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Climatic controls of Holocene fire patterns in southern South America

Cathy Whitlock [a,*], Patricio I. Moreno [b], Patrick Bartlein [c]

[a] *Department of Earth Sciences, Montana State University, Bozeman, MT 59717, USA*
[b] *Institute of Ecology and Biodiversity and Department of Ecological, Sciences, Universidad de Chile, Santiago, Chile*
[c] *Department of Geography, University of Oregon, Eugene, OR 97403, USA*

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Abstract

Holocene fire–climate–vegetation linkages are mostly understood at individual sites by comparing charcoal and pollen records with other paleoenvironmental proxy and model simulations. This scale of reconstruction often obscures detection of large-scale patterns in past fire activity that are related to changes in regional climate and vegetation. A network of 31 charcoal records from southern South America was examined to assess fire history along a transect from subtropic to subantarctic biomes. The charcoal data indicate that fire activity was greater than present at ca. 12,000 cal yr BP and increased further and was widespread at 9500 cal yr BP. Fire activity decreased and became more spatially variable by 6000 cal yr BP, and this trend continued to present. Atmospheric circulation anomalies during recent high-fire years show a southward shift in westerlies, and paleoclimate model simulations and data syntheses suggest that such conditions may have prevailed for millennia in the early Holocene when the pole-to-equator temperature gradients were weaker and annual temperatures were higher than present, in response to orbital-time-scale insolation changes.

Keywords: Fire history; Patagonia; Charcoal records; Early Holocene climate; Southern westerlies

Introduction

Fire is a critical Earth-system process that has broad consequences for vegetation dynamics, biogeochemical cycling, and atmospheric chemistry. Variations in fire activity were an important trigger of past biotic reorganizations, and they are implicated as a primary agent of ecosystem change in the future (Price and Rind, 1994; Watson et al., 2000; Overpeck et al., 2002). In southern South America (south of lat. 35°S), the occurrence of catastrophic fires in recent years has raised questions about our understanding of fire–climate–vegetation linkages and the role of climate change, fuel buildup and land-use activities in past fires (Morgan et al., 2003). To address these questions requires information on past fire activity and its response to changes in climate and vegetation.

Fire–climate–vegetation linkages are complex on any time scale. In a given year, the likelihood of fire is determined by weather, including precipitation amount, relative humidity, lightning occurrence, air temperature, and wind, which jointly influence fire behavior (including ignition) and fuel moisture/flammability (Pyne et al., 1996). The conditions that give rise to fire weather are, in turn, embedded in large-scale climate anomalies, which in southern South America include variations in the strength and location of the southeast Pacific subtropical high-pressure system and the southern westerlies that govern regional temperature and precipitation anomaly patterns. On interannual and decadal time scales, fires in southern South America have been correlated with climate variations arising from atmosphere/ocean interactions, like the El Niño–Southern Oscillation (ENSO) (Kitzberger, 2002). On century and millennial time scales, changes in fire activity are linked to changes in atmospheric and ocean circulation that affect regional vegetation patterns and fuel conditions. On longer time scales ($>10^3$ yr), fire occurrence is often related to variations in effective moisture arising from changes in the seasonal cycle of insolation, atmospheric composition, and land–ocean interactions (Whitlock and Bartlein, 2004). Past, present, and future human activities also affect fire–climate–

* Corresponding author.
E-mail addresses: whitlock@montana.edu (C. Whitlock), pimoreno@uchile.cl (P.I. Moreno), bartlein@uoregon.edu (P. Bartlein).

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vegetation linkages at all spatial scales (e.g., Foley et al., 2005).

Detailed fire-history studies in southern South America, based on charcoal analysis, have recently become a focus of paleoenvironmental research (e.g., Moreno, 2000; Heusser, 2003; Huber et al., 2004; Whitlock et al., 2006). Two incongruities emerge from site-based studies: first, many sites record highest fire activity during the late-glacial and early Holocene when summer insolation was low, and consequently the direct effects of insolation on surface water- and energy-balance components were also low. This relation between fire and fire-season insolation is opposite of that in western North America (Whitlock et al., 2001). High fire incidence in southern South America during the early Holocene has been attributed to greater climate variability on decadal-to-centennial time scales than at present (Huber et al., 2004), an overall decrease in precipitation of westerly origin (Moreno and León, 2003; Moreno, 2004), and/or deliberate burning by prehistoric peoples (Heusser, 2003). Second, the onset or strengthening of ENSO variability in the middle and late Holocene is associated with an overall decrease in fire frequency at many sites, even though ENSO seems to explain the weather–fuel conditions that create the current fire regime (Kitzberger and Veblen, 2003). This paradox suggests either that the controls that shape fire regimes on long time scales are decoupled from those that operate on short time scales, or that our current understanding of ENSO's role is not adequate to describe the region's fire history on multiple time scales.

