterns suggest a short growing season with prolonged ice-cover and low light availability

314   (Lotter and Bigler, 2000) in Laguna Chepical. This inference can be supported by the lower NDJF

315   temperatures at this time (Fig. 5d), especially prior to BC 800 (de Jong et al, 2013). The high

316   frequency of *Staurosirella pinnata* also suggests low nutrient availability (Michel et al., 2006) and

317   oligotrophic conditions. In summary, air temperatures were lower than today (compared with the

318   second half of the 20th century of the record) and higher precipitation are inferred around Laguna

319   Chepical during this time.

320   5.2.2. AD 1 – AD 800

321   High precipitation inferred from Poaceae persists, although Chenopodiaceae increase slightly (Fig.

322   3), but PAR is lower during this period (Fig. 5b). This may be interpreted as a slight increase in

323   temperature during the warm season. A moderate increase in fire activity inferred from charcoal

324   (Fig. 5b) is observed after AD 1. Today the occurrence of fire events in Central Chile is associated

325 mainly with major changes in the seasonality or inter-annual variability of precipitation. Humid years

326 produce a major accumulation of biomass that may burn in the next dry season (Altamirano et al.,

327 2013; González et al., 2011).

328 From around AD 500 onwards, increases in *Arenaria/Stellaria* (Fig. 3) and higher values of *A.*

329 *veneta* (Fig. 4) suggest an expansion of azonal plants that could be related to disturbance of the

330 shoreline and littoral areas (Markgraf et al., 2009). This can be associated with enhanced short-term

331 (annual) lake-level fluctuations.

332 More abundant benthic-epiphytic diatom species (*Cymbella crassistigmata*, *Amphora veneta*,

333 *Stauroneis* aff. *anceps* and *Epithemia adnata*) (Fig. 4) indicate periods of enhanced primary

334 production in the littoral zone of the lake during the growing season and likely warmer summers.

335 Also, the pronounced oscillations between tychoplanktonic and epiphytic taxa (also benthic taxa)

336 (Fig. 5c) at centennial time scales suggest strong variations in the ice-cover/summer temperatures.

337 This was also found in the summer temperature reconstruction from de Jong et al. (2013; Fig. 5d).

338 Periods with a high frequency of epiphytic and benthic taxa (around AD 1, 200, 450 and 750) are

339 almost all concomitant with mild warm peaks of NDJF temperatures. In contrast, periods of high

340 tychoplanktonic taxa percentages are associated with cooler summer temperatures around AD 100,

341 300 and 550 (Fig. 5c and 5d). During this period the biological record suggests a climate pattern

342 characterized by a marked seasonality and/or high inter-annual climate variability.

343

344 **5.2.3. AD 800 – AD 1800**

345 The decline of Poaceae to ~35% and the increase of sub-Andean (*Ephedra*, Mutisieae-tribe) and

346 Pre-andean elements (Euphorbiaceae, *Baccharis*-type, arboreal taxa) indicate an upward

347 displacement of taxa that are associated with reduced moisture. After AD 1350, Poaceae pollen

348 decreases to low values (~10%) suggesting drier conditions than today around AD 1545 and

349 around AD 1670. Fluctuations in Motiaceae suggest soil disturbance, possibly related to snowpack

350 reduction during dry periods. High percentages of cold tolerant taxa, such as *Azorella/Laretia* and

351 Nassauvieae-tribe, suggest a drop in temperatures. This is consistent with cold summers since AD

352   850 as inferred by de Jong et al. (2013, Fig. 5d). The reduction of fire activity suggests prolonged

353   dry conditions and biomass reduction in the lowlands.

354   Decreases in the frequency of tychoplanktonic taxa relative to the previous period and increases in

355   epiphytic and benthic taxa suggest a reduction in ice-cover on Laguna Chepical. However on sub-

356   millennial timescales, high values of tychoplanktonic taxa around AD 850-1000, 1500 and 1800

357   suggest periods of cooler summer temperatures that correspond with the low summer temperatures

358   recorded by de Jong et al. (2013, Fig. 5d). In contrast, low tychoplanktonic taxa are recorded

359   around AD 1250 and 1700 associated with early break up of ice-cover and, together with the

360   increase of benthic taxa, such *Epithema adnata* and *C. cuspidata* (Fig. 4), suggest higher nutrient

361   availability and littoral disturbance. Here, NDJF temperatures show cold anomalies during those

362   intervals.

363   In summary, pollen and diatom records suggest a decreasing moisture trend during this period

364   caused by decreased precipitation. Sub-millennial-scale variability in the extension of ice-cover in

365   the lake was pronounced, but with a general trend to shorter durations of the ice-cover.

