



## Abrupt Younger Dryas cooling in the northern tropics recorded in lake sediments from the Venezuelan Andes

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### ABSTRACT

A radiocarbon dated sediment record from Laguna de Los Anteosojos, a cirque lake in the Mérida Andes of Venezuela, indicates that warmer and wetter atmospheric conditions occurred in the northern tropics at the onset of the Bølling (~14,600 cal yr BP), and abruptly colder and drier conditions around the time of the Younger Dryas (YD). Geochemical and clastic sediment analyses from Los Anteosojos show that glaciers advanced at ~12,850 cal yr BP, reached their YD maximum extent at ~12,650 cal yr BP, and then retreated until complete deglaciation of the watershed at ~11,750 cal yr BP. The onset of warmer conditions that ended the coldest phase of the YD occurred several hundred years earlier at Los Anteosojos than in the high latitudes of the Northern Hemisphere. During the peak YD glacial advance, glacier equilibrium-line altitudes in the region were ~360 to 480 m lower, and temperature was ~2.2 to 2.9 °C colder than modern. Independent palynological evidence from the Los Anteosojos sediment core indicates that the northern Andes were more arid and at least 2.3 °C colder during the YD. The direction and timing of glacial fluctuations in Venezuela are consistent with observations of marine sediment records from the Cariaco Basin that suggest abrupt cooling occurred at ~12,850 cal yr BP, followed by a shift to higher temperature after ~12,300 cal yr BP. The timing and pattern of climatic changes in northern South America are also consistent with paleoclimate records from the southern Tropical Andes that suggest a southward shift in the position of the Intertropical Convergence Zone occurred at the start of the cooling event, followed by a return to wetter conditions in northern South America during the late stages of the YD. The early warming of the tropical atmosphere and invigoration of the hydrologic cycle likely contributed to the shift to increased temperature in the higher latitudes of the Northern Hemisphere at the end of the late Glacial stage.

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### 1. Introduction

The Younger Dryas cold reversal (YD) between ~12,850 and 11,650 cal yr BP (calibrated years before A.D. 1950) in the Northern Hemisphere (Rasmussen et al., 2006) is evidence that the climate system is capable of rapid changes. Ice core records from Greenland and terrestrial paleoclimate archives from northern Europe indicate that major temperature shifts occurred abruptly at the beginning and end of the YD (Alley, 2000; Bakke et al., 2009). These records highlight the persistence of this regional 1200-year cooling event and the sensitivity of the global climate system to changes in ocean and atmospheric circulation (Broecker, 2006). The exact cause of the YD

cooling event is a subject of current debate, but it occurred during a period of increasing Northern Hemisphere temperature, rising sea-level, and melting ice sheets, which makes the YD a provocative analog for potential climatic surprises that may be generated by today's anthropogenic greenhouse warming (Alley et al., 2003).

Climate models that explore the possible causes of the YD, and other abrupt global temperature shifts, typically favor either tropical (Clement et al., 2001), or high latitude (Broecker, 2006) ocean–atmosphere systems as the dominant driving mechanisms. Well dated paleoclimate records from the low latitudes during this period warrant further investigation because the tropics are the center of the planet's heat budget, with energy transferred to the high latitudes through the oceans and atmosphere. The tropics also modulate atmospheric greenhouse gas concentrations, such as water vapor, carbon dioxide and methane (Broecker, 1997; Sowers, 2006). Therefore, regardless of the initial driver of the YD, the tropics must have played a major role in modulating the climate system during and

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at the termination of the event. Comparison of terrestrial (atmospheric) and marine paleoclimate records from the low latitudes should improve our scientific knowledge of the mechanisms that drove abrupt global temperature shifts during the late Glacial stage.

The pattern of low latitude atmospheric changes during the YD and the connection to high latitude temperature shifts is currently unclear. This is in-part because tropical paleoclimate records present a conflicted pattern of past climatic conditions during the late Glacial stage (e.g. Rodbell et al., 2009), and there are a limited number of well dated terrestrial records spanning this period from South America. Exceptions exist, including ice cores (e.g. Thompson et al., 1998), speleothems (Wang et al., 2004; van Breukelen et al., 2008) and lake sediments (Seltzer et al., 2000; Baker et al., 2001; Rowe et al., 2002), but most of the available records of low latitude terrestrial climatic change are limited to the Southern Hemisphere so comparatively little is known about how the climate system operated in the Northern Tropical Americas during the last Deglaciation.

Lake sediments studies offer certain advantages over other glacial-geologic methods, because they provide continuous records, can be dated precisely with radiocarbon, and multiple proxies can be analyzed at high-resolution to better determine the timing and direction of tropical temperature and humidity fluctuations. Here, we present a new terrestrial sediment record from Laguna de Los Anteojos in the Venezuelan Andes. This continuous sedimentary sequence recovered from a proglacial lake documents the timing, direction and magnitude of local climatic change, and allows for quantitative estimates of atmospheric cooling during the YD. The high-resolution analyses and firm chronology of the Los Anteojos sediments makes it suitable for comparison with other sites across tropical South America to identify the timing and pattern of low latitude climatic change during the YD. We also review and discuss the records of abrupt temperature, circulation and moisture-balance changes in the northern low latitudes of the Americas during the late Glacial stage, and summarize the evidence of the timing and pattern of aridity and temperature changes in tropical South America during the YD.

## 2. Study site

The Laguna de Los Anteojos lake basin ( $8^{\circ}32'17.88''N$ ,  $71^{\circ}4'25.15''W$ , 3920 m a.s.l.) in the Mérida Andes of Venezuela (Figs. 1 and 2) is well situated to record changes in the glacial status of the watershed during the late Glacial stage. The catchment is currently ice-free, as glaciers in the area have retreated during the late Holocene to elevations above  $\sim 4700$  m (Schubert, 1998). The headwall of Los Anteojos

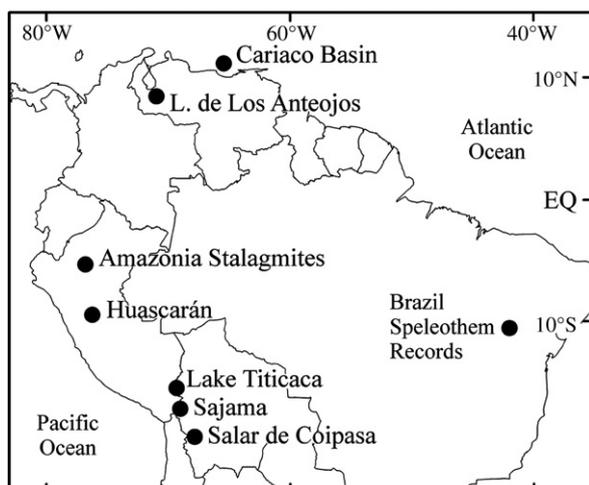


Fig. 1. Map identifying the location of Laguna de Los Anteojos, and the locations of other tropical paleoclimate records discussed in this manuscript.

