Global Change Biology

Global Change Biology (2014) 20, 1929–1942, doi: 10.1111/gcb.12538

Synchronous fire activity in the tropical high Andes: an indication of regional climate forcing

R. M. ROMÁN-CUESTA[1,2], C. CARMONA-MORENO[3], G. LIZCANO[4], M. NEW[4,*], M. SILMAN[5], T. KNOKE[2], Y. MALHI[6], I. OLIVERAS[6,†], H. ASBJORNSEN[7] and M. VUILLE[8]

[1]CREAF. Centre for Ecological Research and Forestry Applications, Facultat de Ciencies. Unitat d' Ecologia Universitat Autonoma de Barcelona, Bellaterra, Barcelona 08193, Spain, [2]Institute of Forest Management, Technische Universität München, Center of Life and Food Sciences Weihenstephan, Hans-Carl-von-Carlowitz-Platz 2, Freising, 85354, Germany, [3]Global Environmental Monitoring Unit, Institute for Environment and Sustainability, European Commission, Joint Research Centre, TP. 440 21020, Ispra, Varese 21027, Italy, [4]School of Geography and the Environment, Oxford University, South Parks Road, Oxford OX13QY, UK, [5]Wake Forest University, Box 7325 Reynolda Station, Winston Salem, NC 27109-7325, USA, [6]Environmental Change Institute, School of Geography and the Environment, Oxford University, South Parks Road, Oxford OX13QY, UK, [7]College of Life Sciences and Agriculture Durham, University of New Hampshire, Durham, NH, USA, [8]Department of Atmospheric and Environmental Sciences Albany, University of Albany, Albany, NY, USA

Abstract

Global climate models suggest enhanced warming of the tropical mid and upper troposphere, with larger temperature rise rates at higher elevations. Changes in fire activity are amongst the most significant ecological consequences of rising temperatures and changing hydrological properties in mountainous ecosystems, and there is a global evidence of increased fire activity with elevation. Whilst fire research has become popular in the tropical lowlands, much less is known of the tropical high Andean region (>2000masl, from Colombia to Bolivia). This study examines fire trends in the high Andes for three ecosystems, the Puna, the Paramo and the Yungas, for the period 1982–2006. We pose three questions: (i) is there an increased fire response with elevation? (ii) does the El Niño- Southern Oscillation control fire activity in this region? (iii) are the observed fire trends human driven (e.g., human practices and their effects on fuel build-up) or climate driven? We did not find evidence of increased fire activity with elevation but, instead, a quasicyclic and synchronous fire response in Ecuador, Peru and Bolivia, suggesting the influence of high-frequency climate forcing on fire responses on a subcontinental scale, in the high Andes. ENSO variability did not show a significant relation to fire activity for these three countries, partly because ENSO variability did not significantly relate to precipitation extremes, although it strongly did to temperature extremes. Whilst ENSO did not individually lead the observed regional fire trends, our results suggest a climate influence on fire activity, mainly through a sawtooth pattern of precipitation (increased rainfall before fire-peak seasons (t-1) followed by drought spells and unusual low temperatures (t0), which is particularly common where fire is carried by low fuel loads (e.g., grasslands and fine fuel). This climatic sawtooth appeared as the main driver of fire trends, above local human influences and fuel build-up cyclicity.

Keywords: Andes, climate change, ENSO, fire, fuel load, grasslands, MEI, paramo, precipitation, Puna

Received 7 October 2013 and accepted 27 November 2013

Introduction

Synchronous with the global temperature rise, ongoing warming in the tropical Andes has been reported for the last 60 years (up to 0.11 °C per decade; Vuille & Bradley, 2000; Vuille *et al.*, 2008). This temperature increase has been paralleled by unprecedented glacial retreat from Venezuela to Chile (Thompson *et al.*, 1985; Francou *et al.*, 2003; Soruco *et al.*, 2009; Vimeux *et al.*, 2009; Rabatel *et al.*, 2013). Most global climate models (GCMs) suggest enhanced warming of the tropical mid and upper troposphere (Fu *et al.*, 2011). Consequently, rates of temperature rise are expected to be larger at higher elevations than at lower elevations, as has already been reported in the Alps (Büntgen *et al.*, 2006), the Rocky Mountains (Westerling *et al.*, 2006), and the Tibetan Plateau (Liu *et al.*, 2009). Research by Bradley *et al.* (2006) concluded that in the South American continent, maximum temperature increases are

Correspondence: R. M. Román-Cuesta, tel. +93581 2848, fax +93581 1312, e-mail: rosaromancuesta@gmail.com
*Present address: African Climate and Development Initiative, University of Cape Town, Rondebosch, 7701 Cape Town, South Africa
†Present address: Nature Conservation and Plant Ecology, Wageningen Institute for Environment and Climate Research, Building Number 100, Droevendaalsesteeg 3a, 6708 PB, Wageningen

expected to particularly affect the higher elevations of the Andes in Ecuador, Peru, Bolivia and northern Chile (>4 °C, projected changes between 1990–1999 and 2090–2099).

Changes in fire activity represent some of the most significant ecological consequences of rising temperatures and changing hydrological properties in mountainous ecosystems. Westerling *et al.* (2006) reported a significant increase in the number of large forest fires (e.g., > 400 ha) in the Rocky Mountains (1970–2003) since the mid-80s. This increase has disproportionately affected higher over lower elevations, with increases peaking at 2130 masl. Similarly, Hemp (2005) reported mountain treeline retreats on Mount Kilimanjaro of ~500 m due to an increase in fire frequency, affecting 15 000 ha of montane forests during 1976–2002.

Whilst there is an abundance of research on fire dynamics in the temperate Andes (Kitzberger *et al*., 1997, 2001; Veblen *et al*., 1999; Grau & Veblen, 2000), much less is known about fire trends and fire drivers in the tropical high Andean region (defined here as land above 2000 masl, 10°N–20°S), where climatic stresses are most strongly reported (Vuille *et al*., 2008), and where human pressures are intense (Sarmiento & Frolich, 2002). We thus know little of the extent of recent changes in fire activity in the tropical high Andes and their connection to regional climate. Many studies in the American continent have shown synchrony of fire responses at regional scales (Swetnam, 1993; Grissino-Mayer & Swetnam, 2000; Kitzberger *et al*., 2001; Phillips *et al*., 2009) implying climate forcing on fire activity on a subcontinental scale (e.g., El Niño/La Niña phenomena and the North Atlantic Oscillation (NAO)) over more local human influences, and underscoring the importance of exogenous factors in ecosystem dynamics.

The tropical high Andes are a natural laboratory to document changes in climate and its effect on fire activity due to the existence of highly flammable ecosystems (e.g., Puna, Paramo), whose current location is the result of long-term human fires (Laegaard, 1992; Sarmiento & Frolich, 2002; Bush *et al*., 2005; DiPasquale *et al*., 2008), that are strongly influenced by regional climate oscillations (e.g., El Niño/la Niña, NAO) (Vuille, 1999; Vuille *et al*., 2000b, 2003; Garreaud & Aceituno, 2001; Garreaud *et al*., 2003; Dillehay & Kolata, 2004). In this article we will evaluate three hypotheses:

Hypothesis 1: *Differential increase of regional fire activity with elevation.* Observing the global trend of increase fire activity with elevation, we expect a similar increased response in the tropical high Andes, compared to the lowlands.

Hypothesis 2: Regionally synchronous fire responses through ENSO influence. As it has been observed in other ENSO-influenced fire regimes and due to the importance of the ENSO in the tropical high Andes, we expect synchrony in regional droughts and fire responses.

Hypothesis 3: *Climate* vs. *human drivers of fire responses.* Humans and their fire practices date back several thousand years in the high Andes (Bush *et al*., 2005). We hypothesize that human influences will have local spatial scales, affecting fire frequencies through fuel build-up, but regional fire frequency will be lead by climatic variables such as precipitation and temperature. We suggest two possible subhypotheses:

1 Fuel hypothesis (e.g., Minnich, 2001): Fire dynamics are human driven and they are strongly controlled by Puna/Paramo grassland fuel build-up recoveries after the last major fire event (i.e. there is no material left to burn until it recovers 4–6 years later);
2 Climate hypothesis (e.g., Keeley & Fortheringham, 2001): Fire dynamics are restricted to climatic influences that produce periodic droughts and high levels of rainfall that content peak fire years through changes in fuel moisture

Materials and methods

Study area

We focus on the tropical high Andes (elevation ≥2000 masl) covering the plateaus and eastern Andean slopes of Venezuela, Colombia, Ecuador, Peru and Bolivia (12°N – 20°S, 84°W–62°W) (Fig. 1). 12°N represents the northernmost distribution of the Andes, whilst the southern threshold (20°S) corresponds to the limit used by other researchers for regional climate coherence (Garreaud *et al*., 2003; Hoffmann, 2003). Vuille & Keiming (2004) also reported that precipitation in the Altiplano becomes episodic below 21°S.

The tropical Andes exhibit strong North-to-South, low-to-high-elevation, and East-to-West precipitation gradients with higher rainfall over (i) northern regions (Northern Ecuador and Colombia), (ii) low-to-mid elevations, and(iii) eastern slopes, due to moisture-bearing easterly trade winds originating over the tropical Atlantic and Amazon basin (Vuille *et al*., 2000b).

