Quaternary Science Reviews 251 (2021) 106730

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Short communication

# An early Holocene westerly minimum in the southern mid-latitudes

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A R T I C L E I N F O

*Article history:*
Received 12 October 2020
Received in revised form
15 November 2020
Accepted 16 November 2020
Available online 3 December 2020

*Keywords:*
Early holocene westerly minimum
Southern middle latitudes
Southern westerly winds
Southwestern patagonia
Atmospheric CO2 holocene

A B S T R A C T

An important coupled ocean-atmospheric system in the mid- and high latitudes involves the Southern Westerly Winds (SWW) and the Southern Ocean (SO), which controls climate in the southernmost third of the world, deep water formation, and ventilation of $CO_2$ from the deep ocean. Most studies have examined its role as a driver of atmospheric $CO_2$ concentrations during glacial terminations, but very few have investigated its influence during the Holocene, i.e. the current interglacial. A fundamental problem, however, is resolving whether the SWW strength increased or declined during the early Holocene (~11.5 −7.5 ka, ka = 1000 cal yr BP) in sectors adjacent to the Drake Passage. Here we assess past changes in SWW influence over the last ~17,000 years using terrestrial paleoclimate records from southwestern Patagonia (~52°S). We detect a zonally symmetric Early Holocene Westerly Minimum which diminished wind stress and upwelling on the SO, contributing to a contemporary decline in atmospheric $CO_2$ concentrations and enrichment in the stable carbon isotope ratio of atmospheric $CO_2$ ($\delta^{13}C_{atm}$). Our mid-latitude data also indicate a shift to strong SWW influence at ~7.5 ka which correlates with a sustained increase in atmospheric $CO_2$ and halt in the $\delta^{13}C_{atm}$ rise, suggesting enhancement of high-latitude ocean ventilation by an invigorated SWW-SO coupled system.



## Author contribution

P.I.M. designed the study, obtained the funding and sedimentary samples, and wrote the manuscript with contributions from all co-authors.

W.I.H. contributed with data and ideas, helped obtain the sedimentary samples, and participated in writing and editing the manuscript.

O.H.P. contributed with data and ideas, and participated in editing the manuscript.

C.A.H. contributed with data and ideas, and participated in editing the manuscript.

M.S.F. contributed with data and ideas, obtained the funding and sedimentary samples, and participated in editing the manuscript.

R.D.G. contributed with climate analysis, and participated in editing the manuscript.

R.P.V-M. designed the study, contributed with ideas, obtained the funding and sedimentary samples, and participated in editing the manuscript.

## 1. Introduction

Resolving the paleoclimate history of the middle latitudes of the Southern Hemisphere is key for examining the initiation and propagation of climate signals of hemispheric and global significance. This region is under the permanent influence of the SWW, which exhibit a remarkable zonal symmetry owing to the absence of major landmasses within this latitudinal range besides the poleward tapering of the South American continent (40°-56°S). A

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https://doi.org/10.1016/j.quascirev.2020.106730
0277-3791/

growing number of empirical and modeling studies have attempted to document and understand the functioning of the SWW-SO coupled system (Lamy et al., 2007; Marinov et al., 2006; Russell and Toggweiler, 2004; Toggweiler et al., 2006), and examine its future response to human-induced climate change. One critical feature in this system is the strength of the SWW over the Drake Passage (56°-60°S), a ~500 km-wide gateway between Cape Horn and the Antarctic Peninsula through which the Antarctic Circumpolar current, among other water masses, connect the Pacific and Atlantic Oceans.

The SWW encompass extratropical South America and its present climate core at ~55°S intersects the southern tip of the continent (Fig. 1), thus enabling the study of past variations of the westerlies on terrestrial environments. Previous studies have proposed that the core of the SWW shifted equatorward during the Last Glacial Maximum delivering excess precipitation to central Chile (30°-40°S) (Heusser, 1983; Heusser et al., 1999; Lamy et al., 1999) and northwestern Patagonia (40°-44°S); alternatively, Markgraf (1989, 1993) and Markgraf et al. (2000) interpreted a poleward shift of the SWW during the LGM. Equatorward-shifted SWW may have reduced the zonal flow over the latitude of the Drake Passage and subantarctic region (>56°S) as well as wind stress on the surface of the SO. These changes resulted in increased ocean stratification, reduction of deep upwelling and $CO_2$ ventilation and, consequently, lowering of atmospheric $CO_2$ concentrations and high $\delta^{13}C_{atm}$ values (−6.4‰), as revealed by Antarctic ice core records. An inferred poleward shift of the SWW core during the Last Glacial Termination (T1 = ~17.8−11.7 ka) (Anderson et al., 2009; Moreno, 2020) was contemporaneous with a deglacial rise in atmospheric $CO_2$ concentrations and a ~0.22‰ depletion in $\delta^{13}C_{atm}$ (Monnin et al., 2001; Schmitt et al., 2012), however, the empirical basis for these atmospheric circulation changes (including millennial-scale changes in their position and strength) remains insufficiently constrained.