366

367   **5.2.4. AD 1800 – AD 2006**

368   The recovery of Poaceae and the increase in PAR after AD 1800 (Fig. 5) indicate a return to

369   relatively humid and cool conditions that peaked around AD 1850-1900. After AD 1970, Poaceae

370   fall and the increase of Sub-Andean (*Ephedra*) and pre-Andean (Euphorbiaceae, Chenopodiaceae)

371   taxa indicates the upward movement of vegetation belts to modern altitudes (Fig. 3 and 5a). Plant

372   communities responded to the recent warming in the subtropical Andes (Falvey and Garreaud,

373   2009) and also to the increased frequency of dry years (Quintana and Aceituno, 2012). Additionally,

374   warmer summers would lead to lower lake levels allowing the expansion of *Arenaria/Stellaria* in the

375   shoreline. Moreover, the high frequency of the diatom species *D. stelligera, Ulnaria ulna* and

376   *Cocconeis placentula* suggests warm waters, enhanced thermal stratification, and/or increased

377   nitrogen loadings (Martínez de Marco and Triacanna, 2012; Saros and Anderson, 2014; Smol and

378   Stoermer, 2010). Major anthropogenic changes, such as the rise of pollen of non-native plants

379   (Asteraroideae-subfamily, *Plantago*, *Rumex* -not shown- and Urticaceae), are observed since AD

380   1850. This is related to the intensification of human activities in the area, such as cattle grazing.

381   After AD 1950, pollen of arboreal taxa decrease and charcoal fluxes reach maximum values

382   indicating high fire activity and a reduction of the woody plants in the lowland. This process can also

383   be related to human disturbances. Since AD 1975, the sclerophyllous montane and low altitude

384   woodlands and shrubland of central Chile have experienced a cover decline of 1.7% per year due

385   to land use changes, firewood/charcoal exploitation and human-set fires (Montenegro et al., 2004;

386   Schulz et al., 2010). Human-related diatom changes are evident in the increase in planktonic

387   species (*Stephanodiscus* spp. and *Discotella stelligera*) after AD 1885/1900 (Fig. 4) as the result of

388   the artificial dam built in AD 1885. This dam prompted a lake level rise and slight eutrophication.

389   In summary, the Laguna Chepical pollen record shows the wettest periods between 700 BC

390   and AD 700 and the driest period around AD 1400-1800. On the other hand, the diatom record

391   shows high variability at sub-millennial time scales associated with the length of the ice-cover on the

392   lake. Variability is more pronounced during the last 2000 years.

393

394   **5.3. Late Holocene regional paleoclimate evolution**

395   Laguna Chepical shows relatively wet conditions during the late Holocene, which is coherent with

396   other paleoclimatological records between 27°S and 34°S located in coastal areas (such as

397   Quintero and Palo Colorado; Maldonado and Villagrán, 2006; Villagrán and Varela, 1990), in the

398   lowlands (Laguna Aculeo, 33°50'S; 350 m a.s.l.; Jenny et al., 2003; Villa-Martínez et al., 2003), in

399   marine records of Central Chile (Lamy et al., 1999), and in Andean areas between 27°-33°S

400   (Grosjean et al., 1997; Veit, 1996). These moist conditions were associated with an equatorward

401   expansion of the Southern Westerlies Wind Belt (SWWB) relative to patterns during the early and

402   mid-Holocene (Lamy et al., 2010).

403   In more detail, high Poaceae values (Fig. 6a), extended ice-cover inferred by the diatom record

404   (Fig. 5c) and lower NDJF temperatures (Fig. 5d) suggest particularly wet conditions and relatively

405   cold summer temperatures (Fig. 5d) at Laguna Chepical between 1100 BC – 1 AD. This is

406 consistent with documented glacier advances ca. 3000-2200 cal yr BP (BC 1000-200) (Fig. 6d)

407 (Grosjean et al., 1998). Wet years are strongly correlated with increased snowpack (Masiokas et al.,

408 2006; Masiokas et al., 2010), whereas changes in the equilibrium line altitude of glaciers are

409 dependent on summer temperatures (Carrasco et al., 2005), suggesting that, during the first

410 millennium BC, extended snow cover occurred in the basin of Laguna Chepical.

411 Since AD 1, Laguna Chepical displays a shift from wet and relatively cool stable conditions toward

412 increased seasonality and/or high inter-annual climate variability, as suggested by the expansion of

413 warm plant taxa (eg. Chenopodiaceae), aquatic shoreline disturbance indicators

414 (*Arenaria/Stelleraria*, especially after AD 500), increased epiphytic and benthic taxa and a mild

415 increase in fire activity. These changes to higher variability are typical for a major influence of the El

416 Niño - Southern Oscillation (ENSO). ENSO plays a key role in the inter-annual to decadal variability

417 of rainfall and temperature in central Chile (Garreaud et al., 2008; Montecinos and Aceituno, 2003;

418 Quintana and Aceituno, 2012). Paleorecords from western tropical South America indicate a peak

419 in ENSO activity around 2000 yrs BP (Jenny et al., 2003; Moy et al., 2002; Rein et al., 2005;

