GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G50680.1

Manuscript received 18 August 2022
Revised manuscript received 31 October 2022
Manuscript accepted 1 November 2022

Published online 20 January 2023

Concordant changes in late Holocene hydroclimate across southern Patagonia modulated by westerly winds and the El Niño–Southern Oscillation

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ABSTRACT

The southern westerly winds influence weather patterns and water resources across the southern high-latitude regions, with important socioeconomic impacts. The strengthening and poleward migration of these winds since the late 20th century also have implications for regional environmental change, including drought, wildfire, and sea-ice loss. However, it is challenging to recognize the natural variability of the westerlies and predict their future behavior, as those recent changes have been influenced by anthropogenic factors. We present a 4200-yr-long record from a southern Patagonian peatland in a location that is sensitive to changes in the position and/or strength of the westerlies. Our $\delta^{13}C$ record shows a 6‰ increasing trend from 4200 to 1200 cal. yr B.P., indicating a progressive, millennial-scale increase in peatland moisture. This long-term trend is attributed to an increase in moisture induced by strengthening southern westerly winds associated with a change in the mean state of the El Niño–Southern Oscillation (ENSO) system. Superimposed on this millennial trend, centennial-scale shifts in hydroclimate persist into modern times. We suggest that a "paleo"–Southern Annular Mode, which is linked to tropical Pacific climate, with dry events contemporaneous with positive phases and La Niña–like conditions, is responsible for this enhanced hydroclimate variability. Overall, our results point to millennial- and centennial-scale changes in hydroclimate during the late Holocene that link tropical Pacific climate variability with the Southern Annular Mode and the southern westerlies, with far-reaching implications for future changes in the southern high latitudes, including CO_2 ventilation from the Southern Ocean.

INTRODUCTION

Across the southern high-latitude landmasses, recent variability and changes in the southern westerly winds have been linked to water security issues and weather extremes, including droughts and wildfire (Garreaud, 2018), as well as Antarctic ice sheet losses, with implications for sea-level rise (Holland et al., 2019). Intensification and southward migration of these winds since the late 20th century are also known to strengthen ocean circulation and upwelling around the Antarctic continent, reduce sea-ice extent, and decrease the Southern Ocean carbon sink capacity (Toggweiler et al., 2006). In extratropical South America, the poleward migration of the westerlies is linked to the positive phase of the Southern Annular Mode, which is defined as the zonal mean atmospheric pressure difference between the midlatitudes (∼40°S) and Antarctica (∼65°S). The Southern Annular Mode is considered to be the leading cause of interannual variability for Southern Hemisphere climates (Gillett et al., 2006). While there is agreement on the direction, magnitude, and causes of changes in the Southern Annular Mode since the 1940s (Mayewski et al., 2015), the pre-industrial "baseline" patterns at centennial to millennial scales, and their causal relationships to different drivers, remain poorly understood (Lamy et al., 2010). For instance, while paleo-evidence from Antarctica suggests that the ongoing positive phase exceeds natural variability from the past millennium (Abram et al., 2014), it is unclear whether pre-industrial changes in the Southern Annular Mode were caused by solar forcing, internal variability, or other physical processes (Wright et al., 2022). Notwithstanding this uncertainty, the El Niño–Southern Oscillation (ENSO) regime was suggested as one such internal feature that could explain past changes in the Southern Annular Mode, with a statistically significant (negative) relationship between paleopositive phases and La Niña–like conditions (Fogt et al., 2011; Dätwyler et al., 2020). However, this empirical relationship has only been tested for the past millennium (Abram et al., 2014), and conclusions based on reanalysis and modeling show considerable divergence (Yu et al., 2015).

