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

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Abstract

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, lack of 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 (a)integrate pollen and charcoal dataset available east of the Andes through the analysis of modern and past hydric balance dynamics and (b)compare their behaviour to western Andean or Pacific SWW- sensitive records to interpret possible environmental variability at centennial time scales 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 site locations, expansion/contraction and intensity changes of the SWW belt 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 contracted intense SWW between 2000-750 cal yrs BP and northward expanded- weaker SWW between 750-200 cal yrs BP. These SWW variations are synchronous with 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 SAM and ENSO variability especially during the last millennia. For the last century we infer more intense and poleward contracted SWW, however, pollen trends may be biased by European settlement during this period. Our composite pollen- based SWW indices shows the potential of pollen dataset integration to

improve the understanding of paleohydric variability especially for the last 2000 years in Patagonia.

1. Introduction

Patagonia is the only land form in the Southern Hemisphere that is affected by the complete range of the Southern Hemisphere Westerly Winds (SWW). The interaction between the SWW behaviour and the Andes drives the development of a wide range of vegetation units from Valdivian rainforest to dwarf shrub steppe deserts in a sharp west-east precipitation gradient. The SWW constitute an important zonal circulation system that dominates the dynamics of Southern Hemisphere mid-latitude climate. Furthermore, they influence not only southern South America ecosistems, they affect 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; Lamy et al., 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, lack of 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).

Generally two periods of major climatic variability have been strongly discussed especially for the last millennia. The "Little Ice Age" (LIA) usually refers to climatic anomalies over the Northern Hemisphere between the 13^{th} and mid-19^{th} century (750-150 cal yrs BP). The LIA is well documented in the Northern Hemisphere, where a huge variety of chronicles, historical documents, proxy- based reconstructions and also temperature measurements indicate cooler and wetter conditions (Meyer and Wagner, 2008). In fact, within the LIA, a period with even lower temperatures has been pointed out as the Maunder Minimum (MM; 1645-1715 A.D./ 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). Patagonian climatic and environmental changes during LIA have been registered and described in Andean environments by glaciological and dendrochronological studies (e.g. Ruiz et al., 2012; Masiokas et al., 2010; Masiokas et al., 2009a,b). However there is no consensus about the synchronicity of Andean changes with extra-andean environmental variability and the major environmental forcings involved (Haberzettl et al., 2005; Moy et al., 2009). 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. 9^{th}-13^{th} centuries/ 1150-750 cal yrs BP; Jones et al., 2001; Osborn and Briffa, 2006). Recently, Neukom et al. (2010; 2011; 2014) pointed to a number of climatic variations occurring during the last millennium in Southern South America. The comparison of Northern and Southern Hemisphere extreme periods carried out by Neukom et al. (2014), showed that warm extreme periods in the Southern Hemisphere took place ~200 years (between 13th-15thcentury/ 950-750 cal yrs BP) after the Northern Hemisphere MWP. Nonetheless the authors show coherent extreme cool conditions in both hemispheres around 1600 A.D. (350 cal. yrs BP).

Pollen records derived from lakes and bogs represent one of the most abundant paleoclimate archives in Southern 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 timescales in Andean and extra-andean Patagonia (e.g. Heusser and Heusser, 2006; Mancini et al., 2008; Markgraf et al., 2003; Moreno et al., 2009). However, pollen based paleoenvironmental reconstruction with highly- precise chronology in Patagonia for the last millennia are scarce (Fletcher and Moreno, 2012; Huber and Markgraf, 2003a; Moreno et al., 2014;Whitlock et al., 2006; Wille et al., 2007). These authors presented different Patagonian 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 dataset 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.

Disentangling the relationship between western Andean and Eastern Andean past environmental and climatic signals would improve Southern South America database use for past or future climate modelling. Since 2009, new pollen and charcoal records from bogs 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., 2012a,b, 2014; Mancini, 2009; Marcos et al., 2012a,b; Sottile et al., 2012; Sottile, 2014). In this work we (a)integrate pollen and charcoal dataset available east of the Andes through the analysis of modern and past hydric balance dynamics and (b)compare their behaviour to western Andean or Pacific SWW- sensitive records to interpret possible environmental variability at centennial time scales 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. Eastern Patagonia is 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 core of the SWW is currently located at 50-52°S. Wind speed of SWW is stronger during austral summer, peaking between 45°-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,U850)~0.8), a sharp transition just to the east of the mountain ridge and negative values over the Argentinean Patagonia (Fig. 1c, Garreaud et al., 2013; Moreno et al., 2014). During years with stronger than average westerly flow increased precipitation to the west of the Andes and decreased precipitation over the lowlands to the east is observed. 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).

