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Centennial-scale dynamics of the Southern Hemisphere Westerly Winds across the Drake Passage over the past two millennia

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ABSTRACT

The Southern Hemisphere Westerly Winds (SHWW) exert important controls on regional and global climate. Instrumental and reanalysis records indicate strengthening and poleward contraction of the SHWW belt since the late twentieth century. Such changes also have implications for Southern Ocean upwelling and CO_2 degassing. Therefore, a better understanding of the long-term SHWW behaviors and dynamics beyond recent decades is critical for projecting future changes. Here, we applied isotope analysis of *Sphagnum* moss cellulose from a peat bog in southernmost Patagonia (~54°S) to reconstruct changes in oxygen isotope composition of precipitation ($\delta^{18}O_p$) that could elucidate past shifts in moisture sources and trajectories. We interpreted the positive shifts in $\delta^{18}O_p$ to indicate weaker SHWW and, importantly, more frequent easterly flows that enhance moisture supply sourced from the Atlantic Ocean. In contrast, negative shifts in $\delta^{18}O_p$ indicate stronger SHWW and intensification of the Andean rain shadow. Our data, along with other evidence from southernmost Patagonia and the Antarctic Peninsula, suggest a coherent pattern of centennial-scale variability in SHWW strength on either side of the Drake Passage over the past two millennia, probably as a teleconnection response to El Niño–Southern Oscillation–like variability. Our study implies that investigations of past changes in the SHWW and associated teleconnection mechanisms should consider synoptic-scale atmospheric circulation patterns, rather than seeing SHWW as a simplistic west-to-east (zonal) wind-flow pattern, particularly on the time scales over which the SHWW express zonal asymmetry among different sectors of the Southern Ocean.

INTRODUCTION

The lack of extensive landmasses in the Southern Hemisphere midlatitudes allows for development of the strong Southern Hemisphere Westerly Winds (SHWW), which are an important component of the global ocean-atmosphere coupled system. Their strength and latitudinal position are largely controlled by the Southern Annular Mode (SAM)—a dominant pattern of Southern Hemisphere extratropical climate variability—defined as the gradient of zonal mean sea-level pressure between 40°S and 65°S (Marshall, 2003). The observed late-twentieth-century positive shift in the SAM and the strengthening and poleward contraction of the SHWW have influenced temperature and precipitation distribution in the Southern Hemisphere extratropics (Villalba et al., 2012). This recent shift has been attributed to ozone depletion and rising greenhouse gas concentrations, both of which are anthropogenic in origin (Abram et al., 2014). However, the long-term natural variability and dynamics of the SHWW are still poorly understood.

Several studies have suggested that pronounced and zonally symmetric changes in SHWW strength and/or position over millennial time scales have regulated atmospheric CO_2 concentration, including its rise during the last deglaciation (Fletcher and Moreno, 2012; Mayr et al., 2013). However, there is a lack of agreement as to variability and dynamics of the SHWW during the Holocene (Lamy et al., 2010; Moreno et al., 2010), particularly since the mid-Holocene, when the modern El Niño–Southern Oscillation (ENSO) regime was established (Fletcher and Moreno, 2012; Mariani et al., 2017). This uncertainty impedes our understanding of the drivers of SHWW variability and associated teleconnection mechanisms. Hence, it is essential to develop continuous paleoclimate records in SHWW-influenced regions with robust chronology and reliable proxy interpretations. Our study focused on centennial-scale SHWW variability in southernmost Patagonia over the past two millennia by developing a new high-resolution, radiocarbon-dated peat record.

