Variability in the Southern Annular Mode determines wildfire activity in Patagonia

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[1] Under the current global warming trend, wildfire activity is expected to decrease in biomass-limited fire regimes but increase in drought-limited fire regimes with abundant biomass. We examined the effects of the Southern Annular Mode (SAM) on interannual variability in wildfire activity in xeric woodland and temperate rainforest ecosystems across a latitudinal range of 10° in temperate southwestern South America (SSA). Based on 42 fire history sites based on nearly 600 fire-scarred trees (the largest available dataset of annually resolved tree-ring records of fire activity in the Southern Hemisphere), we show that years of widespread fire in both xeric woodland and rainforest ecosystems are associated with positive departures of SAM. The association of positive SAM with increased fire activity is explained by the teleconnection of SAM to spring drought across most of SSA. During the late 20th century, only the rainforest ecosystem shows a strong increase in fire activity, which is consistent both with upward trends in SAM and with warming conditions. We attribute the lack of increased burning in the xeric woodland environment to socioeconomic factors and fire behavior (low severity) that facilitate more effective fire suppression in the xeric woodland habitat. Given projected future increases in SAM and the associated warm-dry trend, wildfire activity in much of SSA is likely to increase during the 21st century. **Citation:** Holz, A., and T. T. Veblen (2011), Variability in the Southern Annular Mode determines wildfire activity in Patagonia, *Geophys. Res. Lett.*, *38*, L14710, doi:10.1029/2011GL047674.

1. Introduction

[2] Fire is a key biophysical process that influences forests across the earth [*Krawchuk et al.*, 2009; *Bowman et al.*, 2009]. Recent upsurges in areas burned on all continents with forests have been attributed to land-use practices in some regions [*Meyn et al.*, 2007] and more generally to climate trends [*Bowman et al.*, 2009]. Global and regional trends in wildfire activity are increasingly being linked to global warming and the synchronizing of fire weather conditions at distant locations via teleconnections induced by major climatic oscillations, such as the El Niño Southern Oscillation (ENSO [*Le Page et al.*, 2008]). Regional-scale studies of climate influences on wildfire activity over periods of a century or more are mainly limited to northern temperate latitudes [e.g., *Kitzberger et al.*, 2007; *Trouet et al.*, 2010]. However, recent increases in wildfire activity apparently linked to warming have been observed in many southern temperate ecosystems [*Veblen et al.*, 2008; *Wilson et al.*, 2010]. In the current study, we use multi-century tree-ring reconstructed fire histories from southwestern South America (SSA) to analyze long-term climatic influences on wildfire activity.

[3] In southern South America (i.e., south of ca. 37°S), the warmest tree-ring reconstructed temperatures in the last 400 years occur during the second half of the 20th century [*Villalba et al.*, 2003]. Warming and drying trends in this region during the second half of the 20th century have been related to an upward (positive) trend in the Southern Annual Mode (SAM) [*Aravena and Luckman*, 2009; *Garreaud et al.*, 2009]. SAM (also known as the Antarctic Oscillation) is the leading driver of extratropical climate variability in the southern hemisphere and is characterized by a seesaw pattern of synchronous zonal sea level pressure anomalies of one sign centered in the Antarctic and of the opposite sign on a circum-global band at ca. 40 to 50°S [*Fogt et al.*, 2009]. The positive phase of SAM is associated with decreased surface pressure over Antarctica and a strengthening and poleward shift of the Southern Hemisphere (SH) westerlies [*Garreaud et al.*, 2009]. Interannual positive anomalies of SAM are associated with higher temperatures [*Garreaud et al.*, 2009] and lower precipitation [*Aravena and Luckman*, 2009] in SSA. Since the inception of SAM measurement in 1948, its annual and seasonal values have experienced a strong upward trend (Figure 1; $p < 0.01$ [*Thompson and Solomon*, 2002; *Marshall*, 2003]). Reconstructions of SAM identify this post-1948 upward trend, which parallels warmer conditions in the post-1950s throughout the SH [*Smith and Reynolds*, 2005], as the strongest trend during the last 150 years [*Fogt et al.*, 2009]. Climate models that successfully reproduce the ca. 50-year upward trend in observed SAM, relate its positive trend to increased greenhouse gases and reduced stratospheric ozone concentrations, and conclude that SAM will continue in its positive, drought-inducing phase over the 21st century [*Fyfe and Saenko*, 2006; *Miller et al.*, 2006].