(Figure 1)

The southern annular mode (SAM) is the main process of low frequencies circulation variability in the Southern Hemisphere (also referred as the Antarctic Oscillation or high-latitude mode) (Silvestri and Vera, 2009). This zonal mean atmospheric pressure difference between the mid-latitudes (40°S) and Antarctica (65° S) shows a positive (negative) phase associated with negative (positive) pressure anomalies over Antarctica and positive (negative) anomalies at middle latitudes. As the SAM positive phase determines the strengthening and poleward contraction of the Southern Hemisphere westerly jet stream it has a profound influence on the rain distribution over southern South America (Silvestri and Vera, 2009). 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°-48°S (Holz and Veblen, 2011; Mundo et al., 2013; Veblen et al., 1999; Villalba et al., 2012). Similarly to negative ENSO phase, during negative multivariate ENSO index values (La Niña like), the South Pacific anticyclone strengthen and moves southward (Aceituno, 1988). Furthermore, during positive ENSO phase, there is an overall decrease in the strength of the wind field and a slight reduction in precipitation in western Patagonia (Moy et al., 2009). Particularly, there is an overall reduction in summer precipitation and warmer surface air temperature in Northern Patagonia during positive ENSO (e.g. Mundo et al., 2013). Rutllant and Fuenzalida (1991) showed sinoptical scenarios showing 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. These phenomena favour a northward displacement of the storm tracks between 33-39°S (Garreaud and Aceituno, 2007; Garreaud et al., 2009; Montecinos et al., 2000; Moreno et al., 2010).

2.2. Northern Patagonia vegetation

Eastern Andean communities in northern Patagonia between 40-44°S present four major N-S and W-E oriented ecological transitions. The first (ca. 72°W) from tree/epiphyte species rich Valdivian rainforest to structurally poorer species rich *Nothofagus*-dominated forests. This transition zone coincides approximately with eastern areas of low Andean longitudinal valleys and where precipitation drops below ca 3000- 2500 mm year^{-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 diverse shrublands composed of heliophillous species (Iglesias et al., 2014). This transition occurs where annual precipitation drops below ca 1800 mm year^{-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 c. 600-800 mm year^{-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). Following the precipitation gradient, Patagonian grass and shrub steppes cover plains and plateaus eastward at approximately 70°W between 600-300 mm year^{-1}, with a significant decrease on above ground vegetation cover (León et al., 1998). Below 300 mm year^{-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 year^{-1} (Mancini et al., 2008). Between 1000-600 mm of annual precipitation closed deciduous forests 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 600-400 mm year^{-1}. Eastward between 400- 200 mm year^{-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”).

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

3.1. Site selection criteria

In order to reconstruct the past 2000 years of environmental variability on different landscape of eastern Andean Patagonia, we selected continuous pollen and charcoal records from lakes and peatbogs (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 yrs^{-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-2K criteria (see Supplementary material, section 1, for details).

(Table 1)

3.2. Pollen indices estimation

The analysis of species traits dominance on different communities to assess functional structure of ecosystems, throughout the classification of species on Plant Functional Types (PFTs), have provided an alternative approach to disentangle how multiple processes (micro and macroclimatic conditions or disturbances) affecting ecosystems attributes (Box, 1981; Díaz and Cabido, 2001; Mouillot et al., 2012; Prentice and Webb, 1998). Annual precipitation controls vegetation distribution and functional characteristics of the ecosystems of Andean and Extra-andean Patagonia (Paruelo et al., 2004, Tonello et al., 2009), whereas mean annual temperature in conjunction with strong winds produces high evaporation rates having a strong effect on plant growth (Paruelo et al., 2001). At landscape scale, several authors have demonstrated that plant species are also limited by hydric balance conditions determined by top-down processes (tree canopy in forested areas, Sottile et al., 2015) or geomorphological characteristics (Golluscio and Sala, 1993; Jobbágy et al., 1996; Marcos and Mancini, 2012). Thus, reconstructing past species abundances for the last millennia in a wide spatial range at Patagonia would allow us to hypothesize about regional hydric balance changes.

Pollen assemblages reflect general patterns in vegetation, thus they are a valuable tool for reconstructing past ecosystem functioning in terms of past hydric balance. Nevertheless, pollen representation is biased by several factors such as differences in pollen production, dispersal or preservation (Faegri and Iversen, 1992; Prentice, 1988). According to Jacobson and Bradshaw (1981) sedimentary deposits from depositional areas <~2 hectares present pollen mainly from local to extralocal vegetation and minor representation of regional vegetation, specially by highly productive and anemophilous species. In Argentina, the studies about pollen dispersal carried out by Pérez et al (2009 y 2014) demonstrate that anemophilous pollen presents long trajectories from western Andean slopes to eastern Andean and extra-andean environments related to synoptic scale processes. *Nothofagus* is the main genera of Patagonian forest trees and has been extensively used as forest indicator at local and extralocal scale (e.g. Bianchi and Ariztegui, 2012; Markgraf et al., 2007; Mancini, 2009; Sottile et al., 2012) since the Pleistocene- Holocene transition. Nonetheless, *Nothofagus* pollen has been reported to reach more than a thousand kilometres far from its source area (Gasmmann and Perez, 2006),therefore the analysis of Nothofaus/Poaceae ratio has been used to infer changes in forest/steppe cover at regional scales from Potrok Aike lake several kilometres eastward of the forest-steppe ecotone (e.g. Wille et al., 2007). Sottile (2014) compared surface pollen samples with *Nothofagus* cover registered in satellite images and inferred *Nothofagus* pollen source area by regression functions of increasing concentric areas oriented following the dominant wind direction surrounding surface pollen samples. The author concluded that the 80% of *Nothofagus* pollen source area was an area of 1500 meters of diameter oriented to main wind direction and 20% to regional source areas with an r^2= 0.75. Marcos and Mancini (2012) highlighted the representation of main taxa of Patagonian and Monte steppe shrub and herbs at local scale. The authors demonstrated that most herb and shrub pollen-vegetation representation were associated at local scale due to the high grade of entomophily of the steppe species.