420 Riedinger et al., 2002; Rodbell et al., 1999; Rodbell et al., 2008). Given the high negative

421 correlation of the Southern Oscillation Index (SOI) and rainfall in the research area (Fig. 1a)

422 (Quintana and Aceituno, 2012), we compare the annually interpolated Poaceae percentage (as our

423 best moisture indicator) and the annually reconstructed SOI index from Yan et al. (2011) for the

424 past 2000 years (Fig. 6b; the window for the running correlations is 500 years). While there was no

425 correlation between Poaceae frequency (Fig. 6a) and SOI in the 1st Millennium AD, strongly

426 negative correlations were observed during the last millennium (AD 1100-1750; running correlation

427 ~R= -0.8) (Fig. 6c), suggesting that phases with negative SOI (El Niño-like mean conditions) are

428 correlated with high moisture at our study site, whereas periods with positive SOI (La Niña-like

429 mean conditions) correlate with periods of low moisture. This applies mostly to winter precipitation

430 and is consistent with diagnostics from current climatology (Quintana and Aceituno, 2012).

431

432 From around AD 1000 onward, conditions wetter-than-today are maintained, although at a slightly

433 lower level than during the previous period. In addition, extended ice-cover is inferred, except

434   around AD 1250, where the earlier break-up is inconsistent with the continuous cold summer

435   temperatures since AD 800 in Laguna Chepical (Fig. 5d) (de Jong et al, 2015). Conversely, warm

436   summers are also recorded in the lowlands at this time and attributed to the Medieval Climate

437   Anomaly (MCA: AD 1000-1400) between AD 1150 and AD 1350 (von Gunten et al., 2009). It is

438   possible that only the diatom community responded to minor changes in the length of ice-cover at

439   this time. More evident in the diatom (Fig. 5c) and clay content record (Fig. 5d) are the cold

440   conditions during the Little Ice Age (LIA: 1400-1850), associated with relatively low summer

441   temperatures. This is also recorded in the lowlands (von Gunten et al., 2009). Interestingly, the

442   warm summers during 18th century, are also found in summer temperature reconstructions in

443   southern South America (Neukom et al, 2010).

444   Relatively dry pulses during the LIA in Laguna Chepical (Fig. 6a) are also observed in palynological

445   records the Andes (Lake Laja, 36° 54°S; 1360 m a.s.l.), in coastal records at 32°S (Fig. 6e)

446   (Maldonado and Villagrán, 2006) and Andean tree-rings records between 32° and 38°S. Here, the

447   driest decades are concentrated between the 16th and the mid-18th century (Le Quesne et al., 2009;

448   Masiokas et al., 2012). The short but distinct cold and wet pulse around AD 1600 (Fig. 6a) observed

449   in Laguna Chepical is concomitant with glacier advances in the eastern subtropical Andes (Fig. 6d)

450   (Espizua, 2005; Espizua and Pitte, 2009). At the same time, high flood frequency and freshwater

451   conditions between AD 1400 and 1600 were inferred in lowland Laguna Aculeo (Fig. 6f, 33'50°S)

452   (Jenny et al., 2002). Finally, the mid-19th century wet pulse (Fig. 6a) and glacier re-advances (Fig.

453   6d) are consistent with a shift toward a negative SOI phase. In general, our findings are also in

454   agreement with studies in the south central Andes (Laguna San Pedro; 38°26'S; 913 m a.s.l.),

455   which indicate that during the MCA El Niño-like mean conditions prevailed, whereas during the LIA,

456   La Niña-like mean conditions dominated (Fletcher and Moreno, 2012).

457   The last 100 yrs provide evidence for the sensitive response of Andean plants to multi-year to multi-

458   decadal precipitation changes. The positive SOI during the 1950-1970s (Quintana and Aceituno,

459   2012), combined with the warmest summers between the 1940s and 1970s (de Jong et al., 2013),

460   suggest not only a reduction in moisture, but also altitudinal shifts in plants, such as the upward

461   movement of Pre-Andean species and the expansion of azonal taxa (Fig. 3 and 5a). Additionally,

462   the significant rise of planktonic diatom taxa after AD 1980, particularly *Discostella* species, could

463   be a response to the recent warming shift in temperatures. This has also been observed in many

464   alpine and high-latitude lakes in the Northern Hemisphere (Enache et al., 2011; Karst-Riddoch et

465   al., 2005; Rühland et al., 2008).