[4] Widespread wildfires in SSA are strongly associated with seasonal and annual drought [*Veblen et al.*, 2008]. In northern Patagonia (hereafter NP) years of widespread fire in fuel-limited xeric woodlands in the ecotone between mesic forests and the dry steppe are often preceded by moist conditions that increase fine fuel (i.e., grass) production [*Kitzberger et al.*, 1997]. In mesic *Nothofagus* forests and rainforests in NP and in southern Chile (hereafter SC) fires coincide with extreme warm and dry spring-summers [*Kitzberger et al.*, 1997; *Veblen et al.*, 1999; *Holz*, 2009]. Most fires in SC and NP occur in the summer (February [*Kitzberger et al.*, 1997; CONAF, unpublished data, available at http://www.conaf.cl/seccion/incendios-forestales.html]). Years of widespread fires in NP and SC are tele-

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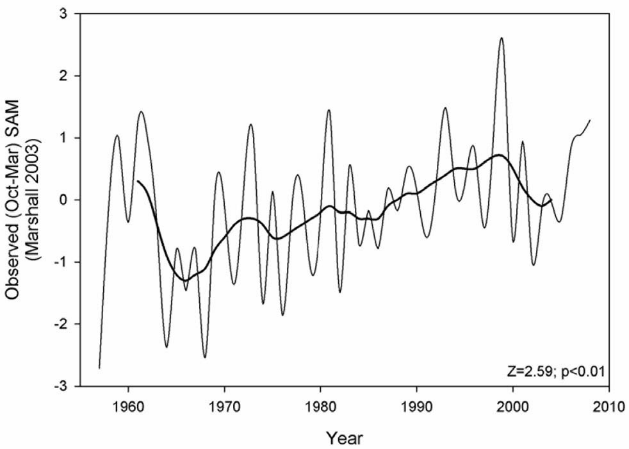

Figure 1. Mean Spring-Summer (Oct–Mar) values of observed SAM for 1957–2008 [*Marshall*, 2003] (http://www.nerc-bas.ac.uk/icd/gjma/sam.html). A low-pass Gaussian filter (bold-line) is shown to highlight the low-frequency trend (10-yr window). Statistics of the Mann-Kendall trend test of randomness (Z and p-value) are shown (the series was tested for lag-1 correlation and proved not to be significant; p > 0.05).

connected to variability in sea level pressure in the Antarctic Peninsula-South America sector of the Southern Ocean at ca. 50–60°S (i.e., a surrogate for SAM) and its tree-ring reconstruction over the period 1746 to 1984 [*Veblen et al.*, 1999; *Holz*, 2009]. During the second half of the 20th century, when SAM has been in an upward trend, statistical associations of widespread fires in SC with positive SAM have strengthened in comparison with the previous 100 years [*Holz*, 2009].

[5] Intuitively, warming associated with a positive trend in SAM is expected to result in increased fire activity in SSA. However, actual effects of warming on wildfire activity in any particular ecosystem type depend on availability of biomass to burn as well as ignition sources [*Krawchuk et al.*, 2009]. In some ecosystems, such as xeric temperate woodlands where availability of abundant grass fuels is an important determinant of fire spread, warming may result in less fire activity due to reduced moisture for the growth of grasses [*Krawchuk et al.*, 2009]. Consequently, in the current study we compare the effects of SAM-related climate warming on wildfire activity in two ecosystem types with contrasting fuel types: xeric *Austrocedrus chilensis* woodlands in NP and rainforests dominated by *Pilgerodendron uviferum* in SC.