Pollen indexes are valuable mathematical tools that have been largely used in Palynology not only for the prevention and treatment of polinosis (Sofiev and Bergmann 2013) but also in Quaternary studies to extraxt ecological trends from pollen assemblages through pollen taxa with ecological affinities (eg. arboreal pollen- non arboreal pollen ratios, Nothofagus – Poaceae ratios, local vs regional pollen types ratios etc.) (Herzschuh, 2007, Fletcher and Moreno 2012)

Based on these evidences, we have selected some pollen taxa indicators of local and extralocal vegetation characteristics to infer environmental conditions. Then we constructed past pollen-based paleohydric balance indices (PBI). Main pollen taxa were considered suggesting above/below hydric availability at every site, following paleoecological and modern pollen-vegetation calibrations highlighted in previous published works and field observations (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, See Supplementary material, section 2 and 5 for details). Each PBI 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 Supplementary material, section 2 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 smoothing spline with a smoothing factor of 0.2 (Cleveland, 1979, 1981, de Boor, 2001) and plotted the 95% confidence band based on a 999 bootstrap replicate technique. Modern hydric balance of every site was compared to paleohydric values in reference to the pollen samples with an age of ca. 1900 AD of every record (preventing possible changes on pollen spectra related to European settlement).

Also, composite pollen based index for northern and southern Patagonia were performed using all datasets 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

Andean pollen records in Northern Patagonia present a positive (Precipitation,U850) correlation while Bajo de la Quinta present negative values (Fig. 1c). Also, Andean records present the highest differences between DJF and JJA precipitation values (Fig. 1d). Thus, Northern Patagonian pollen based paleohydric balance allow us to reconstruct past variability especially in terms of seasonality (fig. 2). 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- 750 cal. yrs BP (Fig. 2.b,c,d). Since 750 cal. yrs BP, there is a raising trend to positive paleohydric values peaking ca. 250-300 cal. yrs BP (Fig. 2.b,c,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 mm yr^{-1} in Lake Trébol; < 8 mmyr^{-1}; < 143 mm yr^{-1} in Lake Mosquito and < 268 mm yr^{-1} in Mallín Pollux between 1600-750 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. A comparison with modern hydric balance values, suggests Bajo de la Quinta registered paleohydric values < -516 mm yr^{-1} between 1600- 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- 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.

(Figure 2)

4.2. Southern Patagonia

Most Southern Patagonian pollen records present negative or null r(Precipitation,U850)(Fig. 1c) and low seasonality values (Fig. 1d). The lowest r(Precipitation,U850) values are registered at Paisano Desconocido, La Tercera and Cabo Vírgenes (<-0.4).Thus, changes in paleohydric balance in this sites may be related to changes in SWW strength. 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 (Península Avellaneda Alto, Península Avellaneda Bajo, Paisano Desconocido, La Tercera, Cabo Vírgenes). Thus interpretation of the paleohydric balance index from these sites may be related to changes on local conditions. Regional category includes records thatin recent pollen samples present higher amounts of pollen typesfrom largerdistances (>3km southwestward) than pollen from vegetation surrounding areas of the deposition site (Cerro Frías and Río Rubens). Thus, we interpret regional paleohydric balance indices not as changes on hydric balance in a single site but throughout the forest-ecotone region from these two sites.

Southern Patagonian Forest (Península Avellaneda Alto & Bajo) and Forest-steppe ecotone (Cerro Frías, Río Rubens) PBIs present positive values between 2000-750 cal yrs BP, suggesting above average water availability on Andean communities (Fig. 3). On the contrary steppe records (Paisano Desconocido, La Tercera, Cabo Vírgenes) 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 Península Avellandea Alto &Península Avellaneda Bajo (>104 and 67 mm yr^{-1}, respectively) previous to 750 cal yr BP. Steppe sites suggest values similar to modern ones in Paisano Desconocido (~-163 mm yr^{-1}), higher than modern values in La Tercera (>-146 mm yr^{-1}) and lower than modern values in Cabo Vírgenes (<-303 mm yr^{-1}).

After 750 cal yrs BP, forest and forest-steppe sites exhibit a decreasing trend in PBIs (Fig. 3). Península Avellaneda Alto and Península Avellaneda Bajo indices suggest paleohydric values < 104 and <67 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 (Paisano Desconocido>163 mm yr^{-1}; La Tercera>146 mm yr^{-1}; Cabo Vírgenes> -303 mmyr^{-1}). Fire activity exhibit synchronous CHAR patterns especially between 2000-1700 cal yrs BP and 750- 250 cal yrs BP in southern Patagonian charcoal records.