The period of interest here is the late Holocene (4200 cal. [calibrated] yr B.P. onward), when the modern ENSO regime was established (Mariani et al., 2017). Our study documented millennial- and centennial-scale shifts in vegetation and plant-specific isotopic compositions in a peat bog located in southernmost Patagonia, in a zone that is highly sensitive to changes in the strength or position of the southern westerlies, based on previous paleoenvironmental records (Fig. 1A; Lamy et al., 2010; Moreno et al., 2018). We argue that the millennial-scale trend in moisture increase is attributable to large-scale shifts in mid- and high-latitude atmospheric circulation and an associated change in the mean state of the ENSO system. As for the centennial-scale changes, we contend that a "paleo"–Southern Annular Mode that is linked to Pacific climate, with dry events contemporaneous with positive phases and La Niña–like conditions, is responsible for enhanced hydroclimate variability.

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CITATION: Loisel, J., et al., 2023, Concordant changes in late Holocene hydroclimate across southern Patagonia modulated by westerly winds and the El Niño–Southern Oscillation: Geology, v. 51, p. 247–251, https://doi.org/10.1130/G50680.1

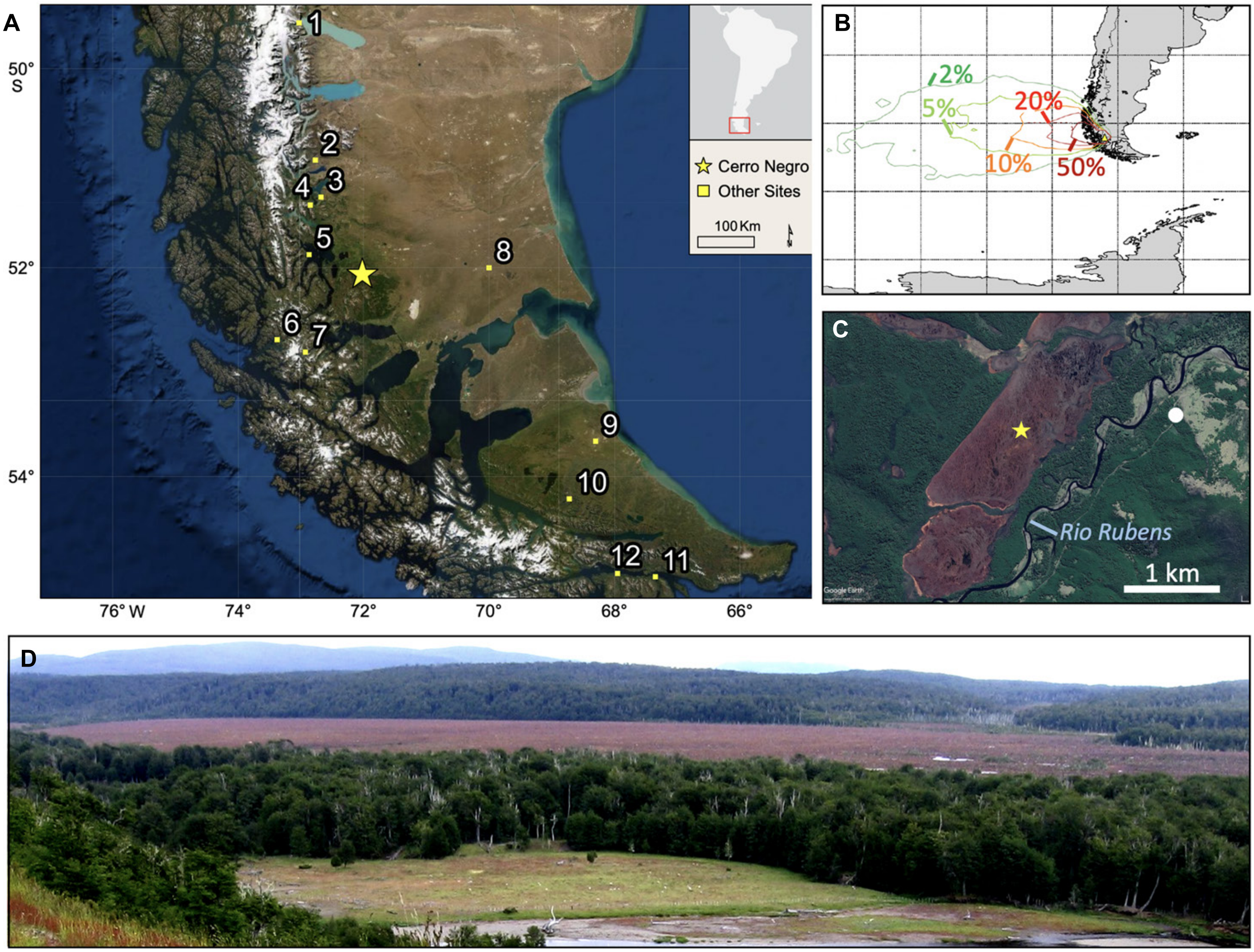

Figure 1. Study region. (A) Southern South America and location of sites mentioned in the text; star represents our Cerro Negro (Patagonia) site. 1—Glacier Torre (Reynhout et al., 2019); 2—Vega Nandu (Villa-Martínez and Moreno, 2007); 3—Lago Pato (Roberts et al., 2022); 4—Lago Cipreses (Moreno et al., 2018); 5—Lago Guanaco (Moreno et al., 2014); 6—Marcelo Arevalo (Schimpf et al., 2011); 7—GC2 (Lamy et al., 2010); 8—Laguna Potrok Aike (Mayr et al., 2007); 9—Laguna Carmen (Laprida et al., 2021); 10—Ariel Peatland (Xia et al., 2018); 11—Caleta Eugenia (McCulloch et al., 2019); 12—Punta Burslem (McCulloch et al., 2020). (B) Back-trajectory frequency analysis (modeled using HYSPLIT [https://www.arl.noaa.gov/hysplit/]) showing that the only moisture transport pathway for our site is through the westerlies from the Pacific Ocean. (C,D) Location (52.07°S, 72.03°W) and photo of Cerro Negro peat bog. Star in C represents the coring location; circle represents the vantage point from which the photograph in D was taken.

