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Centennial-scale trends in the Southern Annular Mode revealed by hemisphere-wide fire and hydroclimatic trends over the past 2400 years

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ABSTRACT

Millennial-scale latitudinal shifts in the southern westerly winds (SWW) drive changes in Southern Ocean upwelling, leading to changes in atmospheric CO_2 levels, thereby affecting the global climate and carbon cycle. Our aim here is to understand whether century-scale shifts in the SWW also drive changes in atmospheric CO_2 content. We report new multiproxy lake sediment data from southwest Tasmania, Australia, that show centennial-scale changes in vegetation and fire activity over the past 2400 yr. We compare our results with existing data from southern South America and reveal synchronous and in-phase centennial-scale trends in vegetation and fire activity between southwest Tasmania and southern South America over the past 2400 yr. Interannual to centennial-scale rainfall anomalies and fire activity in both these regions are significantly correlated with shifts in the SWW associated with the Southern Annular Mode (SAM; atmospheric variability of the Southern Hemisphere). Thus, we interpret the centennial-scale trends we have identified as reflecting century-scale SAM-like shifts in the SWW over the past 2400 yr. We identify covariance between our inferred century-scale shifts in the SWW and Antarctic ice core CO_2 values, demonstrating that the SWW-CO_2 relationship operating at a millennial scale also operates at a centennial scale through the past 2400 yr. Our results indicate a possible westerly-driven modulation of recent increases in global atmospheric CO_2 content that could potentially exacerbate current greenhouse gas–related warming.

INTRODUCTION

The southern westerly winds (SWW) are an important component of the global climate system, driving hemispheric-scale trends in climate (Garreaud, 2007; Gillett et al., 2006), terrestrial ecosystem processes and fire activity (Fletcher and Moreno, 2012), oceanic upwelling and biogeochemical cycling (Anderson et al., 2009; Marinov et al., 2006), as well as modulating global atmospheric CO_2 concentration (Toggweiler et al., 2006), dust fluxes (Lamy et al., 2014), and thermoclimate (Denton et al., 2010). Currently, the SWW are shifting southward and strengthening over the Southern Ocean in an apparent response to stratospheric ozone depletion (Perlwitz, 2011; Perlwitz et al., 2008). This shift is associated with a positive trend in the Southern Annular Mode (SAM), the primary mode of atmospheric variability in the middle and high latitudes of the Southern Hemisphere, and has the potential to amplify the effects of anthropogenic climate change via a degassing of CO_2 from the Southern Ocean into the atmosphere (Lovenduski et al., 2007). While the potential for a compounding impact of increased atmospheric CO_2 concentrations resulting from the persistent positive trend in SAM (Perlwitz, 2011) has serious implications for the trajectory of climatic change, it is currently unknown whether submillennial-scale shifts in the SWW also drive changes in atmospheric CO_2 content. We use changes in vegetation and fire activity at sites located in zones highly sensitive to changes in the SWW to (1) understand centennial-scale SWW dynamics over the past 2400 yr, and (2) assess the relationship between centennial-scale changes in the SWW and atmospheric CO_2.

The SWW are a zonally symmetric system that drives precipitation and temperature regimes across the mid- to high latitudes of all southern landmasses (Fletcher and Moreno, 2012; Garreaud et al., 2009) (Fig. 1). A recent pollen-based reconstruction of rainforest and fire dynamics from a site proximal to the moisture-determined forest-steppe ecotone at 52°S in southern Chile reveals centennial-scale shifts in moisture balance over the past 3000 yr (Moreno et al., 2014). Fires are climate limited in southern Chilean rainforests, and these shifts are interpreted as reflecting shifts in moisture balance driven by SAM-like shifts in the SWW. Despite consistency with other southern South American climate proxy data sets, the lack of synthesis with data from elsewhere within the SWW zone precludes a test of whether these represent hemisphere-wide SWW changes related to SAM or whether they are a more localized eastern Pacific Ocean trend. A new 1000 yr proxy-based reconstruction of SAM reveals that the recent SWW trend exceeds natural SWW variability during the last millennium (Abram et al., 2014). Such a departure from historical variability threatens the water security of all southern landmasses under the influence of the SWW and is responsible for a sharp increase in fire activity in southwest Tasmania, Australia (Mariani and Fletcher, 2016).