We examined all available charcoal records from southern South America to identify regional patterns of fire activity during the last 12,000 yr. A transect of charcoal records spanning 20° of latitude from broad sclerophyllous woodland to subantarctic deciduous forest/steppe was compiled to identify periods with positive and negative fire anomalies relative to present conditions, as well as locations of greatest change in past fire activity. At this geographic scale, the controls of fire are changes in climate and fuel conditions, whereas site-specific and human factors are less important (Carcaillet et al., 2002; Marlon et al., 2006). To seek an explanation for paleofire patterns, we examined the climate conditions that gave rise to high-fire years in recent decades, as well as paleoclimate reconstructions of past intervals when fire activity was high.

Data and methods

Charcoal data

Advances in the analysis and interpretation of charcoal records preserved in lakes and wetlands have greatly improved our understanding of fire history (see Whitlock and Anderson, 2003). Most charcoal methods are broadly similar, focusing on (1) quantifying charcoal content in lake cores, (2) determining an appropriate age model, (3) converting direct measurements to charcoal accumulation rates (CHAR; particles or area cm^{-2} yr^{-1}) or percentage data in reference to pollen abundance, and (4) extracting fire signal from noise. Macroscopic charcoal particles are examined in investigations concerned with reconstructing local fire regimes. Contiguous core sampling provides the temporal resolution necessary to detect individual fire events from background levels of charcoal. Microscopic charcoal particles (<100 μm in diameter tallied on pollen slides) travel long distances and thus offer a less-spatially resolved picture of fire activity. Pollen-slide charcoal records are usually developed from widely spaced core samples, and only general trends in fire activity can be inferred. Although the temporal and spatial information provided by these two approaches is different, changes in charcoal abundance by either method are adequate to resolve periods of high and low fire activity.

In order to utilize different types of data, we focused on differences in overall charcoal abundance over time in a network of sites from lat. 35.5 to 55°S. Target dates of 12,000, 9500, 6000, and 3000 cal yr BP were chosen for examination because they involve different configurations of the large-scale controls of climate change on orbital time scales (e.g., ice sheet size, insolation, greenhouse gases). We chose 500 cal yr BP, just prior to European settlement, to represent the "present" because this period featured natural conditions prior to extensive land modification. Differences in charcoal abundance relative to present (Figs. 1A–D) and to the previous target time (Figs. 1F–G) were examined. Assumptions about the different source areas and transport mechanisms of macroscopic and microscopic charcoal data limit our interpretation to "higher", "lower" or "no change" in the comparisons.

Thirty-one charcoal records were considered for this study (Fig. 1E, Table 1). In each case, chronologies were converted to calendar years using CALIB 5.0 (Stuiver et al., 1998) in order to identify the target periods (Fig. 1E). The charcoal value was based on samples ±500 yr of the target date. The pre-European level at the top of the record was determined by identifying the charcoal level prior to the presence of nonnative pollen taxa (e.g., *Rumex*, *Pinus*) or the level prior to recent, often abrupt changes in charcoal abundance caused by European forest clearance or fire suppression.

Modern fire and climate data

Annual area burned in southern South America provided by the Corporación Nacional Forestal–Chile (CONAF; http://www.conaf.cl), made available through the Global Fire Monitoring Center (GFMC; http://www.fire.uni-freiburg.de/), includes data for the 1977 through 2004 fire seasons (Fig. 2). We examined the total area burned in administrative districts X (Los Lagos) and XI (Aysén) (lat. 39–49°S). Comparisons with other compilations (e.g., Kitzberger and Veblen, 2003; Lara et al., 2003; Kitzberger, unpublished data) suggest that these data adequately represent fire activity in the region.

We used the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (Kistler et al., 2001; hereafter "NCEP data") to examine the present-day controls of fire in the region (see Shinker et al. (2006) for the strategies and limitations of this approach for understanding paleoenvironmental records). Anomalies of several variables for summer (December to February) were created by subtracting the long-