[6] Years of widespread fire in the tree-ring reconstructed fire history record for *Austrocedrus* in NP are strongly associated with dry years that follow, by one to a few years, years of moister winter-springs that enhance the production of grass fuels [*Kitzberger et al.*, 1997; *Veblen et al.*, 1999]. Most fire events in the *Austrocedrus* woodlands are low-severity fires that are more likely to be suppressed as reflected by the sharp decline in tree-ring recorded fires following the implementation of a fire suppression policy in the mid-20th century in NP [*Kitzberger et al.*, 1997; *Veblen et al.*, 1999]. In contrast, in the rainforest region of SC biomass is not limiting to fire spread and years of widespread fire depend only on extreme drought that desiccates fuels, not on preceding wet episodes [*Holz*, 2009]. Also in contrast to NP, in SC there is no evidence of effective fire suppression [*Holz*, 2009]. Although lightning ignites some fires in both regions, accidental or intentional burning by humans is the primary source of ignition. By limiting analyses to years of widespread fire (i.e., synchronous scarring of many disjunct sites separated by >10 km), in the current study we focus on interannual variability in weather conditions suitable for fire spread rather than unlikely interannual variability in human attempts to set fires. Both regions have experienced significant growth in human populations in the latter part of the 20th century, and in the interpretation of multi-decadal scale trends in wildfire activity we consider the potential influence of changes in the frequencies of human-set fires. Based on the largest dataset of high-resolution, tree-ring based fire scar histories (598 fire-scarred trees collected at 42 sites from 39 to 48° lat S) analyzed to date for any area in the SH, we examine the spatial and temporal variability of fire-climate interactions in these two extensive ecosystem types over the past two and a half centuries. Specifically, we examined interannual variability in fire activity potentially related to SAM, and we explored the climatic mechanisms driving SAM's influence on fire activity in SSA.

2. Material and Methods

[7] Fire-scar records for NP were obtained mainly from the xeric conifer *Austrocedrus* (91% of trees sampled) in the rainshadow east of the Andes (~39–43°S; 21 sites [*Veblen et al.*, 1999]), and for SC from *Pilgerodendron* (100% of trees sampled) in rainforests on the western side of the Andes in SC (~42–48°S; 21 sites [*Holz*, 2009]; Table S1 in the auxiliary material and Figure 2a).[1] Annual fire indices were computed as the percentage of sites recording fire based on a minimum of at least two synchronously scarred trees per site. The start year of each individual site fire chronology was defined by the first year when ≥2 trees were scarred synchronously (starting in 1504 and 1559 in NP and SC, respectively). To focus on years when regional weather was conducive to extensive fire spread (hereafter widespread fire years), years were only included in the analyses if ≥10% of all sites (each separated by many 10s of kms) and a minimum of 5 sites in each region recorded fire (starting in 1525 and 1612 in NP and SC, respectively). Effective fire suppression by national park authorities is evident in the fire record of the NP region [*Veblen et al.*, 2008], and consequently the time period analyzed ends in 1932. In contrast, in the SC region there is no evidence of effective fire suppression [*Holz and Veblen*, 2011] and consequently the full record is analyzed (ends in 2004; Figure 2b).

[8] Chi-square tests were conducted to examine interannual synchrony of widespread fire activity between NP and SC for the 1612–1932 period. Synchrony in years of widespread fires between the two regions would imply control by regional climate variation. Regional fire chronologies were compared to a tree-ring reconstruction of mean zonal sea level pressure anomalies (MSLPA) at c. 60°S in

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047674.