Atmospheric $CO_2$ concentrations reached a deglacial maximum of ~270 ppmv at ~11.5 ka, followed by a conspicuous ~12 ppmv decline and ~0.3‰ $\delta^{13}C_{atm}$ enrichment during the early Holocene (~11.5−7 ka) (Monnin et al., 2001; Schmitt et al., 2012). A gradual and sustained ~25 ppmv $CO_2$ rise started at ~7 ka and led to pre industrial values of ~280 ppmv and leveling of $\delta^{13}C_{atm}$ at ~6.35‰. These natural variations in the Carbon cycle afford benchmarks against which test the performance of earth system models about the behavior of the SO Carbon sink during the Holocene. Developments in this field will improve our capacity for predicting future responses of the SO under various climate change scenarios. The extent to which changes in atmospheric $CO_2$ concentrations

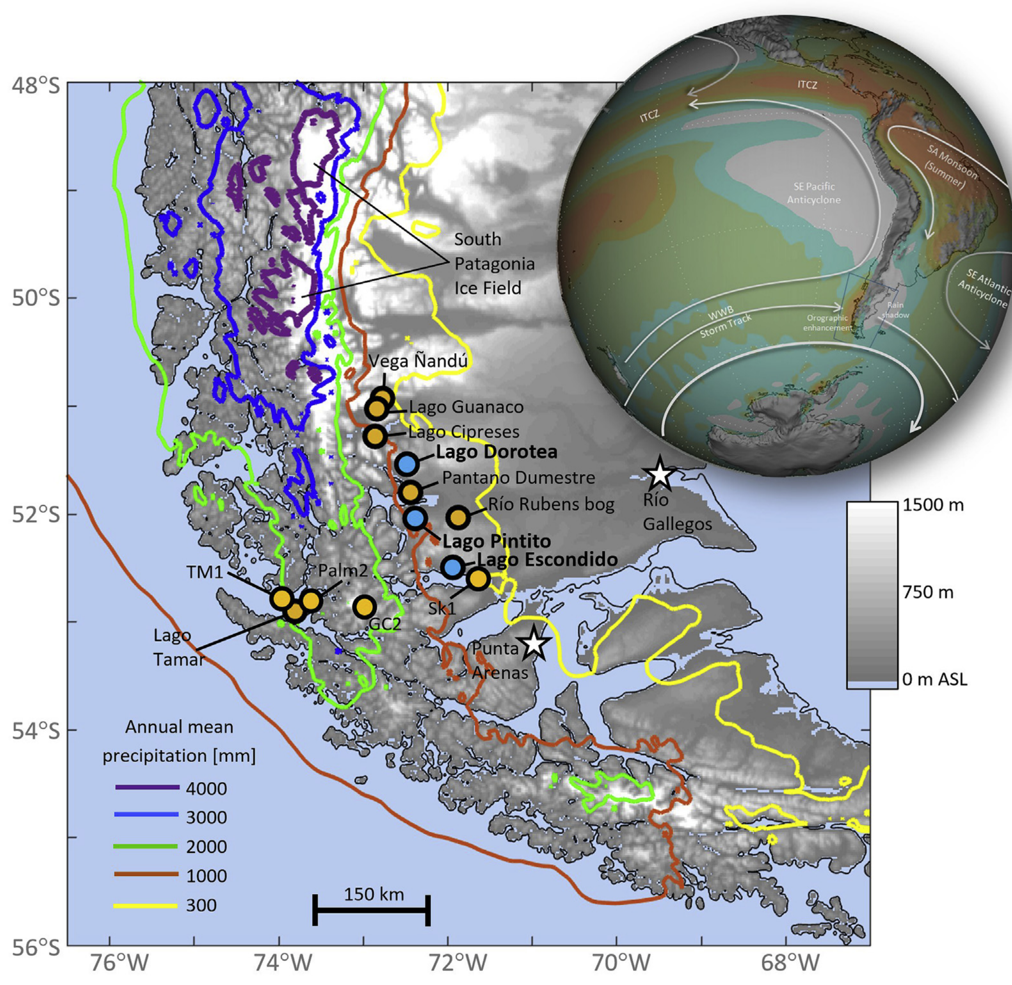


**Fig. 1.** Topographic map (shading from Shuttle Radar Topography Mission) of Southern Patagonia with indication of the sites new sites reported in this study (blue circles), previously published sites (orange circles), and nearby cities (stars). The color contours are the annual mean precipitation from the CR2Met dataset (Alvarez-Garreton et al., 2018). The globe in the upper inset shows the global precipitation (from CMAP, orange are values > 2000 mm/yr) and the main circulation features of the Southern Hemisphere. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

