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Eastern Andean environmental and climate synthesis for the last 2000 years BP from terrestrial pollen and charcoal records of Patagonia

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Abstract

The Southern Hemisphere Westerly Winds (SWW) constitute an important zonal circulation system that dominates the dynamics of Southern Hemisphere mid-latitude climate. Little is known about climatic changes in the Southern South America in comparison to the Northern Hemisphere due to the low density of proxy records, and adequate chronology and sampling resolution to address environmental changes of the last 2000 years. Since 2009, new pollen and charcoal records from bog and lakes in northern and southern Patagonia at the east side of the Andes have been published with an adequate calibration of pollen assemblages related to modern vegetation and ecological behaviour. In this work we improve the chronological control of some eastern Andean previously published sequences and integrate pollen and charcoal dataset available east of the Andes to interpret possible environmental and SWW variability at centennial time scales. Through the analysis of modern and past hydric balance dynamics we compare these scenarios with other western Andean SWW sensitive proxy records for the last 2000 years. Due to the distinct precipitation regimes that exist between Northern (40–45° S) and Southern Patagonia (48–52° S) pollen sites locations, shifts on latitudinal and strength of the SWW results in large changes on hydric availability on forest and steppe communities. Therefore, we can interpret fossil pollen dataset as changes on paleohydric balance at every single site by the construction of paleohydric indices and comparison to charcoal records during the last 2000 cal yrs BP. Our composite pollen-based Northern and Southern Patagonia indices can be interpreted as changes in latitudinal variation and intensity of the SWW respectively. Dataset integration suggest poleward SWW between 2000 and 750 cal yrs BP and northward-weaker SWW during the Little Ice Age (750–200 cal yrs BP). These SWW variations are synchronous to Patagonian fire activity major shifts. We found an in phase fire regime (in terms of timing of biomass burning) between northern Patagonia Monte shrubland and Southern Patagonia steppe environments. Conversely, there is an antiphase fire regime between

Northern and Southern Patagonia forest and forest-steppe ecotone environments. SWW variability may be associated to ENSO variability especially during the last millennia. For the last 200 cal yrs BP we can concluded that the SWW belt were more intense and poleward than the previous interval. Our composite pollen-based SWW indices show the potential of pollen dataset integration to improve the understanding of paleohydric variability especially for the last 2000 millennial in Patagonia.

1 Introduction

The Southern Hemisphere Westerly Winds (SWW) constitute an important zonal circulation system that dominates the dynamics of Southern Hemisphere mid-latitude climate. Furthermore, they influence the global ocean circulation through wind-driven upwelling of deep water in the Southern Ocean and may play a significant role in the global climate system through the control of the CO_2 budget in the Southern Ocean (Anderson et al., 2009; Toggweiler et al., 2006; Varma et al., 2011). The understanding of the variability and the impact of various forcings on the SWW has been discussed by the study of different proxy and modelling approaches especially at millennial time scales during the Holocene (e.g. Fletcher and Moreno, 2011; Kilian and Lamy, 2012; Lamy et al., 2001, 2010; Varma et al., 2012; Whitlock et al., 2007). Little, however, is known about climatic changes in the Southern Hemisphere in comparison to the Northern Hemisphere due to the low density of proxy records, and adequate chronology and sampling resolution to address environmental changes of the last 2000 years (Moy et al., 2009; Villalba et al., 2009). Nevertheless, the few available records point towards significant fluctuations in both temperature and precipitation occurring during this period (Jones and Mann, 2004; Masiokas et al., 2009; Tonello et al., 2009). On this time scale orbital boundary conditions only changed slightly and thus internal variability, solar and volcanic forcing played a dominant role before the humans became noticeable (Jones and Mann, 2004; Wilmes et al., 2012).

The “Little Ice Age” (LIA) usually refers to climatic anomalies over the Northern Hemisphere between the 13th and mid-19th century (750–150 cal yrs BP). The LIA is well documented in northern Europe and North America, where a huge variety of chronicles, historical documents, proxy-based reconstructions and also temperature measurements indicate cooler and wetter conditions (Meyer and Wagner, 2008). Within LIA, a period with even lower temperatures was the Maunder Minimum (MM; AD 1645–1715/305–235 cal yrs BP). Proxy and modelling studies point to a prominent influence of solar forcing causing the MM (Eddy, 1976; Zorita et al., 2004). At the beginning of the last millennium, a period of warmer conditions, especially over Europe, has been documented: the so-called Medieval Warm Period (MWP; ca 9th–13th centuries/1150–750 cal yrs BP; Jones et al., 2001; Osborn and Briffa, 2006). Recently, Neukom et al. (2010, 2011, 2014) points to a number of climatic variations occurring during the last millennium in Southern South America. The authors showed that the Southern Hemisphere response to external forcing may be delayed in approximately two centuries respect to Northern Hemisphere medieval times with high temperatures and coherent extreme cool conditions in both hemispheres around AD 1600 (350 cal yrs BP).

Pollen records derived from lakes and bogs represent one of the most abundant paleoclimate archives in South America. Since the pioneering work by Auer (1933, 1958), many studies have reconstructed the ecological and climatic history over the Pleistocene and Holocene periods at millennial time scale (e.g. Heusser and Heusser, 2006; Mancini et al., 2008; Markgraf et al., 2003; Moreno et al., 2009). There are few pollen based paleoenvironmental reconstruction with highly-precise chronology in Patagonia for the last millennia (Fletcher and Moreno, 2012b; Huber and Markgraf, 2003a; Moreno et al., 2014; Whitlock et al., 2006; Wille et al., 2007). These authors presented different Patagonia climatic variability scenarios for the last 2000 years. Moy et al. (2009) and Kilian and Lamy (2012) suggest that the different signal shown in these data set could be attributed to the location of the records in different ecological environments; the depositional environment, and local differences in the sensitivity of eastern Andean vegetation ecotones to changes in precipitation.