MATERIALS AND METHODS

Cerro Negro (CN) is a *Sphagnum*-dominated peat bog found near the forest-steppe ecotone in southern Patagonia (52.07°S, 72.03°W; Fig. 1A). The study area receives moisture solely from the Pacific Ocean (Fig. 1B). Core PAT10-CN was extracted by the lead author in 2010 (Fig. 1C); peat inception began at 9200 cal. yr B.P., and the peatland switched from fen to bog at 4200 cal. yr B.P. (Table S1 in the Supplemental Material[1]). Our study focused on the bog section. Core chronology was constrained by 12 radiocarbon dates (Table S1 and Fig. S1). Plant macrofossil analysis, *Sphagnum magellanicum* stem cellulose $\delta^{13}C$ measurements, and compound-specific deuterium isotope (δD) analysis from *n*-alkane C_{23}—the known biomarker for *Sphagnum* (Nichols et al., 2006)—were performed at 2 cm increments along the core (see the Supplemental Material).

MILLENNIAL-SCALE HYDROCLIMATE MODULATIONS

Our $\delta^{13}C$ record from *Sphagnum* cellulose shows a large increase of ~6‰ (values ranging from −31‰ to −19‰) from 4000 to 1200 cal. yr B.P. (Fig. 2). As for the past millennium, it is interpreted as a time period dominated by centennial-scale shifts. This large isotopic signal is interpreted as increasing peatland surface moisture on the basis of our regional analysis of 30 modern *S. magellanicum* samples, which showed a clear relationship (Pearson's $R = -0.77$) between $\delta^{13}C$ and water table depth (Fig. S2), in line with findings from other modern-process studies (Xia et al., 2020). The correlation between $\delta^{13}C$ and water table depth relates to CO_2 diffusion across the *Sphagnum* membrane: the wetter the *Sphagnum* tissue, the thicker is the water film around the photosynthetic cells, and the harder it is for CO_2 to diffuse to the plant. As a response, "wet" *Sphagnum* discriminates less against the heavy isotope (^{13}C), yielding higher $\delta^{13}C$ values.