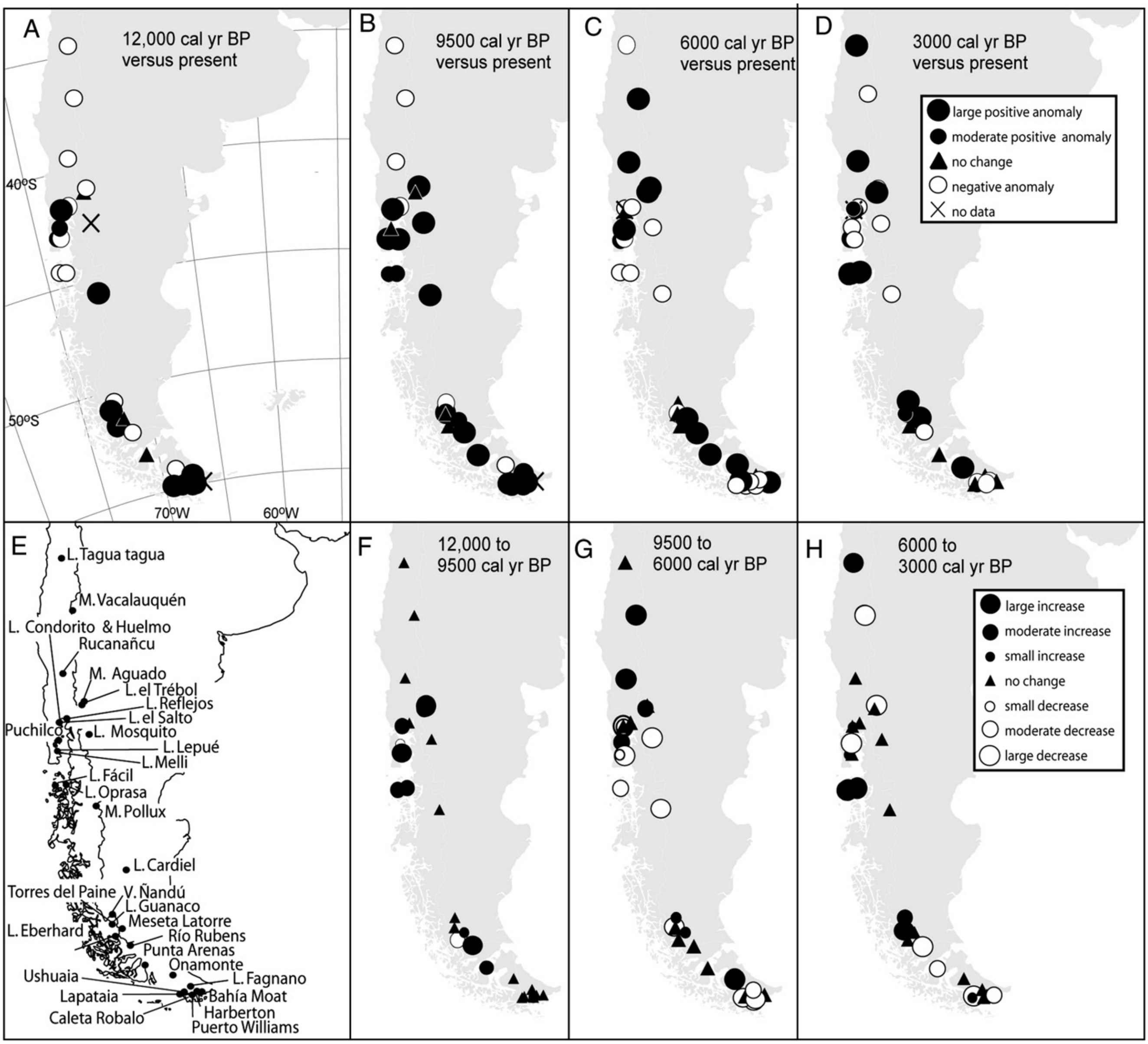

Figure 1. Comparison of fire activity based on charcoal abundance in southern South America records. Maps A through D show anomalies between target periods and the present day (500 cal yr BP) for (A) 12,000 cal yr BP; (B) 9500 cal yr BP; (C) 6000 cal yr BP; and (D) 3000 cal yr BP. Symbols indicate positive or negative anomalies relative to the present (i.e. 500 cal yr BP); Map E shows site locations. Maps F through H: Charcoal difference maps for (F) 12,000 to 9500 cal yr BP; (G) 9500 to 6000 cal yr BP; and (H) 6000 to 3000 cal yr BP. Symbols on difference maps indicate increasing or decreasing charcoal levels relative to the preceding period.

term (1971–2000) means for those variables (Fig. 3). An initial examination of these anomalies over the length of the fire record suggested that the latitude and strength of the southern westerlies were important for explaining interannual variability in area burned. Consequently, a zonal-wind index was calculated as the difference between the longitudinal averages (110°W to 102.5°W) of the east–west component of the 500-mb wind speeds (u_{500}) for latitudinal zones from 52.5 to 65°S and from 37.5° to 50°S. Large positive values of this index indicate a southward shift in the axis of stronger westerlies. (Note that this index differs from the "zonal index" defined by latitudinal differences in 500-mb heights, which is commonly used to described the wave pattern of upper-level winds; see Shinker et al., 2006.) This index is similar to that proposed by Masiokas et al. (2006) as a way to characterize interannual variations in snowpack in the Central Andes. The Multivariate ENSO Index (MEI; Wolter and Timlin (1998)) was used as an index of ENSO (El Niño/Southern Oscillation), because it is a composite of several ENSO indicators.