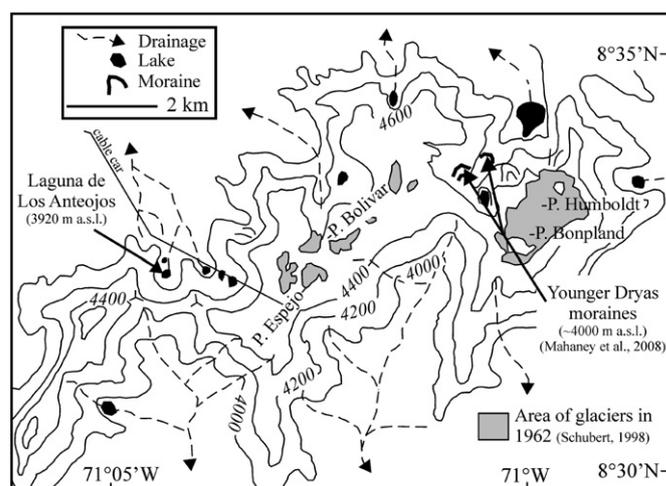


Fig. 2. Glacial-geologic map of the Laguna de Los Anteojos watershed and surrounding region (modified from Schubert, 1998). The modern (A.D. 1962) ice limit is  $\sim 4600$  m a.s.l. (Polissar et al., 2006). Younger Dryas moraines were mapped below Pico Humboldt at  $\sim 4000$  m a.s.l. (Mahaney et al., 2008), and were used in combination with results from this study for  $\Delta ELA$  and paleo-temperature reconstructions.

( $\sim 4400$  m a.s.l.) is situated in a position that is glaciated only under moderately strong cooling events, and most of the sediments that have accumulated in the lake since its inception are organic-rich. The lake is relatively small ( $\sim 0.04$  km<sup>2</sup>) and deep ( $\sim 9$  m) with a steep  $\sim 1$  km<sup>2</sup> catchment set in a north-facing cirque, and the coring site at Los Anteojos is directly down-valley from a paleo-glacier headwall (Schubert, 1972). The bedrock of the watershed consists predominantly of quartzo-feldspathic meta-sediments (Schubert, 1972; Hackley et al., 2005), and is therefore moderately resistant to weathering and erosion. The steep walls of the basin amphitheater keep the lake well protected from wind mixing, and the deep water combined with seasonal stratification minimizes the influence of bioturbation of the sediments. The bathymetry of the lake is simple, with a single bowl-shaped basin surrounded by broad, shallow ( $\sim 1$  m deep) shelves. These combined characteristics allow the lake to preserve continuous, finely laminated sediments.

The Mérida Andes were extensively glaciated at times during the late Glacial stage (Mahaney et al., 2008) and the Holocene (Stansell et al., 2005; Polissar et al., 2006; Stansell et al., 2007a). Today, the climate of the Venezuelan Andes is intermediate between the inner and outer tropics, with the majority of precipitation accumulating during boreal summer, and humidity is high year-round (Azocar and Monasterio, 1980). The wet and generally cloudy environment makes glacier mass-balance in this part of the Andes sensitive mostly to temperature changes (Kaser and Osmaston, 2002).

The alpine vegetation in the Mérida Andes has two major biomes: the páramo above  $\sim 3000$  m, and the montane cloud forest below. The highest part of the páramo, referred to as the desert páramo, or periglacial zone, is located below  $\sim 4700$  m and defines the altitudinal boundary between seasonal and permanent snow cover (Monasterio, 1980). The elevation limit of these vegetation boundaries varies by up to a few hundred meters in this region of the Andes, and is mainly controlled by annual average temperature and minor differences caused by local precipitation patterns.

Precipitation in the area around Los Anteojos is relatively high (1550 mm/yr), and biomes in this region are situated slightly higher than elsewhere in the Mérida Andes. For example, the upper montane cloud forest extends up to 3200 m, and the desert páramo extends to between 4400 and 4700 m, which is also the uppermost limit of plant life (Berg and Suchi, 2001). Located at 3920 m elevation, Los Anteojos is situated in an intermediate position within the páramo biome, dominated by grasses and typical columnar rosettes of *Espeletia* that

are reflected in modern pollen assemblages by the dominance of Asteraceae and Poaceae (Rull, 2006). *Podocarpus* is one of the main arboreal components of the upper layer of Andean forests, and its pollen has been used as an indicator of changes in tree-line altitude and climatically-driven oscillations (Salgado-Labouriau, 1979). Lower and middle páramo levels are characterized by high to medium percentages of *Podocarpus*, while desert páramo is completely dominated by Asteraceae and Poaceae. A special type of forest dominated by dwarf *Polylepis* trees also occurs in small patches within the páramos, and is well represented around the lake. The pollen of these trees has low wind-dispersion power and is not transported very far from where it grows (Rull, 2006).

### 3. Methods

#### 3.1. Coring

In January, 2007, a 425-cm long continuous percussion piston core was collected in a single polycarbonate tube from the depocenter of Los Anteojos in ~9 m of water. A surface core was also collected from the same location and extruded in the field at a 0.5 cm interval to capture the sediment–water interface, and to collect the uppermost 30 cm of flocculent material that was not recovered in the percussion core. The total sediment thickness is 455 cm for the composite late Glacial and Holocene sections. The core was described and cut into 1.5 m-long sections in the field, and all samples were transported to the Sediment Geochemistry Laboratory at the University of Pittsburgh.

#### 3.2. Sediment chronology and age model

The sections of sediment used for dating were wet sieved using a 63  $\mu\text{m}$  screen, and macrofossils >63  $\mu\text{m}$  were picked using jewelers tweezers and a dissecting microscope. Radiocarbon samples were pretreated following established acid–base–acid pretreatment procedures (Abbott and Stafford, 1996). Six radiocarbon dates on aquatic macrofossil samples, spanning the early Holocene and late Glacial stage were isolated. The samples were transported to the Keck Carbon Cycle Accelerator Mass Spectrometer Laboratory at the University of California, Irvine where they were combusted, reduced to graphite and measured. The radiocarbon ages were calibrated and converted to calendar years before present (cal yr BP) using CALIB 6.0 with the IntCal09 dataset (Reimer et al., 2009), with present defined as A.D. 1950. The calibrated ages used here are the maximum likelihood values exported by the CALIB program, and the 2-sigma error ranges along with the median ages from CALIB are presented in Table 1. An age–depth model (Fig. 3) was constructed using a 3rd order polynomial fit between the median calibrated radiocarbon age values.

We note that using the radiocarbon method to date deposits during the late Glacial stage is potentially problematic because of uncertainties in the ability to calibrate values during this time span, however, recent calibration curves have improved the precision of radiocarbon ages in this age range (Hughen et al., 2004a; Reimer et al.,

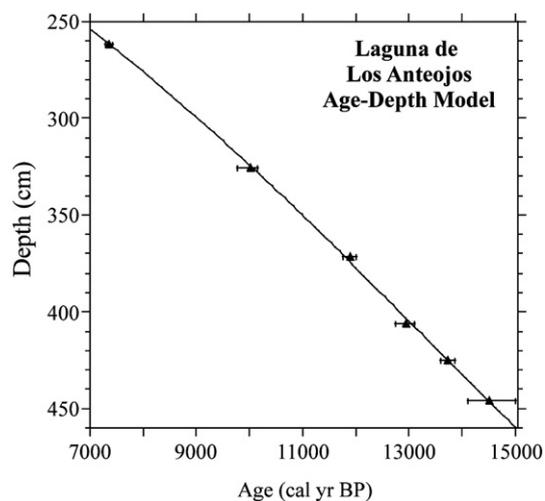


Fig. 3. The age–depth model for the Laguna de Los Anteojos sediment core based on a 3rd order polynomial fit ( $r^2 = 0.99$ ) between 6 radiocarbon dated aquatic macrofossils (Table 1).