Since 2009, new pollen and charcoal records from bog and lakes in northern and southern Patagonia at the east side of the Andes have been published with an adequate calibration of pollen assemblages related to modern vegetation and ecological behaviour (Bamonte and Mancini, 2011; Bamonte et al., 2014; Echeverria et al., 2014; Iglesias, 2013; Iglesias and Whitlock, 2014; Iglesias et al., 2012, 2014; Mancini, 2009; Marcos et al., 2012a, b; Sottile et al., 2012; Sottile, 2014). In this work we improve the chronological control of some eastern Andean previously published sequences and integrate pollen and charcoal dataset available east of the Andes to interpret possible environmental and SWW variability at centennial time scales. Through the analysis of modern and past hydric balance dynamics we compare these scenarios with other western Andean SWW sensitive proxy records for the last 2000 years.

2 Modern eastern Andean Patagonia environmental setting

2.1 Climate

Most of Patagonia is dominated by air masses coming from the Pacific Ocean. The Patagonian region is located between the semipermanent anticyclones of the Pacific and the Atlantic oceans at approximately 30° S and the subpolar low pressure belt at approximately 60° S (Prohaska, 1976). The strong, constant west winds (westerlies) are dominant across the region. The seasonal movement of the low and high pressure systems and the equatorward ocean currents determine the precipitation pattern. During winter, the subpolar low is more intense. This situation, combined with the equatorial displacement of the Pacific High Pressure System and with ocean temperatures that are higher than the continental temperatures, leads to an increase in precipitation during this season. The northeastern and the southeastern parts of the region are additionally affected by air masses coming from the Atlantic Ocean. This Atlantic influence results in a more even seasonal distribution of precipitation in this part of Patagonia (Paruelo et al., 1998).

The Andes play a crucial role in determining the climate of Patagonia. The north–south distribution of the mountains imposes an important barrier for humid air masses coming from the Pacific Ocean. Most of the water in these maritime air masses is dropped on the Chilean side, and air becomes hotter and drier through adiabatic warming as it descends on the Argentine side of the Andes (Fig. 1a). The westerlies are strongest during austral summer, peaking between 45 and 55° S. During austral winter, the jet stream moves into subtropical latitudes (its axis is about 30° S) and the low-level westerlies expand equatorward but weaken, particularly at ~ 50° S (Garreaud et al., 2009) (Fig. 1b).

Over Patagonia, the inter-annual correlation between precipitation and zonal wind at 850 hPa (U850) using annual means exhibits positive values increasing from Pacific to a maximum along the Chilean coast and the western slope of the Andes ($r(P,\mathrm{U850}) \sim 0.8$), a sharp transition just to the east of the mountain ridge and negative values over the Argentinean Patagonia. During years with stronger than average westerly flow features increased precipitation to the west of the Andes and decreased precipitation over the lowlands to the east. The marked west-east precipitation gradient over Patagonia is always present but it is slightly less in those years with weaker than average westerly flow aloft (Garreaud et al., 2013).

When averaged over the year, an ENSO warm event (positive multivariate ENSO index values) is associated with an overall decrease in the strength of the wind field and a slight reduction in precipitation in western Patagonia (Moy et al., 2009). Northern Patagonia exhibits an overall reduction in summer precipitation and warmer surface air temperature. Of particular relevance is the frequent occurrence of long-lived, tropospheric deep anticyclonic anomalies west of the southern tip of South America (below 40° S and centered at 50° S, 100° W) during El Niño years (Rutllant and Fuenzalida, 1991). These phenomena favour a northward displacement of the storm tracks between 33 and 39° S (Garreaud and Aceituno, 2007; Garreaud et al., 2009; Montecinos et al., 2000; Moreno et al., 2010). During negative multivariate ENSO index values (La Niña like), the South Pacific anticyclone strengthen and moves southward (Aceituno, 1988). Similarly, during the positive phase of Southern Annular Mode (SAM), the SWW intensifies and moves southward, decreasing precipitation above 48° S, favouring the occurrence of forest fires between 39 and 48° S (Holz and Veblen, 2011; Mundo et al., 2013; Veblen et al., 1999; Villalba et al., 2012).

2.2 Northern Patagonia vegetation

Eastern Andean communities in Northern Patagonia between 40 and 44° S present four major transitions. The first (ca 72° W) from tree/epiphyte species rich Valdivian rainforest to structurally more simple poor species *Nothofagus*-dominated forests. This transition zone coincides approximately with eastern areas of low Andean longitudinal valleys and where precipitation drops below ca 3000–2500 $\text{mm}\,\text{yr}^{-1}$. A second sharp transition occurs further east (ca 71.6° W) where the continuous *Nothofagus* forest cover breaks up giving rise to first patchy but further east more extensive species rich shrublands composed of heliophyllous species (Iglesias et al., 2014). This transition occurs where annual precipitation drops below ca 1800 $\text{mm}\,\text{yr}^{-1}$. Finally, a third transition takes place at ca 71–71.2° W where easternmost small outpost trees population (*Nothofagus pumilio* and *Austrocedrus chilensis*) intermingle within the Patagonian steppe matrix. This transition coincides with rainfall areas below ca 600–800 $\text{mm}\,\text{yr}^{-1}$ (Iglesias et al., 2014). South of 44° S, *Austrocedrus chilensis* disappear and only *Nothofagus* tree patches intermingle between steppe patches (Veblen et al., 1997). Patagonian grass and shrub steppes cover plains and plateaus eastward $\sim$ 70° W between 600 and 300 $\text{mm}\,\text{yr}^{-1}$, with a significant decrease on above-ground vegetation cover following precipitation gradient (León et al., 1998). Below 300 $\text{mm}\,\text{yr}^{-1}$, Patagonian steppe is replaced by “Monte” shrubland vegetation (Fig. 1a). Monte shrub communities are arranged as two-phase mosaic composed by a phase of perennial grasses and shrub-dominated patches alternating with sparse cover (Bisigato et al., 2009).