originated from variations in the SWW-SO coupled system during the Holocene has not been explored in sufficient detail in the literature (Fletcher and Moreno, 2011). An outstanding question is whether the SWW core shifted poleward during the early Holocene, or whether their strength declined below modern values in regions adjacent to the Drake Passage. This conundrum originates from divergences in studies utilizing marine, fjord, lake, and bog records from southwestern Patagonia (51°-53°S)(Fig. 1), which point to either anomalously high (Lamy et al., 2010) or anomalously low (Moreno et al., 2010) SWW influence in this critical sector of the southern mid-latitudes during the early Holocene.

Here we present results from small closed-basin lakes immediately east of the Andean divide in southwestern Patagonia between 51°S and 53°S to decipher the timing and direction of past changes in regional SWW strength since ~17 ka. Our findings build and expand upon previous studies from the Última Esperanza province of southwestern Patagonia (Fig. 1) by (i) examining maritime sectors that traverse the continental divide, (ii) extending the stratigraphic range from ~17 ka to the present, (iii) reporting new detailed precisely dated records with median time spacing $\leq$60 years between samples, (iv) adding an aquatic ecosystem perspective to infer past changes in lake level, and (v) examining changes in terrestrial ecosystem response along past gradients in hydrologic balance before, during, and after the controversial early Holocene. We compare our results with published data from northwestern Patagonian sites to examine the behavior of the SWW over western Patagonia, and report new results from western Tasmania (42°S) to assess the hemispheric significance of our findings.

## 2. Study area

Extratropical storms embedded in the SWW constitute the sole source of precipitation that sustains mountain glaciers, icefields, and temperate forests along western Patagonia (40°-56°S) (Garreaud et al., 2013). They deliver large precipitation amounts along the windward slopes of the Andes as moist air masses are forced to ascend driven by orographic effects, followed by some spillover across the cordillera, and downstream subsidence on the leeward slopes, generating a marked rain shadow that extends east toward the extra-Andean region. Local precipitation is positively correlated with the zonal component of the low level wind along the western sectors, and this correlation persists in locations 50–70 km east of the Andean divide by the spillover effect. Subsidence and acceleration of cold, moisture-deprived winds induce negative correlations between low-level wind speeds and precipitation further to the east of the cordillera (Garreaud et al., 2013).

The strength of the SSW exhibits substantial year to year variability in current climate that often organizes in two circumpolar bands with opposite anomalies centered at ~40°S and ~60°S (Garreaud et al., 2013). This dipolar structure is part of the positive/negative phases of the Southern Annular Mode (SAM) (Gong and Wang, 1999; Thompson and Wallace, 2000) and results in divergent anomalies of precipitation along Patagonia given the strong control that the zonal flow exert in that region. During the SAM positive phase the SWW increase in the Antarctic periphery and decrease at mid-latitudes, thus increasing precipitation in the southernmost part of South America (>50°S) while reducing precipitation in north Patagonia (~40°S). The opposite condition (wet northern Patagonia, dry Tierra del Fuego) prevails during SAM negative phase.

The annual amount (Fig. 1) and seasonality of precipitation (Supplementary Table 2), in conjunction with temperature gradients across and along the Andes, greatly influence the composition and distribution of the vegetation and fire regimes throughout western Patagonia. A west-to-east transect across the Andes at latitudes 51°-53°S traverses Magellanic Moorland communities along the windswept hyperhumid sectors adjacent to the Pacific coast, which are replaced by evergreen forests dominated by *Nothofagus betuloides* in the western Andean foothills, deciduous forests dominated by *N. pumilio* and *N. antarctica* further inland, and Patagonian Steppe east of the Andes(Villa-Martinez and Moreno, 2007). This zonation reflects the eastward decline in precipitation and rainshadow effect discussed above. The Andean treeline gives way to sparsely vegetated high-Andean grassland and scrubland at ~700 masl in the alpine zone in response to colder conditions and prolonged snow cover. Wildfires along the humid ecosystems of western Patagonia are controlled by the occurrence of dry summers, as the temporal and spatial continuity of fuels do not constitute limiting factors (Holz et al., 2012). Fire-scar tree-ring dated records from western Patagonia show a positive correlation of fire scars with SAM over the last centuries (Holz and Veblen, 2012). These findings are consistent with the occurrence of negative anomalies in summer precipitation and positive anomalies in summer temperature during the positive anomalies of SAM (Garreaud et al., 2013).