Due to a combination of topographic, climatic, and anthropogenic factors the Andes encompass a diversity of ecosystems and landscapes with different fire vulnerabilities. In this article, we worked with three high Andean ecosystems: Puna, Panamos, and Yungas. Moreover, to contrast the role of elevation on fire behaviour, we also chose a lowland grassland ecosystem: Los Llanos savannas (WWF Global 200 project, Olson *et al*., 2001).

Fig. 1 The tropical high Andean region corresponds to elevations above 2000 masl from Venezuela to Bolivia within latitudes between 12°N to 20°S. The location of Puna, Paramos and Yungas are shown in the map, based on Olson *et al*., 2001 WWF Global 200 project.

1. The Puna (ca. 3 00 000 km^2) corresponds to the high elevation grassland ecosystems of central and southern Peru and Bolivia and are typically drier than the Paramos. The Puna is generally formed by herbaceous species such as *Calamagrostis, Festuca* or *Stipa*; shrubs (*Aciachne, Adesmia, Margyricarpus, Parastrephia* and *Tetraglochin*), and some trees in areas protected from night frosts and fire (*Baccharis, Berberis, Brachyotum, Chuquiraga, Clethra, Escallonia, Gynoxys, Miconia, Myrsine, Weinmannia, Alnus,* and *Polylepis spp*).
2. The Paramo (ca.46 000 km^2) corresponds to wetter areas in the Northern Andes, covering the upper parts of the tropical Andes from Southern Venezuela to Northern Peru. Plant communities are characterized by bunchgrasses (*Calamagrostis and Festuca*), dwarf bamboos (*Chusquea*), shrubs of the *Asteraceae, Ericaceae, Melastomataceae,* and *Hypericaceae* families, and especially in the northernmost distributions, giant rosette-plants such as Espeletia (*Asteracea*) and Puya (*Bromeliaceae*).
3. The Yungas (ca.60 000 km^2): The Yungas is an area of varied topography ranging from humid forest ecosystems with abundance of the *Clusiaceae, Lauraceae and Fabacaeae* families) and subtropical seasonal forest (*Clusiaceae, Moraceae, Myristicaceae* families), to pastures. This narrow geographical band runs for more than 4000 km, from Northern Venezuela to Northern Argentina, on the eastern slopes of the Andes. As warm, moist air from the Amazon rainforest moves westward, it rises up the eastern side of the Andes, cools and condenses, forming a zone of high precipitation and seasonally persistent cloud cover (Salinas *et al*., 2011).
4. The llanos Savannas (3 90 000 km^2) This ecoregion is the best example of tropical savannas in South America with high floristic and habitat diversity. It includes tropical and subtropical shrublands, grasslands and savannas (with abundance of the *Gramineae* and *Poaceae* families with genus that define savanna types such as *Melinis* (an introduced African grass), *Trachypogon, Paspalum, Leptocoryphium, Mesosetum* and *Andropogon*, located in Colombia and Venezuela (Blydenstein, 1967). Being one of the world's largest wetland complexes, the region has its share of streams, rivers, and marshes, and with them many species not typically found in savanna ecosystems (e.g., palms such as *Mauritia*, and trees such as *Inga, Combretum, Gustavia, Pterocarpus*, etc.).

Data sets

Elevation. We used the NASA Shuttle Radar Topography Mission (SRTM) 90 m data (Farr *et al*., 2007) to create spatial masks of elevation (>2000 masl) that were applied to all the layers in this research.

Fire datasets. We chose satellite-based fire datasets due to the unavailability of local, regional or national ground-based fire datasets in the tropical Andes (Bradley & Millington, 2006). We selected two different fire datasets: the Global Burned Surface (GBS) (1982–1999) (Carmona-Moreno *et al*., 2005), and MODIS thermal anomalies (2000–2006) (MOD14A2) (Justice *et al*., 2002), and filtered them by elevation. These databases rely on different fire algorithms (GBS considers changes in temperature and reflection of burned areas, whilst MOD14A2 mainly focuses on temperature thresholds). They have similar temporal resolution (i.e. weekly composites), but different spatial resolution (8 km for GBS vs. 1 km MODIS), and there is no time overlap to compare and calibrate their performance. Both fire databases have caveats, but have been successfully used to assess fire trends (Carmona-Moreno *et al*., 2005; Armenteras-Pascual *et al*., 2011). We estimated standardized fire anomalies for each dataset.

$$\text{Annual fire anomly}_{t,j} = [\text{Fire pixel count}_{t,j} - \text{Fire mean pixel count}_j]/\sigma_j \quad (1)$$

where t represents each year, j each fire dataset period: 1982–1999 or 2000–2006. σ is the standard deviation of fire per each dataset.

Climate datasets. We used the University of Delaware, Willmott dataset (Legates & Willmott, 1990; Willmott & Robeson, 1995) to analyse climate variability above 2000 m. This dataset offers monthly 0.5º× 0.5º gridded data of precipitation (mm) and air temperature (°C). Climate analyses were run for the period 1982–2006. We used (1970–2006) for calculation of mean climatology.

We ran all climate analyses for four time periods:

1. Dry season: April to September for each year of the data series;
2. Wet season: October$_{t\text{-}1}$–March$_{t0}$, where $t0$ means the current year and *t-1* the year before, for the whole data series;
3. Hydrological year: October$_{t\text{-}1}$–September$_{t0}$ for each year.

4. Calendar year: January –December for each year. As calendar and hydrological years consistently showed similar results, we used calendar years for analyses because fire data were also reported on a calendar basis.

Data analyses

Climate patterns in the Andes are strongly affected by latitude. After a first biogeographical analysis of fire trends for the region, we chose to run further fire analyses on a per country basis, as a proxy for latitude. For those countries where we found major fire responses we ran more detailed climate-fire analyses.

Climate analyses. Climate composites—A preliminary analysis of temporal fire trends showed a strong cyclical pattern (Figs 2 and 3). We therefore ran climate composites to identify the climatic differences associated with high fire-activity years (1985, 1989, 1995, 2000, 2003, 2005) and low fire-activity years (1984, 1988, 1993, 1999, 2002, 2004). Final products are digital layers with the per pixel standardized anomalies of mean cumulative precipitation and mean temperature, for the three considered time periods (i.e. dry season, wet season and calendar year), for each composite (i.e. peak fire years and low fire years) (Eqn.2).

$$\text{Precipitation}_{composite\_anamoly} = [\text{Prec}_{high\ or\ low\ fire\ years} - \text{Prec mean}_{1982-2006}]/\sigma_{1982-2006} \quad (2)$$

10th and 90th climate percentiles

To analyse the role of extreme climate on fire trends, we chose the 10th and 90th percentiles of temperature and rainfall. Final products represent the percent of area >2000 masl with severe drought (≤10th percentile) or extreme temperature (≥ 90th percentile) for each country, for each time period (dry, wet, annual), for the fire-peak years or fire low years (t = 0), and for the year before (t-1).

To evaluate the climatic responses of peak and low fire years, we contrasted their composite temperatures and precipitation levels against the complete time record using bootstrap simulations. These simulations randomly selected years and calculated their expected means (n = 1000) (Grau & Veblen, 2000). In each case, the number of randomly selected years equaled the number of fire years (n = 6 both for the high and low fire composites). Analyses were run for the three temporal seasons (dry, wet, annual). We used Kruskal–Wallis statistical tests to evaluate differences between the composite values and the full record values for both temperature and precipitation.

Fire analyses. Linear mixed model—As a reinforcement analysis of the role of climate, we ran a Linear Mixed Model (LMM) with Restricted Maximum

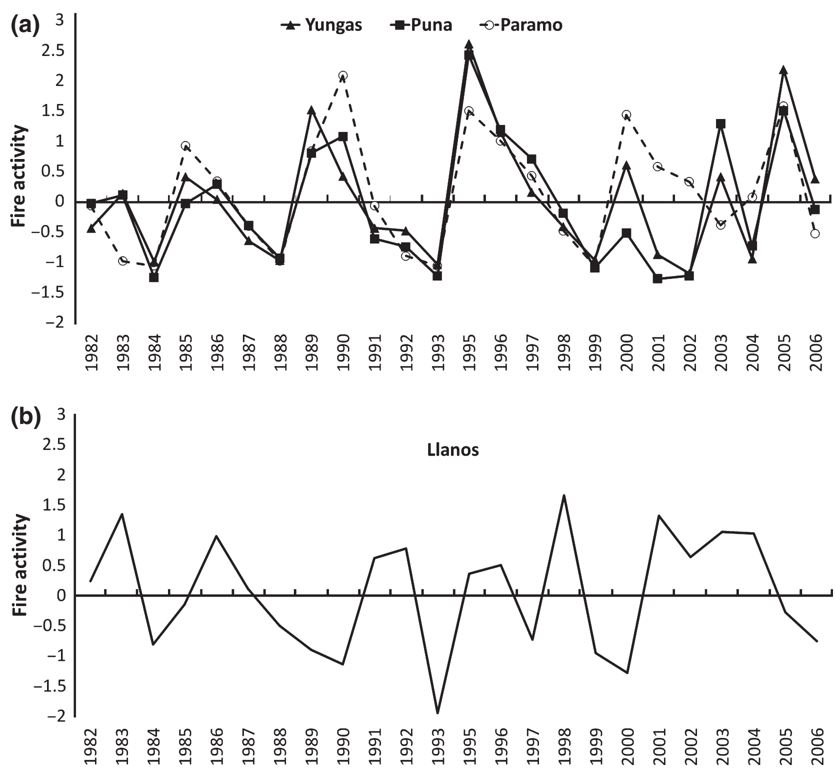

Fig. 2 Standardized annual fire anomalies for Puna, Paramo and Yungas (>2000 masl) (a), and for the Llanos (b), for 1982–2006.

