RAPID CLIMATE CHANGE IN THE TROPICAL AMERICAS DURING THE LATE-GLACIAL INTERVAL AND THE HOLOCENE

by

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Till deposits, related to advances of mountain glaciers, and lake sediments record periods of abrupt warming and cooling during the Late Glacial interval (LG) (17,500 to 11,650 cal yr BP) in the northern tropical Andes. The synchronicity of temperature shifts in the tropical mountains and high northern latitudes during this period indicates that the low latitude atmosphere played a major role in LG abrupt climate change. Generally, the northern tropics are cold and dry when temperatures are lower in the North Atlantic region, and the opposite occurs during warm periods. The pattern of abrupt seesaw-like hemispheric temperature shifts, and the apparent link to tropical atmospheric dynamics, demonstrates the importance of low latitude circulation and water vapor feedbacks in rapid climate change.

Geologic evidence from the precipitation-sensitive southern tropical Andes were used to reconstruct periods of ice advances and retreats during the Late Holocene. Neoglaciation in the Cordillera Raura of Peru began at ~3100 cal yr BP, marking a transition to a prolonged period of increased moisture transport to the Andes. The most extensive neoglacial advance took place locally during the Little Ice Age when conditions were both wetter and colder. The long-term, Holocene pattern of renewed ice cover in this region of the Andes was probably enhanced by astronomical forcing and convection-driven changes in moisture availability. Short-term glacial variability during the neoglacial was likely driven mostly by a combination of solar, atmospheric and oceanic processes.

Lake sediments from the Pacific region of Nicaragua were used to record changes in the regional moisture balance during the late Holocene (~1600 cal yr BP to the present). Oxygen isotope values of calcium carbonate down-core identify periods of lake level fluctuations that resulted from changes in precipitation and evaporation rates. The driest regional conditions recorded in the isotope data are coincident with the onset of Little Ice Age cooling. This abrupt transition to more arid atmospheric conditions at 700 cal yr BP is consistent with other records from the northern tropics and subtropics that suggest hydrologic changes in the tropics were connected to high latitude climate variability during the late Holocene.

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1. INTRODUCTION

In the near future, rising ocean and atmosphere temperatures will result in changes in the hydrologic cycle and water resources on a global scale. The Intergovernmental Panel on Climate Change predicts that these hazards will especially impact developing regions, with increasing water resource stresses in the tropics and subtropics as the balance between precipitation and evaporation shifts to drier conditions and longer periods of drought. In order to isolate and better understand the natural versus man-made variability within the climate system, a major focus of my research has been the development of records of temperature changes and drought history from Central and South America on time-scales that are relevant to studying the relationship between humans and environmental change.

From a practical perspective, glaciers are primary sources of fresh water to developing regions throughout the tropical Americas, making these locations particularly vulnerable to glacial oscillations and future hydrologic variability. From a paleoclimate perspective, the tropics receive most of the planet's incoming solar radiation and are the center of the global hydrological cycle, and they in turn affect global climate through circulation, energy balance and water vapor feedbacks. Documenting tropical glacier mass-balance changes is therefore important, as characterization of low latitude atmospheric temperature and humidity changes are fundamental from both a resource perspective, and for further understanding and modeling global climate dynamics.

The role of tropical atmospheric dynamics in abrupt climate change during the Late Glacial interval and the Holocene are the primary research topics of this dissertation. The climate history of the northern and southern Tropical Andes during these intervals can be reconstructed with glacier mass-balance studies and lake sediment archives of environmental change. Through these methods, I am most interested in testing the hypothesis that abrupt climate change events in the tropics are synchronous with high latitude variability, and the low latitude ocean-atmosphere system is a major driver in global humidity and temperature changes. As a framework for this discussion, I have compiled proxy records for comparison from polar, tropical, marine and alpine locations.