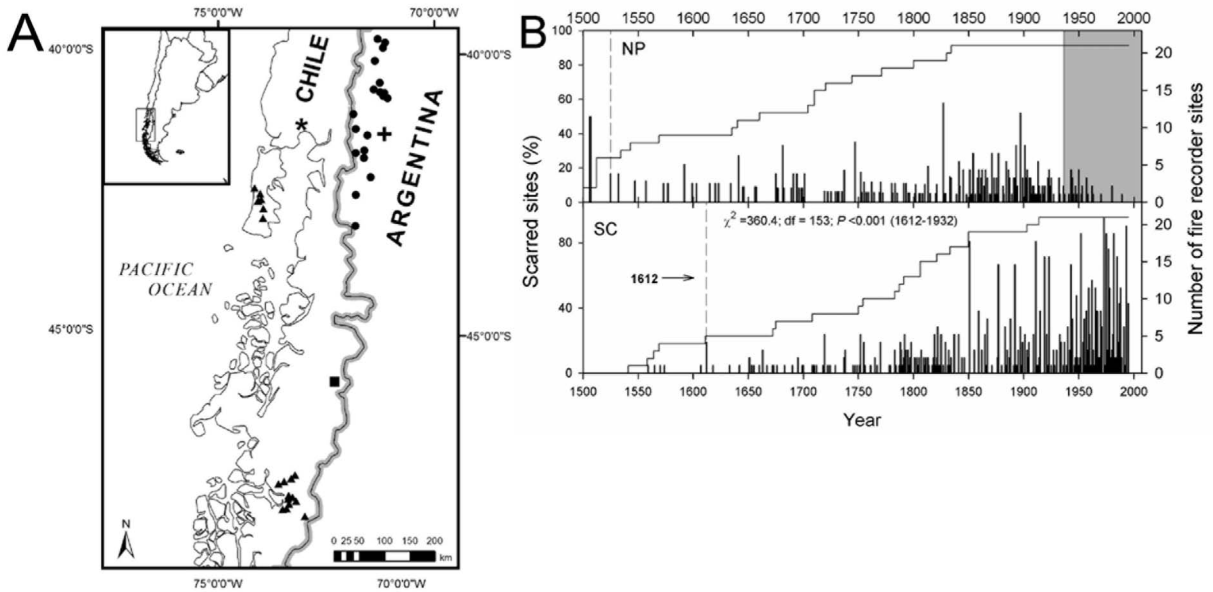

Figure 2. (a) Locations of the regional fire-chronologies in northern Patagonia (NP, circles) and southern Chile (SC, triangles), and of the Puerto Montt (asterisk), Bariloche (cross) and Balmaceda (square) climate stations. (b) Time series (1500–2004) of all fire events and sample depth of each region's chronologies (grey area represents the fire suppression period (post-1932) in the NP area). Chi-square and p-value are shown for the two time series of widespread fire years (≥10% of all sites in each area, with a minimum of two scarred trees per site, and of 5 sites per study area recording fire). Vertical dashed-lines and "1612→" indicate the start year of the fire chronology and of analysis.

the Antarctic Peninsula-South America sector as an index of the SAM (Nov–Feb (1746–1984) MSLP index [*Villalba et al.*, 1997]). We extended the SAM reconstruction to 2004 (i.e., the last fire date in our SC dataset), using the detrended values from the instrumental records of the SAM (following procedures of *Schoennagel et al.* [2007] and *Holz* [2009]). The periods analyzed for potential relationships of fire activity to SAM are 1746–1932 and 1746–2004 in NP and SC, respectively; the first widespread fire year is 1747 and 1755 in NP and SC, respectively (Figure 2b).

[9] Superposed Epoch Analysis (SEA) was used to quantify interannual-scale relationships between fire events and the SAM by superposing a 4-year window of contemporaneous and lagged departures from the mean tree-ring reconstructed SAM index over each fire year (i.e., from 2 years prior to 1 year after fire [*Baisan and Swetnam*, 1990]). SEA was performed for widespread fire years and for non-fire years. Significance levels were determined from bootstrapped confidence intervals estimated (95%) from Monte Carlo simulations [*Mooney and Duval*, 1993]. To identify potential climate mechanisms by which SAM variability affects local wildfire activity in SSA, we computed interannual-scale correlation functions between the SAM index (Nov–Feb) and instrumental data from the most reliable and longest climate records near the sample areas (Puerto Montt [41°25′S/73°05′W; 85 m.a.s.l.; 1950–2000], Bariloche [41°09′S/71°16′W, 825 m.a.s.l.; 1950–2000], and Balmaceda [45°55′S/71°41′W; 309 m.a.s.l.; 1950–2000 for precipitation, 1962–2000 for temperature]). We computed bootstrapped confidence intervals [*Biondi and Waikul*, 2004] to estimate the significance of correlation function coefficients. In addi1tion, for the period prior to the initiation of these instrumental records (i.e., pre-1950), we computed SEA between widespread fire years in each region and multiproxy gridded summer temperature reconstruction (Dec–Feb, STR; 0.5° × 0.5° grid resolution; 40–50°S/70–75°W; 1498–1995 [*Neukom et al.*, 2010a]) and summer precipitation reconstruction (Dec–Feb, SPR; 0.5° × 0.5° grid resolution; 40–50°S/70–75°W; 990–1995 [*Neukom et al.*, 2010b]) for the overlapping period of analysis in both regions (i.e., 1612–1932). Correlations between SAM and Neukom's reconstructions were also performed.