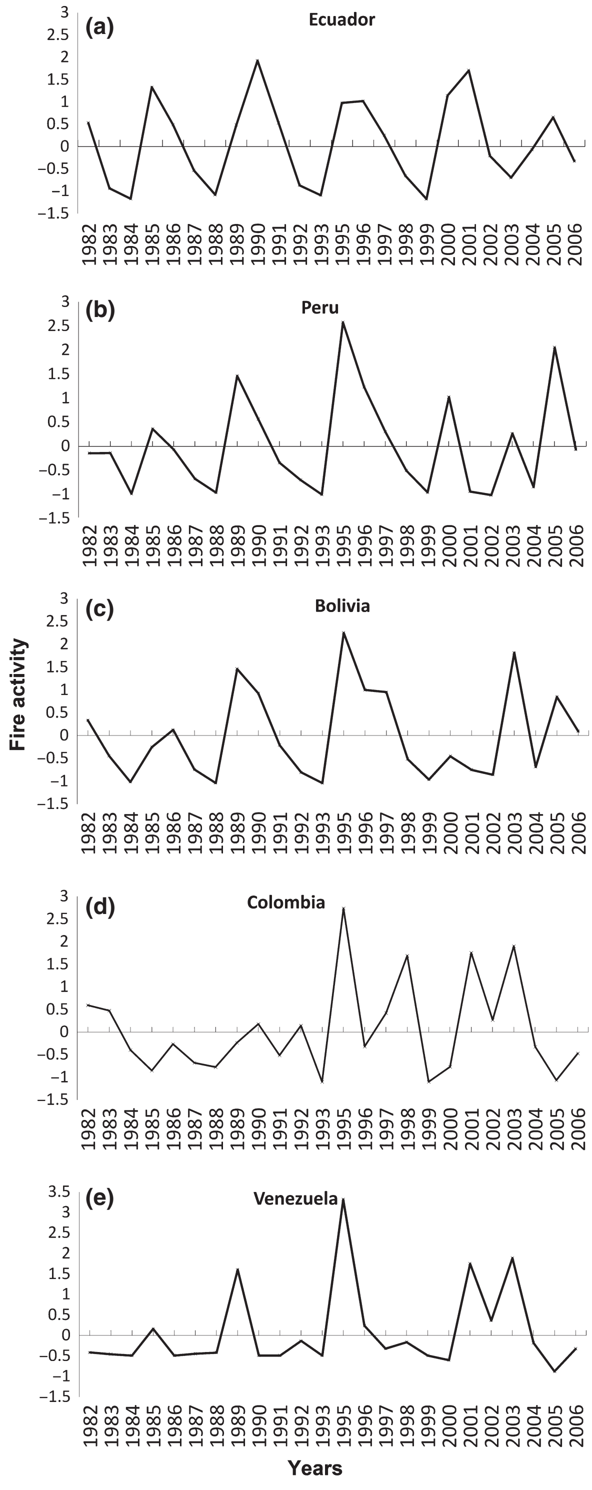

Fig. 3 Standardized annual fire anomalies per country [Ecuador (a)], Peru (b) and Bolivia (c), Colombia (d), and Venezuela (e) for elevations >2000 masl, for 1982–2006.

Likelihood (REML), to evaluate the relative importance of the different climatic variables on fire trends, for those countries that showed higher climate influences (Ecuador, Peru and Bolivia). LMMs are parametric linear models for clustered, longitudinal or repeated-measures data that quantify the relationships between a continuous dependent variable, and several predictor variables which involve a mix of fixed and random effects (Verbeke & Molenberghs, 2000; West *et al.*, 2007). As we had annual fire responses as repeated measures and countries as the clustering factor, LMM seemed appropriate. We selected REML because likelihood-based approaches can accommodate data that are missing at random (Rubin, 1976) (e.g., we had random missing climate data, for certain countries, for certain years), and it is preferred to Maximum Likelihood (ML) when the sample size is small (n = 72 in our case), because REML then provides less biased estimates of random effect standard deviations than ML (Bolker *et al.*, 2009). Moreover, compared to ML, REML offers unbiased estimates of the covariance parameters (Patterson & Thompson, 1971). We run our LMM with the SAS software Version 9.2 of the SAS System for Windows. SAS Institute Inc. Cary, NC, USA. Table 1 summarizes the original variables considered in our analysis. The saturated model was reduced by using the Bayesian Information Criteria (BIC) eliminating the least significant term until there was no further decrease in BIC. Table 3 displays only those variables that were significant at $P \leq 0.05$.

Fire responses among countries—We ran Spearman correlations to search for fire relationships among countries.

ENSO-MEI Index—We selected the Multivariate ENSO Index (MEI) to capture ENSO variability (Wolter & Timlin, 1993), available on-line from the NOAA Earth System Research Laboratory. The MEI is a bimonthly product calculated as the first unrotated principal components of six climate variables over the tropical Pacific, and it has been used to identify the presence and intensity of El Niño/la Niña episodes. To evaluate the role of ENSO on the climatic variability of the high elevation Andes, we correlated changes in the MEI index with the 10th and 90th percentiles of precipitation and temperature (Spearman Rho correlation) (1982–2006). We chose the MEI mean signal for the months of December to March to represent its annual evolution, as larger ENSO signal are known to occur during these months. We also correlated MEI indices and fire anomalies.

Fuel analyses. To test the fuel hypothesis and the potential role of fuel build-up behind fire responses, we monitored high elevation Puna/Paramo grassland fires from 1982 to 1999. We wanted to evaluate if the

Table 1 Summary of the variables used in the Linear Mixed Model (LMM) model. We originally considered 12 variables representing climate extremes based on the percent of a country's land affected by severe climate events (e.g., >90th percentile of temperature (heat waves), <10th percentiles of precipitation (drought spells), and eight variables representing climate means. *t*0 = same year, *t*-1 = year before

	Independent variables	
Dependent variable	Continuous variables	Factors
Fire anomalies: 1982–2006, 24 years (1994 was not available in the original fire GBS database)	Precipitation wet season>90th percentile t-1	Countries: Ecuador, Peru, Bolivia.
	Precipitation dry season>90th percentile t-1	
	Precipitation wet season>90th percentile t0	
	Precipitation dry season>90th percentile t0	
	Precipitation wet season<10th percentile t0	
	Precipitation dry season<10th percentile t0	
	Precipitation wet season<10th percentile t-1	
	Precipitation dry season<10th percentile t-1	
	Temperature wet season>90th percentile t0	
	Temperature dry season>90th percentile t0	
	Temperature wet season<10th percentile t0	
	Temperature dry season<10th percentile t0	
	Mean Precipitation dry season t0	
	Mean Precipitation wet season t0	
	Mean Precipitation dry season _t-1	
	Mean Precipitation wet season t-1	
	Mean Temperature dry season t0	
	Mean Temperature wet season t0	
	Mean Temperature dry season t-1	
	Mean Temperature wet season t-1	

same areas that had burned during a peak year remained unburned for a certain time and then simultaneously reburned in the following fire-peak year(s). This could be answered by following one or two consecutive fire peaks. Therefore, we focused on one fire database only (GBS 1982–1999). Moreover, from the year 2000 the fire database changes satellite (from AVHRR to MODIS) and their absolute fire responses could not be directly compared.

Results

Hypothesis 1: Differential increase of regional fire activity with elevation

Figure 2 shows standardized fire anomalies for the Puna, Paramo and Yungas, contrasted to the fire response of the lowland grassland ecosystem of Los Llanos, from 1982 to 2006. Three main trends emerge: (i) a marked regional fire cyclicity for the high Andean ecosystems with fire peaks every 4–6 years (e.g., 1985, 1989 1995, 2003, 2005) and fire lows (e.g., 1984, 1993, 1999, 2004) with no visible increasing trend of fire activity; and (ii) a significant positive correlation among fires in Paramos, Puna and Yungas,, which was stronger for Yungas–Puna ($r = 0.88$, $P \leq 0.0001$), than for Yungas–Paramo ($r = 0.66$, $P \leq 0.0001$) and than for Puna–Paramo ($r = 0.52$, $P \leq 0.005$), and (iii) no statistical correlation between the fire responses of Los Llanos and the high Andean ecosystems, with Los Llanos showing different temporal trends, mainly peaking on El Niño years (e.g., 1983, 1992, 1998, 2003).

Hypothesis 2: regionally synchronous fire responses through ENSO influence

To identify if the observed regional fire trends in the Paramo, Puna occurred simultaneously along the entire tropical high Andean region, we plotted fire responses per country (>2000 masl), as a proxy for latitude (Fig. 3). This figure shows quasisynchronous and cyclic fire response in three countries: Ecuador (with remarkably well defined fire cycles: almost constant amplitude and periodicity), Peru, and Bolivia, with significant positive correlations among them at $P \leq 0.005$ [Ecuador–Peru ($\rho = 0.64$), Ecuador–Bolivia ($\rho = 0.56$), and Peru–Bolivia ($\rho = 0.89$)]. Colombia and Venezuela's fire responses did not show significant correlations to Ecuador, Peru or Bolivia.