Here we present multiproxy lake sediment data (organic and inorganic geochemistry, pollen, charcoal, and near-visible light reflectance) spanning the past 2400 yr from Lake Vera, a glacial lake in southwest Tasmania (42°16′28.53″S, 145°52′47.73″E). Lake Vera is located within cool temperate rainforest and is within the zone of strongest correlation between the SWW and precipitation on Earth (Gillett et al., 2006) (Figs. 1C, 1D, and 2B), receiving ~1600 mm of solely SWW-derived rainfall per year. The study site is located within a steep-sided and hydrologically closed basin situated at 667 m above sea level. Vegetation within the lake catchment is dominated by hygrophyllous rainforest trees (*Nothofagus cunninghamii*, *Phyllocladus aspleniifolius*, *Lagarostrobos franklinii*). Fires in southwest Tasmania are climate limited

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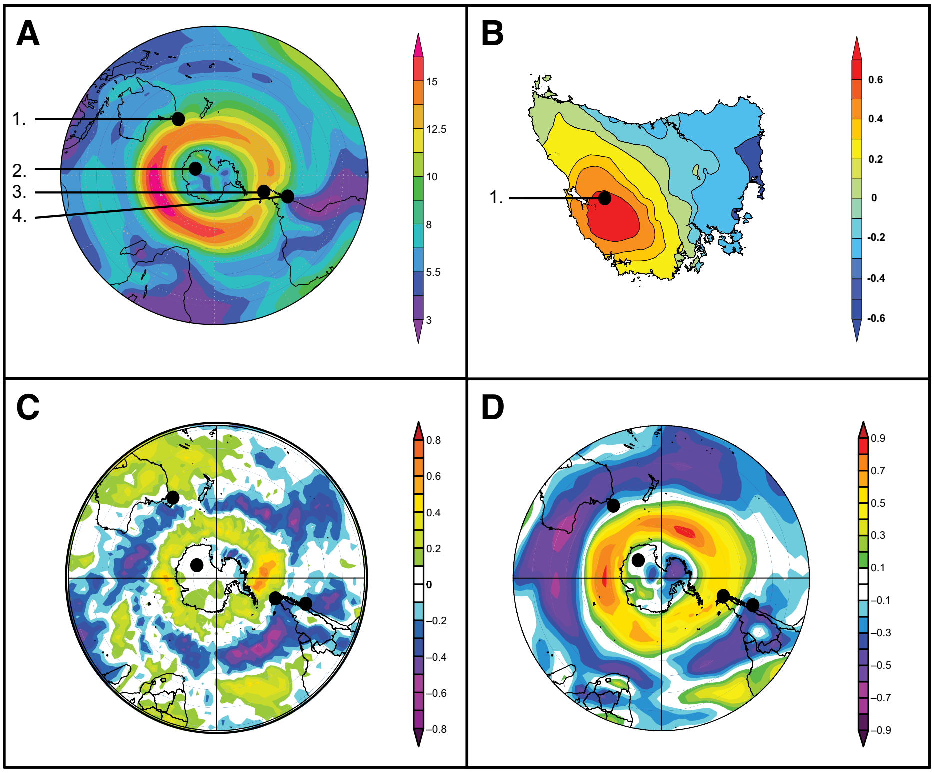
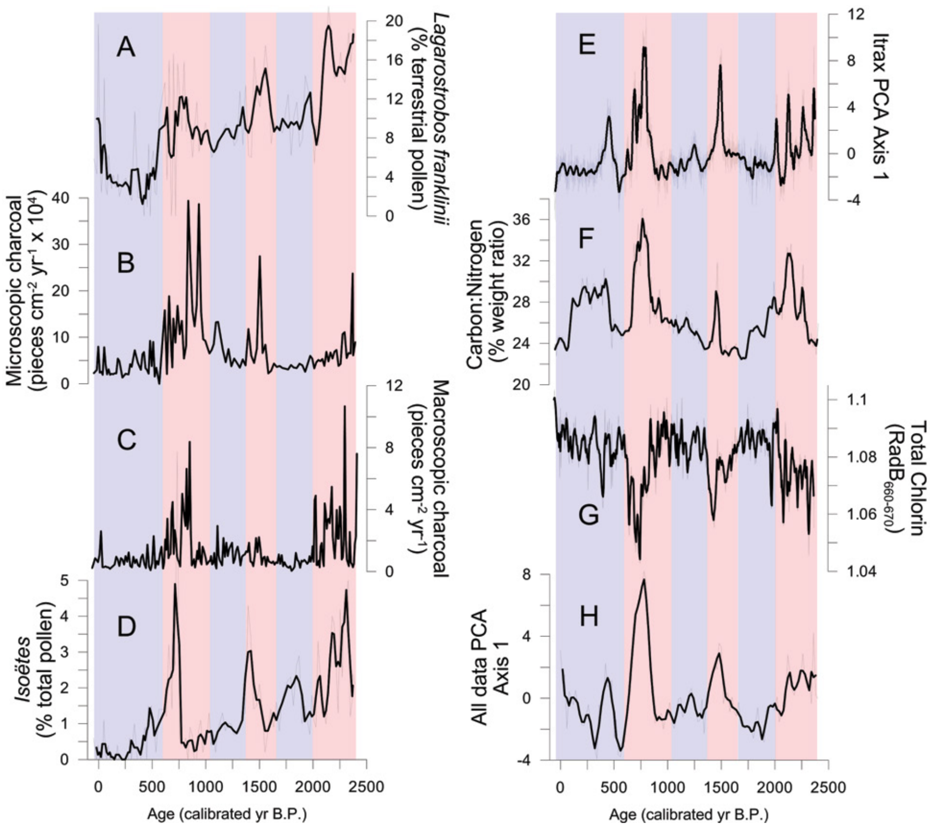