2.3 Southern Patagonia vegetation

South of 47° S, the forest communities impoverished due to the low temperatures of the growing season. Mixed evergreen-deciduous forest of *Nothofagus betuloides* and *N. pumilio* develop on eastern Andean lowland areas with annual precipitation above 800 mm yr^{-1} (Mancini et al., 2008). Between 1000 and 600 mm of annual precipitation closed deciduous forest of *N. pumilio* develop from the tree line to lowlands. These closed forest communities become progressively open with tree patches of *N. pumilio* and *N. antarctica* with high cover of tall xerophytic shrubs and grass species between 600 and 400 mm yr^{-1}. Eastward between 400 and 200 mm yr^{-1} a grass steppe covers a narrow and discontinuous strip along the extra-Andean and the Patagonian plateau and the southeastern tip of the continent dominated by *Festuca* spp., cushions plants and isolated shrub patches (Boelcke et al., 1985; Mancini et al., 2012). At the Patagonian plateau, the shrub steppe distribution is primarily related to the availability of water which is actually controlled by unpredictable precipitation inputs, runoff redistribution and edaphic diversity and is clearly reflected by the vegetation differences between the plateaus and valley and ravines (“cañadones”) (Mancini et al., 2012).

2.4 Fire regime

The occurrence of wildfires is largely controlled by climatic variability through its action of modifying fine fuel build up rates and fuel desiccation. On the easternmost Patagonian communities where steppe bunchgrasses dominate, fires are limited by fuel amounts and continuity (Kitzberger, 2012; Sottile et al., 2012). Because fine fuels (grasses) are highly responsive to precipitation pulses, during rainy growing seasons, systems that normally do not spread efficiently due to lack of fuel loads suddenly become more prone for developing large fires (Morgan et al., 2003). Years with high net primary productivity and rainy springs/summers have also been highlighted as factors favouring fire occurrence in Monte shrubland communities (Hardtke, 2014).

Further west in the transition or higher in altitude, in the realm of the tall *Nothofagus* forests fine fuels are less important and coarse fuels that require long drying periods dominate. Here fires are exclusively associated to strong droughts lasting several months, beginning during the winter, the time when soils are replenished with water (Kitzberger, 2012). Whenever dry winter-springs associate with warm summers, wet forests ignite and spread fire without significant natural fire breaks (Mermoz et al., 2005). These strong drought events not only produce larger fires but also more severe events that create conditions that provide less regeneration opportunities to obligate seed dispersed species (such as *N. dombeyi* or *N. pumilio*; Kitzberger et al., 2005) and more opportunities for the rapid expansion of resprouting shrubland species. Markgraf and Anderson (1994) postulated that even though lightning are scarce in southern Patagonia, they might have been more frequent in the past under different climatic conditions as fire ignition sources.

3 Material and methods

In order to reconstruct the past 2000 years of environmental variability on different landscapes of eastern Andean Patagonia, we selected continuous pollen and charcoal records from lakes and peat-bogs (Table 1) where data sets fulfil some qualitative criteria explained as follows:

Dataset availability: pollen records previously published and available at Neotoma Paleoecology Database (http://www.neotomadb.org) and pollen/charcoal records from Paleoecology and Palynology Lab database (UNMdP-IIMyC, CONICET).

Chronology and temporal resolution: proxy data series must have a chronology based on more than 2 dating for the last 2300 yrs BP. The time series should at least have a mean sampling resolution of one sample 200 $\mathrm{yr\,s^{-1}}$.

Also, the sites selected for this work, fulfil more than four criteria of 2 K proxy records for paleoclimate reconstructions according to the PAGES-2 K criteria (see Supplement, Sect. 3, for details).

We constructed past pollen-based paleohydric balance indices. Main pollen taxa were considered suggesting above/below hydric availability at every site, following paleoecological and modern pollen-vegetation calibrations highlighted on previous published works (Bamonte and Mancini, 2011; Bamonte et al., 2014; Bianchi and Ariztegui, 2012; Echeverria et al., 2014; Iglesias, 2013; Iglesias and Whitlock, 2014; Iglesias et al., 2012, 2014; Mancini, 2007, 2009; Mancini et al., 2012; Marcos and Mancini, 2012; Marcos et al., 2012a; Paez et al., 2001; Sottile et al., 2012; Sottile, 2014). Each paleohydric balance was calculated as the standardized ratio between the sum (in percentages) of positive hydric availability taxa and the sum of negative hydric availability taxa (see Supplement, Sect. 4 for details). Standarization of every ratio was calculated by subtracting the mean and dividing by the standard deviation. In order to highlight the general trend of every site index, we apply a locally weighted scatterplot 0.2 smoothing spline (Cleveland, 1979, 1981) and plotted the 95 % confidence band based on a 999 bootstrap replicate technique. Modern hydric balance of every site (Table 1) was compared to paleohydric values in reference to the pollen samples with an age of ca AD 1900 of every record (preventing possible changes on pollen spectra related to European settlement).

Also, composite pollen-based indices for Northern and Southern Patagonia were performed using all dataset available for each region. In order to highlight the general positive/negative trends of every region index, we applied a locally weighted 0.2 smoothing spline and plotted the 95 % confidence band based on a 999 bootstrap replicate technique.

4 Results

4.1 Northern Patagonia

Northern Patagonian pollen based paleohydric balance allow us to reconstruct past variability especially in terms of seasonality. Assuming that Northern Patagonian forest and Monte shrubland development, are favoured by spring-summer rain, positive (negative) values suggest above (below) average spring-summer precipitation. *Nothofagus*-*Austrocedrus* forest and *Nothofagus* forest/steppe transitions records present mainly negative values between 1600 and 750 cal yrs BP (Fig. 2b–d). Since 750 cal yrs BP, there is a raising trend to positive paleohydric values peaking ca 250–300 cal yrs BP (Fig. 2b–d). On the contrary, Lake Trébol present the opposite trend during the last 2000 yrs. The comparison of past paleohydric balance to modern hydric balance suggest $> 493.7\,\mathrm{mm\,yr^{-1}}$ in Lake Trébol; $< 8.60\,\mathrm{mm\,yr^{-1}}$; $< 143.2\,\mathrm{mm\,yr^{-1}}$ in Lake Mosquito and $< 268.4\,\mathrm{mm\,yr^{-1}}$ in Mallín Pollux between 1600 and 750 cal yr BP.