(Figure 3)

5. Discussion

5.1. Controls over hydric balance in Northern and Southern Patagonia

The late Holocene changes in paleohydric balance reconstructed from Northern Patagonian pollen records could be interpreted in terms of drier/humid summers (higher/lower seasonality) which may be related to latitudinal expansion/contraction of the northern limit of the SWW belt. Thus, when modelling all Northern Patagonian datasets we perform a composite pollen based- Northern Patagonia SWW belt latitudinal variation index between 40°-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. Lake El Trébol is the record with higher r(Precipitation, U850) (Fig.1c) between Northern Patagonia pollen records. These patterns 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 (northward expansion of the SWW belt) peaking between 400-200 cal. yrs BP (Fig. 4c). This northward expansion of the SWW might favour 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 400-200 cal yrs BP, Atlantic humid air masses reached the continent probably under weak SWW (Marcos et al., 2012a; Marcos et al., 2014). Therefore we can interpret dominant summer-like conditions in terms of hydric balance in northern Patagonia between 1600-750 cal yrs BP and winter-like conditions between 750- 200 cal yrs BP.

During the last century, there is a remarkable decrease in the Northern Patagonia pollen based index suggesting higher than before precipitation seasonality toward present day conditions between 40- 45°S. Even though over this period pollen spectra might be biased by 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 a northward expanded SWW belt, humid summers would avoid coarse fuel desiccation in forested areas between 1600-750 cal. yrs BP. Also during these period, intense SWW would avoid Atlantic humid air flow masses reaching to Bajo de la Quinta determining low biomass availability for fire propagation. On the contrary, during a southward contraction of SWW belt, fire activity increases on forest communities likely related to coarse fuel desiccation and high biomass availability on eastern Monte shrublands 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 comparison between Forest and Forest-steppe ecotone pollen records selected in these work present similar trends to those western Andean records in Southern Patagonia highly correlated to SWW strength (Stalagmite MA1 & Lago Fagnano, Fig. 4). Thus, despite the slight negative or null r(precipitation, U850) of these pollen record location, they may be positively correlated to past SWW strength variability contrarily to steppe pollen records that present an opposite behaviour. Based on this assumption, the late Holocene changes in paleohydric balance reconstructed from Southern Patagonian pollen records could be interpreted in terms of intensity variation of the SWW belt. Noticeably, these sequences are not significantly affected by seasonal variability (Fig. 1d) but might be mainly affected by changes on SWW intensity. During years with stronger than average SWW precipitation increases to the west of the Andes and decreases over the lowlands to the east (Garreaud et al., 2013). Based on Forest and Forest-steppe ecotone records behaviour we hypothesize that increased precipitation during intensified SWW would reach even to the highlands of the eastern flank of the Andes. Therefore we expect that hydric balance increases in forest areas and decreases in grass steppe extra-Andean environments during intensified SWW. Conversely, the marked west-east precipitation gradient is slightly less pronounced 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). Indeed, Moreno et al. (2014) highlighted that SAM positive phases cause the highest easterly anomalies around ~40°S.

Thus, when modelling all Southern Patagonian datasets we perform a composite pollen based-Southern Patagonia SWW intensity variation index between 48°-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 smoothering 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 a brief period of intensified SWW. Since then, the Southern Patagonia index values decrease to modern ones, thus we interpret a slight weakening of the SWW up towards 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 in-phase behaviour of fire occurrence in extra-andean steppe and Monte shrublands.

Anthropogenic fires may represent an extra driving factor favouring fire activity between 1000-2000 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-

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 indicating 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 A.D) coincides with major shifts inferred at the climate system throughout the world (Bertrand et al., 2014). , Here, we compare our inferred paleohydric and SWW variations interpreted through our Northern and Southern Patagonia composite pollen indices during the last 2000 years to western Andean regional precipitation and other 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* versus 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 750cal yrs BP, followed by a gradual shift towards the equator between 750 and 450cal 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). Similarly, other marine records show increases in precipitation of SWW origin between 750-200 cal yr BP at 41°S (Lamy et al., 2001) and 44°S (Sepulveda et al., 2009). The coincidence between records from the western side of the Andes and our composite Northern Patagonia SWW belt pollen index supports the reliability of our Northern Patagonian proposed past environmental and climate variability scenarios.

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- 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 Southern Patagonia SWW belt composite pollen based 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- 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 Southe rn 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.

(Figure 4)

5.3. Changes in SWW belt and possible forcing mechanisms

Our SWW belt reconstruction suggest southward contracted intensified westerlies since ca. 1600 cal yrs BP including the MCA (1150- 750 cal yrs BP) and northward expanded 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). Bertrand et al. (2014) stated that SWW belt may respond to different forcing mechanisms at different timescales. They coincides with Koffman et al. (2013) when they suggest that the SWW respond to surface temperature changes on decadal to centennial timescales differing to the seesaw-type redistribution of heat between the hemispheres that was invoked to explain the migration of the SWW belt during the last deglaciation (Anderson et al., 2009; Toggweiler, 2009). 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, modelling data and other pollen records about ENSO and SAM activity over the last 1500 years. During the Northern Hemisphere MCA, La Niña like or weak El Niño and probably positive SAM conditions dominated in Southern South America (Graham et al., 2010; Mann et al., 2009; Moreno et al., 2014; Rein et al., 2004; Seager et al., 2007). On the contrary, after 750 cal. yrs BP more intense El Niño like conditions and/or negative SAM values dominated (Mann et al., 2009; Moreno et al., 2014; Rein et al., 2004; Villalba et al., 2012). The marked decrease in our Northern Patagonia pollen based index suggests a southward shift of the SWW belt storm track during the last century coinciding 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