Figure 1. A: Zonal wind speeds (m/s) in the Southern Hemisphere. B: Correlation between zonal wind speed and rainfall in Tasmania, Australia. C: Correlation between Southern Annular Mode (SAM) and precipitable water in the Southern Hemisphere. D: Correlations between the SAM and zonal wind speed in the Southern Hemisphere. All data are from the U.S. National Oceanic and Atmospheric Administration (NOAA). Numbers indicate locations mentioned in the text: 1—Lake Vera, Tasmania, Australia; 2—EPICA (European Project for Ice Coring in Antarctica) Dome C, Antarctica; 3—Lago Cipreses, Chile; 4—sediment core GeoB3313-1, Chile (see text).



(McWethy et al., 2013) and are significantly correlated with interannual southward shifts of the SWW during positive SAM phases (Mariani and Fletcher, 2016). Thus, we predict that centennial-scale SAM-like shifts in the SWW will be manifested at Lake Vera as shifts in paleofire and vegetation that are synchronous and in phase with the trends identified in southern South America (Moreno et al., 2014). Furthermore, we argue that any evidence for covariance between atmospheric CO_2 content and hemisphere-wide shifts in the SWW revealed by our analysis will provide empirical support for the persistence of an SWW-CO_2 relationship operating at the centennial scale that has profound implications for our understanding of current and future changes in the global climate system.

METHODS

A full description of all methodologies is presented in the GSA Data Repository[1]. A universal gravity corer was used to retrieve a 105 cm mud-water interface core from the deepest (49.5 m) part of Lake Vera. Average annual rainfall at the site is ~2800 mm. The steep catchment is *Nothofagus*-Podocarpaceae cool temperate rainforest and emergent *Eucalyptus* species overtopping rainforest understory. Core chronology is based on statistical modeling of both ^{210}Pb (6) and ^{14}C analyses (4) (Tables DR1 and DR2 and Fig. DR1 in the Data Repository). Pollen and spores were extracted from a total of 116 samples following standard protocols (Faegri et al., 1989), with a minimum count of 300 pollen grains of terrestrial plant taxa achieved for all samples. Microscopic charcoal was tallied along with pollen, and macroscopic charcoal analysis followed standard protocols. Both charcoal sequences were converted to accumulation rates using the age-depth model. A composite

[1]GSA Data Repository item 2018108, detailed methods, results and data presentation, is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org. All data are freely available on the NEOTOMA database (https://www.neotomadb.org/).