## 3. Results

We studied lake sediment cores from the deepest sectors of the small closed-basin lakes Lago Escondido and L. Pintito (Fig. 1), located 6 and 13 km from the coasts of Golfo Almirante Montt and Seno Skyring, respectively, and ~60 km apart from each other. The palynology of L. Escondido and L. Pintito (Fig. 2, Supplementary Figures 1, 2) shows an open landscape dominated by cold-tolerant grasses, forbs, and heath between ~17 and ~14 ka, along with persistently low abundance (mean: 1.3%) of arboreal pollen (AP), chiefly *Nothofagus*. This was followed by a sustained rise in AP that started at ~14 ka in both sites, reached ~70% at ~12.7 ka, and attained levels >80% from ~11 ka onward. In the meantime, planktonic algae (*Pediastrum, Botryococcus*) attained maximum abundance while the littoral macrophyte *Isoetes* persisted in low numbers (Fig. 2). An abrupt rise in the latter and decline in planktonic algae occurred between ~11.3 and ~7.5 ka, preceded by sudden increases in macroscopic charcoal accumulation rates (CHAR) at ~12.9 ka. CHAR remained at its maximum until ~7.5 ka, contemporaneous with peak AP and littoral macrophytes (Fig. 2). We interpret cold and humid conditions during the initial portion of T1 in southwestern Patagonia, followed by a precipitation increase at ~14 ka that promoted scrubland and woodland encroachment, followed by establishment and persistence of *Nothofagus* forests starting at ~12.7 ka. The predominance of planktonic algae over littoral macrophytes suggest relatively high lake level between ~17 and ~11 ka. The shallow-water macrophyte *Isoetes* increased abruptly between ~11.3 and ~7.5 ka, suggesting a shift of littoral environments toward the deepest sectors of L. Escondido and L. Pintito driven by lake level lowering (Fig. 2). Fire activity started at ~12.9 ka and remained at its maximum between ~11.3 and ~7.5 ka under continued forest dominance (AP ~80%) and a low lake level stand. A transgressive lake level sequence in both sites started at ~7.5 ka, punctuated by brief, centennial-scale reversals centered at ~6.8*, ~5.5, ~4.3*, ~4.1* ~3.5, ~1.5, and ~0.9 ka in the L. Pintito record (Fig. 2; * = statistically significant shifts).

Our pollen record from Lago Dorotea (Fig. 2, Supplementary Figure 3) reveals an open landscape dominated by herbs and shrubs between ~17 and ~7 ka, within which we observe statistically significant shifts in AP at ~14.4 ka (Fig. 3) and ~7 ka that reached peak abundance (>66%) over the last 2000 years. We also present pollen and charcoal records from western Tasmania's Basin lake, which shows a steady increase in rainforest taxa from ~17 to