Even though Bajo de la Quinta shows mainly negative values, its general paleohydric trend follows general forest and forest-steppe transition records behaviour, showing the major paleohydric values after 750 yrs BP (Fig. 2e). A comparison with modern hydric balance values, suggests Bajo de la Quinta registered paleohydric values $< -516.3\,\mathrm{mm\,yr^{-1}}$ between 1600 and 750 cal yrs BP.

Fire activity presents an opposite behaviour between Andean communities and Monte shrubland. The highest Charcoal accumulation rates (CHAR) are registered between 2000 and 750 cal yrs BP in Andean sites while the highest CHAR values in Bajo de la Quinta occur after 500 cal yrs BP. Mallín Pollux and Bajo de la Quinta also register high CHAR values for the last 100 years, which might be related to European settlements.

4.2 Southern Patagonia

Southern Patagonian pollen dataset were classified into two categories (local and regional, sensu Jacobson and Bradshaw, 1981) in response to the pollen source area and the variables selected to calculate past paleohydric balance index. Local dataset category involves pollen records that register past local vegetation variations. These records present a high relationship between surrounding deposition site vegetation pollen indicators and modern pollen samples assemblages (PAA, PAB, MPD, LT, CV). Thus interpretation of the paleohydric balance index from this sites may be related to changes on local conditions. Regional category includes records that on recent pollen samples present higher amounts of pollen types reaching from longer distances (> 3 km southwestward) than pollen from surrounding areas of the deposition site (CF and RR). Thus, we interpret regional paleohydric balance indices not as changes on hydric balance in a single site but throughout the forest-steppe ecotone region.

Southern Patagonian Forest and Forest-steppe ecotone paleohydric indices present positive values between 2000 and 750 cal yrs BP, suggesting above average water availability on Andean communities (Fig. 3). On the contrary steppe records present mainly negative values suggesting dry conditions on extra-andean areas (Fig. 3).

Comparison with modern hydric balance values for pollen records registering local environmental variability, suggest higher than modern hydric balance values for PAA, PAB (> 104.5 and $67.2\,\mathrm{mm\,yr^{-1}}$, respectively) previous to 750 cal yr BP. Steppe sites suggest values similar to modern ones in MPD ($\sim -163.2\,\mathrm{mm\,yr^{-1}}$), higher than modern values in LT ($> -146.6\,\mathrm{mm\,yr^{-1}}$) and lower than modern values in CV ($< -303.7\,\mathrm{mm\,yr^{-1}}$).

After 750 cal yrs BP, Forest and forest-steppe sites exhibit a decreasing trend in paleohydric balance indices (Fig. 3). PAA and PAB indices suggest paleohydric values < 104.5 and $< 67.2\,\mathrm{mm\,yr^{-1}}$, respectively. Steppe sites exhibit the opposite paleohydric trend toward positive values. The three steppe sites suggest significant higher than present values of hydric balance (MPD $> 163.2\,\mathrm{mm\,yr^{-1}}$; LT $> 146.6\,\mathrm{mm\,yr^{-1}}$; CV $>$

$-303.3\,\mathrm{mm\,yr^{-1}}$). Fire activity exhibit synchronous CHAR patterns especially between 2000–1700 and 750–250 cal yrs BP in southern Patagonian charcoal records.

5 Discussion

5.1 Controls over hydric balance in Northern and Southern Patagonia

The late Holocene changes in paleohydric balance reconstructed from Northern Patagonian records could be interpreted in terms of latitudinal variation of the SWW belt, using the modern latitudinal distribution of precipitation seasonality over Patagonia (Fig. 1b) as analogous. Thus, when modelling all Northern Patagonian dataset we perform a composite pollen-based Northern Patagonia SWW belt latitudinal variation index between 40 and 45° S (Fig. 4c). This pollen-based index displays high precipitation seasonality before 750 cal yrs BP. Such a high seasonality likely suggests a more poleward position of the SWW belt, reflecting similar to present day precipitation seasonality (Fig. 4). Nevertheless, Lake Trébol shows high values of paleohydric balance index before 750 cal yrs BP and lower values since 750, around present day hydric values. These pattern joint to the general trend of most northern Patagonian paleohydric balance indices, may reflect intense SWW during winter favouring higher precipitation amounts over areas close to the Andean divide linked to a steeper west-to east precipitation gradient that soften up to present condition since 750 cal yrs BP.

Since 750 cal yrs BP the Northern Patagonia pollen based index shows a remarkable decrease in precipitation seasonality peaking between 400 and 200 cal yrs BP (Fig. 4c). This low seasonality period likely reflects a northward expansion of the SWW favouring increased spring-summer precipitation near the Andes. The similar paleohydric balance of Bajo de la Quinta (Fig. 2e) at the Atlantic coast to those of forest environments suggest that between 400 and 200 cal yrs BP, Atlantic humid air masses reached the continent probably under weak SWW (Marcos et al., 2012a, 2014). Therefore we can interpret dominant summer-like conditions in terms of hydric balance in northern Patagonia between 1600 and 750 cal yrs BP and winter-like conditions between 750 and 200 cal yrs BP.

During the last 200 cal yrs BP, there is a remarkable decrease in the Northern Patagonia pollen based index suggesting higher than before precipitation seasonality toward present day conditions between 40 and 45° S. Even though pollen spectra might be biased for the last 100 years, the decreasing trend in Northern Patagonia pollen based index, precedes European arrival (Fig. 4c).