2009). Moreover, the uncertainty of any one of our ages is minimized by the robust and almost linear relationship between depth and the median calibrated values of the 6 radiocarbon ages. It should also be noted that there is no limestone in the watershed to produce a hard-water effect, and soils are weakly developed, especially immediately following deglaciation, which limits the input of aged carbon from the catchment.

#### 3.3. Sedimentology and geochemistry

Bulk density (BD) was measured on 1  $\text{cm}^3$  samples, taken every centimeter down-core (Fig. 4). The samples were weighed wet, and again after drying in a 60 °C oven for 24 h. Total carbon (C) and nitrogen (N) were measured every 2 to 5 cm on 1  $\text{cm}^3$  samples at the University of Arizona Stable Isotope Laboratory, and are presented as atomic ratios. Total organic matter was measured every centimeter by loss-on-ignition (LOI) at 550 °C (Dean, 1974). There is no measurable calcium carbonate in the sediments, based on LOI measurements made after burning at 1000 °C and the lack of  $\text{CO}_2$  produced during acidification for C and N measurements. Bulk sediment geochemistry was measured every 0.1 cm using an ITRAX scanning X-ray fluorescence (XRF) instrument (Croudace et al., 2006) at the University of Minnesota-Duluth Large Lakes Observatory, and the values are presented in counts per second (CPS). Magnetic susceptibility was measured at a 0.2 cm interval using a Tamiscan high-resolution surface scanning sensor connected to a Bartington susceptibility meter at the University of Pittsburgh.

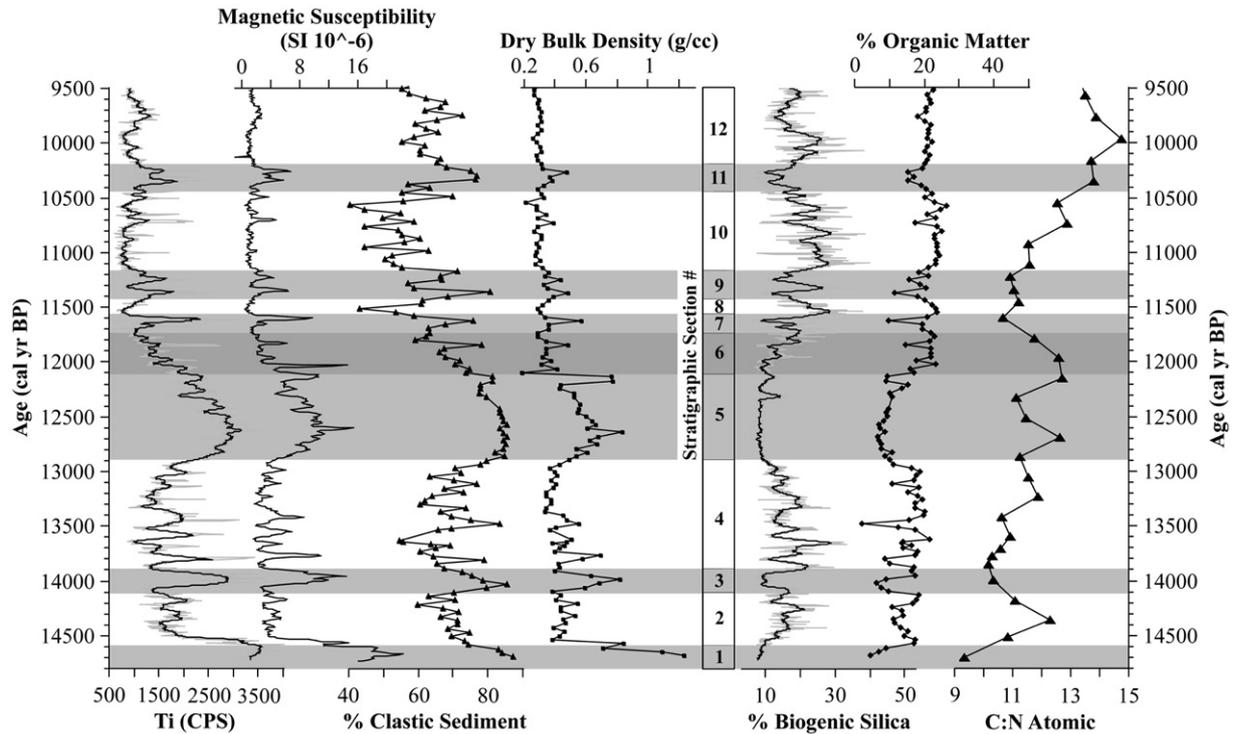
#### 3.4. Biogenic silica and clastic sediments

Weight percentage biogenic silica ( $\text{bSiO}_2$ ) (Figs. 4 and 6) was measured on freeze-dried samples at the University of Alberta Department of Earth and Atmospheric Sciences. Samples for analysis were collected from centimeter-thick sections, taken every 2 to 5 cm down-core. A modified wet alkali sequential digestion method (DeMaster, 1979; DeMaster, 1981; Conley, 1998) was used on approximately 30 mg of freeze-dried sediment (Conley and Schelske, 2001), which allows for separation of  $\text{bSiO}_2$  and the minerogenic, aluminosilicate fraction. The amount of soluble silicic acid ( $\text{H}_4\text{SiO}_4$ ) extract was then analyzed using the heteropoly blue method (Clescerl et al., 1999) with a Beckman DU 520 spectrophotometer operating at 815 nm. The method precision for duplicate digestions gave an average standard deviation of 0.52 while duplicate analysis on all the extracts gave relative differences of <10%.

Table 1

Radiocarbon ages of aquatic macrofossils used in study. Calibrated ages are in calendar years before A.D. 1950 (cal yr BP). Ages presented are the median maximum likelihood values (parentheses) and the 95.4% probability range.

Lab #	Depth (cm)	Measured $^{14}\text{C}$ age	Measured error ( $\pm$ )	2 $\sigma$ calibrated age (cal yr BP)
UCI-37537	262	6420	20	7290-(7365)-7420
UCI-37511	326	8850	20	9780-(10,010)-10,150
UCI-37538	372	10,180	25	11,760-(11,890)-12,000
UCI-37539	406	11,060	30	12,760-(12,960)-13,100
UCI-37540	425	11,880	35	13,590-(13,740)-13,870
UCI-37623	446	12,430	80	14,110-(14,520)-15,020



**Fig. 4.** Stratigraphic column (see Supplemental Table A1 in the Appendix) and sediment core data from Laguna de Los Anteosojos including Titanium (Ti) in counts per second (CPS), magnetic susceptibility (SI units), clastic sediment (wt.%), bulk density ( $\text{g cm}^{-3}$ ), biogenic silica (wt.%), organic matter (wt.%), and carbon and nitrogen (atomic ratio) plotted versus age. The Ti and biogenic silica data were filtered using a LOWESS function (0.01 tension), and are presented as raw (gray line) and filtered values (black line). The gray shading marks major changes in the sedimentological and geochemical profiles that were used to interpret the timing of climatic changes in the Venezuelan Andes.