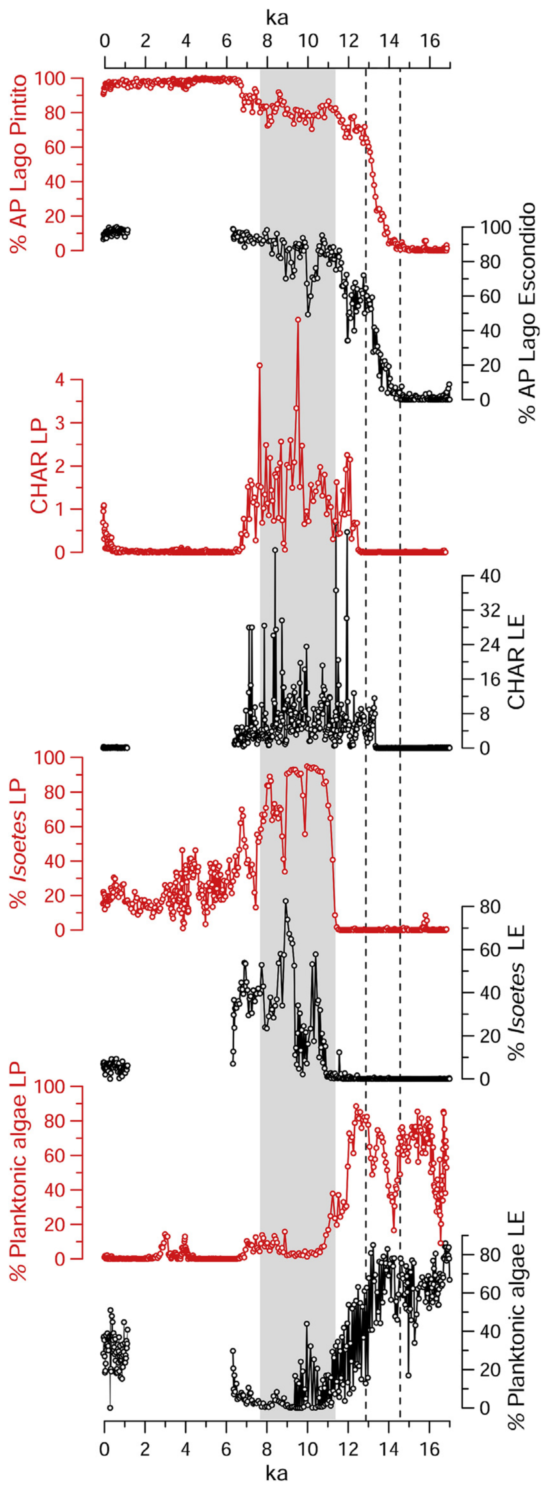


**Fig. 2.** Percent abundance of Arboreal Pollen (AP), the littoral macrophyte *Isoetes*, and freshwater planktonic microalgae (*Pediastrum* + *Botryococcus*) from the Lago Escondido (LE, black lines) and L. Pintito (LP, red lines) records located in southwestern Patagonia. Also shown are the macroscopic Charcoal Accumulation Rate (CHAR) curves from both sites. The vertical gray ribbon compasses the Early Holocene Westerly Minimum (EHWM), the vertical dashed lines constrain the timing of the Antarctic Cold Reversal. The L. Pintito record is continuous over the last ~17,000 years, the LE record has a hiatus between ~6.2 and ~1.2 ka. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

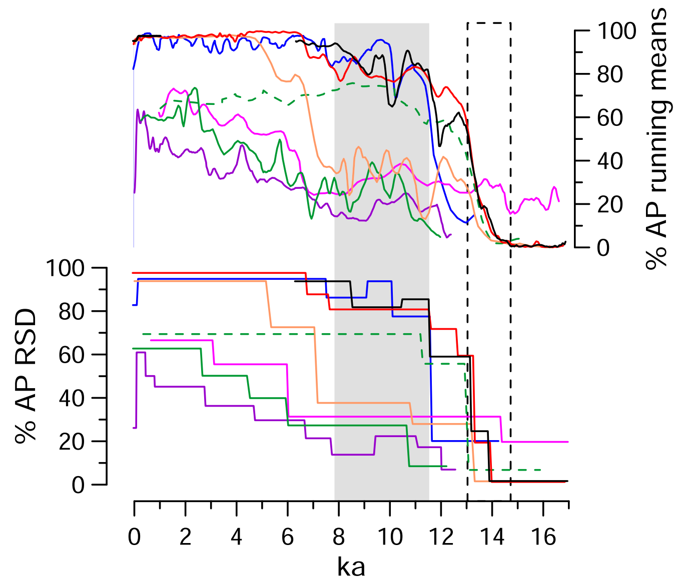


**Fig. 3.** Upper panel: Running weighted means for the %AP series from multiple sites in the study area. Lower panel: regime shift detection algorithm (Rodionov, 2004) applied to the means of the raw AP% data from L. Pintito (red line), L. Escondido (black line), L. Dorotea (magenta line), L. Cipreses (blue line) (Moreno et al., 2018a), Río Rubens bog (Huber et al., 2004) (orange line), Vega Ñandú (Villa-Martinez and Moreno, 2007) (green line), and L. Guanaco (Moreno et al., 2010) (purple line) pollen records. Note that the western sites feature an early rise in %AP that led to the establishment of *Nothofagus* forests (AP> 70%) prior to the EHWM, whereas the %AP increase was more modest in inland sites, started 1500–2000 years later and stalled/reversed during the EHWM. All of the latter sites show statistically significant increases in *Nothofagus* that culminated in *Nothofagus* scrublands or scattered woodland (AP≤ 60%) during the last millennium, with the exception of the Río Rubens site that led to the formation of *Nothofagus* forests starting at ~5 ka. The dashed gray line portrays the %AP record from L. Tamar (Lamy et al., 2010), the westernmost and southernmost record under analysis (Fig. 1). Notice that the onset of AP rise, as well as the timing and magnitude of AP variations during the Holocene are similar to the L. Escondido and L. Pintito records, suggesting similar responses to a common climate/environmental history. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

~12 ka (Fig. 4), a persistent decline between ~11.3 and ~8.9 ka contemporaneous with peak CHAR, followed by a rise in rainforest trees between ~9 and ~7 ka and subsequent declines in both variables toward the present.