Precipitation seasonality inferences coincide with centennial fire activity in northern Patagonia. We found an antiphase behaviour of fire occurrence between western and eastward environments. During southward displacement of SWW, fire activity increases on forest communities likely related to coarse fuel desiccation and low biomass availability on eastern Monte shrublands avoiding fire propagation (Fig. 2e). On the contrary, during periods of winter-like conditions, fire activity increases on Monte shrublands, likely related to an increase in biomass favoured by Atlantic Humid air flow masses. Iglesias and Whitlock (2014) presented northern Patagonia biomass burning general trends since the last 18 000 cal yrs BP and compared them to environmental and archaeological information. They interpret that variations in indigenous population densities were not associated with fluctuations in regional or watershed-scale fire occurrence, suggesting that climate–vegetation–fire linkages in northern Patagonia evolved with minimal or very localized human influences before European Settlement (Iglesias and Whitlock, 2014). On the Atlantic coast, archaeological records suggest high anthropogenic activity ca 1000 cal yrs BP with a decreasing trend up to present day (Marcos and Ortega, 2014). Thus, patterns of fire activity increase since ca 500 cal yrs BP in Bajo de la Quinta are likely related to climate variability and lightning sources.

The late Holocene changes in paleohydric balance reconstructed from Southern Patagonian records could be interpreted in terms of intensity variation of the SWW belt, using the modern latitudinal distribution of precipitation seasonality over Patagonia (Fig. 1b) as analogous. These sequences are not significantly affected by seasonal variability but mainly affected by changes on SWW intensity (Garreaud et al., 2013). During years with stronger than average SWW precipitation increased to the west of the Andes and decreased over the lowlands to the east (Garreaud et al., 2013). Therefore we expect that hydric balance increases in forest areas (especially those with present day positive hydric balance values) and decreases in grass steppe extra-Andean environments. Conversely, the marked west–east precipitation gradient is slightly less in those years with weaker than average westerly flow, thus we expect lower than average hydric balance values on forest areas and higher than average hydric balance values in grass steppe extra-Andean environments. Atlantic humid air masses probably increase hydric balance values on steppe records next to the Atlantic coast during periods of weaker westerlies (Agosta et al., 2015).

Thus, when modelling all Southern Patagonian datasets we perform a composite pollen-based Southern Patagonia SWW intensity variation index between 48 and 52° S (Fig. 4) by considering forest and forest-steppe ecotone index values and inverse steppe index values. Figure 4 shows the scatterplot dataset and smothering spline of Local and Regional records from southern Patagonia. This pollen-based index displays intense SWW before 750 cal yrs BP and weaker SWW since 750 cal yrs BP, peaking ca 500–600 cal yrs BP (Fig. 4). The Southern Patagonia index increases slightly toward ca 250–300 cal yrs BP suggesting an intensification pulse of the SWW. Since then, the Southern Patagonia index values decreases to modern ones, thus we interpret a slight weakening of the SWW up to modern conditions.

In contrast to Northern Patagonia regional fire behaviour, Southern Patagonia fire activity trends on forest and steppe communities are synchronous. The maximum fire activity in southern Patagonia occurs during weaker westerlies (on steppe environments especially previous to 1600 cal yrs BP, Fig. 2). Therefore we interpret an antiphase behaviour between northern and southern forest communities and an inphase behaviour of fire occurrence in extra-andean steppe and Monte shrublands.

Anthropogenic fires may represent an extra driving factor favouring fire activity between 1000 and 2000 cal yrs BP in southwestern Patagonia due to the more intense and extensive archaeological signal registered for this area (Franco et al., 2004). However, fire activity registered between 250 and 750 cal years BP is probably related to natural lightning sources since archaeological signal decreases during the last 1000 cal yrs BP in southwestern Patagonia related to an eastward population migration (Franco et al., 2004).

5.2 Comparison with western Andean precipitation and SWW belt records

The timing of major SWW changes in latitudinal shift and intensity recorded by the pollen-based Eastern Andean Northern and Southern Patagonia indices performed in this work at 750 cal yrs BP (1200 AD) roughly corresponds to a major reorganization of the climate system throughout the world, which is frequently associated to the Little Ice Age originally described in the Northern Hemisphere. Here, we compare our inferred-SWW variation during the last 2000 years to western Andean regional precipitation and SWW reconstructions.

Fletcher and Moreno (2012) studied a pollen and charcoal record from Laguna San Pedro (38° S, Fig. 1) located on the western side of the Andes and performed a *Nothofagus* vs. Poaceae (N/P) index to infer changes in humidity during the last 1500 years. The N/P index shows similar behaviour to our pollen-based Northern Patagonia SWW index (Fig. 4a). Indeed, a brief peak on both indices is registered ca 1100/1400 cal yrs BP, suggesting a short period of lower precipitation seasonality under a long term trend of higher precipitation seasonality at both sides of the Andes range. The charcoal record from Laguna San Pedro coincides with eastern Andean Northern Patagonia fire activity during the last 2000 years.

Bertrand et al. (2014) performed a precipitation seasonality index by analysing past two millennia sedimentation changes at Quitralco fjord (46° S, Fig. 1). The authors suggests a poleward-shifted SWW belt between 1350 and 750 cal yrs BP, followed by a gradual shift towards the equator between 750 and 450 cal yrs BP, and stabilization in a sustained northward position between 450 and 0 cal yrs BP (Fig. 4b). The most recent return to a slightly poleward shifted SWW recorded at Quitralco fjord, is in agreement with recent trends observed in climatological data (Bertrand et al., 2014). The coincidence between Bertrand's sedimentation based seasonality index and our composite pollen-based Northern Patagonia SWW belt index supports the reliability of our Northern Patagonian proposed past environmental and climate variability scenarios. Similarly, other marine records shows increases on precipitation of SWW origin between 750 and 200 cal yr BP at 41° S (Lamy et al., 2001) and 44° S (Sepulveda et al., 2009).