This dissertation comprises four chapters that are each written with the intent to publish them as separate journal articles. The first 2 manuscripts are a discussion of abrupt Late Glacial interval cooling and warming events in the Northern Hemisphere. We know from the northern tropical marine records that the low and high latitude climate systems were more-or-less in phase during the Late Glacial interval, but the tropical atmospheric records are much less understood. The first half of this dissertation therefore expands our knowledge of the causes of abrupt climate change by providing records of high altitude temperature and humidity shifts that are synchronous with the variability recorded in the Greenland ice core records of arctic climate change. This work emphasizes that the northern tropical atmosphere must have played a major role in driving and modulating the pattern of temperature change at the end of the Pleistocene.

The third manuscript presented in this dissertation (Chapter 4) contributes to our overall understanding of Late Holocene climate change by presenting a ~5000 year record of atmospheric conditions in the southern tropical Andes. Here I emphasize that the climate variability during the Holocene was driven less by the role of decaying ice sheets and more by combination of solar and orbital mechanisms. The work presented here also emphasizes that the neoglacial must have also been driven, in part, by ocean and atmospheric mechanisms that triggered powerful feedbacks that are ultimately capable of producing bigger climate shifts than insolation and solar forcing alone.

Climate change impacts society the most through changes in the hydrologic cycle and water resources availability. In order to better understand the potential societal impacts of environmental changes in developing regions, the final manuscript (Chapter 5) presents a record of moisture-balance variability from the Pacific region of Nicaragua. Lake sediment cores are the principal sources of data for this manuscript because they contain biological and authigenic carbonate fractions that can be measured for stable isotopes ($\delta^{13}C$ and $\delta^{18}O$). The records presented here reveal an abrupt shift to more arid conditions during the Northern Hemisphere Little Ice Age, and further highlight the connection between low and high latitude climate variability and the sensitivity of the global climate system to changes in tropical hydrology.

2. ABRUPT YOUNGER DRYAS COOLING AND EARLY WARMING IN THE NORTHERN TROPICAL ANDES

2.1. INTRODUCTION

The YD cold reversal between ~12,850 and 11,650 cal yr BP (calibrated years before A.D. 1950) in the Northern Hemisphere (Rasmussen et al., 2006) shows that the climate system is capable of rapid changes. The abruptness of transitions during past climate shifts, and the sensitivity of the global climate system to changes in ocean and atmospheric circulation (Broecker, 2006) make the them provocative analogues for potential climatic surprises that may take place in response to production of anthropogenic greenhouse gases. Data from the Venezuelan Andes show that the high altitudes of the Northern Hemisphere tropics became abruptly colder and drier coevally with the onset of the YD in the Arctic. However, the return to warmer and wetter conditions in the Andes occurred gradually, beginning approximately 400 years earlier than in the high northern latitudes. Low latitude atmospheric changes during this time would have had a profound effect on circulation and tropical ocean surface salinities, that in turn could have affected North Atlantic conditions (Schmidt et al., 2004) and eventually triggered a return to warmer conditions in the high northern latitudes (Steffensen et al., 2008).

Climate models that address the origins of the YD commonly favor either tropical (Clement and Peterson, 2008) or North Atlantic (Broecker, 2006) ocean-atmosphere systems as the dominant driving mechanism. The perspective from the tropics highlights the importance of the low latitude hydrologic cycle in modulating global temperatures (Seager et al., 2000). However, the pattern of low latitude YD climate change and the connection to high latitude variability is unclear because tropical paleoclimate records have been interpreted in conflicting ways and contain uncertainties with respect to timing of the climatic intervals. For example, evidence from Peruvian ice cores suggest that southern South America experienced a cold and wet reversal during the YD (Thompson et al., 1998). In contrast, mountain glaciers in precipitation-sensitive regions of Peru retreated as a result of reduced snowfall (Rodbell and Seltzer, 2000), which is corroborated by lake records of moisture-balance in the region (Seltzer et al., 2000). Evidence of a YD-equivalent glacial advance in the equatorial Andes (Clapperton et al., 1997) is also debatable (Rodbell and Seltzer, 2000).