## 4. Discussion

We interpret past changes in hydrologic balance in the Lago Escondido and L. Pintito records as changes in local SWW strength at millennial timescale since ~17 ka, considering the modern positive correlation between near-surface wind speeds and local precipitation in this sector of southwestern Patagonia. Our results suggest relatively weak westerlies between ~17–14 ka, strong winds between ~14–12.9 ka, a reversal toward minimum strength between ~11.3–7.5 ka through transitional conditions between ~12.9–11.3 ka, and strong SWW since ~7.5 ka. Within the latter we observe centennial-scale variability superimposed upon the transgressive lake level trend since ~6.8 ka. These findings replicate previous studies in the region (Moreno et al., 2010, 2012, 2018a) but contrast with Lamy et al.'s (2010) paleoclimate interpretations of peak SWW influence based on marine, fjord, lake and bog records from the western sector of southwestern Patagonia at ~53°S.

We assess the pan-Patagonian significance of our southwestern Patagonian results comparing with the northwestern Patagonian region, which is located ~1300 km north of the zone of present-day SWW core, and also features positive correlations between local

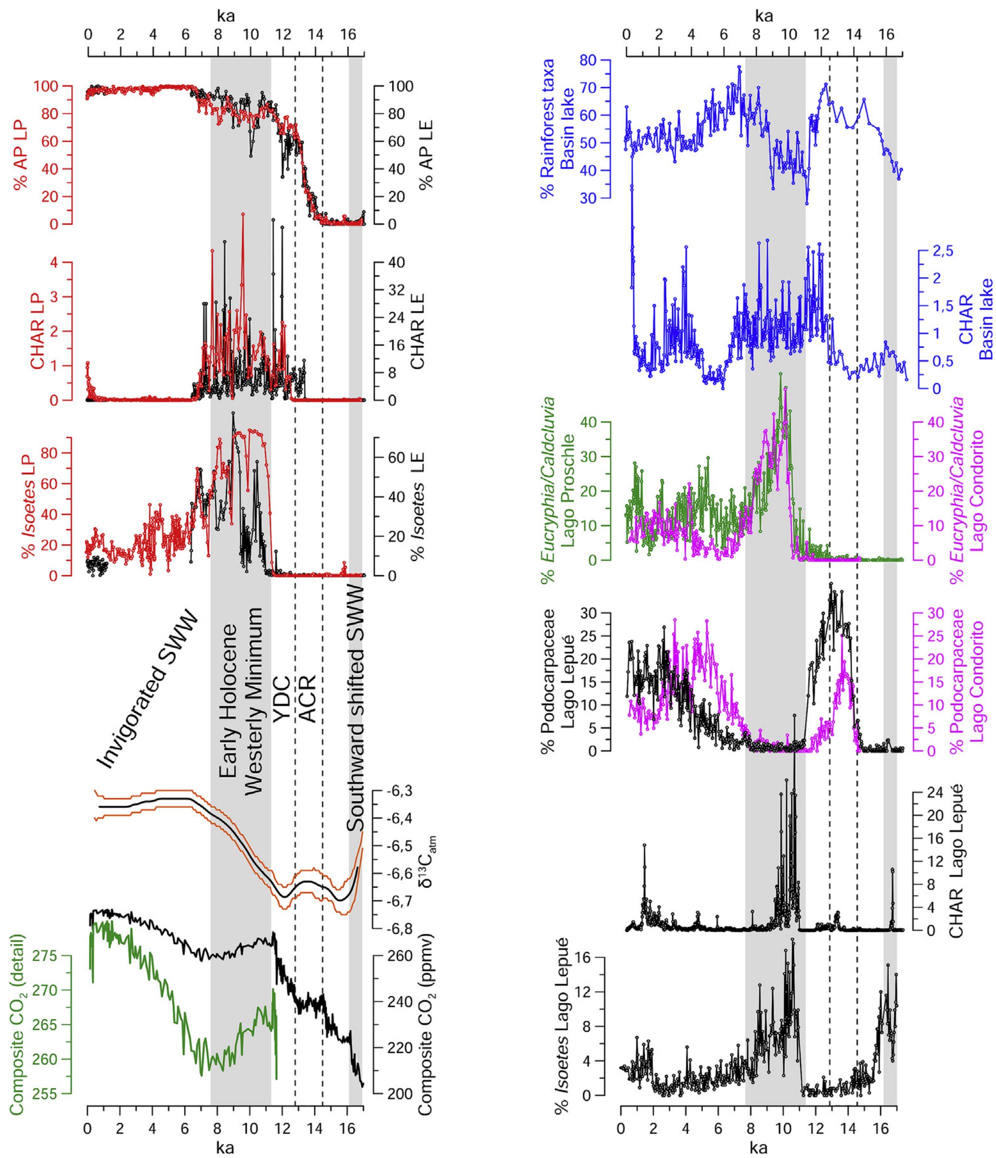


**Fig. 4.** Comparison of mid-latitude records from Basin lake (western Tasmania) with northwestern Patagonian sites Lago Proschle (41° 52.151′S, 72° 46.680′W, 54 masl) (Moreno, 2020), L. Condorito (41° 38.652′S, 73° 5.419′W, 72 masl) (Moreno, 2004) and L. Lepué (42° 48.358′S, 73° 42.862′W, 127 masl) (Pesce and Moreno, 2014), the southwestern Patagonian sites L. Escondido and L. Pintito, and Antarctic ice core data: Monte Carlo average (black line) and ±1 standard deviation (orange lines) of the stable carbon isotope ratio of atmospheric $CO_2$ ($\delta^{13}C_{atm}$) (Schmitt et al., 2012), along with the atmospheric $CO_2$ concentrations (Monnin et al., 2001). The left vertical gray ribbon compasses the EHWM, the vertical dashed lines constrain the timing of the Antarctic Cold Reversal (ACR), also shown is the Younger Dryas Chron (YDC). The vertical gray ribbon in the far right indicates a poleward shift of the SWW during the earliest phase of T1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

near-surface wind speeds and precipitation in modern climate (Garreaud et al., 2013). Recall that zonal wind anomalies in modern climate tend to be out-of-phase between the northern and southern halves of Patagonia at seasonal and annual time scales, thus causing a see-saw in precipitation anomalies between northwestern and southwestern Patagonia (Garreaud et al., 2013). Stratigraphic data from three small closed-basin northwestern Patagonian lakes (Moreno, 2004, 2020; Moreno and Videla, 2016) (Fig. 4) show variations in littoral macrophytes, CHAR, and terrestrial vegetation, suggesting millennial-scale shifts in hydrologic balance since ~17.8 ka, namely: low lake level along with fire activity between ~17.8–16.4 and ~11.3–7.5 ka, and high lake level stands with diminished fire activity between ~16.4–11 and ~7.5–0 ka. Within these millennial-scale trends, the terrestrial vegetation record allows detection of: (i) an accentuation of the precipitation