466   The changes in the landscape seen today in the Andean cordillera are unprecedented, at least for

467   the last 3100 years. In the context of the last 100 years, humans became the main catalysts in the

468   degradation of ecosystems; they added additional stress and pressure on the survival of plant

469   communities (Beniston, 2003). The fire peaks since the 1960s combined with decreases in arboreal

470   taxa (Fig. 3) suggest that the modern fire regime is human-related. Moreover, the National Forest

471   Corporation (CONAF: www.conaf.cl) fire records for this region (AD 1976-2006) show that, between

472   AD 1984 and 1991, 100,000 ha were burned. This is twice the rate compared with the preceding

473   seven years (1976-1983) when 50,000 ha were burned. Furthermore, ENSO events (ie. 1982/1983)

474   may have stimulated wildfires due to higher biomass accumulation available to burn (González et

475   al., 2011). However, the return to a higher occurrence of Poaceae and PAR values during the late

476   1980s and the 1990s, which was concomitant with the increase of wet years mostly related to the

477   warm phase of ENSO (Quintana and Aceituno, 2012), supports previous studies indicating the

478   importance of El Niño events in reducing the water deficit in high mountain regions (Christie et al.,

479   2011; Holmgren and Scheffer, 2001; Vuille and Milana, 2007).

480

481   **6. Concluding remarks**

482   We report significant climate-driven changes in the high Subtropical Andean plant and diatom

483   communities as revealed by a sediment record from an Andean lake during the past 3100 yrs. Both

484   pollen and diatom records show variability at millennial to sub-centennial timescales and, during the

485   past century, at multi-annual to multi-decadal scales. The main responses of vegetation are

486   modulated by moisture coming from precipitation associated with the SWWB. To a lesser extent,

487   temperature also plays a role in the plant distribution, especially for the lowland taxa. In Laguna

488   Chepical, the diatom assemblages responded to the lake ice-cover dynamics, which is affected by

489   the late-spring/summer temperature regime. Wet and relatively cold phases characterized the early

490   late-Holocene (BC 1100 - AD 1) in Laguna Chepical. Since around AD 1, wet conditions persisted.

491   However, high variability in diatom assemblages suggests sub-millenial variations in the ice-cover,

492   which are similar to the late-spring/summer temperatures changes observed in de Jong et al.

493   (2013). During the last millennium, moisture variability in this region was likely related to the

494   Southern Oscillation: the MCA was relatively wet consistent with El Niño-like mean conditions;

495   whereas the LIA was relatively dry and cold reflecting La Niña-like mean conditions. Nevertheless,

496   wet events were also present, especially around AD 1600. The warming trend, drought and human-

497   related activities produced important changes in the diatom and plant communities, first around

498   1885/1900 (dam build) and then, since the mid-20th century.

499

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507

508   **7. References**

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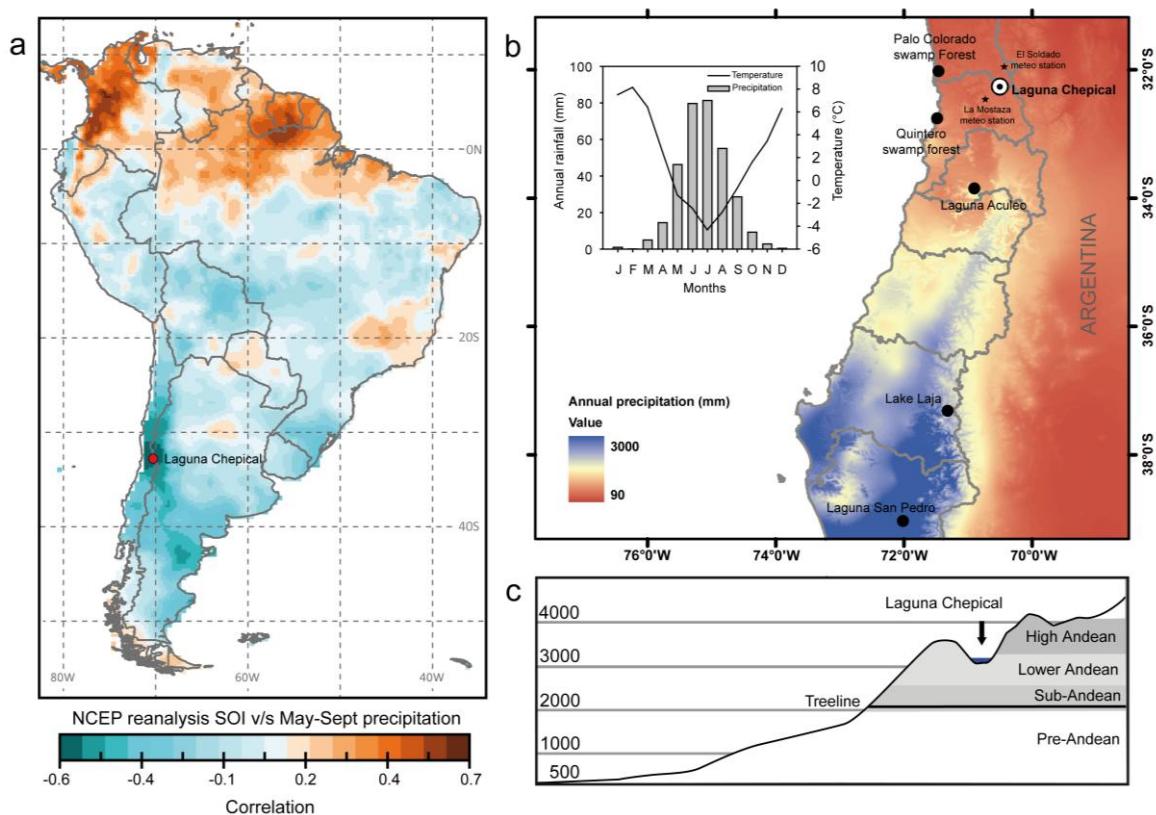
FIGURES