Results and discussion

Paleofire activity

Striking features in the network of South American fire records are: (1) the first evidence of fire at the end of the

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Table 1
Site information and fire anomalies for target periods

Site Name	Latitude	Longitude	Reference	Anomaly (cal yr BP relative to 500 cal yr BP)[a]				Difference from previous period[b]		
				12,000	9500	6000	3000	12,000 to 9500	9500 to 6000	6000 to 3000
L. Tagua Tagua	34.480000	71.150000	Heusser, 2003	L	L	L	H	0	0	3
M. Vacalauquén	36.887562	71.065948	Anderson, unpublished	L	L	H	L	0	3	−3
Rucañancu	39.550000	72.300000	Heusser, 2003	L	L	H	H	0	3	0
M. Aguado	40.972939	71.335488	Markgraf and Bianchi, 1999	L		H	L	3	0	−3
L. el Trébol	41.070438	71.492823	Whitlock et al., 2006	N	N	H	H	2	2	0
L. Oprasa	44.355592	73.655587	Haberle and Bennett, 2004	L	M	L	H	2	−2	3
Huelmo	41.621564	73.092275	Moreno and León, 2003	H	H	?	?	0	?	?
L. Reflejos	41.551399	72.598320	Moreno, unpublished	L	L	L	L	0	0	0
L. el Salto	41.613863	73.099449	Moreno, unpublished	N	H	L	L	2	−3	0
L. Condorito	41.652774	73.088735	Moreno, 2004	H	H	N	M	0	−2	1
Puchilco	42.370993	73.453836	Heusser, 2003	M	N	H	L	−1	2	−3
L. Mosquito	42.490676	71.398532	Whitlock et al., 2006	?	H	L	L	?	−3	0
L. Lepué	42.805901	73.713066	Moreno, unpublished	M	H	M	H	1	−1	1
L. Melli	42.829972	73.499988	Abarzúa and Moreno, unpublished	L	H	L	L	3	−3	0
L. Fácil	44.323597	74.289878	Haberle and Bennett, 2004	L	M	L	H	2	−2	3
M. Pollux	45.662034	71.831480	Whitlock and Markgraf, unpublished	H	H	L	L	0	−3	0
Vega Ñandú	50.555798	72.455798	Villa, unpublished	L	L	N	H	0	1	2
Torres del Paine	50.982424	72.670348	Heusser, 2003	H	H	L	H	0	−3	3
L. Guanaco	50.998112	72.696851	Francois, unpublished	?	?	?	M	0	0	1
Mesta Latorre	51.310000	72.030000	Huber et al., 2004	0	M	H	H	1	1	0
L. Eberhard	51.560403	72.670921	Cárdenas, unpublished	H	N	N	N	−2	0	0
Río Rubens	52.028340	71.636574	Huber et al., 2004	L	H	H	L	3	0	−3
Punta Arenas	53.150000	70.950000	Heusser, 2003	N	H	H	N	2	0	−2
Onamonte	53.900000	68.950000	Heusser, 2003	L	L	H	H	0	3	0
Caleta Robalo	54.930000	67.630000	Heusser, 2003	M	H	L	L	1	−3	0
L. Fagnano	54.570000	67.620000	Heusser, 2003	H	H	N	N	0	−2	0
Ushuaia	54.800000	68.380000	Heusser, 2003	H	H	H	L	0	0	−3
Lapataia	54.830872	68.577080	Heusser, 2003	H	H	L	N	0	−3	1
Harberton	54.865410	67.345097	Markgraf, 1993	H	H	L	L	0	−3	0
Bahía Moat	54.919913	66.771826	Heusser, 2003	?	?	H	N	?	?	−2
Puerto Williams	54.930000	67.620000	Heusser, 1987	H	H	L	L	0	−3	0

[a] H large positive anomaly; M moderately positive anomaly; L negative anomaly; N no changes, ?=No data.
[b] +3 large increase; +2 moderate increase; +1 small increase; 0 no change; −1 small decrease; −2 moderate decrease; −3 large decrease.

late-glacial and high levels of charcoal in the late-glacial in southern Patagonia and Tierra del Fuego at 12,000 cal yr BP; (2) high fire activity in sites south of lat. 40°S in the early Holocene (9500 cal yr BP); (3) differences in fire activity in the middle Holocene (6000 cal yr BP) between high-, mid- and low-latitude sites; and (4) spatially variable patterns in the late Holocene (3000 cal yr BP). These patterns can be explained by regional climate and vegetation changes as well as prehistoric human population trends.