In Southern Patagonia, Lake Potrok Aike (52° S) is located where precipitation is negatively correlated with westerly wind strength (Habertzettl et al., 2005). These authors inferred increased lake levels associated to easterly humid flows during weaker westerlies between 490 and 0 cal yrs BP. Further south, the MA1 stalagmite record (53° S, Fig. 1) also provides evidence for a decrease in annual precipitation, and therefore a weakening of the westerlies, since 1000 cal yrs BP (Schimpf et al., 2011, Fig. 4d) synchronously with our composite pollen-based Southern Patagonia SWW belt index. Similarly, the sediment record from Lago Fagnano (Waldmann et al., 2010; Fig. 1) suggests a decrease in precipitation of westerly origin, represented by a decrease in iron supply between 750 and 100 cal yrs BP (Fig. 4e). These independent records and Koffman et al. (2013) interpretations of westerlies strength throughout changes in the grain-size of dust particles in the WAIS Divide ice core at Antarctic Peninsula, supports the sensitivity of our Southern Patagonia SWW belt composite pollen-based index to environmental variability.

The slight intensification of the SWW belt ca 300 cal yrs BP, coincide with major glaciers advances in southern Patagonia (Aniya, 2013; Masiokas et al., 2009; Mercer et al., 1982; Strelin et al., 2008; Wenzens, 1999) and a Southern Hemisphere extreme cold period inferred by Neukom et al. (2014). Therefore the synergic direction of low temperatures and an increase in hydric balance may have favoured Maunder Minimum glacier advances in Southern Patagonia.

5.3 Changes in SWW belt and possible forcing mechanisms

Our SWW belt reconstruction suggest southward intensified westerlies since ca 1600 cal yrs BP including the MCA (1150–750 cal yrs BP) and northward weaker westerlies during LIA (750–150 cal yrs BP, Fig. 4c). During LIA, atmospheric cooling in the Southern Hemisphere would have caused a northward shift of the SWW and contraction of the Southern Hemisphere Hadley Cell (Koffman et al., 2013). General circulation model (GCM) experiments have shown that the latitudinal extent of the Hadley cell circulation is sensitive to changes in global surface temperatures, with warmer temperatures causing an expansion of the Hadley cell (Frierson et al., 2007). These changes in the Hadley cell width are likely driven by shifts in the latitude where baroclinic eddies begin to occur; as surface temperatures warm, the transition from baroclinic stability to instability shifts poleward, driving the eddy-driven Southern Hemisphere storm track southward (Frierson et al., 2007; Lu et al., 2010). This proposed mechanism implies that the SWW respond to surface temperature changes on decadal to centennial timescales (Koffman et al., 2013). The mechanism proposed above differs from the seesaw-type redistribution of heat between the hemispheres that was invoked to explain the migration of the SWWB during the last deglaciation (Anderson et al., 2009; Toggweiler, 2009). This suggests that the SWWB may respond to different forcing mechanisms at different timescales (Bertrand et al., 2014). Varma et al. (2011) presented proxy and model evidence that centennial-scale variability in the position of the SWW is significantly influence by fluctuations in solar activity during the past 3000 years. They argued that periods of lower solar activity were associated with annual-mean northward shifts of the SWW, whereas periods of higher solar activity were linked to annual-mean poleward displacements of the SWW.

Finally, our results coincide with other inferences predominantly from sea-surface temperature and modelling data about ENSO activity over the last 1500 years, where during the MCA, La Niña like or weak El Niño conditions and probably positive SAM dominates in Southern South America (Graham et al., 2010; Mann et al., 2009; Rein et al., 2004; Seager et al., 2007). On the contrary, during LIA dominated more intense El Niño like conditions and negative SAM values (Mann et al., 2009; Rein et al., 2004; Villalba et al., 2012). The marked decreased in our Northern Patagonia pollen based index suggesting a southward shift of the SWW belt storm track during the last decades coincides with modern climate data measurements (Archer and Caldeira, 2008; Hu and Fu, 2007) linked to the poleward migration of the descending branch of the Hadley cell (Villalba et al., 2012).

6 Conclusions

Pollen and Charcoal records from eastern Andean Patagonia from lake and peatbog records were successfully used to reconstruct late Holocene paleohydric and fire activity variability related to SWW latitudinal and strength variability. Due to the distinct precipitation regimes that exist between Northern (40–45° S) and Southern Patagonia (48–52° S) pollen sites locations, shifts on latitudinal and strength of the SWW results in large changes on hydric availability on forest and steppe communities. Therefore, we can interpret fossil available pollen dataset as changes on paleohydric balance at every single site by the construction of paleohydric indices and comparison to charcoal records during the last 2000 cal yrs BP. Our composite pollen-based Northern and Southern Patagonia indices can be interpreted as changes in latitudinal variation and intensity of the SWW respectively. Our eastern Andean pollen and charcoal records synthesis suggest SWW variations during the last 2000 cal yrs BP at centennial scales, with poleward SWW between 1750 and 750 cal yrs BP and northward, weaker SWW between 750 and 200 cal yrs BP. These SWW variations are synchronous to Patagonian fire activity major shifts. We found an in phase fire regime (in terms of timing of biomass burning) between northern Patagonia Monte shrubland and Southern Patagonia steppe environments. Conversely, there is an antiphase fire regime between Northern and Southern Patagonia forest and forest-steppe ecotone environments. For the last 200 cal yrs BP we can concluded that the SWW belt were more intense and poleward than the previous interval, but the last 100 cal yrs BP were controversial by the European establishment. Comparison with other precipitation and SWW sensitive Patagonia records from western Andes present coincident late Holocene climatic scenarios. Our composite pollen-based SWW indices shows the potential of integrating pollen dataset at regional scales to improve the understanding of paleohydric variability supported in strongly calibrated pollen-vegetation calibration especially for the last 2000 millennial. However, the scarce availability of continuous pollen or charcoal records on eastern extra-Andean environments still challenge the understanding of past environmental changes on eastern Andean Northern and Southern Patagonia. Our results encourage future palynological research to develop new pollen dataset with high sample resolution and chronological control for the last millennia to calibrate pollen records to other decadal resolution proxy (e.g. dendrocronologycal data, sedimentary or isotopic records). The correspondence of our SWW reconstruction with proposed ENSO variability during LIA and MCA, suggests ENSO-Patagonia centennial scale tele-connection.