WESTERLY VERSUS EASTERLY WINDS IN PATAGONIA

Southern Patagonia is the only continental landmass within the SHWW core belt (~50°S–55°S). The Patagonian Andes lie perpendicular to the prevailing westerly winds and constitute an orographic divide, with a dramatic decrease in precipitation from the Pacific to the Atlantic coasts (Fig. 1B). This mountain chain creates tight coupling between wind speed and hydrology, with stronger westerly wind inducing more precipitation on the windward side, but less precipitation (rain shadow) and more evaporative conditions on the leeward side (Garreaud et al., 2013). Recent studies have suggested that the easterly wind flows, despite being less frequent in this region, tend to cause intense rainfall events fed by moisture from the Atlantic Ocean, which is an additional source of precipitation for the eastern side of Patagonia (Mayr et al., 2007a; Agosta et al., 2015; Quade and Kaplan, 2017). A backward trajectory analysis of present-day air parcels indeed showed two dominant air parcel transport pathways: one from the westerly winds, and the other with a (north)easterly origin (Fig. 1A). If the easterly wind frequency and the proportion of Atlantic-sourced moisture were greater when the SHWW was blocked and/or weaker, the westerly caused rain shadow effect operating today would be reduced; thus, it would

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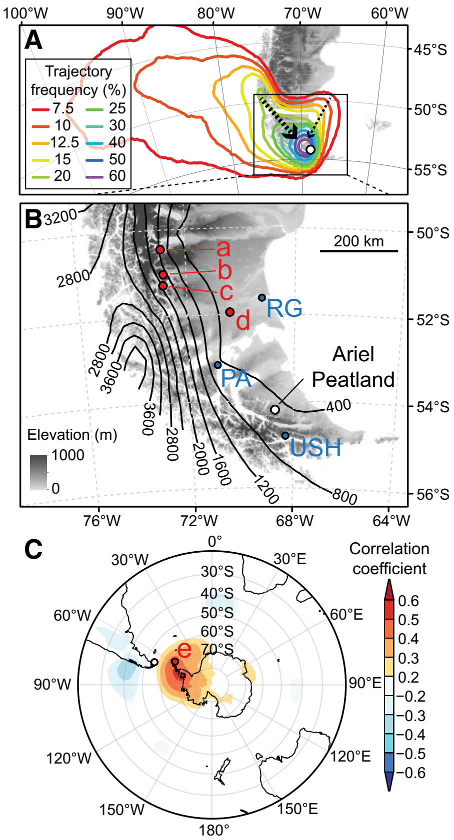

Figure 1. Location of paleoclimate sites and atmospheric trajectories. A: Trajectory frequency contours showing two dominant moisture sources and transport pathways (indicated by arrows). All rainfall-producing backward trajectories during September–May, 2005–2017, were modeled using HYSPLIT (https://www.ready.noaa.gov/HYSPLIT.php) starting from Ariel Peatland (marked by white circle) at height of 500 m for 120 h duration, and trajectory path data were binned by 1° × 1° to produce contour. B: Digital elevation map of southernmost Patagonia overlaid by precipitation isohyet in mm/yr (black lines; New et al., 2002). C: Spatial correlation between percentage of monthly easterly-related trajectories (extracted from trajectory data in A; Fig. DR6 [see footnote 1]) and European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis sea-level pressure. Red symbols in B and C show sites discussed in this study: a—Catalon Marsh; b—Lago Guanaco; c—Lago Cipreses; d—Laguna Potrok Aike; e—James Ross Island (in part C). Blue symbols in B also show major cities in this region: RG—Río Gallegos, Argentina; PA—Punta Arenas, Chile; USH—Ushuaia, Argentina.

be wetter on the eastern side of the Andean climate divide (Mayr et al., 2007a).

The contribution of easterly wind moisture in the past can be traced using water isotopes. The easterly wind flows experience less upstream orographic and rainout effects than the westerly wind flows (Stern and Blisniuk, 2002; Daley et al., 2012). This results in much higher oxygen isotope ratio values in precipitation ($\delta^{18}O_p$), as indicated by an event-based rainfall isotope study at ~52°S in Argentinian Patagonia (RG and study site "d" in Fig. 1B), which showed an ~7‰ difference between westerly and easterly signatures (Mayr et al., 2007b).