The establishment of open woodland after 15,000 cal yr BP in southern South America implies warming conditions associated with deglaciation. Cool conditions developed between 13,300 and 11,700 cal yr BP, a period that has been named the Huelmo/Mascardi Cold Reversal in the Chilean and Argentine Lake Districts (Hajdas et al., 2003); its onset precedes that of the Younger Dryas Cold Interval (Alley, 2000) in the North Atlantic by 500 yr. Increases in macroscopic and microscopic charcoal levels after 13,000 cal yr BP suggest that the end of the late-glacial period was arid enough or had sufficient climate variability for fuel levels to support fire, especially at high latitudes.

The early Holocene (9500 cal yr BP) featured low contrasts between summer and winter insolation, along with higher-than-present annual insolation. Charcoal levels were higher than at present and increased from 12,000 cal yr BP levels at nearly all sites south of lat. 40°S (Figs. 1B and F), even at extremely wet sites on the Chonos Archipelago (lat. 44–46°S) (L. Fácil and L. Oprasa). Pollen data indicate an open forest with thermophilous elements in the early Holocene, and other proxy evidence suggests lower lake levels and limited glaciation (Whitlock et al., 2001; Moreno and León, 2003; Abarzúa et al., 2004; Huber et al., 2004). In contrast to widespread burning at mid and high latitudes, sites north of lat. 40°S indicate low fire activity with little change from 12,000 cal yr BP conditions.

The middle Holocene (6000 cal yr BP) was a transitional period of increasing summer insolation and decreasing winter insolation in the southern hemisphere. It also marked the onset (Moy, et al., 2002; Markgraf and Diaz, 2000) or increased importance (Rodó and Rodriguez-Arias, 2004) of ENSO variability. The charcoal anomaly map for 6000 cal yr BP reveals broad latitudinal differences (Fig. 1C). Fire activity was higher than present at 6000 cal yr BP in sites north of lat. 42°S, but at most sites, levels were lower than at 9500 cal yr BP (Fig. 1G). South of lat. 50°S, fire activity was

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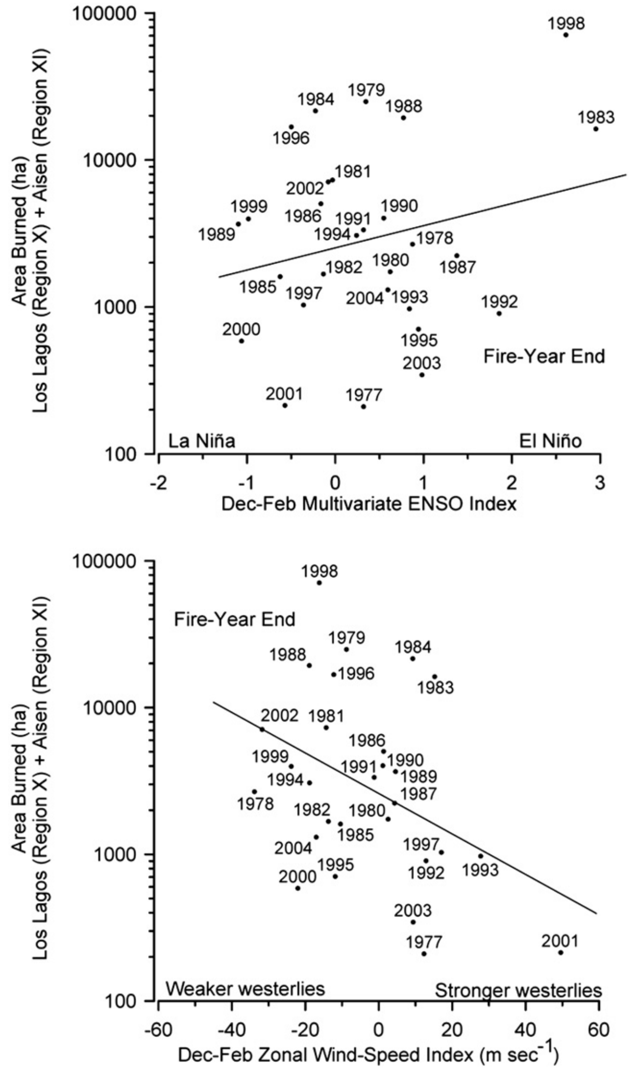

Figure 2. Scatter diagrams showing the relationship of area burned and the Multivariate ENSO Index (MEI, top) and a 500-mb zonal wind-speed index (the difference in average zonal wind speed (the u-component of 500-mb winds) between lat. 37.5 and 50°S, and 52.5 and 67.5°S, and from long. 110 to 102.5°W, positive values indicate stronger-than-normal and southward-shifted westerly winds). The relationship between area burned and MEI is not significant ($p=0.30$), whereas that between area burned and the zonal wind-speed index is ($p<0.05$). Note: the fire season for southern South America runs from October through March and is indexed by the year of the end of the season.

also above present levels at most sites but lower than at 9500 cal yr BP. In mid latitudes, fire activity was lower or similar to present at 6000 cal yr BP. This regionalization of fire activity occurred with the transition from persistent early-Holocene aridity to high late-Holocene climate variability.