rise judging from a prominent rise in cold-tolerant hygrophilous conifers of the Podocarpaceae family between ~14.5 and ~12.8 ka (Fig. 4), followed by a decline between ~12.8 and ~11 ka coeval with forest fires; (ii) a prominent decline in precipitation indicated by a rise in the thermophilous/drought-tolerant rainforest tree *Eucryphia/Caldcluvia* between ~11 and ~7.5 ka (Fig. 4) coeval with peak *Isoetes* and CHAR; and (iii) onset of precipitation variability at centennial timescale at ~6.4 ka.

Taken together, the results from northwestern and southwestern Patagonia suggest weak westerlies impinging upon the middle latitudes of South America between ~11.3 and 7.5 ka, defining an Early Holocene Westerly Minimum (EHWM) throughout Patagonia (40°-53°S). This conspicuous in-phase period features persistence of forest vegetation, intense fire activity, and lake level lowering along western Patagonia. In contrast, more inland sites in southwestern Patagonia, including our Lago Dorotea record, reveal a halt or reversal in the deglacial AP rise, and dominance of scrublands or grasslands with a relatively minor component of *Nothofagus* (AP <40%), during the EHWM (Fig. 3). This contrast suggests that: (i) afforestation of the southwestern Patagonian region was a gradual millennial-scale process initiated from western populations, (ii) this process was modulated by the amount of precipitation spillover across the southwestern Patagonian Andes, and (iii) a steeper-than-present west-to-east vegetation gradient was present during the early Holocene. Forest development near L. Escondido and L. Pintito resulted from an arboreal expansion event that took place during the Antarctic Cold Reversal (ACR: ~14.5–12.9 ka), driven by a broad Patagonian-wide shift toward wetter conditions resulting from strong SWW influence (Moreno, 2020; Moreno et al., 2012; Vilanova et al., 2019). Subsequent fire disturbance during the Younger Dryas chron (YDC: ~12.9–11.7 ka) drove a ~10% decline in AP between ~12.1 and ~11.8 ka in L. Pintito, and a ~30% reversal in the AP rising trend between ~12.7 and ~12 ka in L. Escondido. Because the limiting factor for wildfire occurrence in humid Patagonian forests is desiccation of fuels by summer droughts, we interpret the commencement of forest fires near L. Escondido and L. Pintito, and northwestern Patagonia as well, as a precipitation decline during the YDC. Fire activity reached its maximum during the EHWM, driving a ~12% decline in AP between ~10.7 and 10.2 ka in LP, and a ~35% decline between ~10.5 and 10 ka in L. Escondido. These changes did not disrupt the dominance of *Nothofagus* forests but caused intermittent, reversible openings of the forest canopy in the context of a persistently negative hydrologic-balance state (low lake level). We also point out that the northwestern and southwestern Patagonian data show an asymmetry in SWW influence during the initial portion of T1 (~17.8–16.4 ka), as tends to occur in high frequency variations in current climate, with modest fire activity and low lake level in northwestern Patagonia and lack of similar anomalies in southwestern Patagonia (Fig. 4). We interpret this contrast as evidence for an early T1, post-LGM poleward shift of the SWW.