The use of pollen indices based on plant functional types responding to hydric balance conditions jointed with past fire dynamics based on charcoal records allowed us to hypothesize about past paleoenvironmental variability at different landscapes of Eastern Andean Patagonia. The integration of pollen records by estimating composed pollen indices with sites of similar modern climate behavior, enable us to infer major circulation shifts in terms of SWW latitudinal and strength variability during the last 2000 cal. 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. 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 2000yrs at centennial scales, with poleward contracted SWW between 1750-750 cal yrs BP and northward expanded, weaker SWW between 750-200 cal yrs BP. These SWW variations are synchronous with 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 century we suggest that the SWW belt was more intense and poleward than during the previous interval. However, this trend may be biased by possible vegetation changes occurred after European establishment. The comparison of this trend with other precipitation and SWW sensitive Patagonia records from western Andes show coincident late Holocene climatic scenarios. Our composite pollen- based SWW indices show the potential of integrating pollen dataset at regional scales to improve the understanding of the paleohydric balance variability especially for the last 2000 yrs. However, the scarce availability of continuous pollen or charcoal records on eastern extra-Andean environments still challenges the understanding of past environmental changes on eastern Andean Northern and Southern Patagonia. Our results encourage future palynological research to develop new pollen datasets with high sample resolution and chronological control for the last millennia to correlate pollen records to other decadal resolution proxies (e.g.dendrochronological data, sedimentary or isotopic records).

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Figure captions:

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) Correlation values between annual precipitation and zonal winds at 850 hPa (U850) modified from Garreaud et al., 2013 and Moreno et al., 2014. (d) The seasonality index was calculated as the ratio between summer precipitation and winter (DJF/JJA). Values lower (higher) than 0 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.

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

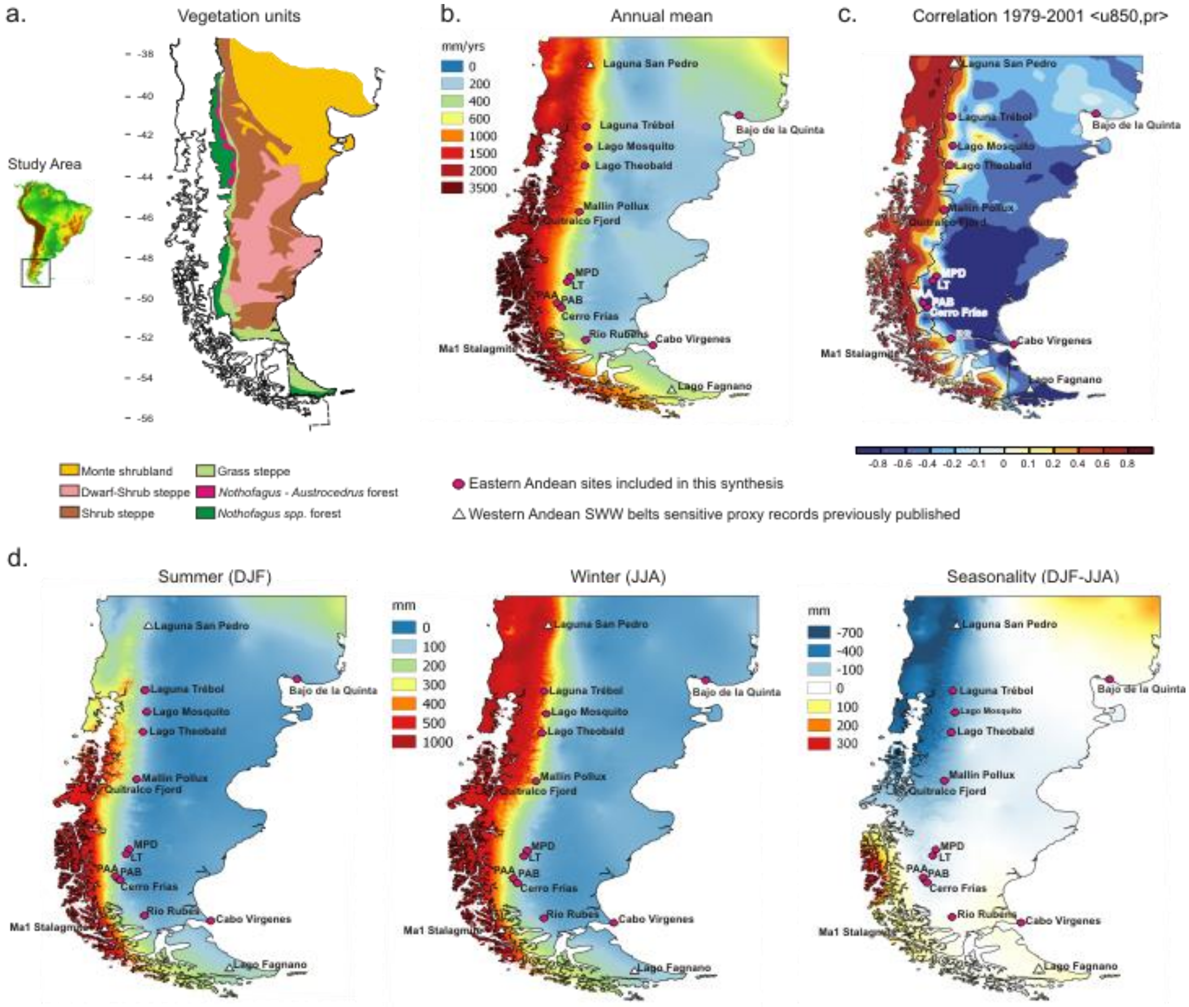
Figure 4. Regional synthesis with composite pollen based Northern and Southern indices (c) and comparison to other Southern Westerly Wind belt sensitive proxy records of Patagonia: (a) Fletcher and Moreno, 2012; (b) Bertrand et al., 2014; (d) Schimpf et al., 2011 and (e) Waldmann et al., 2010. Light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