3000 cal yr BP featured increasing seasonal contrasts in insolation, high ENSO-related interannual variability, and increasing human populations (see McEwan et al., 1997). Fire activity was spatially variable with higher-than-present charcoal anomalies at some sites, lower-than-present values at others, and no change at still others. The pattern represents more geographic variability in the sign of the charcoal anomalies compared with levels at 6000 cal yr BP (Fig. 1H). Two sites in the Argentine lake district, L. el Trébol and L. Mosquito, register a shift from crown fires (with abundant wood charcoal) to surface fires (with abundant grass charcoal) between 6000 and 3000 cal yr BP (Whitlock et al., 2006). Surface fires are usually small and require interannual or interdecadal fluctuations in moisture in order to grow and then burn fine fuels (Veblen et al., 2003). Fires were more frequent in NW Patagonia (lat. 40–43°S) and the Chonos Archipelago, despite an increase in mesophytic forest. Many high-latitude sites had little or no charcoal in middle and late Holocene sediments after 6000 cal yr BP, and records between 3000 cal yr BP and present from Tierra del Fuego generally feature no change or lower values at 3000 cal yr BP.

Controls of early Holocene fire patterns

Pollen data provide no evidence to suggest that widespread fire activity in the early Holocene was a response to large-scale shifts in vegetation (Markgraf, 1993; Heusser, 2003), and, in fact, the records indicate that vegetation and fire changes were not synchronous in many regions. Moreover, the fact that fires occurred throughout southern South America in the early Holocene during a period of reduced summer insolation is counterintuitive to our understanding of the large-scale controls of Holocene fire and vegetation history in western North America (Whitlock and Bartlein, 2004). There, high fire activity and an expansion of xerophytic taxa are attributed to the early-Holocene insolation maximum and its direct effects on surface water and energy balance and indirect effects on the strength of the northeastern Pacific subtropical high-pressure system and associated subsidence.

Recent climate patterns during high fire years in Chile and Argentina can be used to evaluate some alternative hypotheses for explaining the Holocene fire record of southern South America, including (1) mechanisms related to ENSO, and its

Figure 3. Summer (December–February) composite anomalies of climate variables from the NCEP reanalysis data set for high-area burned years, along with the long-term (1971–2000) means of these variables (bottom row). *500 mb height anomalies* (first column): during high-fire years, a positive anomaly (i.e. a stronger ridge) prevails to the southwest of the southern tip of South America (orange), forming a dipole (indicated by positive and negative signs) with a negative (blue) height anomaly over northern Argentina. *Anomalies of 500-mb wind speeds* (second column): orange indicates slower-than-normal wind speeds, and blue is faster-than-normal. The particular longitudinal patterns in each of the years show weaker-than-normal winds over the continent (orange band), and stronger-than-normal winds (blue band) to the south of the southern tip of the continent (i.e. a southward shift in the band of fastest westerlies). The approximate locations of the strongest anomalous components of flow are indicated by arrows. *Anomalies of 500-mb vertical velocities* (third column), and *precipitation anomalies* (fourth column): abnormal subsidence over southern South America (orange) results in lower-than-normal precipitation (orange regions in fourth column). *Temperature anomalies* (fifth column): the tropical Pacific temperature anomalies can be used to gauge the state of ENSO for each case (i.e. strong and weak El Niño or warm-phase conditions for 1997–98 and 1987–88 respectively, and cool-phase or La Niña conditions for 1988–89 and 2001–02.) Red boxes on the bottom-left panel indicate the regions used for calculating the zonal-wind index (see text for details).