3. Results

[10] Each of the two regional fire chronologies included 21 sample sites. These included 432 fire recorder trees for NP and 166 fire recorder trees in SC, recording the earliest fires in 1506 and 1559, respectively (Table S1). Fire years are frequent in both records during the period analyzed for relationships with SAM (post-1746); the main contrast between the two records is the decline in fire frequency in NP during the post-1932 fire suppression period vs. continued frequent fire years to the present in SC (Figure 2b). The annual time series of years of widespread fire (≥10% of scarred sites) are in synchrony with each other during the period of overlap with the tree-ring reconstruction of SAM and before fire suppression was implemented in NP (1612–1932; χ^2 = 360.4; P < 0.001; Figure 2b).

[11] In both study areas, mean SAM is significantly above average during years of widespread fire (P < 0.05; Figures 3a and 3b). Conversely, during years in which no fire scars were recorded, SAM is significantly negative in both study areas (P < 0.05; Figures 3c and 3d). Additionally, no significant 1–2 year lags between SAM departures and fire years were observed in either region (Figures 3a and 3b).

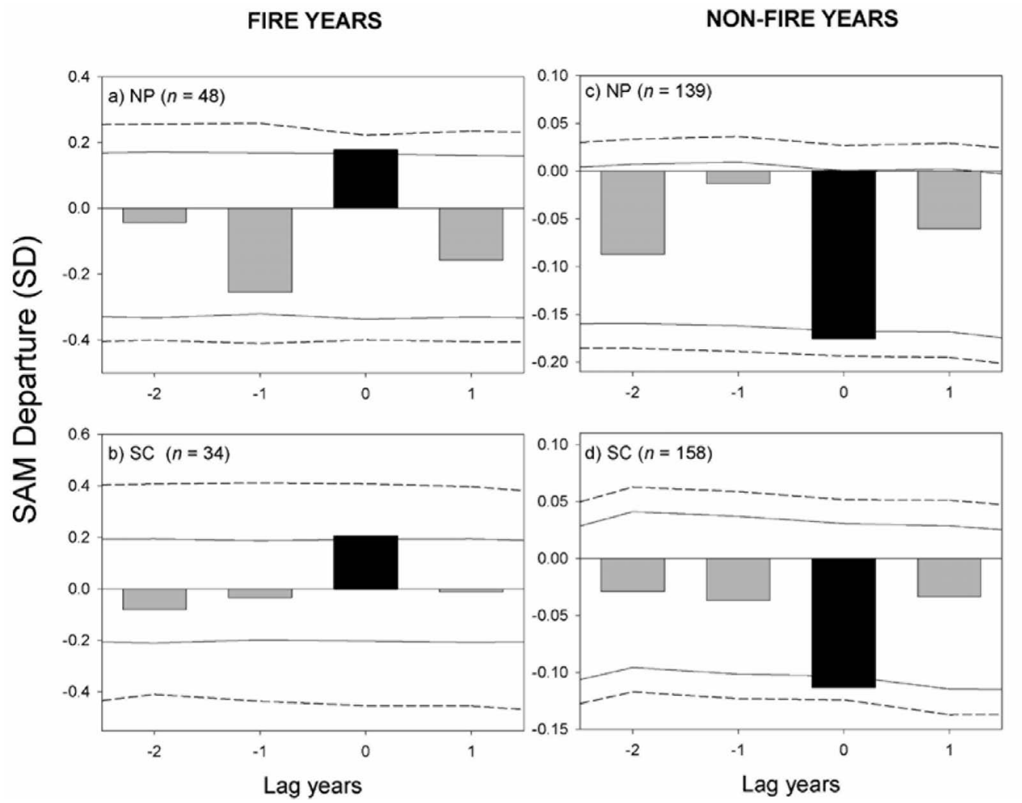

Figure 3. Departures (SDs) from mean values for tree-ring reconstructed indices of SAM (Dec–Feb [*Villalba et al.*, 1997]) for 4-yr windows (t − 2 to t + 1) centered on years of widespread (≥10% of sites) wildfires in (a) the NP (1746–1932) and (b) SC (1746–2004) regions, and also on non-fire years in (c) NP and (d) SC. Black bars indicate statistically significant departures (P < 0.05) from the mean. Horizontal lines represent 95% CIs derived from 1000 Monte Carlo simulations.

At this interannual-scale, positive SAM is associated with drier and warmer springs than average during the second half of the 20th century (Figure S1). In addition, the SPR is significantly above average during years −1 and −2 preceding (NP; $P < 0.01$) and year −2 preceding (SC; $P < 0.05$) widespread fire years (Figure S2), respectively. In contrast, no association was found between fire activity in either region and STR (Figure S2), nor between the reconstructed SAM and either of Neukom's reconstructions (r = −0.07 for SPR and r = −0.06 for STR).

4. Discussion

[12] Interannual variability in tree-ring reconstructed wildfire activity in xeric woodland and rainforest ecosystems across a latitudinal range of 10° in temperate SSA is strongly related to variability in SAM. Years of widespread fire are highly correlated between the two study areas (Figure 2b), which strongly implies broad-scale climate control of wildfire activity. Years of widespread wildfires in both the NP and SC regions are years during which SAM is significantly above average. SAM is positively correlated with annual air temperature south of 40°S in SSA [*Garreaud et al.