Biogenic silica content is also represented in Si/Ti values, measured using scanning XRF (Brown et al., 2007). The Si/Ti values for the Los Anteosojos core were converted to weight percent biogenic silica using linear regression ( $r^2 = 0.44$ ,  $p < 0.001$ ) between the XRF data and the weight percent values that were measured independently (Stansell, 2009). The percent clastic sediment values were calculated as the residual amount after summing the percentages of organic matter and biogenic silica, and subtracting this from 100% since there is no carbonate in the sediments.

### 3.5. Palynology

Volumetric samples ( $2 \text{ cm}^3$ ) were taken every 2 to 5 cm for pollen analyses. A modern surface sample was collected for comparison from the same coring location. An additional modern sample from Laguna Negra ( $8^\circ 47' 11.61'' \text{N}$ ,  $70^\circ 48' 21.44'' \text{W}$ , 3470 m) was also analyzed for comparison. These samples were processed using standard palynological techniques (Bennett and Willis, 2001), after spiking with Lycopodium tablets (batch #124961, average 12,542 spores/tablet). Slides were mounted in silicone oil without sealing. Pollen and spore identifications were made according to available datasets for the region (van der Hammen and Gonzalez, 1960; Murillo and Bless, 1978; Salgado-Labouriau, 1984; Tyron and Lugardon, 1991). Counts were conducted until a minimum of 300 pollen and spores were tabulated (excluding the superabundant *Isoetes*) and counting continued until the saturation of diversity was reached (Rull, 1987). The pollen sum (Fig. 5) includes all pollen types. The diagram was built and zoned with *psimpoll*, using the Optimal Splitting by Information Content (OSIC) and broken-stick methods (Bennett, 1996).

### 3.6. Paleo-temperature calculation

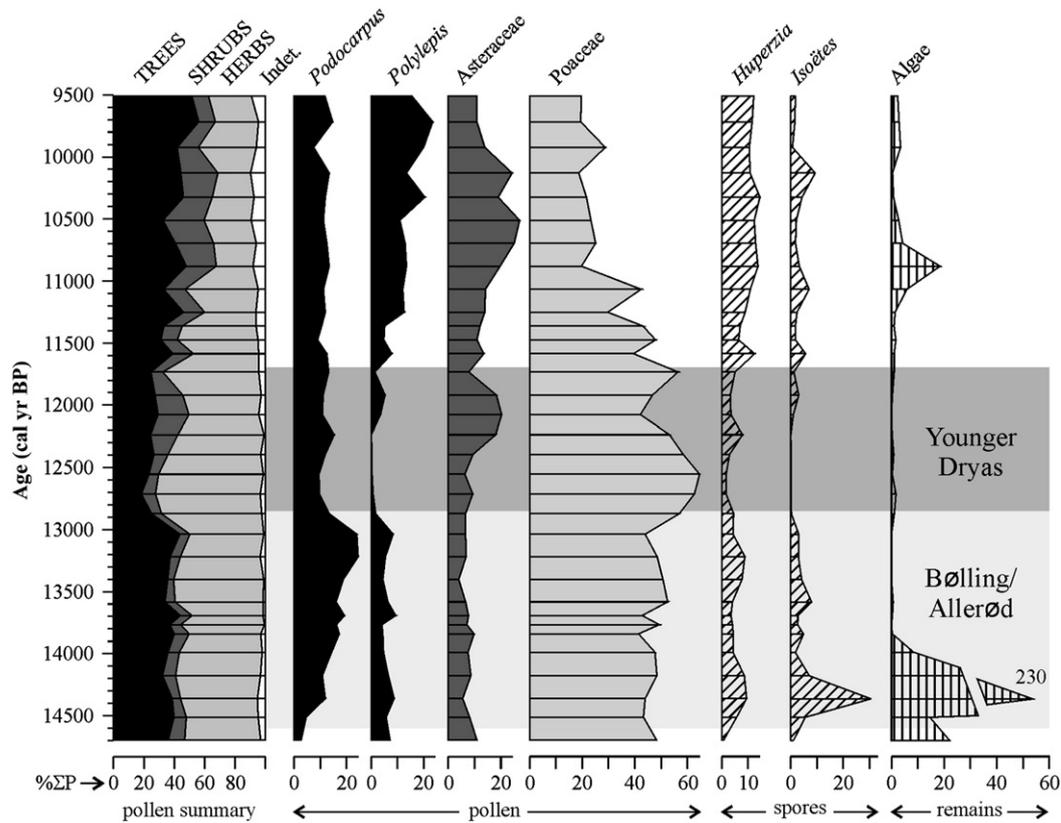
The YD ice position in the Mérida Andes is well defined in the Pico Humboldt region (Mahaney et al., 2008) that is  $\sim 5 \text{ km}$  northeast of

Los Anteosojos (Fig. 2). Paleo-equilibrium-line altitudes (ELA's) were determined by applying the terminus-headwall altitude ratio (THAR) method (Porter, 2001) with a range of values from 0.2 to 0.4 to the elevation of mapped moraines below Pico Humboldt, and assuming the modern and YD headwall values were both 4870 m. These low THAR values were applied using the rationale that the majority of tropical glacier surface areas are in the accumulation zones and tongues are short due to steep ablation gradients (Kaser and Georges, 1999; Benn et al., 2005; Osmaston et al., 2005). Using the same THAR method as above, the modern ELA was determined from the ice limit identified in aerial photos taken in A.D. 1962 (Polissar et al., 2006). Paleo-temperature estimates for the YD were then calculated for the  $\Delta \text{ELA}$  amounts relative to the pre-21st century values, by applying an atmospheric lapse rate calculation method of  $-6.0 \text{ }^\circ \text{C km}^{-1}$  (Porter, 2001).

## 4. Results

### 4.1. Sedimentology and geochemistry

There are two clear end-member sediment facies in the Los Anteosojos record (see Supplemental Table A1 in the Appendix). First are sections dominated by clastic (mineralogical) sediment characterized by high values of titanium (Ti), magnetic susceptibility and dry bulk density ( $> 0.5 \text{ g cm}^{-3}$ ). These clastic-rich sections are low in organic-matter content ( $< 10\%$ ) and light gray in color (GLEY 1 8/1). In contrast, there are sections of the core with low clastic sediment content that have low values of Ti, magnetic susceptibility and dry bulk density ( $< 0.5 \text{ g cm}^{-3}$ ). These sections with low clastic sediment concentrations are high in organic-matter content ( $> 15\%$ ) and dark brown in color (7.5YR 2.5/1). The low carbon to nitrogen (C:N) atomic ratios (9–15) of the sediments indicate that the organic material is mostly of aquatic origin, with a limited contribution of



**Fig. 5.** Diagram of the major Laguna de Los Anteosjos palynological trends expressed in percentage of the pollen sum ( $\Sigma P$ ). The column at the left is a summary of all pollen taxa subdivided into three categories representing forest (trees) and páramo (shrubs and herbs) communities. The more sensitive pollen types are depicted individually. The shaded boxes highlight the timing of the B–A and Younger Dryas in the Northern Hemisphere.

organic matter from the weakly developed soils in the catchment (Meyers and Ishiwatari, 1993).