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Table 1. Sites selected for Eastern Andean environmental synthesis. Asterisks points improved chronological control of dataset for this work (see Supplement, Sect. 2). Precipitation and temperature values to calculate Hydric balance index was imported from WorldClim database (http://www.worldclim.org: Hijmans et al., 2005) into GIS software (QGis 2.6.1). Data were first interpolated by krigging method and then monthly values were extracted and the mean values were calculated for sampled sites. Hydric balance index was calculated for each site as the ratio between annual precipitation and potential evapotranspiration. Potential evapotranspiration values were estimated according to Thornthwaite (1948).

Site (coordinates)	Modern hydric balance ($\mathrm{mm\,yr^{-1}}$)	Vegetation	Data set resolution ($\mathrm{sample\,yrs^{-1}}$)	Number of datings (radiocarbon or Pb2010) during the last 2300 years	References
Lake Trébol −41.15° S −71.32° W	493.7	*N. dombeyi* and *Austrocedrus chilensis* forest	136	3	Whitlock et al. (2006), Iglesias (2013), Iglesias and Whitlock (2014), Iglesias et al. (2014)
Lake Theobald −43.48° S −71.58° W	8.60	*N. dombeyi* and *Austrocedrus chilensis*/ steppe	156	2	Iglesias and Whitlock (2014), Iglesias et al. (2014)
Lake Mosquito −42.49° S −71.39° W	143.2	*Austrocedrus chilensis* stands/steppe	53	5	Whitlock et al. (2006), Iglesias et al. (2012, 2014), Iglesias (2013), Iglesias and Whitlock (2014)
Mallín Pollux −45.69° S −71.84° W	264.4	*N. pumilio* and *N. antarctica* forest/steppe	114	3	Markgraf et al. (2007)
Bajo de la Quinta (BQ) −40.92° S −64.33° W	−516.3	Monte shrubland	136	3*	Marcos et al. (2012a, b, 2014)
PAA peat-bog −50.26° S −72.85° W	104.5	*N. pumilio* forest	61	3	Sottile (2014), this work, Supplement (Sect. S1)
PAB peat-bog −50.26° S −72.84° W	67.2	*N. pumilio* forest and *N. antarctica* stepppe	85	3	Echeverría et al. (2014)
Cerro Frías peat-bog (CF) −50.41° S −72.71° W	−65	Forest/steppe ecotone	92	2	Mancini (2009), Sottile et al. (2014)
Río Rubens peat-bog (RR) −52.06° S −71.51° W	−189.8	Forest steppe/ecotone	60	9	Huber and Markgraf (2003a, b), Huber et al. (2004), Markgraf andHuber (2010)
Mallín Paisano Desconocido (MPD) −48.95° S −72.23° W	−163.2	Grass steppe	159	2	Bamonte et al. (2014)
La Tercera peat-bog (LT) −49.182° S −72.37° W	−146.6	Grass steppe	171	2*	Bamonte and Mancini (2011), Sottile et al. (2012)
Mallín Cabo Vírgenes (CV) −52.32° S −68.38° W	−303.7	Grass steppe	61	2 (in the last 1100 years)	Mancini (2007), Mancini and Graham (2014)

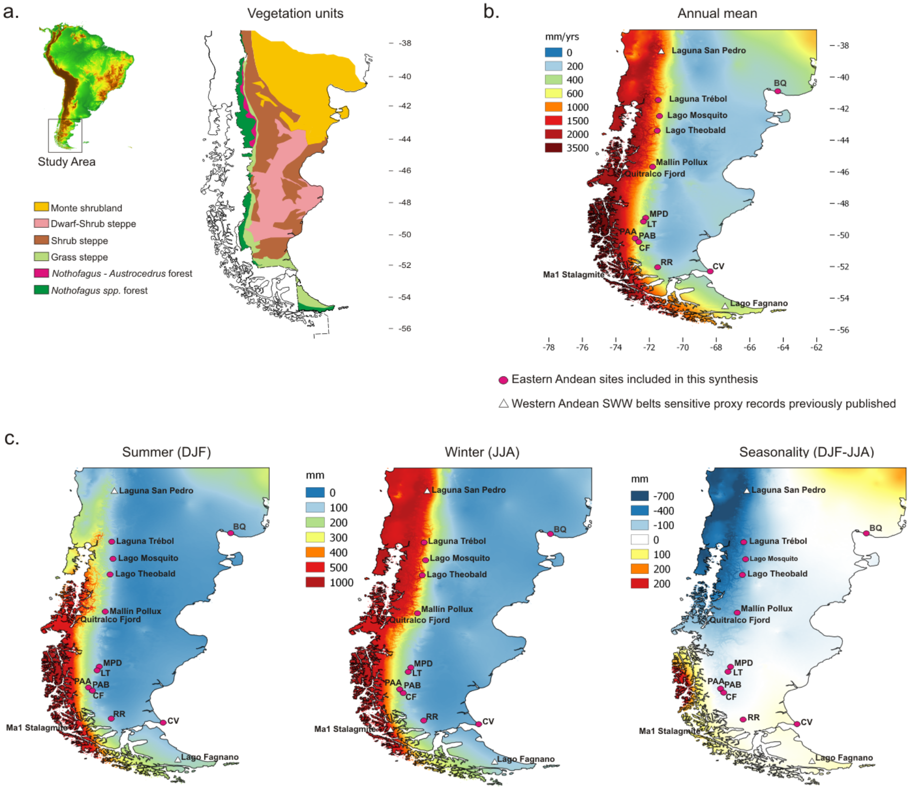

Figure 1. Modern hydroclimatology (1950–2000) of Patagonia. **(a)** Main vegetation units of eastern Andean Patagonia modified from Cabrera (1971), León et al. (1998) and Mancini et al. (2012). **(b)** Annual mean precipitation. **(c)** The seasonality index was calculated as the ratio between summer precipitation and winter (DJF/JJA). Values lower (higher) than 1 are therefore indicative of regions where precipitation is higher (lower) in winter than in summer. Austral winter (JJA) and summer (DJF) precipitation and difference between the two (seasonality). The precipitation maps were created using data from the Worldclim database (Hijmans et al., 2005).