Table 1. Sites selected for Eastern Andean environmental synthesis. Asterisks points improved chronological control of dataset for this work (see Supplementary material, section 4). Precipitation and temperature values to calculate Hydric balance index was imported from WorldClim database (http://www.worldclim.org/current.htm: 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)

Table 1

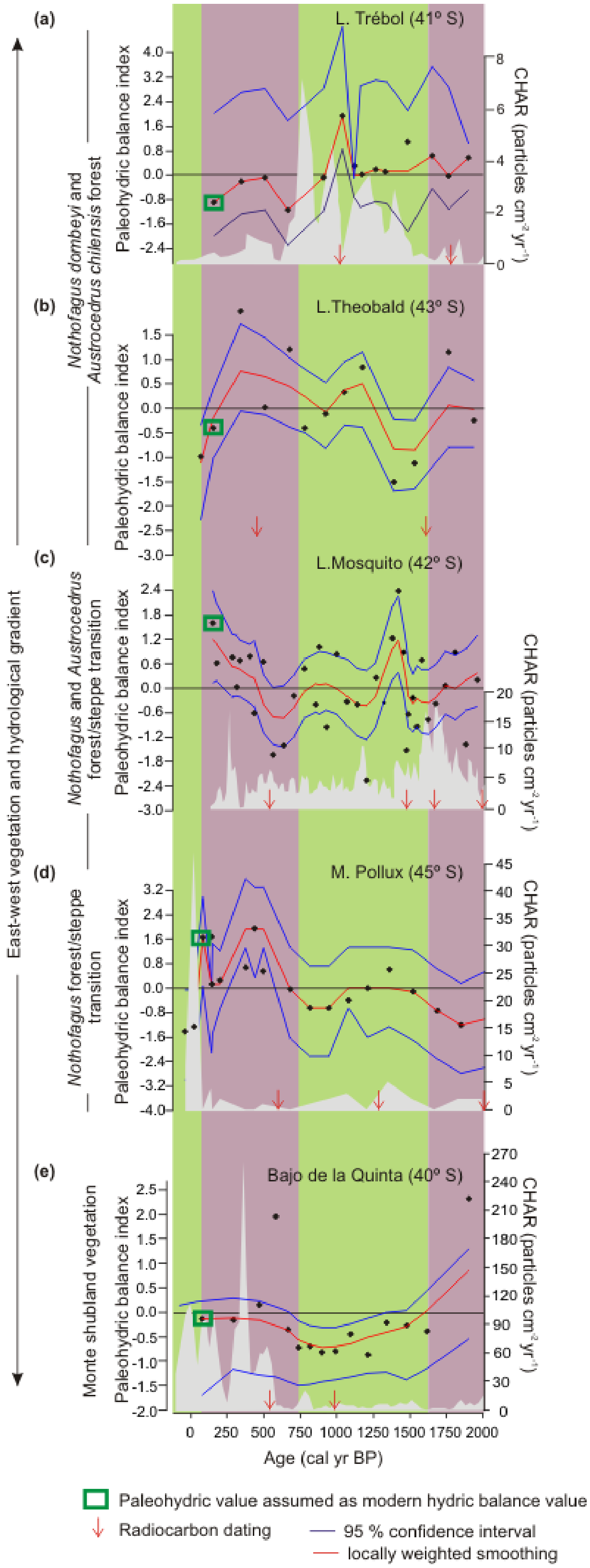
Site (coordinates)	Modern hydric balance (mm yr^{-1})	Vegetation	Data set resolution (sample yrs^{-1})	Number of datings (radiocarbon or Pb2010) during the last 2300 yrs	References
Lake Trébol -41.15°S -71.32°W	493.7	*N. dombeyi* and *Austrocedrus chilensis* forest	136	3	Whitlock et al., 2006; Iglesias, 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; Iglesias, 2013; Iglesias and Whitlock, 2014; Iglesias et al., 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; Marcos et al., 2012b; Marcos et al. 2014
Península Avellaneda Alto peatbog -50.26°S -72.85°W	104.5	*N. pumilio* forest	61	3	Sottile, 2014; This work, Supplementary material (section 3)
Península Avellaneda Bajo peatbog -50.26°S -72.84°W	67.2	*N. pumilio* forest and *N. antarctica*/ steppe	85	3	Echeverría et al., 2014
Cerro Frías peatbog -50.41°S -72°.71°W	-65	Forest/steppe ecotone	92	2	Mancini, 2009; Sottile et al., 2014
Río Rubens peatbog -52.06°S -71.51°W	-189.8	Forest steppe/ecotone	60	9	Huber and Markgraf, 2003a; Huber and Markgraf, 2003b; Huber et al., 2004; Markgraf and Huber, 2010.
Mallín Paisano Desconocido -48.95°S -72.23°W	-163.2	Grass steppe	159	2	Bamonte et al., 2014
La Tercera peatbog -49.182°S -72.37°W	-146.6	Grass steppe	171	2*	Bamonte and Mancini; 2011; Sottile et al., 2012
Mallín Cabo Vírgenes -52.32°S -68.38°W	-303.7	Grass steppe	61	2 (in the last 1100 yrs)	Mancini, 2007; Mancini and Graham, 2014