The age–depth model is almost linear from 14,600 to 7000 cal yr BP (Fig. 3). Sedimentation rates are nearly constant through the late Glacial stage, and the different sediment facies reflect shifts in source material between sections that are dominantly clastic sediment, to layers that are composed mostly of organic matter and biogenic silica. Clastic sediments were relatively high before  $\sim 14,600$  cal yr BP, and low from  $\sim 14,600$  to 14,100 cal yr BP. A brief, yet pronounced, increase in detrital sediments took place between  $\sim 14,100$  and 13,900 cal yr BP, followed by a second period of overall lower values between  $\sim 13,900$  and 12,850 cal yr BP. Clastic sediments were again high between  $\sim 12,850$  and 12,100 cal yr BP, but a trend toward lower values began at  $\sim 12,650$  cal yr BP, and continued to decrease until  $\sim 11,750$  cal yr BP (Fig. 6). There were also short-lived and relatively small magnitude, increases in clastic sediments between  $\sim 11,750$  and 11,550 cal yr BP, from 11,450 to 11,150 cal yr BP, and again from 10,450 to 10,200 cal yr BP.

#### 4.2. Paleoecological record from Laguna de Los Anteosjos

Modern analog studies and previous work were used here to interpret the Los Anteosjos palynological record (Salgado-Labouriau, 1979; Rull, 2006). In this study, we focused on the major vegetation types and the transitions between them in the Los Anteosjos sediments to identify the timing and magnitude of altitudinal shifts in vegetation zones, and estimate temperature and moisture-balance changes during the late Glacial stage. Fluctuations of these altitudinal boundaries through time, as recorded by palynological analysis, have been used to characterize past climatic conditions in the Mérida Andes (e.g. Rull et al., 2005 and references therein). A more detailed palynological analysis for Los Anteosjos identified more than 70 pollen and spore

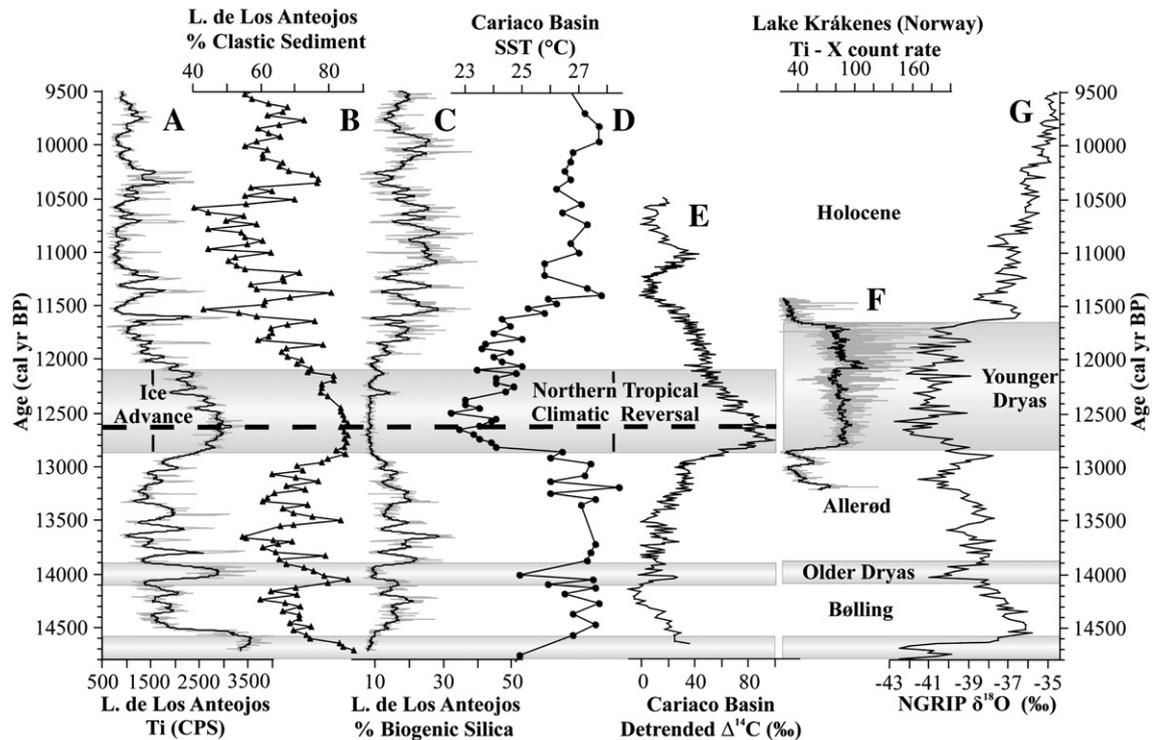
types that are beyond the scope of this paper, and will be published elsewhere (Rull et al., in review).

The regional vegetation between  $\sim 14,600$  and 12,850 cal yr BP was generally similar to today, but the density of Asteraceae tall rosettes and Poaceae were lower, in relation to grasses. *Polylepis* was also present, but the moderately low values in this section of the core suggest that it had a limited presence on the landscape during this interval. *Podocarpus* values were relatively high, progressively increased in this section, and reached peak values at  $\sim 13,200$  cal yr BP. The presence of dominant algae (including *Pediastrum*, *Botryococcus*, *Debarya*, *Mougeotia*, *Spirogyra* and *Zygnema*) decreased, and values of *Isoetes* and *Huperzia* were intermediate between  $\sim 13,900$  and 12,850 cal yr BP.

A major shift in the Los Anteosjos palynological trends occurred after  $\sim 12,850$  cal yr BP (Fig. 5). For example, aquatic remains (algae, *Isoetes*) and *Huperzia* are indicators of moisture-balance changes, and were lower in abundance. A major lowering of tree and shrub-like pollen types in the Los Anteosjos record also occurred after  $\sim 12,850$  cal yr BP, and lasted until  $\sim 12,100$  cal yr BP. The pollen assemblage of this interval is similar to those found in the periglacial desert zone today that is situated above 4400 m elevation (Berg and Suchi, 2001).