Here, we used paired measurements of oxygen and carbon isotopes from *Sphagnum* (peat moss) cellulose along a peat core in southernmost Patagonia as proxies to trace the atmospheric circulation and hydroclimate changes, respectively. This peatland site is closer to the Atlantic coast and, thus, more sensitive to easterly flows that bring in Atlantic moisture than other sites near the Andes (Fig. 1B). The physiological simplicity of *Sphagnum* mosses, which exclusively use meteoric water for photosynthesis, makes the oxygen isotope composition of their cellulose ($\delta^{18}O_{cell}$) document growing-season (mainly during summer) $\delta^{18}O_p$ by a biochemical enrichment factor of ~+27‰ (Daley et al., 2010).

MATERIAL AND METHODS

Sphagnum-dominated peat bogs in southernmost Patagonia are mostly found on the leeward side of the Andes within the cool-temperate deciduous and evergreen forest ecoregion. These ecosystems are characterized by simple plant communities, with *S. magellanicum* covering the entire ground layers (Loisel and Yu, 2013a). Our study site, Ariel Peatland (AP, ~54.2°S; Fig. 1B), was located in the Isla Grande of Tierra del Fuego, Chile. The peat bog surface today is flat without apparent hummock-hollow patterning, and the center is dominated by pure carpets of *S. magellanicum*, with *S. cuspidatum* and *Drepanocladus* spp. (brown moss) occasionally occupying small inundated hollows (Fig. DR1 in the GSA Data Repository[1]). Other bog plants are mainly herbaceous (sedges, rushes, and grasses) or ligneous shrubs, which are mostly found along the edge of the bog. A 205 cm peat core was retrieved at the center of the bog in January 2016.

Sphagnum macrofossil remains were used for accelerator mass spectrometry (AMS) ^{14}C dating, and age-depth modeling was performed using the Bacon program (Fig. DR2 and Table DR1). Plant macrofossils were analyzed at 1 cm intervals to characterize changes in peat botanical composition over time (Loisel and Yu, 2013b). For the top 109 cm section (representing past two millennia), we picked well-preserved *Sphagnum* macrofossil stem fragments (at least 30 pieces from each sample), removed branches and leaves, and extracted cellulose following the alkaline bleaching method (Daley et al., 2010). The purified cellulose samples were measured for oxygen isotope composition on an Elementar PyroCube interfaced to an Isoprime VisION isotope-ratio mass spectrometer (IRMS), and for carbon isotope composition using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 IRMS, both at the Stable Isotope Facility of the University of California–Davis (USA). The laboratory analytical precision was 0.3‰ for $\delta^{18}O$ and 0.2‰ for $\delta^{13}C$.

[1]GSA Data Repository item 2018316, further details on study site, peat core chronology, macrofossil data, modern isotope proxy processes, HYSPLIT analysis, and comparisons with instrumental records, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

ISOTOPE EVIDENCE FOR ATMOSPHERIC CIRCULATION AND HYDROCLIMATE CHANGES

Our $\delta^{18}O_{cell}$ record shows several centennial-scale shifts with an average amplitude of ~2.5‰ over the past two millennia (Fig. 2A). Evaporative enrichment of moss leaf water prior to cellulose biosynthesis is an additional factor influencing $\delta^{18}O_{cell}$. Although previous studies showed that the evaporation effect is minimal in some peat bogs (Daley et al., 2010), our current study suggests that this effect is considerable, which contributes an offset of 1‰–4‰ between $\delta^{18}O_{cell}$ and $\delta^{18}O_p$ (Fig. DR4; also see Loader et al., 2016), probably due to windy conditions. However, changes in the extent of evaporative enrichment in moss leaf water are unlikely to explain the observed variations of $\delta^{18}O_{cell}$ over time. We used cellulose carbon isotope composition ($\delta^{13}C_{cell}$) to constrain the growth conditions of *Sphagnum*, with lower $\delta^{13}C_{cell}$ values indicating more discrimination against atmospheric $^{13}CO_2$ due to a thinner water film, and thus drier