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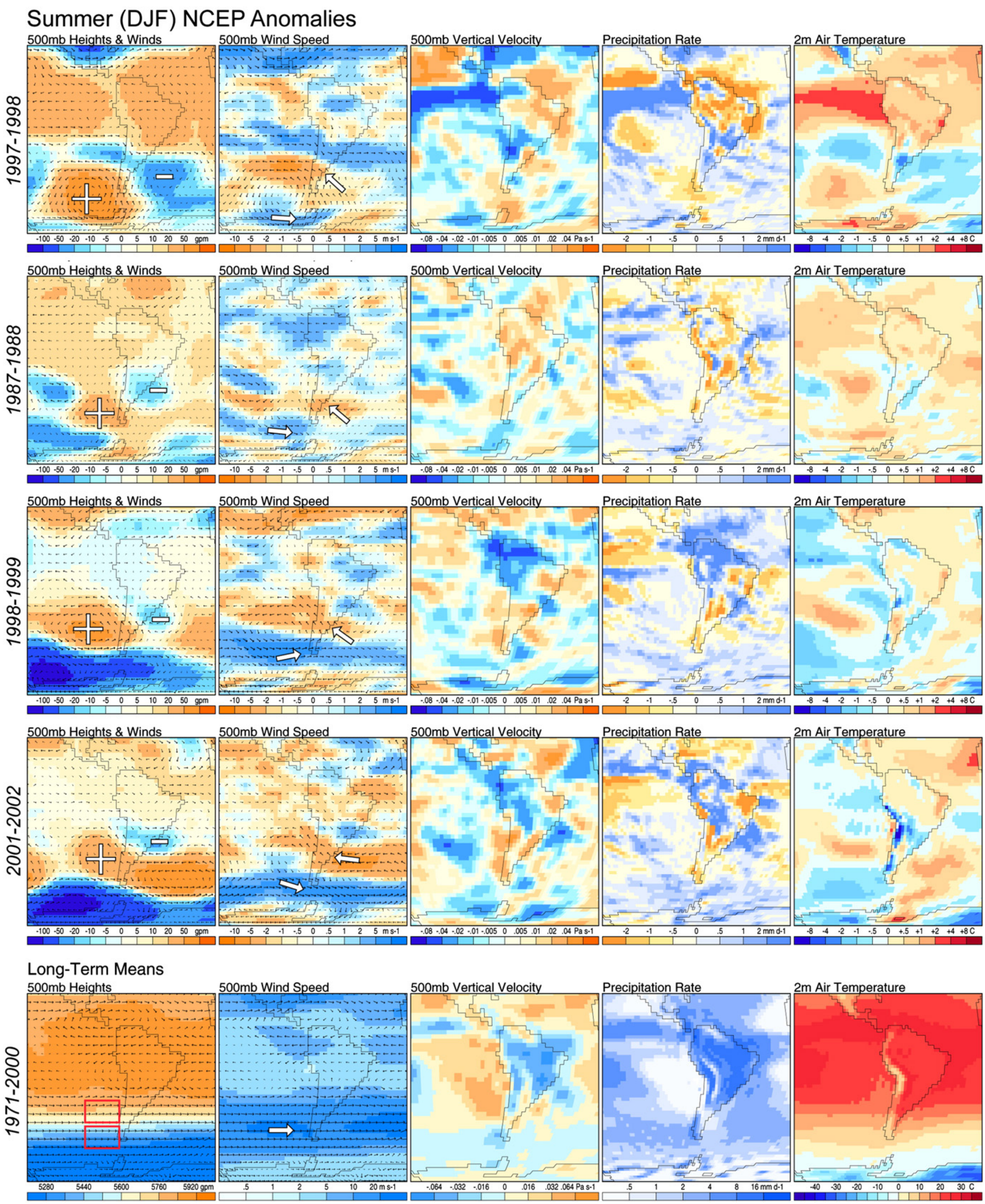
variability over the Holocene (e.g. Kitzberger, 2002); (2) poleward shifts of the southern westerlies in the early Holocene (Markgraf et al., 1992; Lamy et al., 2002; Moreno, 2004; Gilli et al., 2005); and (3) the "carry-over" of the early-Holocene *winter* insolation maximum into subsequent seasons, leading to an earlier onset of the growing season and summer drought (Whitlock et al., 2001; Renssen et al., 2005). The first hypothesis would be rejected by the observation of high fire activity in



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neutral or cool-phase/La Niña years, the second by no or equatorward shifts in westerlies during high fire activity years, and the third by cooler-than-normal conditions during such years.

The first hypothesis is discredited by the fact that the relationship between the Multivariate ENSO Index and recent area burned in Regions X and XI is not significant (Fig. 2 top). Although the highest area burned was recorded during the 1997–98 El Niño, other large-area-burned years occurred under neutral or La Niña conditions. The atmospheric circulation anomalies that prevailed during summer 1997–1998 explain why this year featured a large area burned (Fig. 3): a stronger-than-normal upper-level ridge developed to the southwest of southern South America, the strength of the southern westerlies was reduced, and storm tracks were shifted southward. These features caused weaker-than-normal onshore flow from the Pacific, widespread subsidence over southern South America, and anomalous southeasterly components of both surface and upper-air flow (Fig. 3).