Figure 2. Selected Lake Vera (Tasmania, Australia) sediment core analyses. A: *Lagarostrobos franklinii* pollen. B: Microscopic charcoal (<100 μm). C: Macroscopic charcoal (>125 μm). D: *Isoëtes* pollen. E: X-ray fluorescence–derived geochemistry principal components analysis (PCA) axis 1 (see text). F: C:N ratio. G: Reflectance inferred total chlorin. H: Meta-PCA axis 1 of the full data set collected from Lake Vera. See the Data Repository (see footnote 1) for the full data set and discussion of specific results. Red shaded areas indicate relatively dry phases (positive Southern Annular Mode, SAM, equivalent); blue shaded areas indicate relatively wet phases (negative SAM equivalent); see text for elaboration of SAM phases.

charcoal curve was created by binning both charcoal series in 20 yr age bins and averaging the summed z-scores of each (see the Data Repository; Fig. DR3). Geochemical data were obtained by scanning 2 mm intervals with a multifunction X-ray fluorescence (Itrax; http://www.coxsys.se/) core scanner, and principal component analysis (PCA) on the normalized data was used to extract the major axes of variation in the geochemical data set (see the Data Repository). Analysis of elemental organic carbon and nitrogen content and stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) of the lake sediments was conducted at 5 mm intervals using an elemental analyzer. The sediment was also scanned at 2 mm intervals using a GretagMacBeth-Spectrolino spectrophotometer to obtain reflectance spectra data at 10 nm intervals in the visible light range (380–730 nm). Meta-ordination (PCA) was performed on all data collected in this analysis. All data were binned to 20 yr age bins and normalized to the standard deviate (z-scores) prior to meta-ordination (see the Data Repository) and PCA axis 1 was detrended using linear detrending.

RESULTS

Our multiproxy lake sediment record from Lake Vera reveals clear centennial-scale, fire-driven changes vegetation and sediment geochemistry during the past 2400 yr (Fig. 2). We identify centennial-scale covariance between changes in abundance of *Lagarostrobos franklinii* pollen, a long-lived mast-seeding conifer whose reproduction is triggered by drought stress (Fletcher, 2015), and increased charcoal deposition at Lake Vera (LV) (Figs. 2A–2C). We interpret this covariance as local-scale fire disturbance within the Lake Vera catchment during dry phases that also initiated *L. franklinii* reproduction and pollination. The local fire events at Lake Vera are associated with other demonstrable changes within the catchment: (1) peaks in the littoral aquatic plant *Isoëtes* (Fig. 2D) that reflect lower lake levels (i.e., drier climate), which bring the littoral zone of the lake closer to the coring location; (2) an increased bulk sediment C/N ratio (Fig. 2F) reflecting the deposition of fire-damaged organosols from the catchment; (3) increased influx of detrital elements (Fe, Ti, K, Si) (Fig. 2E; see the Data Repository) that reflect post-fire exposure of the catchment bedrock and erosion of sediment in to the lake; and (4) a drop in total chlorin (Fig. 2G) that reflects a reduction in aquatic productivity in response to the substantial post-fire terrestrial input (see the Data Repository). The primary axis of a meta-ordination (PCA) of the entire proxy data set reveals clear centennial-scale oscillations between dry and wet phases (Fig. 2H). We observe 3 clear dry phases during the past 2400 yr: 2400–2000 (LV1), 1600–1400 (LV2), and 1000–500 yr B.P. (LV3) (B.P. = C.E. 1950). The most recent dry phase, LV3, 1000–500 yr , is the longest over the past 2400 yr and is associated with the most substantial system-wide response, reflected as a marked subsequent invasion of the site by disturbance indicator pollen types (see the Data Repository), indicating a reduction in resilience of the rainforest system after repeated fires (Fletcher et al., 2014) and/or more frequent and widespread fire disturbance during this dry phase.