Figure 1. a) Map of South America showing the spatial correlation between austral winter rainfall and the Southern Oscillation Index (NCEP reanalysis, NOAA) and the location of the study area. Note the strong negative correlation in the region of Laguna Chepical. b) Details of the study area showing Laguna Chepical and the nearest paleorecords discussed in the text, and the gradient of annual precipitation. The ombrothermic graph shows the annual distribution of temperature (El Soldado meteorological station, 32°S, 70°19W, 3290 m a.s.l.) and precipitation (La Mostaza meteorological station, 32°25'S, 70°40'W, 1200 m a.s.l.). c) Altitudinal vegetation belts of the study area.
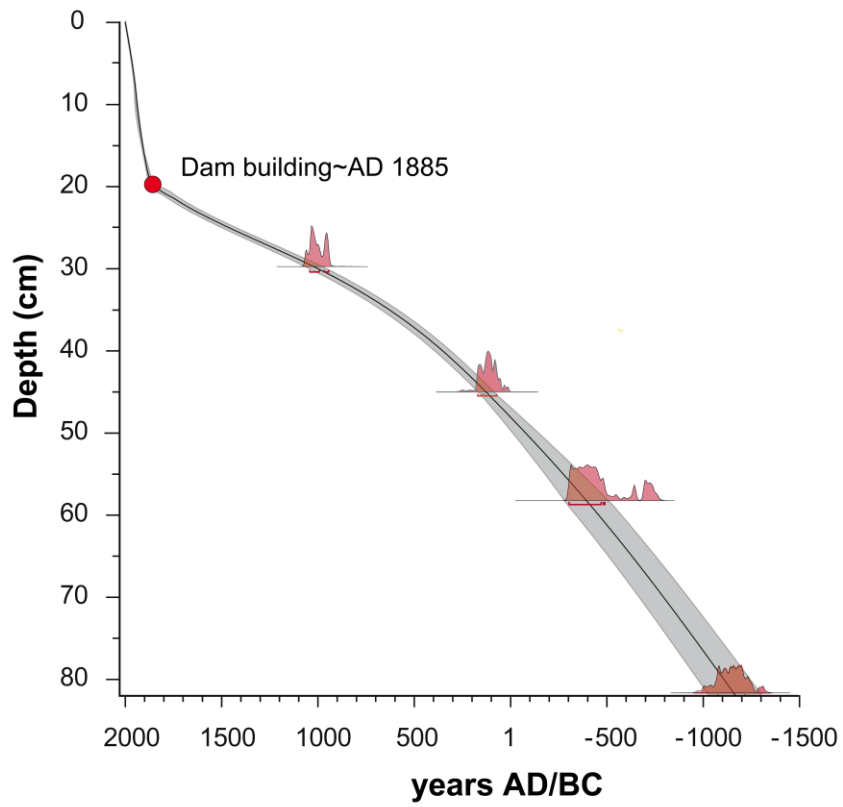
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754 **Figure 2.** Age versus depth model of Laguna Chepical (from de Jong et al., 2013).