The relationship between area burned and a zonal windspeed index (Fig. 2 bottom) reveals the influence of southward shifted westerlies on recent fire activity—years with weaker westerlies over the continent feature high area burned. (The southward shift in the westerlies is shown in the second column of Fig. 3.) This relationship is significant and provides support for the second hypothesis: years with weaker westerlies over the continent are associated with high area burned. The climate anomalies during a selection of years with poleward-shifted westerlies show striking similarities in all of the anomaly patterns except temperature (Fig. 3, fifth column).

The third hypothesis in its simplest form (i.e., positive winter insolation anomalies make spring and summer warmer than normal, thereby favoring fires) is discredited by the recent temperature anomalies, which do not show uniformly warmer-than-normal winter conditions during high-fire years. However, the "carry-over" hypothesis may still be viable for explaining the general state of early-Holocene climates (Renssen et al., 2005), and for reinforcing the effects on fire produced by the mechanisms involved in the second hypothesis.

The considerable longitudinal variation in recent circulation anomalies (Fig. 3) argues against a uniform poleward shift of the westerlies relative to present in the early–Holocene. In particular, the anomalous component of upper-level flow associated with the position of the east–west dipole could have created wetter-than-normal conditions in southeastern Patagonia, while maintaining drier conditions in western areas. This juxtaposition of circulation patterns might explain high lake levels at Lago Cardiel during the early Holocene (lat. 48.8°S, long. 71.21°W) (Markgraf et al., 2003), inasmuch as a more important role for Atlantic moisture east of the Andes at that time could have occurred concurrently with dry conditions and high fire activity west of the Andes. More paleoclimatic data east of the Andes and especially between lat. 46° and 50°S are needed to examine and reconstruct possible shifts in the longitudinal dipole pattern and their influence on east–west precipitation gradients.

Paleoclimate model simulations illustrate a potential mechanism for generating weaker westerlies in the early Holocene and shifting them poleward (Liu et al., 2003; Renssen et al., 2005). Mean annual insolation poleward of lat. 45°S was greater than present in both hemispheres, as a result of higher-than-present obliquity, and less than present in the tropics. These annual insolation anomalies reinforced the effects of high summer insolation in the northern hemisphere and high winter insolation in the southern hemisphere in the simulations. Coupled ocean–atmosphere general circulation models for 8500 cal yr BP, for example, indicate that higher-than-present annual insolation in the southern high latitudes weakened the pole-to-equator temperature gradient and led to a more southerly location of storm tracks than at present (Liu et al., 2003). Higher-than-present annual temperatures under these conditions would have dried fuels earlier in summer and helped initiate earlier onset of the fire season. This carryover effect, coupled with weakened summer storms, would have overwhelmed the effect of low summer insolation. Increased ignitions in the early Holocene may have arisen from greater convectional activity and thunderstorms caused by greater sensible heating. As the latitudinal gradient in temperature increased in the middle and late Holocene, simulated surface windspeed in southern mid latitudes also increased (Renssen et al., 2005).

Conclusions

Holocene fire patterns are evident at regional spatial scales and millennial time scales when high- and low-resolution charcoal data are examined across a broad array of climate and vegetation types. This coarse approach does not provide the nuanced interpretations obtained from single sites, but it does reveal shifts in fire patterns caused by climate change and places vegetation change as a secondary driver of variations in regional fire regimes. To better assess the role of human activity in shaping Holocene fire patterns will require more information on settlement patterns than is currently available.

In southern South America, charcoal data are first recorded in the late-glacial period at or before 12,000 cal yr BP, as a result of warming conditions following the end of the glaciation. In the early Holocene, charcoal levels were high at most sites south of lat. 40°S, during a period of widespread warmth and aridity. Higher-than-present annual insolation and annual temperatures may have led to a weakening and southward shift of storm tracks at this time. This hypothesis can be further tested by extending consideration of records into subtropical monsoonal regions, where the obliquity control would be weaker. Fire patterns in the middle Holocene reveal latitudinal differences that suggest increased summer precipitation at mid latitudes. Spatially heterogeneous fire activity in the late Holocene may have resulted from a breakdown of regional climate controls in the face of greater interannual and interdecadal climate variability as well as increased use of fire by Native peoples; however, sorting among these factors requires a more complete network of charcoal and archeological records. In conclusion, this broad-scale analysis is an important step in understanding South American fire regimes and their history in that it provides large-scale mechanisms for interpreting site-specific paleofire reconstructions, as well as hypotheses to be tested by expanding the paleofire network to new geographic areas.

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