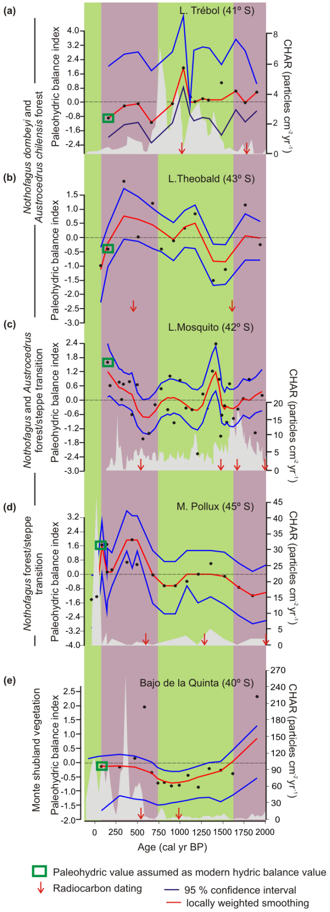

Figure 2. Northern Patagonia paleohydric balance indices. Light green area between present day and 50 cal yr BP indicates European arrival to Patagonia.

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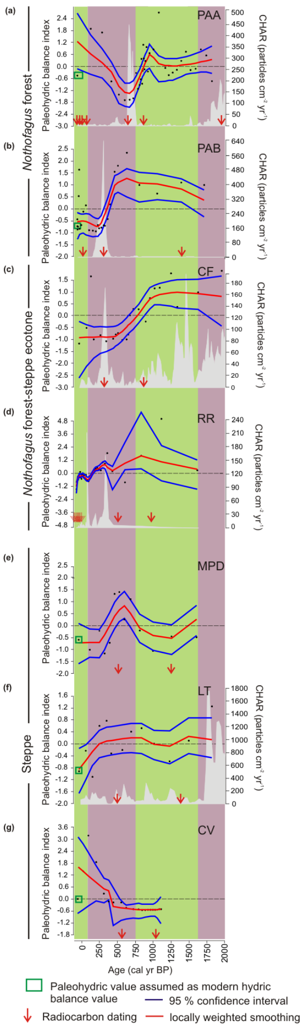

Figure 3. Southern Patagonia paleohydric balance indices. Light green area between present day and 50 cal yr BP indicates European arrival to Patagonia.

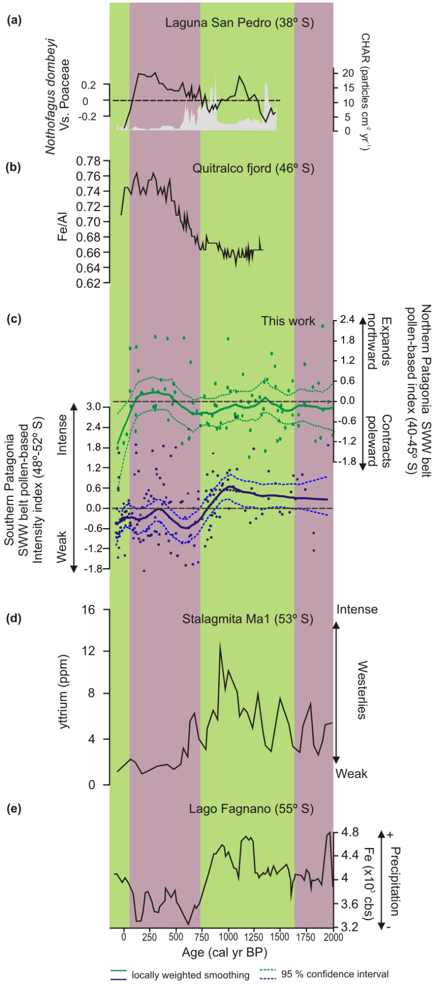
(a)
Laguna San Pedro (38° S)
Nothofagus dombeyi Vs. Poaceae
0.2
0
-0.2
CHAR (particles cm⁻² yr⁻¹)
20
15
10
5
0
(b)
Quitralco fjord (46° S)
Fe/Al
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0.64
0.62
(c)
This work
Southern Patagonia SWW belt pollen-based Intensity index (48°-52° S)
Intense
Weak
3.0
2.4
1.8
1.2
0.6
0.0
-0.6
-1.2
-1.8
Northern Patagonia SWW belt pollen-based index (40-45° S)
Expands northward
Contracts poleward
2.4
1.8
1.2
0.6
0.0
-0.6
-1.2
-1.8
(d)
Stalagmita Ma1 (53° S)
yttrium (ppm)
16
12
8
4
0
Intense
Westerlies
Weak
(e)
Lago Fagnano (55° S)
Fe (x10³ cbs)
4.8
4.4
4
3.6
3.2
Precipitation
+
-
0
250
500
750
1000
1250
1500
1750
2000
Age (cal yr BP)
locally weighted smoothing
95 % confidence interval

Figure 4. Regional synthesis with composite pollen-based Northern and Southern indices **(c)** and comparison to other Southern Westerly Wind belt sensitive proxy records of Patagonia: **(a)** Fletcher and Moreno (2012); **(b)** Bertrand et al. (2014); **(d)** Schimpf et al. (2011) and **(e)** Waldmann et al. (2010). Light green area between present day and 50 cal yr BP indicates European arrival to Patagonia.