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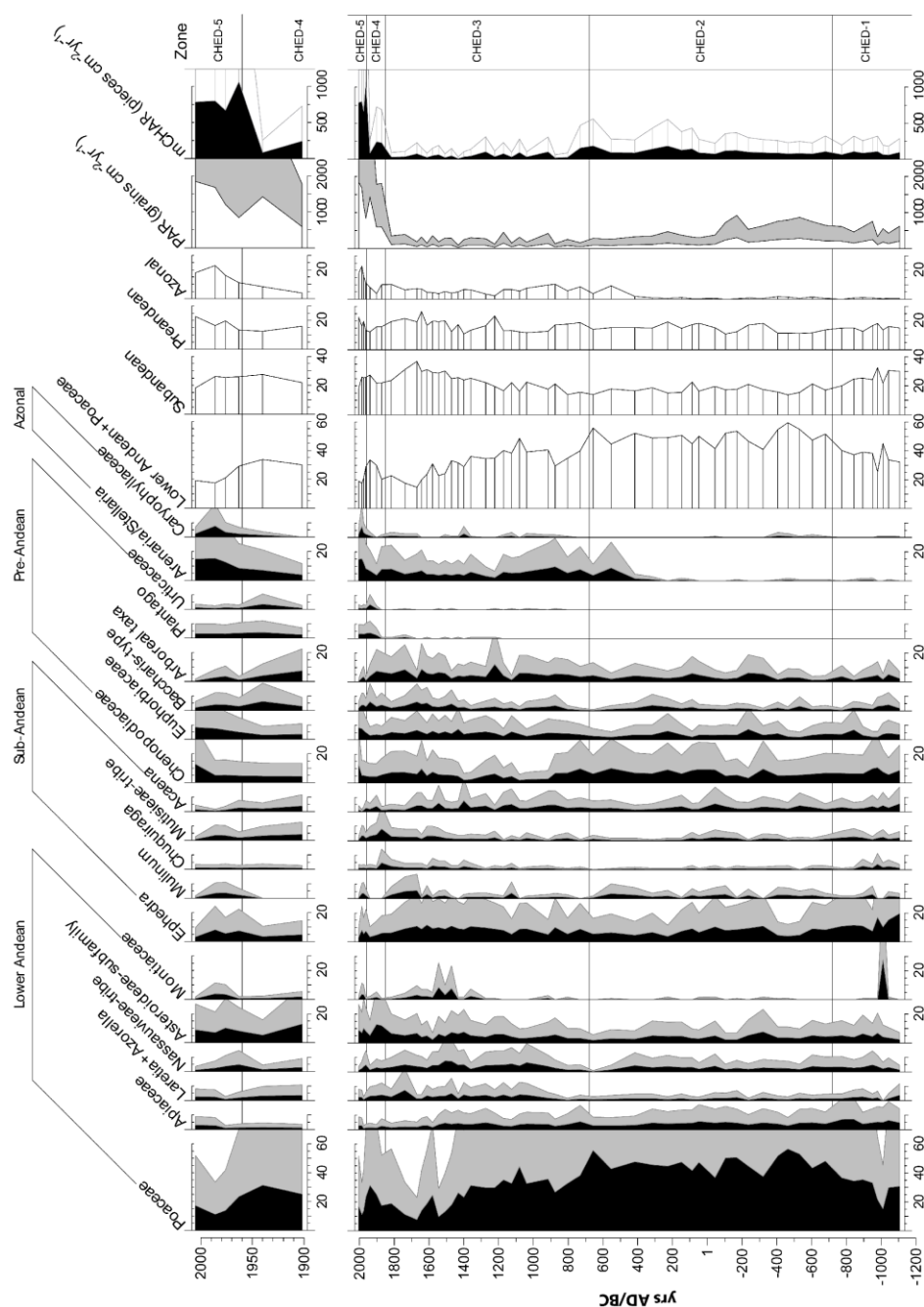
Figure 3. Pollen diagram of Laguna Chepical showing the percentage of the main taxa, pollen

758   accumulation rates (grains cm^{-2} yr^{-1}) and microscopic charcoal accumulation rates (particles cm^{-2} yr^{-1}