Figure 1



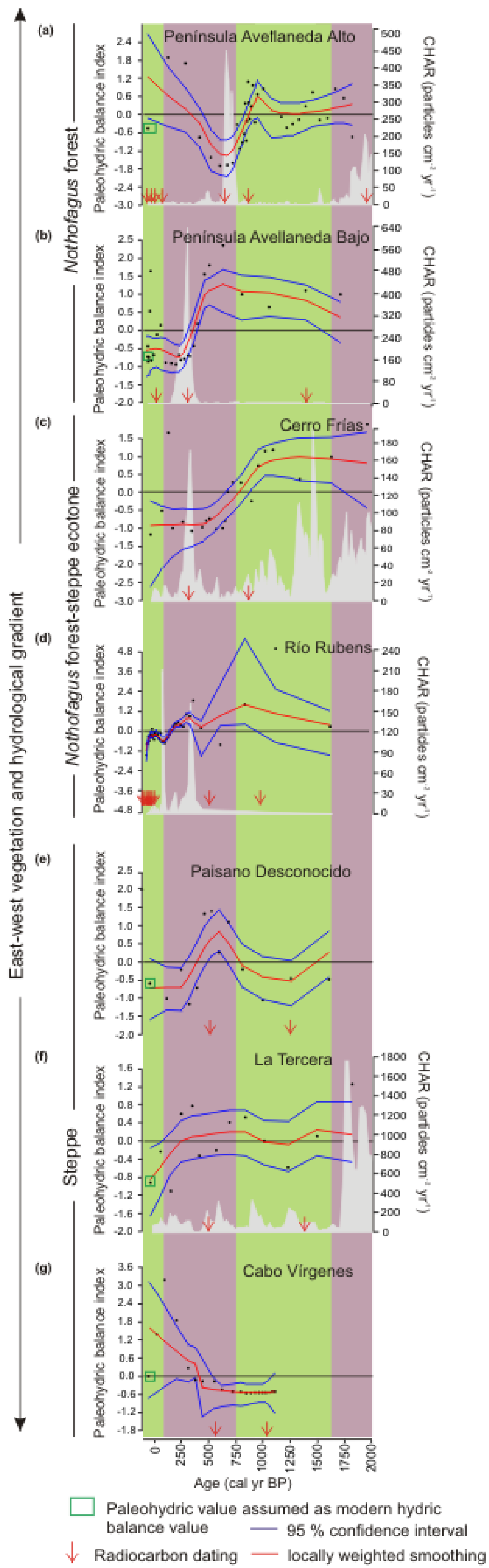
a.
Vegetation units
Study Area
b.
Annual mean
mm/yrs
0
200
400
600
1000
1500
2000
3500
c.
Correlation 1979-2001 <u850,pr>
Laguna San Pedro
Laguna Trébol
Lago Mosquito
Lago Theobald
Bajo de la Quinta
Mallin Pollux
Quitralco Fjord
MPD
LT
PAA
PAB
Cerro Frias
Rio Rubens
Cabo Virgenes
Ma1 Stalagmite
Lago Fagnano
-0.8 -0.6 -0.4 -0.2 -0.1 0 0.1 0.2 0.4 0.6 0.8
Monte shrubland
Dwarf-Shrub steppe
Shrub steppe
Grass steppe
Nothofagus - Austrocedrus forest
Nothofagus spp. forest
Eastern Andean sites included in this synthesis
Western Andean SWW belts sensitive proxy records previously published
d.
Summer (DJF)
Winter (JJA)
Seasonality (DJF-JJA)
mm
0
100
200
300
400
500
1000
mm
-700
-400
-100
0
100
200
300