DISCUSSION

To determine whether the timing of changes observed in Lake Vera is similar to those found on the mid-latitude eastern Pacific rim, we compared the centennial-scale trends in our multiproxy data set with pollen and charcoal trends interpreted as centennial-scale SAM-like trends from Lago Cipreses (LC), in southern Chile (Fig. 3A) (Moreno et al., 2014). The centennial-scale dry phases LV1–LV3 are synchronous and in phase with the centennial-scale dry phases CC2–CC4 found in the LC record (Moreno et al., 2014) (Fig. 3). The synchronicity and direction of these centennial-scale wet and dry phases between Chile and Tasmania, both sites that are dependent solely on SWW-derived rainfall, provide firm evidence for hemisphere-wide shifts in the SWW over the past 2400 yr. The close correspondence between both lake records (Figs. 3A and 3G) and a recent proxy-based SAM reconstruction for the past millennium based on proxy records that span the latitudinal range of the SWW (Abram et al., 2014) (Fig. 3C) clearly reveals the trends to be centennial-scale SAM-like trends occurring over the past 2400 yr. Furthermore, we observe a strong covariance between our data and iron intensity data from core GeoB3313-1 (R/V *Sonne* cruise 102a) obtained from the Chilean continental slope (41°S) (Fig. 3D), a proxy for Andean erosion linked to changes in the amount of precipitation delivered by the SWW in northwest Patagonia (Lamy et al., 2001), supporting hemisphere-wide synchronous SWW changes throughout the past 2400 yr.

Our inferred shifts in the strength and/or position of the SWW through the past 2400 yr correlate with atmospheric CO_2 concentration recorded in both the European Project for Ice Coring in Antarctica (EPICA) Dome C and West Antarctica Ice Sheet (WAIS) Divide ice core records (Ahn et al., 2012; EPICA Community Members, 2004) (Figs. 3E and 3F). While Holocene atmospheric CO_2 content is influenced by a number of Earth system processes, such as terrestrial-biosphere dynamics (Bauska et al., 2015), we observe that the largest change in our