759   ^{1}). The top figure is a zoom for the last 100 yrs. Grey shadows express an exaggeration by factor 3.
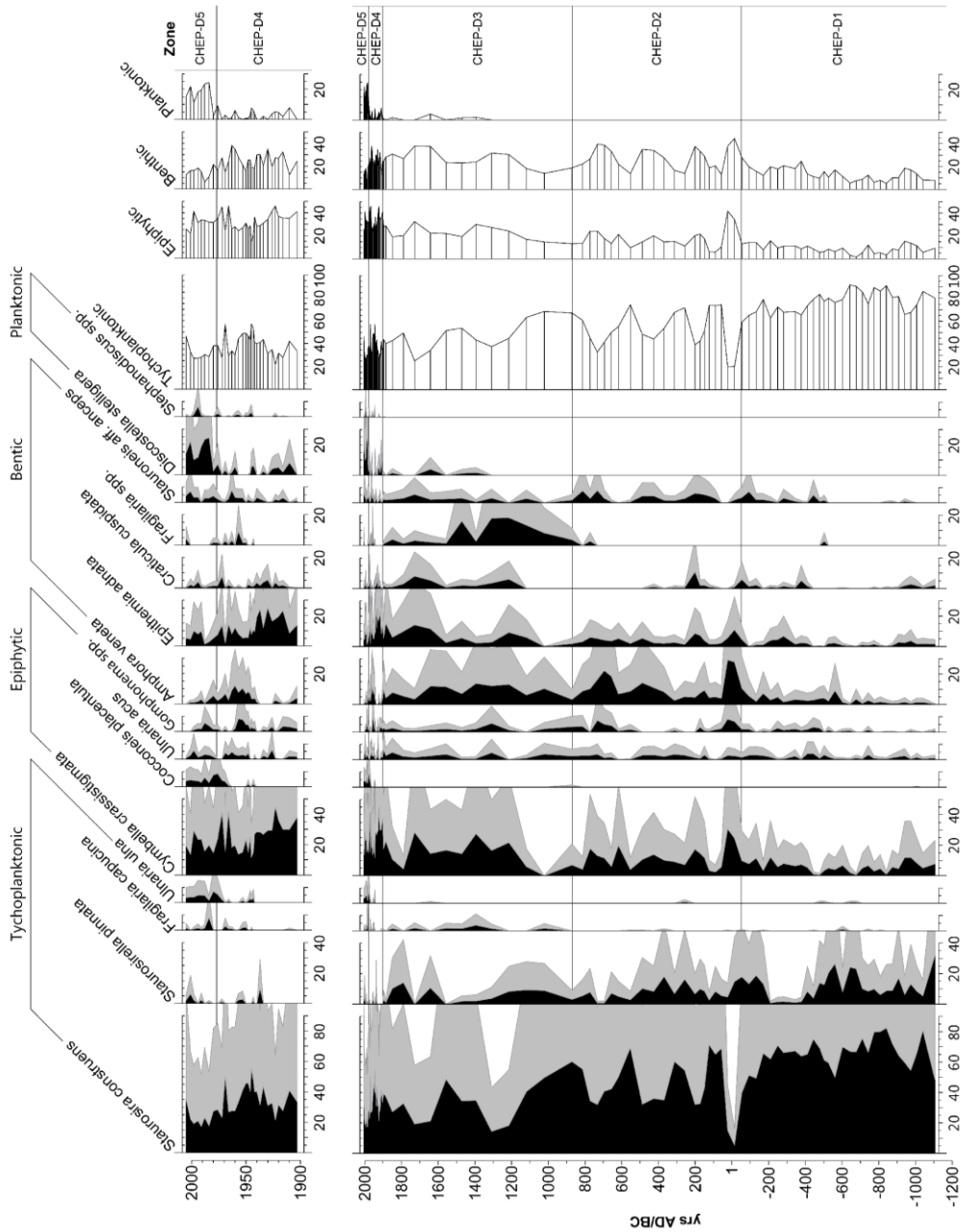
Figure 4. Diatom diagram of Laguna Chepical showing the percentages of the main taxa. The top figure is a zoom for the last 100 yrs. Grey shadows express an exaggeration by factor 3.

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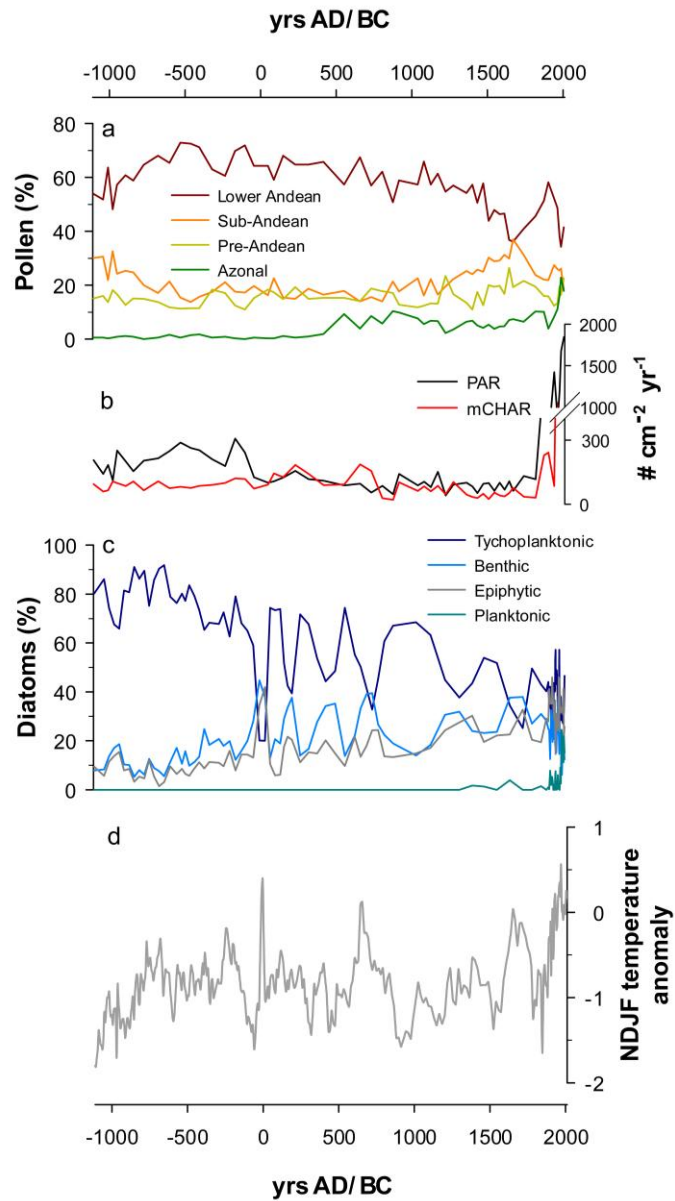
Figure 5. Summary figure of Laguna Chepical: a) Pollen percentages of the vegetation belts; b) Pollen accumulation rates and microscopic charcoal accumulation rates; c) Diatom life form percentages; d) NDJF temperature anomalies (de Jong et al., 2013).