Figure 2



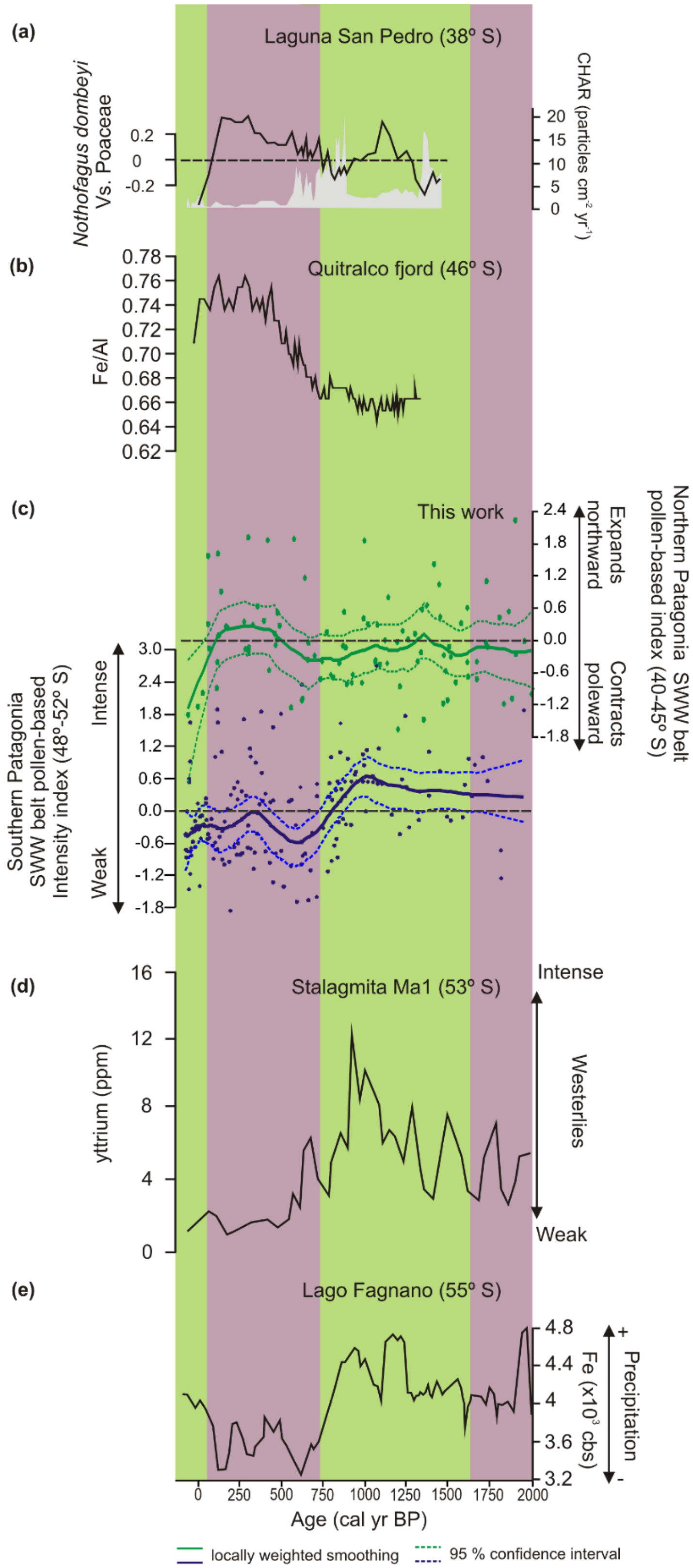
(a)
L. Trébol (41° S)
(b)
L.Theobald (43° S)
(c)
L.Mosquito (42° S)
(d)
M. Pollux (45° S)
(e)
Bajo de la Quinta (40° S)
East-west vegetation and hydrological gradient
Nothofagus dombeyi and Austrocedrus chilensis forest
Nothofagus and Austrocedrus forest/steppe transition
Nothofagus forest/steppe transition
Monte shrubland vegetation
Paleohydric balance index
CHAR (particles cm⁻² yr⁻¹)
Age (cal yr BP)
Paleohydric value assumed as modern hydric balance value
Radiocarbon dating
95 % confidence interval
locally weighted smoothing

Figure 3



East-west vegetation and hydrological gradient
Nothofagus forest
Nothofagus forest-steppe ecotone
Steppe
(a)
Península Avellaneda Alto
(b)
Península Avellaneda Bajo
(c)
Cerro Frías
(d)
Río Rubens
(e)
Paisano Desconocido
(f)
La Tercera
(g)
Cabo Vírgenes
Paleohydric balance index
CHAR (particles cm⁻² yr⁻¹)
Age (cal yr BP)
Paleohydric value assumed as modern hydric balance value
Radiocarbon dating
95 % confidence interval
locally weighted smoothing

Figure 4


(a)
Laguna San Pedro (38º S)
Nothofagus dombeyi Vs. Poaceae
CHAR (particles cm-2 yr-1)
(b)
Quitralco fjord (46º S)
Fe/Al
(c)
This work
Northern Patagonia SWW belt pollen-based index (40-45º S)
Expands northward
Contracts poleward
Southern Patagonia SWW belt pollen-based Intensity index (48º-52º S)
Intense
Weak
(d)
Stalagmita Ma1 (53º S)
yttrium (ppm)
Intense
Westerlies
Weak
(e)
Lago Fagnano (55º S)
Fe (x10³ cbs)
Precipitation
Age (cal yr BP)
locally weighted smoothing
95 % confidence interval