#### 4.3. $\Delta ELA$ and paleo-temperature reconstruction

The lowest limit of YD ice below the northwest face of the Humboldt glacier was mapped at  $\sim 4000$  m (Mahaney et al., 2008). Polissar et al. (2006) used aerial photographs and mapped the lowest A.D. 1962 ice limit in the same region at 4600 m. From these values, the modern (defined as A.D. 1962) ELA is estimated between 4650 and 4710 m, using the minimum and maximum THAR values (0.2 and 0.4). Compared to these modern values, this yields ELA values for the



**Fig. 6.** The Laguna de Los Anteojos data plotted versus age (A–C). Titanium (A) and clastic sediment values (B) co-vary, and both are proxies for watershed erosion and ice margin fluctuations. Biogenic silica (C) is an indicator of lake productivity, and values generally decrease when clastic sediment values are high. Clastic sediments decreased abruptly at ~14,600 cal yr BP, during the onset of Bølling warming. The onset of the YD is recorded in the Los Anteojos sediments as a period of increased clastic sediment concentration and decreased biogenic silica production. Increased clastic sediment input to Los Anteojos during the start of the YD occurred at a time of colder conditions in the Cariaco Basin (D, *Lea et al., 2003*), higher atmospheric  $\Delta^{14}\text{C}$  activity (E, *Hughen et al., 2000*), glacial advance in Northern Europe (F, *Bakke et al., 2009*), and lower temperature recorded in the NGRIP oxygen isotope record (G, *Rasmussen et al., 2006*). The dashed horizontal line indicates the onset of a deglacial trend in the northern Andes at ~12,650 cal yr BP that continued through the end of the YD period. The shift toward a trend of ice retreat and higher temperature in the northern tropics began before the abrupt warming of the high northern latitudes at the end of the YD at ~11,650 cal yr BP. The shading on the left side of the figure highlights periods of cooling and glacial advances in the Venezuelan Andes. The shading on right side of the figure represents the timing of late Glacial cooling events in the high northern latitudes. The Lake Kråkenes record was measured using the same scanning XRF methods as the Los Anteojos record and further highlights the difference in timing of YD cooling and warming between the low and high northern latitudes.

YD of 4170 and 4350 m. These correspond to changes in ELA values ( $\Delta\text{ELA}$ ) of  $-360$  and  $-480$  m, respectively, and these  $\Delta\text{ELA}$  values correspond to a temperature lowering of between 2.2 and 2.9 °C using a lapse rate calculation. It should be noted that these are minimum paleo-temperature estimates compared to today, because glaciers in the Venezuelan Andes are presently retreating rapidly (*Schubert, 1998*). Today, the ELA is probably closer to 4980 m (*Stansell et al., 2007b*), which requires an even greater cooling during the YD to explain the lower ice margins compared to modern. It should also be noted that lapse rate calculations underestimate cooling associated with ice margin lowering in this region of the Andes (*Stansell et al., 2007b*), and future research with better defined ELA limits should apply a more comprehensive method for estimating paleo-temperatures (*Seltzer, 1994*).

## 5. Discussion

The lowermost 140 cm of the 455-cm long composite core from Los Anteojos are the focus of this discussion, and capture the Bølling, Older Dryas, Allerød, YD and the transition into the Holocene (Figs. 4 and 6). Here, we used the interpretive model that the extent of ice cover is the dominant first order control on clastic sediment concentration in alpine lakes in glaciated tropical Andean catchments (*Rodbell et al., 2008*). Glaciers in the Venezuelan Andes are mostly temperature sensitive, and increased glacio-lacustrine sediments in proglacial lake sediments in the Mérida region are reliable indicators of colder conditions (*Polissar et al., 2006*). We thus assume that higher clastic sediment values in the Los Anteojos record are principally indicators of increased glaciation and lower temperatures. In contrast,

periods of reduced ice cover and higher temperatures are represented in the sediment record as sections of low clastic sediment values, and increased biogenic silica and organic matter accumulation. We also used palynological evidence from the Los Anteojos sediment core as independent indicators of late Glacial stage and early Holocene shifts in temperature and moisture-balance.

### 5.1. Climatic Variability from 14,600 to 12,850 cal yr BP in the Northern Tropical Americas

The sedimentological data from Los Anteojos show an overall decreasing trend in clastic sediment concentration through the late Glacial stage and into the Holocene, but there are several periods of ice advance that punctuate the overall deglacial trend in the northern Andes. The basal 5 cm of the core are light gray, coarse-grained sand and silt with low organic matter, pollen and biogenic silica concentrations. Collectively, these characteristics likely reflect a glacial lake proximal to a retreating ice margin. The Ti and clastic sediment data from Los Anteojos indicate that ice extent was variable, but greatly reduced or absent in the watershed soon after ~14,600 cal yr BP. The observed timing and pattern of glacial retreat is consistent with the high northern latitude warming trends recorded in the Greenland ice cores that show higher temperatures during the Bølling and Allerød (B–A) from ~14,600 to 12,850 cal yr BP (*Steffensen et al., 2008*). Pollen evidence from Los Anteojos indicates that tree-line in the Mérida Andes was likely similar to today and conditions were warmer during both these intervals based on the moderate to high percentages of *Polylepis* and *Podocarpus*, and high biogenic silica concentrations indicating greater aquatic productivity in the lake.

The B–A warming trend in the Venezuelan Andes was interrupted between ~14,100 and 13,900 cal yr BP, and higher Ti and clastic sediment values combined with lower biogenic silica concentrations indicate that temperature was colder during this ~200 year interval. This short-lived ice advance between the Bølling and Allerød corresponds to the timing of the Older Dryas cooling event in the Northern Hemisphere (Mangerud et al., 1974). The high spore percentages and algal remains in the Los Anteojos sediment core suggest that conditions were relatively wet during the Bølling. After the Older Dryas, conditions were relatively dry near Los Anteojos during the Allerød, as indicated by a marked shift to lower values for *Isoëtes* and algal remains (Fig. 5).

### 5.2. Northern tropical climatic reversal during the Younger Dryas

The Los Anteojos record has maximum and minimum-limiting AMS  $^{14}\text{C}$  ages that bracket the transition into, and out of, the mineral-rich sediments that represent the YD interval. Within dating uncertainties, the Los Anteojos clastic and biological records indicate that a northern tropical climatic reversal started at about the same time as the YD in the North Atlantic region, as defined by ice core and lake sediment records from the high northern latitudes (Fig. 6). Clastic sediment concentration in Los Anteojos increased at ~12,850 cal yr BP, and peak values were reached at ~12,650 cal yr BP, when temperature was ~2.2 to 2.9 °C lower. After ~12,650 cal yr BP, there was a decreasing trend in clastic sediment and Ti values until ~11,750 cal yr BP, suggesting a shift to higher temperature. Notably, this warming trend began several hundred years before the termination of the high latitude YD event, with clastic and biological proxies in the Los Anteojos sediment core returning to previous values by ~12,100 cal yr BP, 450 years earlier than in the high northern latitudes.

The pollen evidence from Los Anteojos suggests that vegetation zones were ~480 m lower than today during the peak cooling of the YD. The decline in Andean forest trees, represented here by *Podocarpus*, and the increase of major páramo elements (Asteraceae, Poaceae), are further evidence of downward shift in vegetation zones. The absence of *Polylepis* indicates that páramo forests dominated by this tree were not present around the lake during the YD. These *Polylepis* forests presently grow in a wide range of precipitation regimes (Monasterio, 1980), and their disappearance at this stage was unlikely caused by changes in moisture-balance. A temperature-driven downward shift in vegetation zones is a more likely explanation for the observed difference between the late Glacial and modern tree-line. The present upper altitudinal boundary of *Polylepis* in the Venezuelan Andes is around 4300 m (Monasterio, 1980), and the inferred downward displacement was at least 380 m from ~12,850 to 12,100 cal yr BP, when *Polylepis* is completely absent in the Los Anteojos pollen record. The combined evidence indicates that vegetation shifted to elevations that were ~380 to 480 m lower after ~12,850 cal yr BP, and remained lower until ~12,100 cal yr BP. Using the present-day average lapse rate of  $-0.6\text{ °C}/100\text{ m}$  elevation, this shift corresponds to a 2.3 to 2.9 °C decrease in temperature.