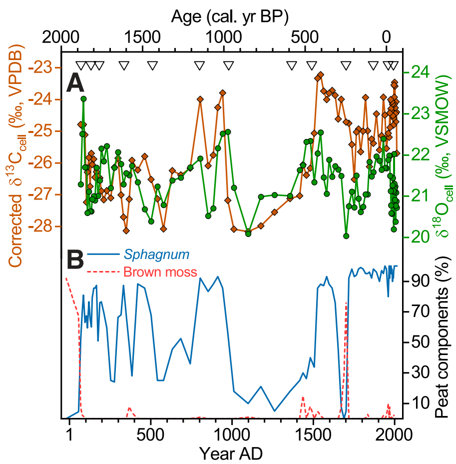

Figure 2. Summary results of Ariel Peatland (Chile) peat-core analysis. A: *Sphagnum*-specific cellulose $\delta^{18}O$ (green circles) and Suess effect–corrected cellulose $\delta^{13}C$ (brown diamonds) records (Suess effect is the decrease in $\delta^{13}C$ from atmospheric CO_2 caused by the anthropogenic combustion of fossil fuels; Leuenberger, 2007). B: *Sphagnum* (blue) and brown moss (dashed red) macrofossil percentages. Black triangles on top represent modeled median calendar ages at depths where ^{14}C dates were measured. VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water.

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and/or more evaporative environment, and vice versa (Rice and Giles, 1996). The results show that down-core $\delta^{18}O_{cell}$ and $\delta^{13}C_{cell}$ data have a positive correlation ($r = 0.43$, $p < 0.001$ for a 20 yr resampled time series; Fig. 2A), inconsistent with the effect of evaporation, which should have resulted in negative correlation (Figs. DR4 and DR5). This observation does not exclude the influence of evaporative enrichment on $\delta^{18}O_{cell}$ values, but it suggests that it is not the primary cause for the observed $\delta^{18}O_{cell}$ shifts over time. Instead, we propose that $\delta^{18}O_{cell}$ values preserve the signal of $\delta^{18}O_{p}$ in this region.

Daley et al. (2012) showed that monthly $\delta^{18}O_{p}$ values in southernmost Patagonia are neither correlated with temperature nor precipitation. Again, this implies that moisture sources and trajectories are important influences on $\delta^{18}O_{p}$ in this region, with unique development of an isotopic rain shadow (Stern and Blisniuk, 2002). This interpretation is supported by the observation that the $\delta^{18}O_{cell}$ record shows negative correlation with the SAM index reconstruction over the last millennium ($r = -0.36$, $p < 0.01$ for a 20 yr resampled time series; Figs. 3B and 3C; Abram et al., 2014). In summary, the $\delta^{18}O_{cell}$ record documents changes in growing-season $\delta^{18}O_{p}$, reflecting centennial-scale shifts in the relative strength between westerly and easterly winds as well as the relative contribution between Pacific- and Atlantic-sourced moisture. Without a conspicuous long-term trend, our record shows shifts to weaker SHWW with more frequent easterly flows during A.D. 180–420, 660–810, 900–1020, 1390–1670, and 1840–1970, and shifts to stronger SHWW with less frequent easterly flows during A.D. 100–180, 420–660, 810–900, 1020–1390, and 1670–1840. The negative shift in $\delta^{18}O_{cell}$ at A.D. 1970 further demonstrates the sensitivity of our proxy to the observed recent atmospheric circulation change (Fig. DR7).