The plant macrofossil record tells a similar story (Fig. 2), though the response time of plant

[1]Supplemental Material. Methodology and Figures S1–S5 and Table S1. Please visit https://doi.org/10.1130/GEOL.S.21743417 to access the supplemental material and contact editing@geosociety.org with any questions.

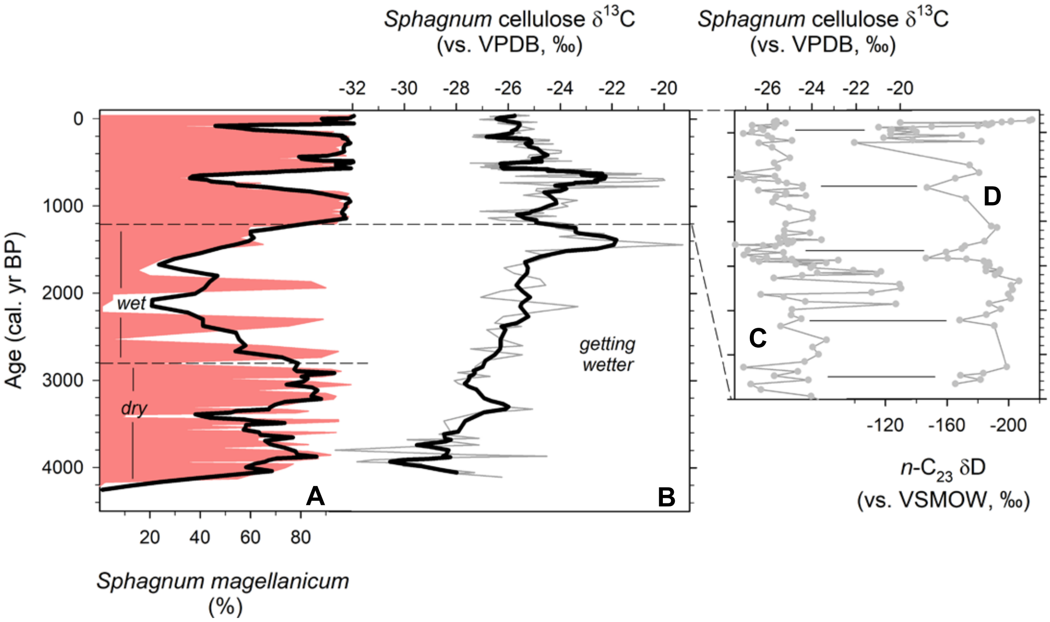

Figure 2. Late Holocene record from core PAT10-CN. (A) *Sphagnum* percentages. (B,C) *Sphagnum* δ¹³C values. (D) *n*-alkane (C_{23}) δD values. Thick lines represent 5 point moving averages. VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water.