The Los Anteojos palynology results combined with previously published work suggest that there was a shift to more arid conditions in the northern Andes at the start of the YD. For example, the decline of *Huperzia*, a fern typical of humid páramos, suggests there was a decrease in moisture availability at the start of the YD (Rull et al., 2005). The decline of *Isoëtes*, a common inhabitant of shallow water páramo lakes, is supporting evidence of more arid conditions. Furthermore, the scarcity or absence of algal remains, suggests that the lake level may have been lower during the YD (Fig. 5). Similarly, Lake Valencia (10°16'N, 67°45'W, 402 m) in northern Venezuela had lower water levels from ~15,350 to 12,500 cal yr BP (Bradbury et al., 1981; Curtis et al., 1999). Further north in Central America, the record from Lake Peten Itza (16°55'N, 89°50'W, 110 m) also indicates drier

conditions (Hodell et al., 2008), and suggests a general pattern of increased aridity over the northern tropics at the start of the YD.

Paleoclimate records from Venezuela and Colombia provide further supporting evidence of a northern tropical cooling event equivalent to the YD. Glacial-geomorphic features dating approximately to YD age (Mahaney et al., 2008) have been identified in the same mountain range as Los Anteojos, near Pico Humboldt (Fig. 2). Likewise, previously published paleoecological evidence from the Venezuelan Andes suggests that a cold reversal took place after 13,800 cal yr BP (Salgado-Labouriau, 1989), and evidence from Colombia suggests that a YD cooling of 1.0 to 3.0 °C occurred in the northern Andes (Van't Veer et al., 2000). Thus, although the ages of deposits from earlier studies in the region do not bracket the YD advances as well as the Los Anteojos record, multiple lines of evidence indicate that an atmospheric cooling event over northern South America started at about 12,850 cal yr BP.

The timing and direction of change identified in the foraminifera-based SST record of the Cariaco Basin (Lea et al., 2003) agree well with the Los Anteojos temperature records during the YD. Specifically, the temperature of Cariaco Basin surface water was  $3.2\text{ °C} \pm 0.5\text{ °C}$  lower at the start of the YD, when it was 2.2 to 2.9 °C colder in the northern Andes. Temperature then increased in the Cariaco Basin by  $0.9\text{ °C} \pm 0.4\text{ °C}$  after 12,300 cal yr BP, and a warming trend progressed through the remaining YD period. This increase in temperature at low elevation in northern South America corresponds closely to the timing of glacial retreat in the Los Anteojos record during the late stages of the YD (Fig. 6).

The records of cooling of the Venezuelan Andes and the Cariaco Basin at the start of the YD are different than the pattern of marine temperature changes that have been presented for other northern tropical regions. For example, temperature increased throughout the YD in the nearby tropical Atlantic Ocean (12°05'N, 61°15'W; 1299 m water depth) (Rühlemann et al., 1999), and at the start of the YD in the Gulf of Mexico (26°57'N, 91°20'W; 2280 m water depth) (Flower et al., 2004). This discrepancy in temperature trends between the Cariaco Basin and Los Anteojos verses elsewhere in the tropical Atlantic and southern Caribbean could in-part be because sea-level was ~60 m lower during the YD, which would have restricted mixing between the Cariaco Basin and the open Caribbean (Wan et al., 2009). Despite this warming trend elsewhere in the northern tropical oceans, the high wind speed over the Cariaco Basin during the YD probably contributed to cooler local surface waters during the early stages of the event, which is consistent with the degree of atmospheric cooling that occurred in the northern Andes.

Glaciers retreated and warming began in the northern tropics consistent with the records of aridity and circulation changes from the Cariaco Basin during the YD. For example, Haug et al. (2001) used measurements of Ti concentrations, interpreted to be a record of terrigenous sediment into the Cariaco Basin from fluvial input, to show that conditions became progressively drier from 12,850 to about 12,000 cal yr BP. Titanium values then began to increase after ~12,000 cal yr BP, and continued a trend of higher values through the onset of the Holocene. A similar pattern is true from the grayscale record from the Cariaco Basin (Hughen et al., 1998; Hughen et al., 2004b), which shows an abrupt shift to darker values, indicative of higher upwelling and stronger trade winds at ~12,850 cal yr BP. The grayscale record then shows a shift to lighter colors after ~12,300 cal yr BP, and another abrupt increase at the end of the YD. Thus, temperature began rising several hundred years before the end of the YD, and this occurred at the same time that the strength of the trade winds weakened, and it became wetter in northern South America.

### 5.3. The Bølling–Allerød and Younger Dryas in southern tropical South America

Characterizing the pattern and timing of atmospheric temperature and aridity changes in the Northern and Southern Hemispheres is

useful for identifying the dynamical link between the low and high latitudes during abrupt climate change events. The stable isotope records from ice cores suggest that the southern tropical Andes experienced relatively warm conditions during the B–A, and lower temperature during the YD (Thompson et al., 1998), which is consistent with the records from the northern tropical Andes. In contrast to the stable isotope records from the tropical ice cores, glaciers in the western regions of the central Andes are mostly sensitive to precipitation changes (Kaser, 2001; Rodbell et al., 2009), and we interpret the published records of changes in ice margin extent in Peru as indicators of past shifts in moisture-balance. Early workers identified a glacial advance on the west side of the Quelccaya Ice Cap of southeastern Peru (14°S) that culminated about 500 years before the YD (Mercer and Palacios, 1977). Similarly, evidence presented from the central Andes of Peru (~9–15°S) imply a glacial advance culminated between 13,170 and 12,920 cal yr BP, and that mountain glaciers retreated during most of the YD (Rodbell and Seltzer, 2000; Seltzer et al., 2002). This is consistent with the ice core records from Sajama that indicate accumulation was lower during the YD cold reversal than it is today (Thompson et al., 1998). Finally, after an extensive review of the literature, Rodbell et al. (2009) concluded that in the central Andes of Peru, well dated moraines record a significant late Glacial re-advance at the onset of the YD, but ice retreated during much of the remaining cold interval, probably due to a shift to drier conditions.

Lake records of late Glacial climatic change from southern tropical South America present a conflicting pattern of moisture-balance changes during the late Glacial stage. For example, Baker et al. (2001) cite evidence from Lake Titicaca (~15°S) of wet conditions on the Peruvian–Bolivian Altiplano during the YD. Likewise, U–Th dating of stranded lacustrine deposits on the southern Altiplano (~19–21°S), were used to date the Coipasa highstand (wet conditions) to sometime between 13,000 and 11,000 cal yr BP, which tentatively correlates to the YD (Placzek et al., 2006). On the other hand, Rowe et al. (2002) used a better-dated composite record from Lake Titicaca to show that lake level lowered during the YD. Likewise, closer to the equator, Seltzer et al. (2000) presented a  $\delta^{18}\text{O}$  record measured on bulk carbonate sediment from Lake Junin (~11°S), and compared it to the ice core record from Huascarán to indicate that effective moisture dropped after ~13,300 cal yr BP, and remained low until ~10,500 cal yr BP.