High precipitation levels brought by a shift to strong SWW since ~7.5 ka suppressed the occurrence of fires and led to closed-canopy forests near Lago Escondido and L. Pintito, which persisted essentially unaltered until the arrival of Chilean/European settlers at ~0.3 ka. Centennial-scale lake level fluctuations in L. Pintito since ~6.8 ka overlap in timing, within age-model confidence intervals, with similar excursions reported from northwestern Patagonia (Moreno, 2020; Moreno and Videla, 2016) and L. Cipreses (Moreno et al., 2018a), a small closed-basin lake located 91 km north of LP. Though coincidental, exact matching of specific events are not to be expected considering that the response capability of a forest community is highly dependent upon local contingencies, thresholds, and ecological interactions, which may modulate the precise realization of short-lived climate-driven changes in the structure and/or composition of the vegetation surrounding the study sites. Instead, we stress that centennial-scale oscillations are evident in both regions after ~6.8 ka. Southwestern Patagonian sites located further inland exhibit sustained increases in AP after ~7.5 ka, which culminated in *Nothofagus*-dominated woodlands and forests during the last millennium (Fig. 3). Fire regimes in those environments shifted in response to precipitation increases and changes in vegetation physiognomy, with sectors dominated by Patagonian steppe exhibiting high frequency and low magnitude of local fires and the opposite in forested areas (Moreno et al., 2018b).

The hemispheric significance of the EHWM is supported by recent studies from the opposite side of the Pacific Ocean, namely: (i) diminished SWW influence in Campbell Island (52°34′S, 169°8′E) between ~12.5 and 9 ka (McGlone et al., 2019), (ii) a decline in SWW speeds between ~11.2 and 7 ka in Macquarie Island (54°38′S, 158°50′E) (Saunders et al., 2018), along with (iii) negative anomalies in the delivery of SWW-sourced precipitation in western Tasmania (42°15′S, 146°30′E) between ~12 and ~8 ka (Mariani and Fletcher, 2017). Our new pollen and charcoal record from Basin lake (Fig. 4), in western Tasmania, shows a shift toward negative hydrologic balance brought by reduced SWW influence between ~11.3 and ~8.9 ka, in agreement with our western Patagonian records. Taken together, multiple terrestrial records between ~40° and ~55°S indicate a zonally symmetric EHWM in the eastern and western Pacific sectors of the Southern Ocean. We interpret this decline of the SWW strength in a broad latitudinal swath in response to reduced baroclinicity during the early Holocene. Lower-than-present meridional gradients in atmospheric pressure resulted from a high-latitude sea surface temperature rise and reduced sea ice cover (Etourneau et al., 2013), concomitant with global sea level rise (Lambeck et al., 2014) and recession of the glacier systems in the Ross sector of East Antarctica (Spector et al., 2017) and the Antarctic Peninsula between ~11 and ~8 ka (Kaplan et al., 2020).

We posit that the EHWM diminished wind stress on the surface of the SO at the latitude of the Drake Passage, and resulted in weakening of the ventilation of $CO_2$-enriched deep ocean waters. This change contributed to the conspicuous decline in atmospheric $CO_2$ concentrations between ~11.5 and ~7 ka and a ~0.3‰ enrichment in $\delta^{13}C_{atm}$ (Monnin et al., 2001; Schmitt et al., 2012) (Fig. 4) recorded in Antarctic ice core records. A shift to stronger SWW at ~7.5 ka in the southern mid-latitudes correlates with a sustained rise in atmospheric $CO_2$, and leveling of $\delta^{13}C_{atm}$ at ~6.35‰, suggesting enhancement of high-latitude ocean ventilation by an invigorated SWW-SO coupled system. We note that alternative explanations involving poleward contraction of the SWW during the early Holocene and weakening thereafter (Lamy et al., 2010) would produce the opposite effect in atmospheric $CO_2$ that is incompatible with the vast majority of data from the zone of SWW influence.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This study was funded by the Chilean Fondo Nacional de Desarrollo Científico y Tecnológico grants 1191435 and 1171773, and the Agencia Nacional de Investigación y Desarrollo Millennium Science Initiative/Millennium Nucleus Paleoclimate NCN17_079, Australian Research Council projects DI110100019, IN140100050 and DP110101950.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106730.

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