Statistical analyses to assess if ENSO was behind these fire trends showed no significant relationship between the MEI and fire anomalies in the tropical high Andes, for the period 1982–2006. We found, however, significant relationships between MEI and climate extremes (Fig. 4a, b): ENSO significantly correlated with temperature extremes >2000 masl (temperatures above 90th percentiles) during the wet season, in the three countries, and was particularly strong in Peru and Bolivia (Table 2), but did not correlate with extreme variations in precipitation (precipitations below 10th percentiles) in any country, in any season (Table 1).

Hypothesis 3: climate vs. human drivers of fire responses

Whilst most fires in the tropical high Andes are human ignited (Bradley & Millington, 2006; Román-Cuesta *et al.*, 2011), the observed synchrony and cyclicity of fire responses in Ecuador, Peru and Bolivia suggest a regional climate influence. From our suggested fuel hypothesis (Minnich, 2001) and climate hypothesis (Keeley & Fortheringham, 2001) we found:

Fuel hypothesis. Puna/Paramo postfire fuel build-up: Fig. 4 shows a 9 year follow-up of those areas that burned in the 1985 and 1989 fire peaks, at high elevations, as a way to follow-up consecutive fire peaks. There is no clear evidence of Puna fuel build-up. In each peak year ca. 75 percent of the original area affected by fire had burned again at the end of our 9 year follow-up period. However, this did not happen in one large episodic event (i.e. such as the next fire-peak year) but rather in several smaller peaks. 20–30 percent of the area burned was reburned only one year after each major fire event (1986, 1990). A similar percentage burned approximately 3–5 years later. These trends suggest that whilst fire cycles of 4–6 years might occur, they are unlikely to correspond to the repeated burning of the same Puna/Paramo regions (Fig. 4). Fuel build-up effects could exist but should then be larger than 9–12 years.

Climate hypothesis. Successive wet and dry periods are thought to alter fire dynamics by sequentially elevating vegetation productivity and then accelerating the fuel

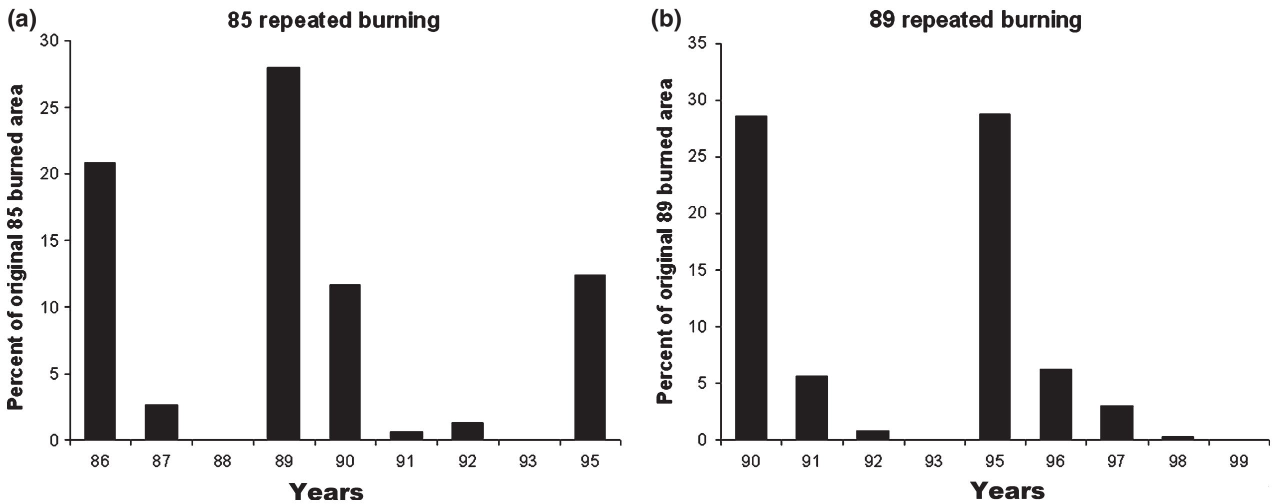

Fig. 4 Evolution of burned Puna after two major fire events (1985 and1989) (a,b respectively). Bars indicate the percent of pixels that originally burned in 1985 or 1989 which also burnt in the following years. The total number of pixels that burned in 1985 that were repeatedly burned up to the year 1995 was 77% for the burned pixels of 1985, and 73% for the burned pixels of 1989.

Table 2 Correlation coefficients for the Multivariate ENSO Index (MEI) and area percentages with severe drought/rainfall excess or severe cold/heat for Bolivia, Peru, and Ecuador, for the wet and dry seasons and for the period 1982–2006

	MEI	Bolivia	Peru	Ecuador
Temperature (>2000 m)				
Percentage area higher than the 90th percentile (warm extreme)	Wet season-Austral summer	0.75**	0.77**	0.56**
	Dry season- Austral winter	ns	0.63**	0.49*
Precipitation (>2000 m)				
Percentage area lower than the 10th percentile (dry extreme)	Wet season-Austral summer	ns	ns	ns
	Dry season- Austral winter	ns	ns	ns

*$P \leq 0.05$, **$P \leq 0.01$.

drying process. To test this hypothesis in the high tropical Andes, we checked (i) the climatic conditions of high vs. low fire years by means of the extreme percentiles (10th and 90th) of precipitation and temperature, and (ii) the precipitation anomalies of the peak and low composite fire years (1982–2006).

The percentile distribution of temperature and precipitation for fire-peak years suggested that three variables control these fire episodes:

1. Precipitation during peak fire years (*t*0) mainly in the dry season, with nonsignificant reductions of precipitation during the wet season (Fig. 5).
2. Precipitation during the wet season of the year before the fire peak (*t*-1) (Fig. 5).
3. Temperature during the peak fire years (*t*0) more marked during the dry season (Fig. 6).

In contrast, low fire years were correlated exclusively with increased precipitation, mainly in the wet season, with no role of temperature being evident (Fig. 7). Two further analyses corroborated the suggested importance of these variables. First, the results of the LMM, which exclusively selected the precipitation *t*-1 during the wet season, the precipitation in the dry season and the temperature in the wet season, with only direct effects being significant, and no significant interaction terms (Table 3).

Second, the climate composites corroborated the observed trends (Fig. 8). This figure shows the spatial