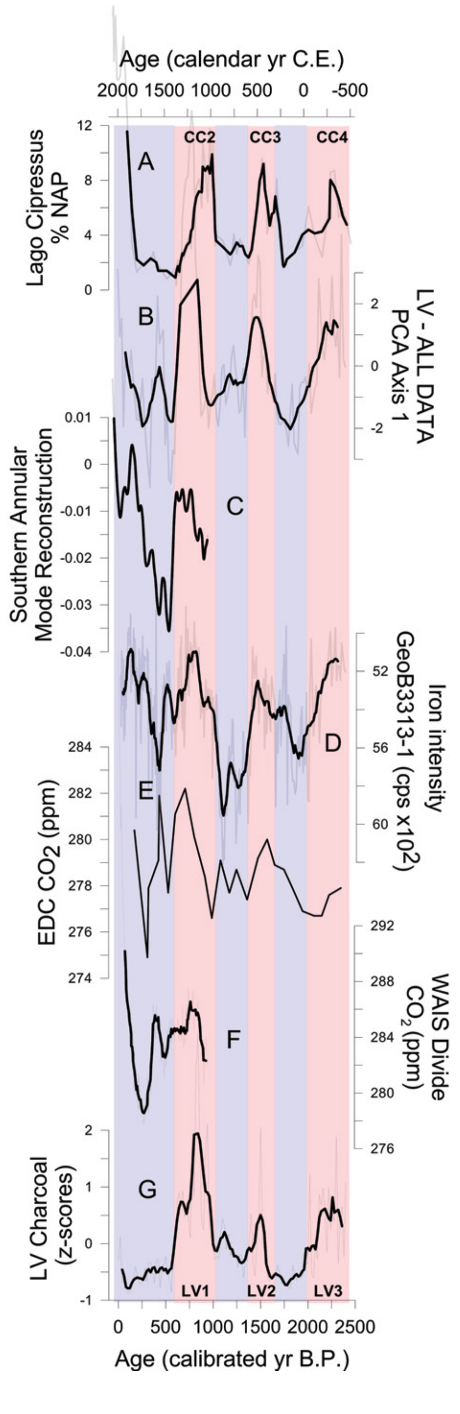


Figure 3. A: Lago Cipreses nonarboreal pollen (NAP) content, southern Patagonia, Chile (Moreno et al., 2014). B: Meta-principal components analysis (PCA) axis 1 of the full Lake Vera (Tasmania, Australia) data set (this study). C: A Southern Annular Mode (SAM) reconstruction (Abram et al., 2014). D: Iron intensity data from sediment core Geob3313-1, central Chile (Lamy et al., 1999). E: CO_2 content of European Project for Ice Coring in Antarctica (EPICA) Dome C, Antarctica (EPICA Community Members, 2004). F: CO_2 content of West Antarctic Ice Sheet (WAIS) Divide, Antarctica (Ahn et al., 2012). G: Summed microscopic and macroscopic charcoal accumulation rate data from Lake Vera (this study; see the Data Repository; see footnote 1). LV1–LV3—Lake Vera dry phases (this study), CC2–CC4—Lago Cipreses (Chile) dry phases (Moreno et al., 2014). Red shaded areas indicate relatively dry phases (positive SAM equivalent); blue shaded areas indicate relatively wet phases (negative SAM equivalent).

record during LV3 coincides with the greatest increase in atmospheric CO_2 concentration in the past 2400 yr, and that the marked CO_2 minima between 400 and 300 yr ago coincides with a strongly negative SAM-like climate state. These trends indicate that, rather than solely a Northern Hemisphere control (Ahn et al., 2012; Bauska et al., 2015), the SWW are important factors influencing centennial-scale CO_2 variations over the past few millennia. This relationship between SAM and atmospheric CO_2 concentrations is consistent with the relationship between millennial-scale shifts in the SWW and atmospheric CO_2 concentrations via SWW wind stress over critical latitudes of the Southern Ocean during the last glacial termination (LGT) (Toggweiler and Russell, 2008; Toggweiler, 2009) and during the early Holocene (Fletcher and Moreno, 2011; Moreno et al., 2010). It is important that the magnitudes of changes in vegetation and fire activity observed through the past 2400 yr at both Lake Vera and Lago Cipreses are not as large as those that occurred through the LGT or early Holocene (Fletcher and Moreno, 2011; Moreno et al., 2010), reflecting smaller scale shifts in the SWW and concomitant changes in rainfall and fire activity through this time. Our data demonstrate that the relationship between SWW dynamics and atmospheric CO_2 persists at a centennial scale and, critically, that the current positive trend in SAM has the potential to further increase CO_2 ventilation of the Southern Ocean and to positively reinforce contemporary and future climate change. The apparent hemisphere-wide modulation of fire activity and terrestrial ecosystem change by SAM that we have observed in our data and by the SWW at longer time scales (Fletcher and Moreno, 2011, 2012) highlights the importance of the SWW across a range of natural systems and speaks to the need for accounting for variability in the SAM when attempting to predict the impacts of global climate change.

ACKNOWLEDGMENTS

We acknowledge Australian Research Council (ARC) grants to Fletcher (DI110100019, IN140100050, and IN170100062) and Bowman (DP110101950) and a Marie Curie International Incoming Fellowship (237001 to Saunders). We thank Scott Nichols, Jared Pedro, Lycy Gayler, and Peter Shimeld for help in the field. We thank J.R. Toggweiler, V. Markgraf, and L. Ely for thoughtful comments on an earlier draft of this manuscript.

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Manuscript received 28 August 2017
Revised manuscript received 18 December 2017
Manuscript accepted 20 December 2017

Printed in USA