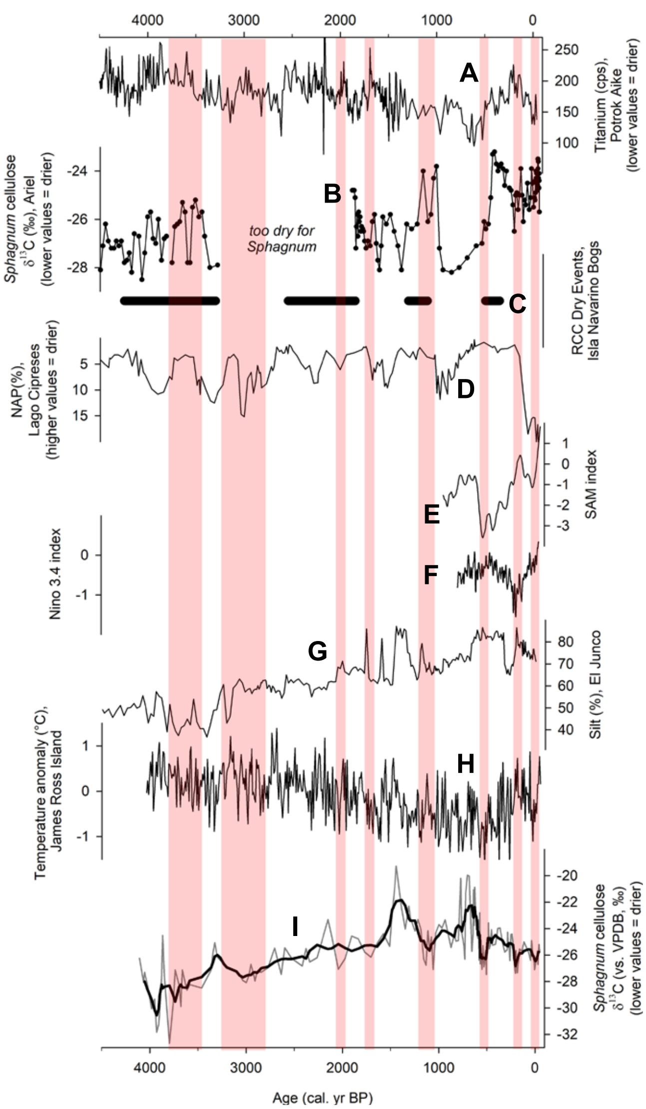

Figure 3. Correlations of regional paleoenvironmental records. (A) Laguna Potrok Aike (Mayr et al., 2007). (B) Ariel peatland (Xia et al., 2018). (C) Isla Navarino (McCulloch et al., 2020), with dry events derived from two peat bogs. RCC—rapid climate change. (D) Lago Cipreses (Moreno et al., 2018); NAP—nonarboreal pollen. (E) Southern Annular Mode (SAM) index (Abram et al., 2014). (F) Niño 3.4 sea-surface temperature index (Emile-Geay et al., 2013). (G) El Junco (Conroy et al., 2008). A–G are located in Patagonia. (H) James Ross Island, Antarctica (Mulvaney et al., 2012). (I) Cerro Negro, Patagonia (this study). Red bars: dry periods as inferred from our Cerro Negro record. VPDB—Vienna Peedee belemnite.

communities seems to be slower than the isotope record. This is expected, with *S. magellanicum* being resilient to hydrological changes, whereas carbon isotopes track growing-season hydrological variability. The site was dominated by *S. magellanicum* from 4200 to 2800 cal. yr B.P., after which *Sphagnum* gave way to brown moss (*Drepanocladus* s.l.) and sedge-like (*Tetroncium magellanicum*) communities, which indicate wetter surface conditions. A well-developed *Sphagnum* cover returned at ca. 1200 cal. yr B.P.

It is noteworthy that a peat bog surface is expected to become somewhat drier over time as its height increases and its surface becomes further isolated from the groundwater. This observation suggests that the progressive wetting reported at CN is allogenic in nature, and opposite to an expected autogenic peatland drying. We also note that our interpretation places *S. magellanicum* as a "dry" plant indicator. Indeed, the study region is wet (mean annual precipitation of ~1500 mm; Lenaerts et al., 2014), and past wetter periods might have created "too wet conditions" for *Sphagnum*.