*, 2009] and with drier annual conditions along the west coast of SSA [*Aravena and Luckman*, 2009]. The association of fire years in the SC region with a greater positive departure of SAM and the near average SAM values for the preceding two years is consistent with the interpretation that fire is dependent exclusively on fuel desiccation during the year of fire occurrence in these rainforests (Figure 3a). In the NP region, the tendency towards a negative departure of SAM in year t-1 (P = 0.17) is consistent with the interpretation that short-term increases in fine fuels contribute to widespread fire in the xeric woodlands of the NP region (Figure 3b). In the region studied, positive SAM is strongly teleconnected with dry spring conditions (but also with warm spring conditions; Figure S1). Drier and warmer springs in previous studies have been shown to be good predictors of wildfire activity in both regions [*Kitzberger et al.*, 1997; *Veblen et al.*, 1999; *Holz*, 2009]. Although most fires occur in summer (Jan–Mar) which is typically warmer and drier than spring, earlier initiation of fuel desiccation during anomalously drier springs would increase fire potential by providing drier fuels earlier in the fire season and would contribute to more extreme drying later in the fire season.

[13] Years of widespread wildfires in both the NP and SC regions are years that follow years above total summer precipitation. As previously documented, large fire years in NP's xeric woodlands are favored by fine fuel build-up during years preceding large events [*Veblen et al.*, 1999]. However, for the SC rainforest region the two year lag of years of widespread fire after higher summer rainfall is unlikely to be due to fuel buildup given the abundance of fuels in these mesic ecosystems. We interpret the latter results as due to: a) the distant locations from the SC region

of the proxy sources used in the gridded SPR, and b) the coarse spatial resolution of Neukom's SPR reconstruction consisting of broad west-to-east grids (70–75°W) extending from near the Atlantic Ocean to our sample sites near the Pacific Ocean. Furthermore, the lack of association between the STR and fire activity in either region is consistent with the determining role of reduced precipitation on fire in these ecosystems [*Veblen et al.*, 1999; *Holz and Veblen*, 2011]. In addition to the limitation of the coarse spatial-resolution of the gridded reconstructions, it is noteworthy that Neukom's reconstructions are for summer whereas SAM-induced drought mostly occurs in the Spring (Figure S1).