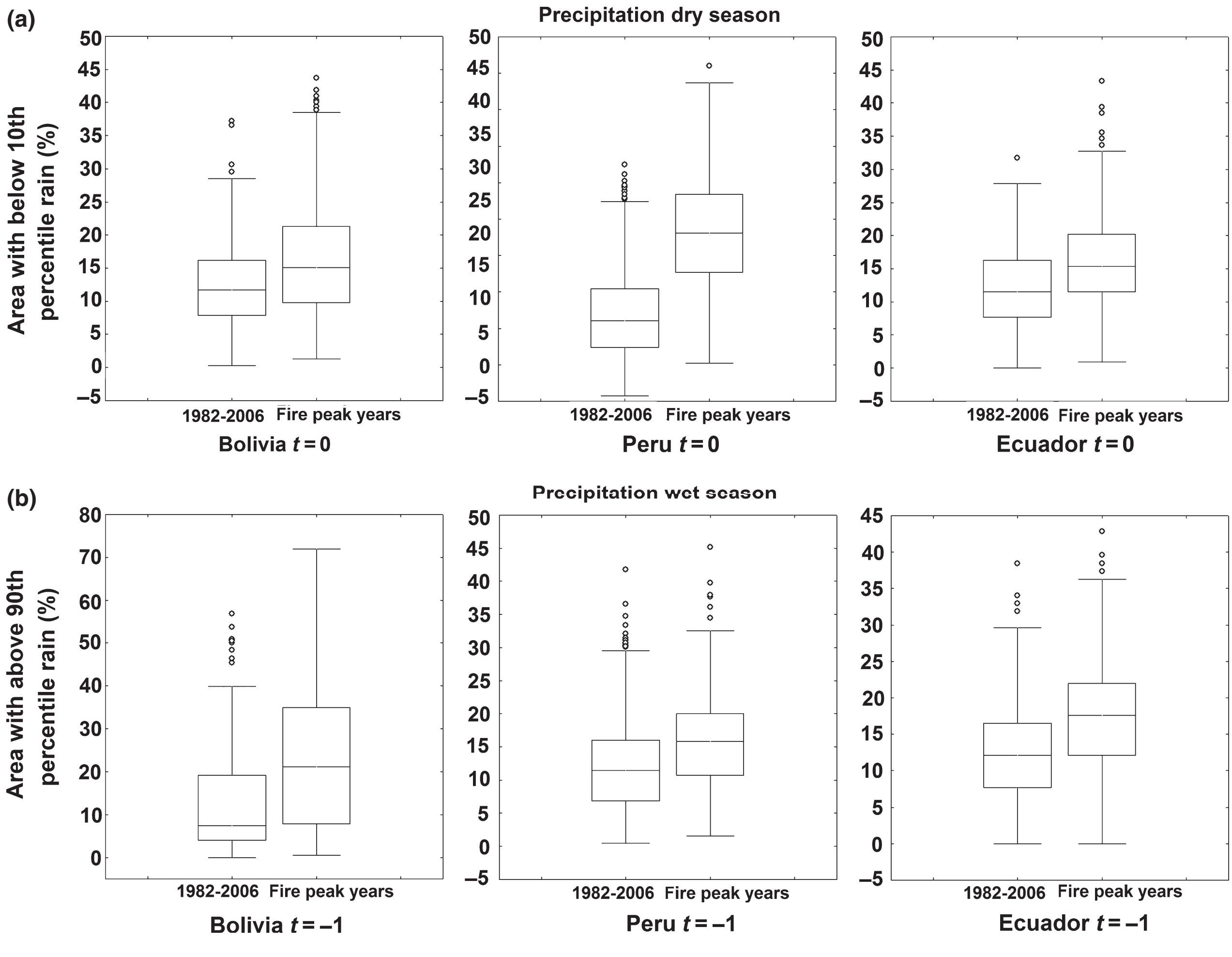

Fig. 5 Percent of area under drought conditions for the peak fire years (t = 0) during the dry season (a), and percent of area under excess rainfall for the year before the fire peaks (*t*-1), during the wet season (b). Boxplots represent the 25th, 50th, and 75th percentiles of percentage areas with precipitation below/above the 10th/90th percentiles. Bars represent 1.5 standard deviations and the outliers are in circles. Left boxplots display the mean rainfall bootstrapped value for 1000 iterated means of n randomly selected years (n = number of peak fire years). Right boxplots represent the mean rainfall value for the peak fire years, in each country, for each considered rainfall season (wet or dry). Median values of bootstrapped and comparative climate boxplots were significant at $P \leq 0.01$ using the Kolmogorov–Smirnov two independent sample test.

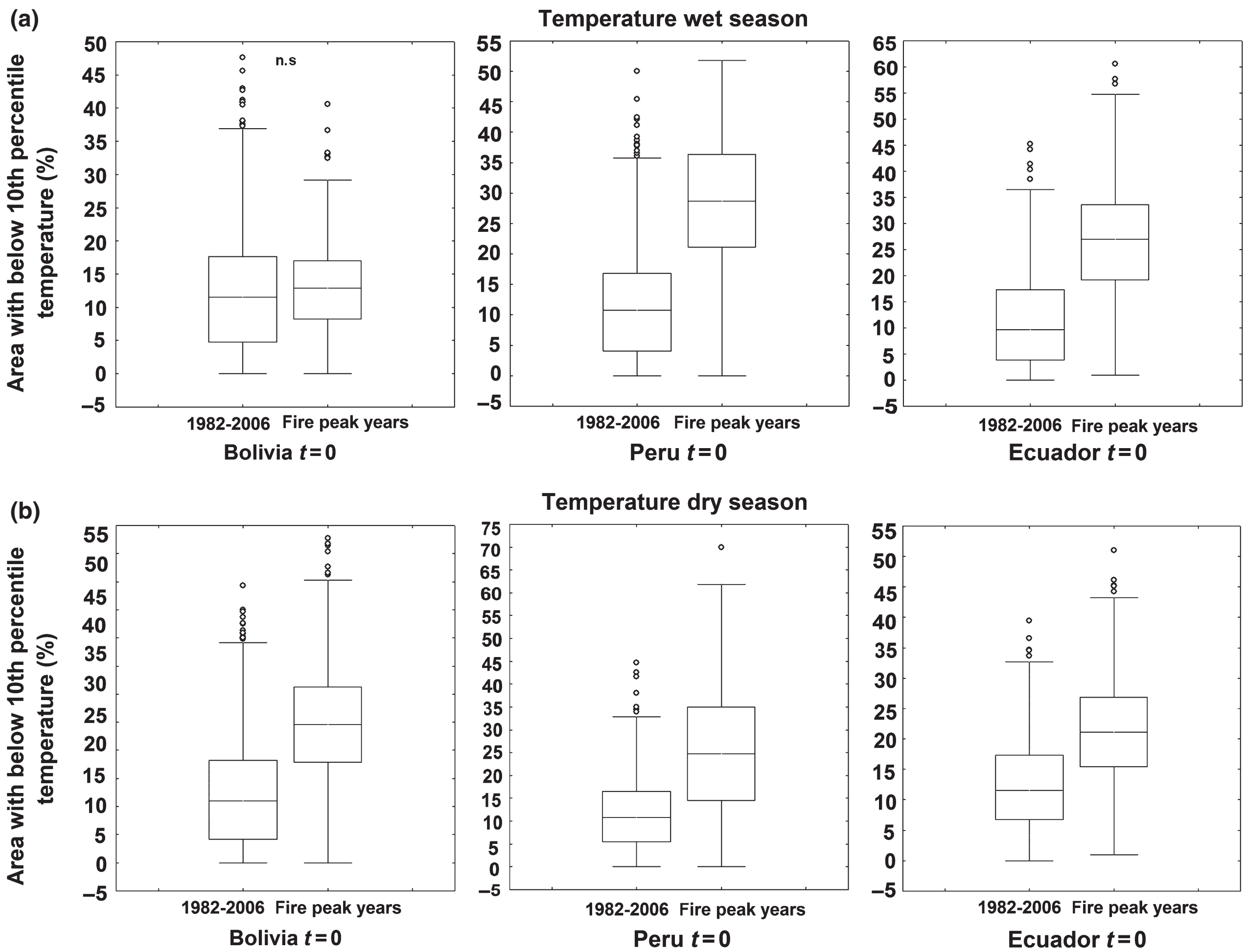

Fig. 6 Percent of area under cold conditions for the fire year (t = 0) during both the dry (a) and wet seasons (b). Boxplots represent the 25th,50th, and 75th percentiles of areas with precipitation below the 10th percentile, with 1.5 standard deviations (bars) and outliers (circles). Left boxplots display the mean temperature bootstrapped value for 1000 iterated means of n randomly selected years (n = number of low fire years). Right boxplots represent the mean temperature value for the peak fire years, in each country, for each considered rainfall season (wet or dry). With the exception of Bolivia during the wet season, all the median values of bootstrapped and comparative climate boxplots were significant at $P \leq 0.01$ using the Kolmogorov–Smirnov two independent sample test.

distribution of mean precipitation anomalies for the composite peak fire years, and low-fire years. There is a mean precipitation decrease along the tropical Andes particularly strong for the southern Peruvian Plateau (drought anomalies between 0.5 and 0.8 standard deviations from the mean)during the wet season, for the composite fire-peak years (Fig. 8). The inverse trend was observed for low fire years with precipitation increases for the central Peruvian Andes and northern Ecuador.

As the composite anomalies show differences from the mean trend and the percentiles show extreme events, these results suggest that for the peak fire years there is a regional reduction in precipitation during the wet season whilst more extreme differences are concentrated in the dry season. For the low-fire years, both precipitation anomalies and extreme events are concentrated in the wet season.

Discussion

In agreement with Andean regional models that foresee the greatest climatic changes for Ecuador, Peru, Bolivia (Bradley *et al.*, 2006; Urrutia & Vuille, 2009), our study also highlights their regional weight when monitoring fire activity. Fire responses in these three countries exhibited two remarkable properties (1982–2006): quasicyclicity, suggesting the influence of a high-frequency climate disturbance; and synchrony, implying climate forcing on fire activity on a subcontinental scale. We did not find evidence of increased fire activity with elevation (hypothesis 1), although we

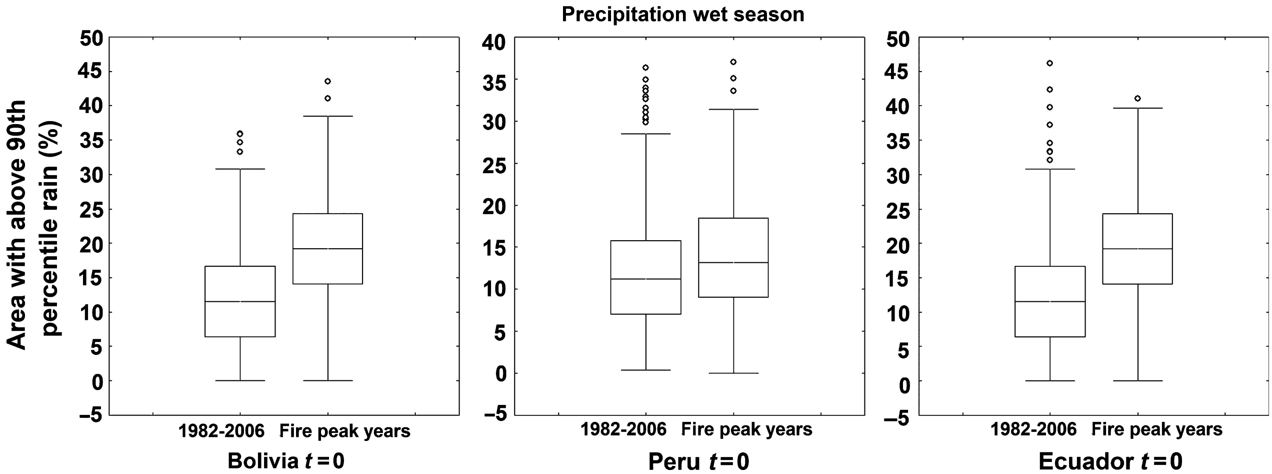

Fig. 7 Percent of area under high rainfall for low fire years (t = 0), during the wet season. Boxplots represent the 25th, 50th, and 75th percentiles of areas with precipitation above the 90th percentile, with 1.5 standard deviations (bars) and outliers (circles). Left boxplots display the mean precipitation bootstrapped value for 1000 iterated means of n randomly selected years (n = number of low fire years). Right boxplots represent the mean precipitation value for the low fire years, in each country, for the wet season.Median values of bootstrapped and comparative climate boxplots were significant at $P \leq 0.01$ using the Kolmogorov–Smirnov two independent sample test.