Another perspective of moisture-balance change on the South American continent during the YD interval is provided by speleothem and travertine records. Data presented by Wang et al. (2004) from the lowlands of northeastern Brazil (~10°S) suggest that the latter part of the YD period from ~12,100 to 11,700 cal yr BP was wet enough to produce travertine, but not sufficiently wet to promote speleothem growth. van Breukelen et al. (2008) noted more positive  $\delta^{18}\text{O}$  values from a speleothem located at ~1000 m elevation in the foothills of the Peruvian Andes (~5°S), indicating that local YD conditions were drier than the preceding B–A interval. Combined, the travertine, speleothem, lake sediment and mountain glacial records produce a mixed signal of climatic variability for southern South America during the late Glacial stage, but the balance of evidence suggests that most regions in the southern tropical Andes were wet at the start of the YD, followed by increased aridity during the remainder of the cold event. Although the directions are the opposite, this pattern is consistent with the timing of moisture-balance changes in northern South America during the YD.

#### 5.4. Comparison between the low and high latitude patterns of Younger Dryas climatic variability

Both Greenland ice cores and proglacial lake sediment records from northern Europe document abrupt atmospheric temperature shifts at the beginning and end of the YD (Rasmussen et al., 2006;

Bakke et al., 2009). The timing of abrupt shifts in the Cariaco Basin grayscale records at ~12,850 and 11,600 cal yr BP are synchronous with changes in the North Atlantic region (Hughen et al., 2000; Peterson et al., 2000), and suggests that large-scale changes in tropical atmospheric circulation occurred in response to high latitude influences (Chiang et al., 2003). A latitudinal shift in the position of the Intertropical Convergence Zone (ITCZ) during the YD (Haug et al., 2001) and the resulting decrease in northern tropical humidity could have contributed to both higher surface wind speeds and cooler surface waters in the Cariaco Basin (Seager et al., 2000). These colder atmospheric conditions would have also cooled the alpine environments and led to the northern tropical ice advance recorded in the Los Anteosojos sediments at the start of the YD. The record of atmospheric cooling over northern South America is consistent with records of lower temperatures over the southern tropical Andes during the YD (e.g. Thompson et al., 1998). It is also noteworthy that temperature shifts at the end of the late Glacial stage across the tropical Andes were generally synchronous with warming and cooling in the Northern Hemisphere, and out of phase with paleoclimate records from the high southern latitudes during and after the Antarctic Cold Reversal (Blunier et al., 1997).

Most of the available records from South America suggest that the northern tropical Andes were more arid while the southern tropical Andes were wetter at the start of the YD. A southward shift in the ITCZ at the start of the YD could explain the colder conditions in the northern tropics while precipitation-sensitive glaciers advanced in the southern tropical mountains. A northerly shift in the ITCZ after ~12,650 cal yr BP would then explain the increased moisture-balance and warming trend in the northern Andes while the southern tropical mountains became more arid throughout the remainder of the YD. High latitude mechanisms probably initiated temperature and humidity changes in the tropical Americas at the start of the YD. However, temperature over land and the hydrology of tropical South America is also strongly influenced by low latitude sea surface temperature, and climatic variability during the YD would have likely also been moderated by the tropical oceans and low latitude atmospheric dynamics (e.g. Clement et al., 2001).

Changes in ocean circulation and the impacts on South American climate dynamics during the YD can be inferred from records of atmospheric  $^{14}\text{C}$  activity (Hughen et al., 2000). At the onset of the YD, atmospheric  $^{14}\text{C}$  activity increased abruptly, peaked between ~12,850 and 12,500 cal yr BP, and subsequently decreased during the remainder of the YD, which is consistent with the onset of alpine warming recorded at Los Anteosojos. The initial increase in atmospheric radiocarbon activity is evidence of changing Atlantic Ocean circulation that may have either been followed by increased formation of North Atlantic Intermediate Water (Hughen et al., 1998), or deep-sea ventilation and warming in the Southern Ocean (Broecker, 1998). In either case, the period of rapid cooling, followed by warming in the northern tropical atmosphere, is consistent with the timing of circulation changes during the YD that has been observed in the marine and atmospheric records from northern South America (Fig. 6). The early warming of the tropical atmosphere, combined with changes in the hydrologic cycle, may have eventually contributed to the abrupt warming of the northern high latitudes at the end of the YD.

#### 5.5. Early Holocene deglaciation in the northern tropical highlands

The transition into the Holocene was marked by an overall trend of warmer and wetter conditions in the Venezuelan Andes after the termination of the YD. The pollen in the Los Anteosojos record (Fig. 5), and in other lake sediment archives from the Venezuelan Andes (Rull et al., 2005), indicate that trees became more dominant in the early Holocene. Likewise, *Huperzia*, *Isoetes* and *Asteraceae* increased near Los Anteosojos after the YD, while grasses decreased. This gradual

warming, however, was interrupted by at least three short-lived and small-magnitude ice advances after ~11,750 cal yr BP (Fig. 4). The end of this series of brief cooling events at ~10,200 cal yr BP in the Mérida Andes, near Los Anteos, corresponded closely to the timing of widespread glacial retreat that took place elsewhere in the Venezuelan Andes at the start of the Holocene (Stansell et al., 2005). These events were also similar to the pattern and timing of ice advances and retreats that are recorded in other regions of the northern tropics (Stansell et al., 2007a), including the highlands of Mexico (Vazquez-Selem and Heine, 2004) and Costa Rica (Orvis and Horn, 2000). Glaciers in the southern tropical Andes remained in a diminished state from ~12,800 to 10,000 cal yr BP (Seltzer et al., 2002), which suggests that the pattern of deglaciation may not have been synchronous in the northern and southern tropics at the end of the late Glacial stage.

## 6. Conclusions

Sediments from Laguna de Los Anteos in the Venezuelan Andes record a series of abrupt climatic changes in the northern tropical atmosphere during the late Glacial stage and early Holocene. After initial warming during the Bølling and Allerød, a YD cold reversal in the northern Andes started at ~12,850 cal yr BP, and peaked by 12,650 cal yr BP, when temperature was 2.2 to 2.9 °C lower than modern. The clastic sediment record from Los Anteos shows a trend of decreasing values and a retreating ice margin between ~12,650 and the end of the YD. The timing of temperature change in the Mérida Andes is similar to what has been observed for the Cariaco Basin SST estimates, which shows cooling occurred at ~12,850 cal yr BP, and moderate warming began in the northern tropics before the end of the YD in the high northern latitudes. Palynological studies from the Venezuelan Andes, combined with paleoclimate records from the Cariaco Basin and the southern tropical Andes, suggest that the ITCZ was in a more southerly position at the start of the YD. The available paleoclimate records suggest that moisture belts then shifted to a more northerly position over the tropical South American continent when it became warmer and wetter in northern tropics during the later stages of the YD. The early warming of the low latitude atmosphere, changes in ocean circulation, and an enhanced tropical hydrologic cycle probably contributed to the abrupt warming of the Northern Hemisphere at the end of the late Glacial stage.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2010.02.040.

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