[14] Previous research has strongly linked wildfire activity in NP to interannual variability in ENSO and associated latitudinal shifts in the southeastern Pacific anticyclone [*Kitzberger and Veblen*, 1997; *Veblen et al.*, 1999]. In contrast, in the rainforest region of SC, ENSO variability is not a good predictor of fire at an interannual scale even though multi-decadal periods of warmer basin-wide Pacific temperatures enhance the fire-promoting effects of positive SAM [*Holz and Veblen*, 2011]. However, the current analysis shows that SAM is a good predictor of wildfire activity in both regions.

[15] Although the post-1950 upward trend in SAM and its strong teleconnection to warming in SSA [*Fyfe and Saenko*, 2006; *Miller et al.*, 2006; *Garreaud et al.*, 2009] is creating weather conditions more conducive to fire spread, the impact of this climate trend on actual wildfire activity in the two study areas is different. In the rainforests of SC, the more favorable weather conditions for fire spread in combination with increased human activity and no effective fire suppression are consistent with the high incidence of fire occurrence since c. 1950. Most of the SC study area is remote from state authority and in a phase of forest resource extraction and conversion to pasture where pioneer occupants exploit extreme drought to burn otherwise highly fire-resistant wet forests [*Holz*, 2009]. In contrast, the NP study area since the mid-20th century has been at a stage of economic development that is dependent on tourism associated with large national parks where infrastructure and state authority facilitate fire suppression [*Veblen et al.*, 2008]. Equally important is the fact that many of the fires in the xeric woodlands are relatively low severity (surface fires) events that are more easily suppressed than crown fires in tall forests. Thus, despite the interannual association of wildfire activity with positive SAM and its upward trend after c. 1950, effective fire suppression appears to have prevented a commensurate increase in burning of xeric woodlands. However, fuel-defined fire hazard in NP is increasing due to woody encroachment associated with fire suppression and planting of introduced conifers [*Veblen et al.*, 2008] so that prevention of crown fires favored by the positive trend in SAM is likely to become more difficult in the near future.

[16] Positive SAM is associated with a weakening and/or poleward shift of the westerlies [*Garreaud et al.*, 2009], and interannual variability in SAM during the late 20th century has recently been linked to the dynamics of ecosystems at numerous locations in the mid- to high-latitudes of the Southern Hemisphere, including stream discharge in northern Patagonia [*Lara et al.*, 2008], rodent population fluctuations in south-central Chile [*Murúa et al.*, 2003], tree defoliating insect outbreaks in southern Argentina [*Paritsis and Veblen*, 2011], and marine ecosystems in the Southern Oceans [*Forcada and Trathan*, 2009]. Given the predicted continuation of the upward trend in SAM, the findings of these studies and the current study on wildfire activity in SSA suggest that broad-scale and important ecological changes related to SAM are already underway.

5. Conclusion

[17] Tree-ring reconstructed fire-scar records beginning in 1506 AD and developed from 42 sample sites from rainforest and xeric woodland habitats in SSA show that interannual variability in wildfire activity is highly synchronous and is teleconnected with variability in SAM. Years of widespread fire in both study areas coincide with positive departures of SAM, which in turn is teleconnected to warm and dry conditions across a large part of SSA. The research reported here helps to clarify how SAM controls weather conditions conducive to widespread fires at broad-scales in SSA. Although fire potential is enhanced by spring drought related to positive SAM in both the NP and SC study areas, effective fire suppression in grassland and xeric woodland habitats is the most likely explanation for a lack of post-1950 increase in wildfire activity in NP. However, as warming and drying trends continue, it is likely that wildfire activity will increase even in woodland areas where fire suppression has previously been effective. Agreement among climate predictions suggests that SAM will continue in its positive, drought-inducing phase thus increasing fire potential during the 21st century in SSA.

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