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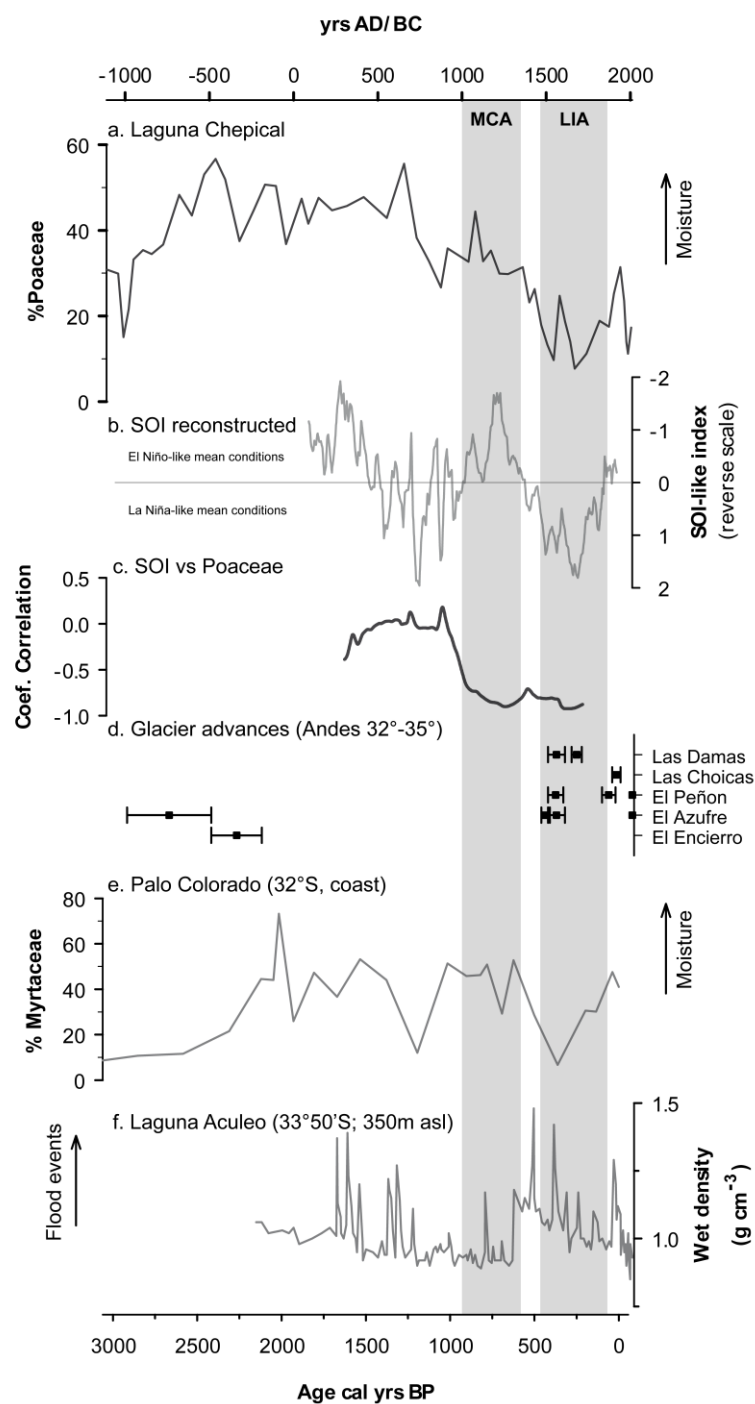
Figure 6. Main results of the Laguna Chepical record and comparison with other records. a) Percentage of Poaceae of Laguna Chepical; b) Southern Oscillation Index AD 50 – 1950 from Yan et al. (2011; note: reverse scale). c) Running correlation between annually interpolated percentages

772   of Poaceae and SOI (AD 300-1700; window width of 500 years; p-vaule < 0.05). First and last 250

773   yrs are cut-out in order to avoid edge effects.; d) Glacier advances in the subtropical Andes

774   (Grosjean et al., 1998; Espizua, 2005; Espizua et al., 2009); e) Myrtaceae percentage of swamp

775   coastal forest of Palo Colorado (Maldonado and Villagrán, 2006); f) Wet density (g cm^{-3}) of Laguna

776   Aculeo (Jenny et al., 2002).