The positive correlation between peat-core $\delta^{18}O_{cell}$ and $\delta^{13}C_{cell}$ data indicates a connection between atmospheric circulation and hydroclimate on the eastern side of the Andes in southernmost Patagonia. The $\delta^{13}C_{cell}$ record supports the interpretation that wetter habitats occurred during the periods of weaker SHWW, and vice versa, due to the rain shadow effect (Fig. 2A). Macrofossil data similarly show that *Sphagnum* spp. remains were largely replaced by dry-adapted vascular plants when the SHWW flows were stronger, but *Sphagnum*-remains abundance became dominant when the easterly flows were more frequent (Fig. 2B; Fig. DR3). While we acknowledge that the interpretations can be confounded by localized ecohydrological feedbacks through internal regulations of hydrological conditions and vegetation communities (Loisel and Yu, 2013b), the bog surface moisture signals recorded at our site seem to be primarily controlled by regional atmospheric circulation patterns.

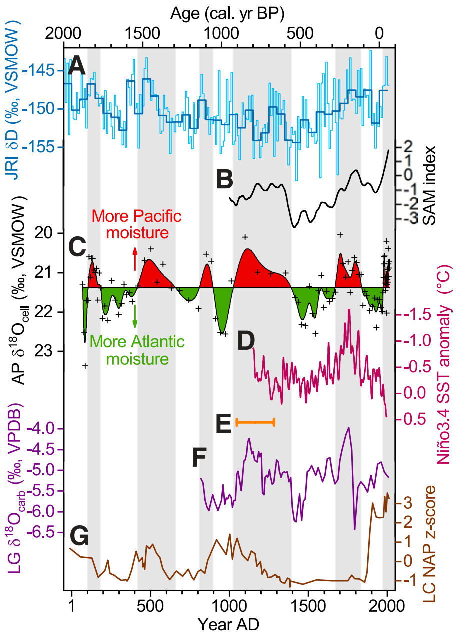

Figure 3. Coherent centennial-scale Southern Hemisphere Westerly Winds (SHWW) variability. A: James Ross Island (JRI) ice-core δD record from Antarctic Peninsula, shown as 10 yr (thin light blue) and 50 yr bin values (thick dark blue; Mulvaney et al., 2012). B: Southern Annular Mode (SAM) index reconstruction (70 yr filtered; Abram et al., 2014). C: Ariel Peatland (AP, Chile) cellulose $\delta^{18}O$ record, shown as cross symbols (raw data) and a locally weighted scatterplot smoothing (LOESS, $\alpha = 0.05$) spline trend line, with periods below and above 2000 yr cellulose $\delta^{18}O$ mean value filled by red and green color, respectively (this study; reverse scale on *y*-axis). D: Niño3.4 region sea-surface temperature (SST) anomaly reconstruction (Emile-Geay et al., 2013; reverse scale on *y*-axis). E: ^{14}C-dated interval of desiccated wetland remains from Catalon Marsh in Chile (Stine, 1994). F: Lago Guanaco (LG) carbonate $\delta^{18}O$ record (Moy et al., 2008) from Chile. G: Lago Cipreses (LC) nonarboreal pollen percentage (NAP) *z*-score record from Chile (Moreno et al., 2014). Gray shaded vertical bars indicate periods of stronger SHWW. VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water.

SHWW VARIABILITY ACROSS THE DRAKE PASSAGE

Paleoclimate studies from the rain shadow area of southernmost Patagonia are in general agreement with our interpretation of centennial-scale SHWW variability in strength. For example, the lake carbonate $\delta^{18}O$ record of closed-basin Lago Guanaco in Chile, which reflects the extent of wind-driven evaporative enrichment, shows periods of stronger SHWW centered at A.D. 1250 and 1700 and weaker SHWW centered at A.D. 950, 1450, and 1850 (Fig. 3F; Moy et al., 2008). Likewise, a paleoecological record of forest cover fragmentations from Lago Cipreses in Chile shows recurrent centennial-scale positive SAM-like dry/warm intervals; the recorded shifts at Lago Cipreses have similar timing as those in our record, with the exception of the A.D. 1670–1840 interval, which is absent from the Lago Cipreses record (Fig. 3G; Moreno et al., 2014). Desiccated wetland remains at the Catalon Marsh in Chile dated back to A.D. 1050–1300 were interpreted to reflect a period of enhanced rain shadow effect caused by strengthening of the SHWW during the "medieval time" (Fig. 3E; Stine, 1994). Furthermore, our $\delta^{18}O_{cell}$ record of SHWW variability shows an in-phase relationship with the James Ross Island ice-core δD record from the Antarctic Peninsula on a centennial scale (Fig. 3A; Mulvaney et al., 2012)—a record also used in SAM index reconstruction over the last millennium (Abram et al., 2014)—but importantly, the relationship is persistent even before the last millennium. Together, these records demonstrate a coherent pattern of centennial-scale variability in SHWW strength on either side of the Drake Passage during the late Holocene, with large magnitudes comparable to the recent anthropogenic shift.