Table 3 Results for the Linear Mixed Model with the Restricted Maximum Likelihood (ML) method, on the influence of climate, country, and years on fire anomaly patterns in the tropical high elevation Andes for Ecuador, Bolivia and Peru, for 1982–2006. Only those fixed effects that were significant are shown (* $P \leq 0.05$, **$P \leq 0.005$, *** $P \leq 0.0005$). Random effects were not significant

Solution for Fixed Effects			
Effect	df	t Value	Pr > |t|
Intercept	62	2.82	**
Precipitation wet season>90th percentile_t-1	62	2.38	*
Precipitation dry season<10th percentile t0	62	3.83	***
Temperature wet season<10th percentile t0	62	2.02	*

acknowledge that 25 years is rather short to strongly conclude on trends in fire activity. Synchronous fire occurred but it did not significantly relate to ENSO variability (hypothesis 2), perhaps because ENSO peaks did not significantly relate to precipitation extremes, although they did to temperature extremes. Whilst ENSO did not seem to *individually* lead the observed regional fire trends, our results suggest that there is a clear climate influence on fire activity (hypothesis 3), through several particular combinations of temperature and precipitation in the year of the fire peaks (t0) and the year immediately before (t-1), both in the dry and wet seasons. Fuel build-up did not play a role.

Increasing fire trends with elevation and observed fire cyclicity (Hypothesis 1)

There is considerable evidence that wildfires have increased globally since the mid-80s in most terrestrial ecosystems (Piñol *et al.*, 1998; Grissino-Mayer & Swetnam, 2000; Westerling *et al.*, 2006; Balshi *et al.*, 2007; Goetz *et al.*, 2007). However, our fire database did not suggest so for the high Andean ecosystems, but showed a marked cyclicity instead (4–6 years). For the temperate Andes, similar fire cycles have been reported with five-year quasicyclic oscillations observed in northern Argentina (Grau & Veblen, 2000). Moreover, Kitzberger *et al.* (2001) reported fire-peak periodicity of 2.1–5.6 years from a wavelet spectral analysis of fire scars in the temperate Andes, and Gonzalez *et al.* (2005) reported a 5.8–7.2 year cycle in a dendrochronological analysis of fire scars in the Chilean Andes. Field evidence adds support to this cyclicity, with numerous field reports of repeated Puna/Paramo burning every 4–6 years (Laegaard, 1992; Keating, 1997; Gade, 1999; Suarez & Medina, 2001). Our results confirm this cyclicity, with the suggestion that whatever the signal behind this trend is, it is strongest at the Equator, which exhibits almost constant frequency and amplitude.

Climate vs. human drivers (Hypothesis 3)

Fuel build-ups could be behind these cycles but there is little information available about Puna/Paramo productivity and about recovery times after disturbance. However, several authors report the importance of fuel

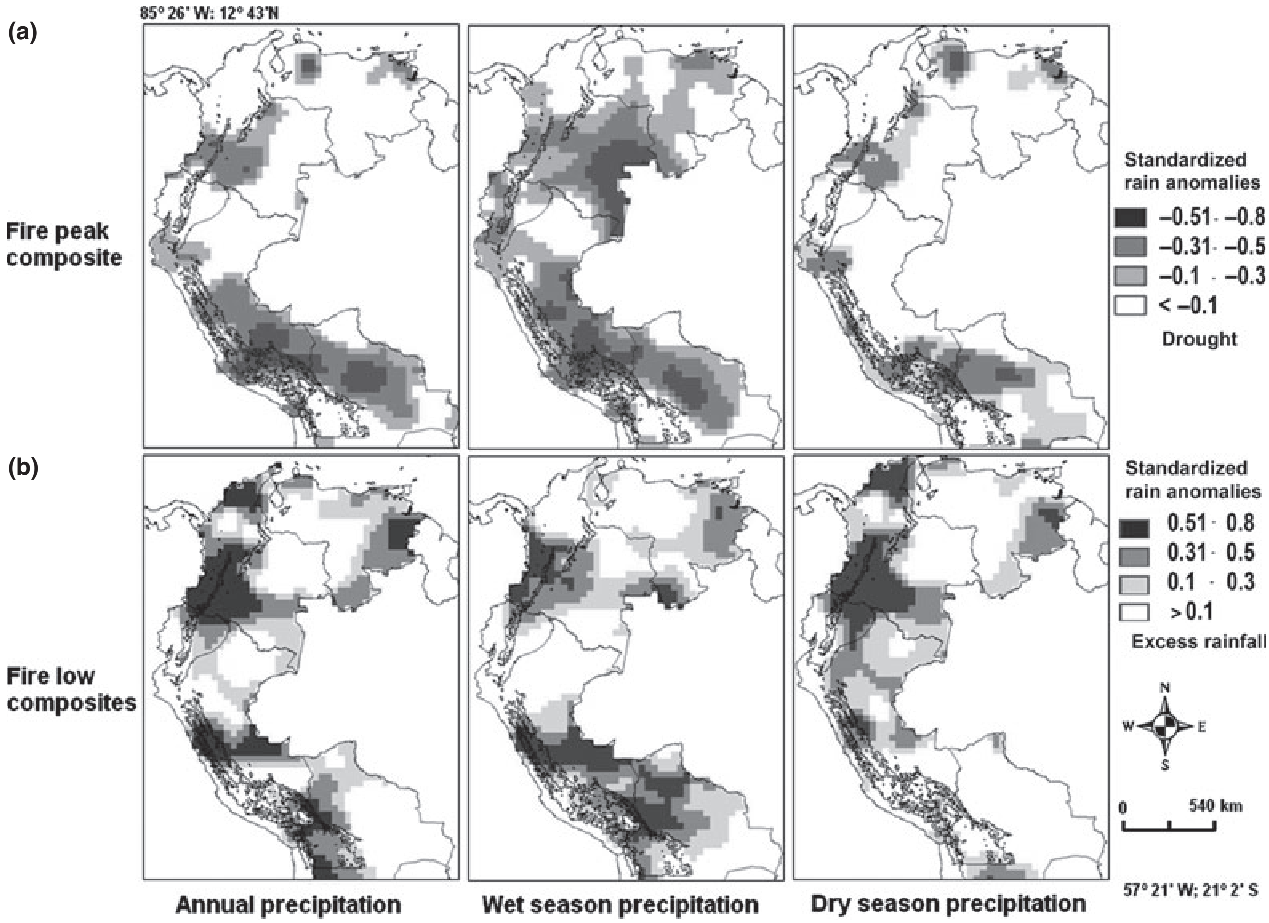

Fig. 8 Composite precipitation for the peak fire years (a) and low fire years (b) for the annual, wet, and dry seasons. Values represent mean standardized anomalies of precipitation for the combined peak years (drought anomalies) or low-fire years (excess rain anomalies), in relation to the climatological means (1982–2006), for each season.

load distribution in preventing fire in these highland ecosystems: Observations of burned Paramo in Ecuador by Laegaard (1992) report that '*when a patch of Paramo with old grass is burned, the fire will simply stop when it reaches the border of another patch that was burned more recently. In other cases and especially in periods with very dry climate, much larger areas, often several hundreds of hectares can be seen burning for days or even for weeks*'. Similar fuel build-ups comments are made by Hofstede (1995b), Keating (1999) and Kessler (2000), regarding the Ecuadorian and Colombian Paramos. Nevertheless, our analyses failed to reveal repeated burning over the same areas in fire-peak years in a period of at least 9–12 years, suggesting that the observed fire cyclicity may be conditioned by local fuel loading, but is driven by changes in the regional climate. Our results were corroborated by a recent study on fire dynamics in the high Andes of Peru, where Fire Return Intervals (FRI) for forests resulted in ca. 65 years and grasslands ca. 37 years (Oliveras *et al.*, in press).