An increase in moisture at the CN site during the late Holocene could be interpreted as a result of stronger westerly flows, as supported by instrumental records that show a positive correlation between the mean zonal wind at 850 hPa and annual precipitation on the eastern edge of the Andes through the "spillover effect" (Moreno et al., 2018). In support of this interpretation, several regional paleorecords (~50°S–56°S) concurrently recorded humid, albeit variable, conditions between ca. 4000 and 1000 cal. yr B.P. (Figs. 1 and 3). Similar hydrological changes were inferred farther south, on Isla Navarino (Chile; McCulloch et al., 2019, 2020). The clear increasing trend in wetness recorded at our site is also strikingly concurrent with the temperature decline recorded on James Ross Island (Mulvaney et al., 2012), pointing to a similar forcing mechanism. On the windward side of the Andes, along the Pacific coast, there is evidence of an increasing trend of precipitation since 3400 cal. yr B.P. (Schimpf et al., 2011). Farther east, at Lagunas Potrok Aike (Mayr et al., 2007) and Carmen (Laprida et al., 2021), decreasing surface runoff and lowering lake levels were interpreted as consequences of strengthening westerlies. In this region, the climate is dominated by the rain-shadow effect, and the strength of westerlies is inversely correlated with precipitation. Overall, we contend that the increasing surface wetness observed at our site was related to an increasingly positive moisture balance brought about by westerlies shifting toward the equator, bringing additional moisture or cooler temperatures across the region. This progressive regional wetting was concordant with increasing Southern Hemisphere insolation seasonality, which may have decreased the pole-to-equator temperature gradient and acted in concert with a southward migration of the Intertropical Convergence Zone (ITCZ) to produce stronger zonal winds (Haug et al., 2001; Conroy et al., 2008). An alternative (but not opposing) mechanism to the observed increasing precipitation trend at the CN site could relate to a progressive change in the mean state (strengthening) of the ENSO system (Liu et al., 2014), which would bring additional moisture by increasing El Niño amplitude and frequency.

CENTENNIAL-SCALE CLIMATE VARIABILITY DURING THE LATE HOLOCENE

Superimposed on the millennial-scale moisture trends at the CN site, centennial-scale shifts between low and high $\delta^{13}C$ values indicate alternating dry and wet periods (Figs. 2 and 3). Among the positive excursions (wet conditions) recorded over the past 4000 yr, the most pronounced ones occurred around 1500–1300 cal. yr B.P. and 750–550 cal. yr B.P. Those wet events are interpreted as negative-like phases of the Southern Annular Mode, which may be linked to increases in El Niño amplitude or frequency. A vegetation shift toward herbaceous plants and brown mosses at 800–600 cal. yr B.P. (Fig. 2) is concordant with the isotope records that suggest wet conditions. Conversely, positive phases (and increases in La Niña) would correspond to the abrupt negative excursions in $\delta^{13}C$ values (dry conditions), with the main ones at 1200–1000, 600–500, and 300–200 cal. yr B.P., as well as 1920–1980 CE. At the CN site, the dry excursions of the past 1500 yr were more pronounced than those that took place over the past 4000 yr (Fig. 2C). We also note that dry *Sphagnum* (low $\delta^{13}C$ values) may be more reliable as a paleohydrological proxy than the wet (high $\delta^{13}C$ values) counterparts (Fig. S5). As C isotope discrimination in *Sphagnum* is related to water retention capacity, the signal becomes more apparent under drier conditions and may lose part of its significance toward the wetter end of the range (Williams and Flanagan, 1996).

The dry periods recorded in *Sphagnum* $\delta^{13}C$ values are highly coherent with large-magnitude positive shifts in *n*-alkane C_{23} δD (Fig. 2; Fig. S4; Pearson's $R = -0.35$). We consider that changes in evaporative enrichment related to peatland hydrology and moisture conditions were the main driver of the recorded changes because (1) the magnitude of change (~40‰ and even up to 100‰) is too large to be attributable to changes in precipitation δD, and the seasonal range in modern precipitation δD in Punta Arenas is less than 30‰ (Daley et al., 2012); (2) there is only one major moisture source (Pacific Ocean) and transport pathway (westerly flows) for site CN (Fig. 1B); and (3) the highly coherent pattern between δD and $\delta^{13}C$ implies common drivers.