Our analysis reveals a vigorous and pronounced variability in SHWW strength on a centennial scale, while last-millennium climate simulations driven by radiative forcing show muted SAM variability before the anthropogenic period (Abram et al., 2014). This contrast indicates the importance of a teleconnection response to ENSO-like variability as a dynamical driver of SAM or SHWW changes throughout the past two millennia (Moreno et al., 2018). Through Rossby wave chains, the ENSO could influence the strength of the Amundsen–Bellingshausen Seas Low, which in turn influences the phase of SAM on an interannual scale, with an association between El Niño (La Niña) conditions and negative (positive) phases of SAM (Fogt et al., 2011). Based on backward trajectory analysis, we find that the monthly frequency of easterly flows arriving at our study site is related to a dipole pattern in the sea-level pressure anomaly between northern Patagonia and the Antarctic Peninsula–Bellingshausen Sea area, the latter of which is located within the ENSO-teleconnection domain (Fig. 1C). Hence, the SHWW dynamics might reflect certain aspects in the strength of the ENSO teleconnection. Indeed, the stronger SHWW during A.D. 1670–1840 was in phase with a Niño3.4 sea-surface temperature (SST) minimum (where Niño3.4 is an ENSO anomaly index, defined as the average of SST anomalies over the region 5°N–5°S, 170°–120°W), while weaker SHWW flows during A.D. 1390–1670 and 1840–1970 were in phase with Niño3.4 SST maxima (Fig. 3D; Emile-Geay et al., 2013), indicating a strong signature of ENSO-like states modulating SHWW strength on a centennial scale before the recent anthropogenic shift. Although the limited length of Niño3.4 SST reconstruction prevents further comparison prior to A.D. 1150, La Niña–like conditions during the Medieval Climate Anomaly, as proposed by other studies (e.g., Cobb et al., 2003), might explain

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intensification of the SHWW starting in A.D. 1020. Reliable ENSO reconstruction is needed to further verify if the teleconnection persisted before the last millennium.

CONCLUSIONS AND IMPLICATION

Our peat moss $\delta^{18}O_{cell}$ record from southernmost Patagonia, along with other records, reveals the centennial-scale variability in SHWW strength across the Drake Passage throughout the past two millennia, which is comparable in magnitude to the recent anthropogenic shift. The record, based on the use of a water isotope tracer, strongly supports that other moisture sources and trajectories other than westerly may have been more important in the past in this region. It is an oversimplification to attribute regional hydroclimate changes to solely westerly flow controls of climate dynamics in southernmost Patagonia. Moreover, the same is likely true in other mid- and high-latitude regions of the Southern Hemisphere. In particular, establishment of the modern ENSO regime since the mid-Holocene has been shown to break the SHWW zonal symmetry (Fletcher and Moreno, 2012; but see Fletcher et al., 2018). Our study provides evidence that synoptic-scale atmospheric circulations in different sectors (Atlantic, Pacific, and Indian Oceans) of the Southern Ocean and their teleconnections/relationships with dominant climate modes need to be considered to better understand regional climate dynamics and CO_2 degassing processes in the past and future (Landschützer et al., 2015).

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