Regionally synchronous fire responses through ENSO influence (Hypothesis 2)

Due to its intrinsic high-frequency oscillation (2–6 years) and its strong influence over large-spatial scales, ENSO has been traditionally invoked as the main climatic force that predisposes the occurrence of widespread high-frequency fires in the Andes through its sawtooth effect on precipitation that is associated with the shifting from El Niño to La Niña conditions (Swetnam, 1993; Veblen *et al.*, 1999; Vuille *et al.*, 2000a; Kitzberger *et al.*, 2001, 2007). Our results, however, cast doubt on the individual importance of ENSO events in influencing high Andean fire trends, as it has already been highlighted in other Andean fire research (Veblen *et al.*, 1999; Grau & Veblen, 2000) (Fig. 9). Hence, whilst we saw a strong covariation between MEI and extreme temperatures in Ecuador, Peru and Bolivia, MEI did not significantly relate to extreme precipitation decreases in the region. This

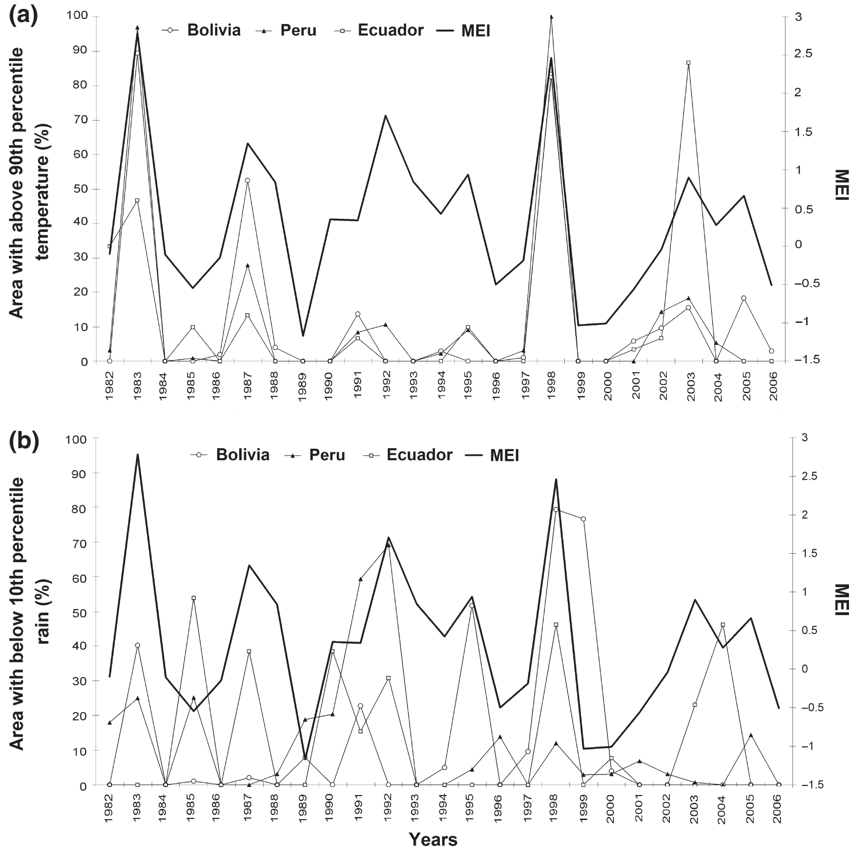

Fig. 9 Covariation of the Multivariate ENSO Index (MEI) (right axis) with extreme temperatures (>90th percentile) (a) and extreme drought (<10th precipitation) (b) (left axis) during the wet season (austral summer) for Ecuador, Peru, and Bolivia.

lack of correlation between ENSO and both decreased precipitation and increased fire activity does not necessarily indicate a lack of response to ENSO variability but it suggests, instead, the importance of additional climatic influences outside the tropical Pacific (i.e. droughts in 1985, 1995, 2005). Both 1995 (Achard *et al.*, 2004) and 2005 (Phillips *et al.*, 2009) have been reported as unprecedented dry years leading to severe fire seasons globally.

In a region like the tropical high elevation Andes where humans have played an important role in shaping landscapes and fire regimes for centuries, the distinction between anthropogenic vs. climatic influences on fire regimes is difficult to draw (Veblen *et al.*, 1999; Dillehay & Kolata, 2004). However, the observed intra-decadal fire synchrony across most of the tropical high elevation Andes more likely relates to high-frequency regional climatic variations than to spatial variability in human activity or fuel build-up. Synchronized fire events in widely scattered locations are strong indicators of regional climatic variations (Swetnam, 1993). Synchronous large fire events have been observed during the 20th century, and are typically coincident with strong drought periods (Swetnam & Betancourt, 1990, 1998; Potter *et al.*, 2003). Our results confirm the existence of a regional precipitation signal that affects the southern tropical high Andes and leads to a simultaneous fire response in Ecuador, Peru and Bolivia. In this line, our climate-fire analysis of the tropical high Andes suggests that a sawtooth pattern of precipitation (increased rainfall before fire-peak seasons (t-1) followed by drought spells (t0) leads major fire events. The effect of a sawtooth precipitation oscillation on fire is particularly evident in ecosystems where fire is carried by low fuel loads (e.g., grasslands, fine fuels), which have short-term vegetation responses to climate. This is the case of the high elevation Andes, the US Pacific Southwest or Northern Mexico (Kitzberger *et al.*, 2007). However, this climate control is exerted through its interaction with fuel availability. Excess rainfall stimulates fine fuel growth through both increased plant productivity and decreased fire activity, leading to more successful fire ignitions and widespread burning during subsequent droughts (Swetnam & Betancourt, 1990, 1998; Swetnam, 1993; Veblen *et al.*, 1999; Kitzberger *et al.*, 2007). Moreover, high fire seasons coincided with anomalously low temperatures in the same year ($t = 0$). One possible causal mechanism is a succession of night frosts that help desiccate pastures and increase their flammability for future burning (as it has been observed in Paraguay's lowland grassland fires in 1999) (L. Rejalaga, Personal communication).

Improved understanding of fire regimes and fire drivers in the tropical high Andes is an important and timely task, not only because the region is suffering from unprecedented climatic changes that affect its ecosystem functioning and threatens biodiversity, but also because the Puna, Paramo and Yungas, are cold-humid ecosystems that accumulate large reservoirs of soil organic carbon. Under drought spells and severe fire episodes, these peatsoils become net carbon sources, whose gross carbon emission rates have conservatively been estimated to range from 0.8 to 1.8 $TgCyr^{-1}$(Román-Cuesta *et al*., 2011). This represents a large regional carbon source that is regionally comparable to South American lowland fire emissions, and is currently unaccounted for.

Acknowledgements

This project is part of a larger research programme studying the effects of climate change and fire in the tropical Andes founded by the Gordon and Betty Moore Foundation. Our gratitude goes to the Alexander von Humboldt Foundation for supporting RMRC's salary, and to the Association for the Conservation of the Amazon for their logistic and financial support. We would also like to thank INRENA for their support and fruitful discussions about protected areas in the Peruvian Andes.

References

Achard F, Eva HD, Mayaux P, Stibig HJ, Belward A (2004) Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical cycles*, **18**, GB2008. doi: 10.1029/2003GB002142.

Armenteras-Pascual D, Retana-Alumbreros J, Molowny-Horas R, Román-Cuesta RM, González-Alonso F, Morales-Rivas M (2011) Characterising fire spatial pattern interactions with climate and vegetation in Colombia. *Agricultural and Forest Meteorology*, **151**, 279–289.

Balshi MS, McGuire AD, Zhuang Q (2007) The role of historical fire disturbance in the carbon dynamics of the panboreal region: a process-based analysis. *Journal of Geophysical Research*, **112**, G02029. doi: 10.1029/2006JG000380.

Blydenstein J (1967) Tropical savanna vegetation of the Llanos of Colombia. *Ecology*, **48**, 1–15.

Bolker BM, Brooks ME, Clark CJ, Geange SW, Poulsen JR, Stevens MHWhite JS (2009) Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology and Evolution*, **24**, 127–135.

Bradley A, Millington C (2006) Spatial and temporal issues in determining biomass burning regimes in Bolivia and Peru. *International Journal of Remote Sensing*, **27**, 2221–2253.

Bradley R, Vuille M, Díaz H, Vergara W (2006) Threats to water supplies in the tropical Andes. *Science*, **312**, 1755–1756.

Büntgen U, Frank D, Nievergelt D, Esper J (2006) Summer temperature variations in the European Alps, AD 755–2004. *Journal of Climate*, **19**, 5606–5623.

Bush M, Hansen B, Rodbell D *et al*. (2005) A 17000-year history of Andean climate and vegetation change from Laguna de Chochos, Peru. *Journal of Quaternary Science*, **20**, 703–714.

Carmona-Moreno C, Belward A, Malingreau JP *et al*. (2005) Characterizing interannual variations in global fire calendar using data from earth observing satellites. *Global Change Biology*, **11**, 1537–1555.

Dillehay T, Kolata A (2004) Long-term human response to uncertain environmental conditions in the Andes. *Proceedings of the National Academy of Science United States of America*, **101**, 4325–4330.

DiPasquale G, Marziano M, Impagliazzo S, Lubritto C, de Natale A, Bader MY (2008) The Holocene treeline in the northern Andes (Ecuador): first evidence from soil charcoal. *Palaeogeography Palaeoclimatology Palaeoecology*, **259**, 17–34.

Farr TG, Rosen P, Caron E *et al*. (2007) The shuttle radar topography mission. *Reviews in Geophysics*, **45**, RG2004. doi: 10.1029/2005RG000183.

Francou B, Vuille M, Wagnon P, Mendoza J, Sicart JE (2003) Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16 S. *Journal of Geophysical Research – Atmospheres*, **108**, 4154–4165.

Fu Q, Manabe S, Johanson C (2011) On the warming in the tropical upper troposphere: models versus observations. *Geophysical Research Letters*, **38**, L15704.

Gade D (1999) Deforestation and reforestation of the central Andean highlands. In: *Nature and Culture in the Andes* (ed Gade D), pp. 42–75. The University of Wisconsin Press, Madison, USA.