Enhanced climate variability during the late Holocene has been abundantly discussed in the literature. In the case of southern Patagonia, the Southern Annular Mode is seen as the main control, with negative phases linked to positive anomalies in precipitation and negative anomalies in air temperature connected to reduced fire activity, glacier advances, forest expansion, peat bog wetting, and lake-level rises (Moreno et al., 2018; Reynhout et al., 2019; McCulloch et al., 2020). At the CN site, the positive phases are associated with decreases in austral summer precipitation and higher temperatures (Moreno et al., 2014), which would make the CN site (and peatlands in general) particularly sensitive to such changes, as the surface moisture balance recorded by the isotopes reflects growing season (i.e., mostly summer) conditions. Across the study region, the records from two bogs on Isla Navarino showed similar responses to our site (Fig. 3). However, the "Cipreses climate cycles" (Moreno et al., 2018), which are dry phases linked to positive phases of the Southern Annular Mode, do not line up with the cycles detected at the CN site or the Isla Navarino bogs (Fig. 3). This discrepancy might be due to chronological uncertainties or to different responses of the proxies used, with *Sphagnum* being more sensitive to summer drought than pollen from (upland) trees, which may be more sensitive to the annual water balance.

The observed increased variability at the centennial scale over the past millennium may be caused by increased variability in tropical sea-surface temperature, which affects the intensity and location of the polar jet, which in turn has teleconnections with the southern westerlies and ENSO (Ding et al., 2012). We argue that a change in the mean state of the ENSO system might have caused millennial-scale changes in moisture. At shorter time scales, ENSO interacts with storm tracks in the South Pacific Ocean through the Rossby wave train, causing a negative association between El Niño (La Niña) conditions and negative (positive) phases of the Southern Annular Mode (Fogt et al., 2011). An increase in the number and intensity of El Niño events could then lead to wet and cool conditions in the study region, as they are characterized by a mean southward shift of the ITCZ in the Pacific Basin (Haug et al., 2001). To this effect, we know that El Niño strength peaked around 2000–1000 cal. yr B.P. (Rein et al., 2005), in line with our wettest surface-moisture reconstruction. Likewise, the Medieval Climate Anomaly was characterized by more La Niña conditions, whereas the Little Ice Age saw more El Niños (Rein et al., 2005), in line with regional findings. While both modern and paleorelationships between ENSO and the Southern Annular Mode remain debated (e.g., Dätwyler et al., 2020), our record indicates a close relationship with ENSO on centennial time scales.

CONCLUSIONS AND IMPLICATIONS

Using a peat-based dual stable-isotope paleohydrological record, we extended the Southern Annular Mode record of the past millennium presented by Abram et al. (2014) to the past ~4000 yr. The $\delta^{13}C$ record from site CN is largely coherent with Abram et al.'s (2014) record over the past millennium (Pearson's $R = -0.34$), with an exception when $\delta^{13}C$ values increased above −22‰ (Fig. S5). Using the CN record to examine the $\delta^{13}C$ relationship with the Southern Annular Mode back in time suggests a persistent cyclical presence at the multicentennial scale throughout the late Holocene that may have been modulated by a teleconnection with ENSO. Our results also indicate that the natural range of variability of the "paleo–Southern Annular Mode"—as reconstructed for the past 4000 yr along our core—was exceeded over the past six centuries, with implications for future water management in the southern high latitudes. This study also highlights the sensitivity of peatland archives to past hydroclimate changes.

ACKNOWLEDGMENTS

We thank Chris Maupin, Kim Cook, Vivian Pope, and Yinsui Zheng for laboratory assistance; Dan Maraldo for the map; and Liliana Kusanovic Marusic for access to Estancia Cerro Negro. Funding was provided by U.S. National Science Foundation grants DEB-1110665 (Z. Yu and J. Loisel) and EAR-1502455 (Y. Huang). We thank three anonymous reviewers.

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