Garreaud R, Aceituno P (2001) Interannual rainfall variability over the South American Altiplano. *Journal of Climate*, **14**, 2779–2789.

Garreaud R, Vuille M, Clement A (2003) The climate of the Altiplano: observed current conditions and mechanisms of past changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **194**, 5–22.

Goetz S, Mack M, Gurney K, Randerson J, Houghton RA (2007) Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. *Environmental Research Letters*, **2**, 045031.

Gonzalez M, Veblen T, Sibold V (2005) Fire history of Araucaria-Nothofagus forest in Villarrica national park, Chile. *Journal of Biogeography*, **32**, 1187–1202.

Grau H, Veblen T (2000) Rainfall variability, fire and vegetation dynamics in neotropical montane ecosystems of north-western Argentina. *Journal of Biogeography*, **27**, 1107–1121.

Grissino-Mayer H, Swetnam T (2000) Century-scale climate forcing of fire regimes in the American southwest. *Holocene*, **10**, 207–214.

Hemp A (2005) Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Global Change Biology*, **11**, 1013–1020.

Hoffmann G (2003) Taking the tropical pulse of the water cycle. *Science*, **301**, 776–777.

Hofstede R (1995b) Recovery after fire in a Colombian páramo grassland: changes in vegetation structure and nutrient status. *Arctic and Alpine Research*, **33**, 158–164.

Justice C, Townshend T, Vermote E *et al*. (2002) An overview of MODIS land data processing and product status. *Remote Sensing of Environment*, **83**, 3–15.

Keating P (1997) Mapping vegetation and anthropogenic disturbances in southern Ecuador with remote sensing techniques: implications for Parks. *Conference of Latin Americanist Geographers*, **23**, 77–90.

Keating P (1999) Changes in páramo vegetation along an elevation gradient in southern Ecuador. *Journal of the Torrey Botanical Society*, **126**, 159–175.

Keeley J, Fortheringham J (2001) History and management of crown-fire ecosystems: summary and response. *Conservation Biology*, **15**, 1561–1567.

Kessler M (2000) Observations on a human-induced fire event at a humid timberline in the Bolivian Andes. *Ecotropica*, **6**, 89–93.

Kitzberger T, Veblen T, Villalba R (1997) Climatic influences on fire regimes along a rain forest-to-xeric woodland gradient in northern Patagonia, Argentina. *Journal of Biogeography*, **24**, 35–47.

Kitzberger T, Swetnam T, Veblen T (2001) Inter-hemispheric synchrony of forest fires and the El Niño-Southern oscillation. *Global Ecology and Biogeography*, **10**, 315–326.

Kitzberger T, Brown T, Heyerdahl E (2007) Contingent Pacific-Atlantic ocean influence on multicentury wildfire synchrony over western North America. *Proceedings of the National Academy of Science United States of America*, **104**, 543–548.

Laegaard S (1992) Influence of fire in the grass Paramo vegetation of Ecuador. In: *Páramo: An Andean Ecosystem Under Human Influence* (eds Balslev H, Luteyn J), pp. 151–170. Academic Press, London. UK.

Legates D, Willmott C (1990) Mean seasonal and spatial variability in gauge-corrected, global precipitation. *International Journal of Climatology*, **10**, 111–127.

Liu X, Chenga Z, Yana L *et al*. (2009) Elevation dependency of recent and future minimum surface air temperature trends in the Tibetan Plateau and its surroundings. *Global and Planetary Change*, **68**, 164–174.

Minnich RA (2001) An integrated model of two fire regimes. *Conservation Biology*, **15**, 1549–1553.

Oliveras I, Anderson L, Malhi Y (in press) Fire regimes and carbon emissions of the tropical Andes. *Global Biogeochemical Cycles*.

Olson D, Dinerstein E, Wikramanayake E *et al*. (2001) Terrestrial ecoregions of the world: a new map of life on Earth. *BioScience*, **51**, 933–938.

Patterson HD, Thompson R (1971) Recovery of inter-block information when block sizes are unequal. *Biometrika*, **58**, 545–554.

Phillips O, Aragao L, Lewis S *et al*. (2009) Drought sensitivity of the Amazon rainforest. *Science*, **323**, 1344–1347.

Piñol J, Terradas J, Lloret F (1998) Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Climatic Change*, **38**, 345–357.

Potter C, Klooster S, Steinbach M *et al*. (2003) Global teleconnections of climate to terrestrial carbon flux. *Journal of Geophysical Research*, **108**, 4556–4560.

Rabatel A, Francou B, Soruco A *et al*. (2013) Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *The Cryosphere*, **7**, 81–102.

Román-Cuesta RM, Salinas N, Asbjornsen H *et al*. (2011) Implications of fires on carbon budgets in Andean cloud montane forests: the importance of peat soils and tree resprouting. *Forest Ecology and Management*, **261**, 1987–1997.

Rubin D (1976) Inference and missing data. *Biometrika*, **63**, 581–590.

Salinas N, Malhi Y, Meir P *et al*. (2011) The sensitivity of tropical leaf litter decomposition to temperature: results from a large-scale leaf translocation experiment along an elevation gradient in Peruvian forests. *New Phytologist*, **189**, 967–977.

Sarmiento F, Frolich L (2002) Andean cloud forest tree lines. naturalness, agriculture and the human dimension. *Mountain Research and Development*, **22**, 278–287.

Soruco A, Vincent C, Francou B *et al*. (2009) Glacier decline between 1963 and 2006 in the cordillera real Bolivia. *Geophysical Research Letters*, **36**, L03502.

Suarez E, Medina G (2001) Vegetation Structure and soil properties in Ecuadorian Paramo grasslands with different histories of burning and grazing. *Arctic, Antarctic and Alpine Research*, **33**, 158–164.

Swetnam T (1993) Fire history and climate change in giant sequoia groves. *Science*, **262**, 885–889.

Swetnam T, Betancourt J (1990) Fire-southern oscillation relations in the southwestern United States. *Science*, **249**, 1017–1020.

Swetnam T, Betancourt J (1998) Mesoscale disturbance and ecological response to decadal climate variability in the American southwest. *Journal of Climate*, **11**, 3128–3147.

Thompson LG, Mosley-Thompson E, Koci JF (1985) A 1500-year record of tropical precipitation in ice cores from the Quelccaya ice cap Peru. *Science*, **229**, 971–973.

Urrutia R, Vuille M (2009) Climate Change projections for the tropical Andes using a regional climate model: temperature and precipitation simulations for the end of the 21st century. *Journal of Geophysical Research*, **114**, D02108.

Veblen T, Kitzberger T, Villalba R *et al*. (1999) Fire history in northern Patagonia: the roles of humans and climatic variation. *Ecological Monographs*, **69**, 47–67.

Verbeke G, Molenberghs G (2000) *Linear Mixed Models for Longitudinal Data*. Springer-Verlag, New York, USA.

Vimeux F, Ginot P, Schwikowski M *et al*. (2009) Climate variability during the last 1000 years inferred from Andean ice cores: a review of recent results. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **281**, 229–241.

Vuille M (1999) Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the southern oscillation. *International Journal of Climatology*, **19**, 1579–1600.

Vuille M, Bradley R (2000) Mean annual temperature trends and their vertical structure in the tropical Andes. *Geophysical Research Letters*, **27**, 3885–3888.

Vuille M, Keiming F (2004) Interannual variability of summertime convective cloudiness and precipitation in the central Andes derived from ISCCP-B3 data. *Journal of Climate*, **17**, 3334–3348.

Vuille M, Bradley R, Keimig F (2000a) Interannual climate variability in the central Andes and its relation to tropical Pacific and Atlantic forcing. *Journal of Geophysical Research*, **105**, 12447–12460.

Vuille M, Bradley R, Keimig F (2000b) Climate variability in the Andes of Ecuador and its relationship to Tropical Pacific and Atlantic sea surface temperature anomalies. *Journal of Climate*, **13**, 2520–2535.

Vuille M, Bradley S, Healy R, Werner M, Hardy D, Thompson L, Keimig F (2003) Modeling $d^{18}O$ in precipitation over the tropical Americas: 2. simulation of the stable isotope signal in Andean ice cores. *Journal of Geophysical Research*, **108**, 4175–4187.

Vuille M, Francou B, Wagnon P *et al*. (2008) Climate change and tropical Andean glaciers – past, present and future. *Earth Science Reviews*, **89**, 79–96.

West B, Welch K, Galecki A (2007) What are linear mixed models (LMMS)? In: *Linear Mixed Models. A practical guide using Statistical software* (eds.West B, Welch K, Galecki A), pp.1–7. Chapman & Hall/CRC. Taylor and Francis Group, Boca Raton, Florida.

Westerling A, Hidalgo H, Cayan D *et al*. (2006) Warming and early spring increase western US forest wildfire activity. *Science*, **313**, 940–943.

Willmott C, Robeson S (1995) Climatologically aided interpolation (CAI) of terrestrial air temperature. *International Journal of Climatology*, **15**, 221–229.

Wolter K, Timlin M (1993) *Monitoring Enso in Coads with a Seasonally Adjusted Principal Component Index*. Proceedings of the 17th Climate Diagnostics Workshop, Norman, OK, NOAA/NMC/CAC, NSSL, Oklahoma Clim. Survey, CIMMS and the School of Meteor. Univ. of Oklahoma, Oklahoma, USA, 52–57.