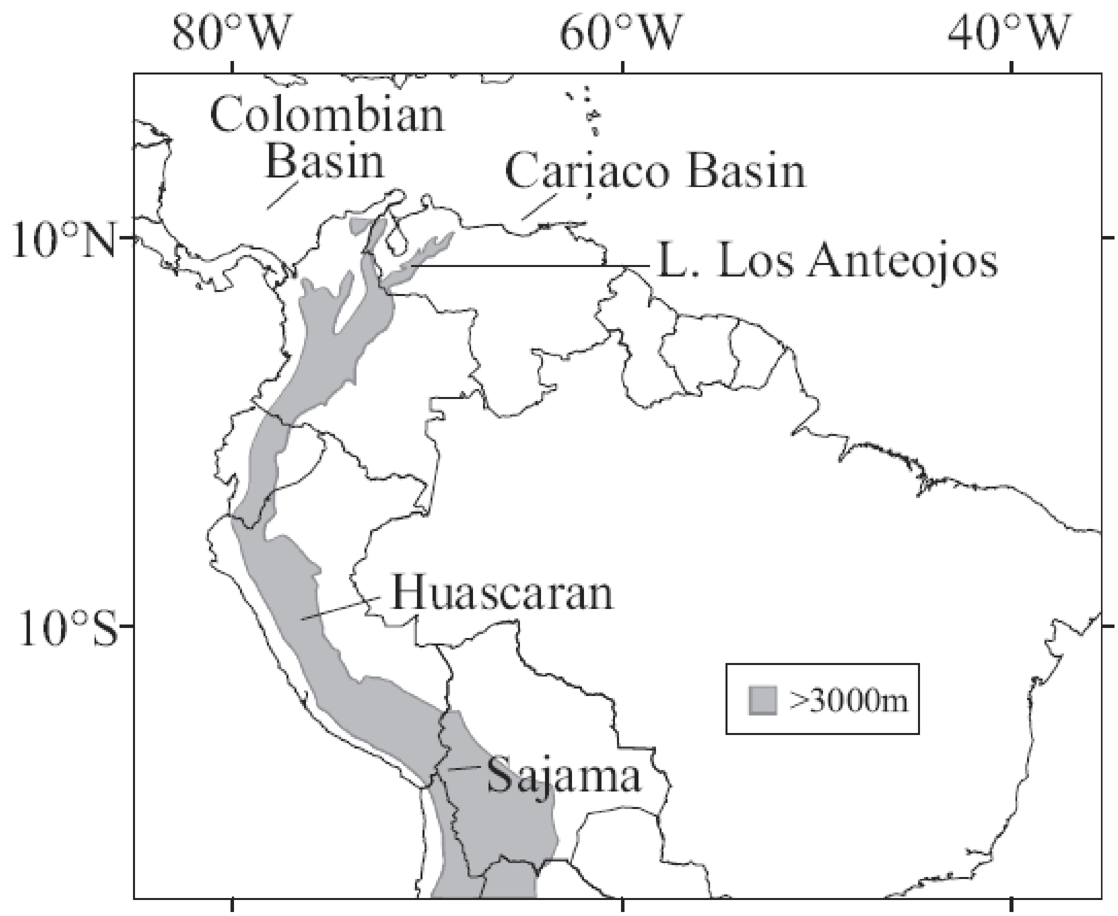

Figure 2.1. Location map of sites mentioned in text.

2.1.1. The Younger Dryas in the Venezuelan Andes

Lake Los Anteojos (hereafter LA) in the Mérida Andes of Venezuela (3920 m a.s.l.) is well situated to record the northern tropical geologic effects of YD climate change (Fig. 2.1). The region was extensively glaciated during the late Pleistocene (Fig. 2.2) (Mahaney et al., 2008), and the lake is directly down-valley from a glacial headwall (max elevation 4400 m). The climate is intermediate between the inner and outer tropics, with the majority of precipitation (1550 mm/yr) accumulating during boreal summer. Humidity is also high year-round (Azocar and Monasterio, 1980) and glaciers in this part of the Andes are therefore sensitive mostly to temperature changes (Kaser and Osmaston, 2002).

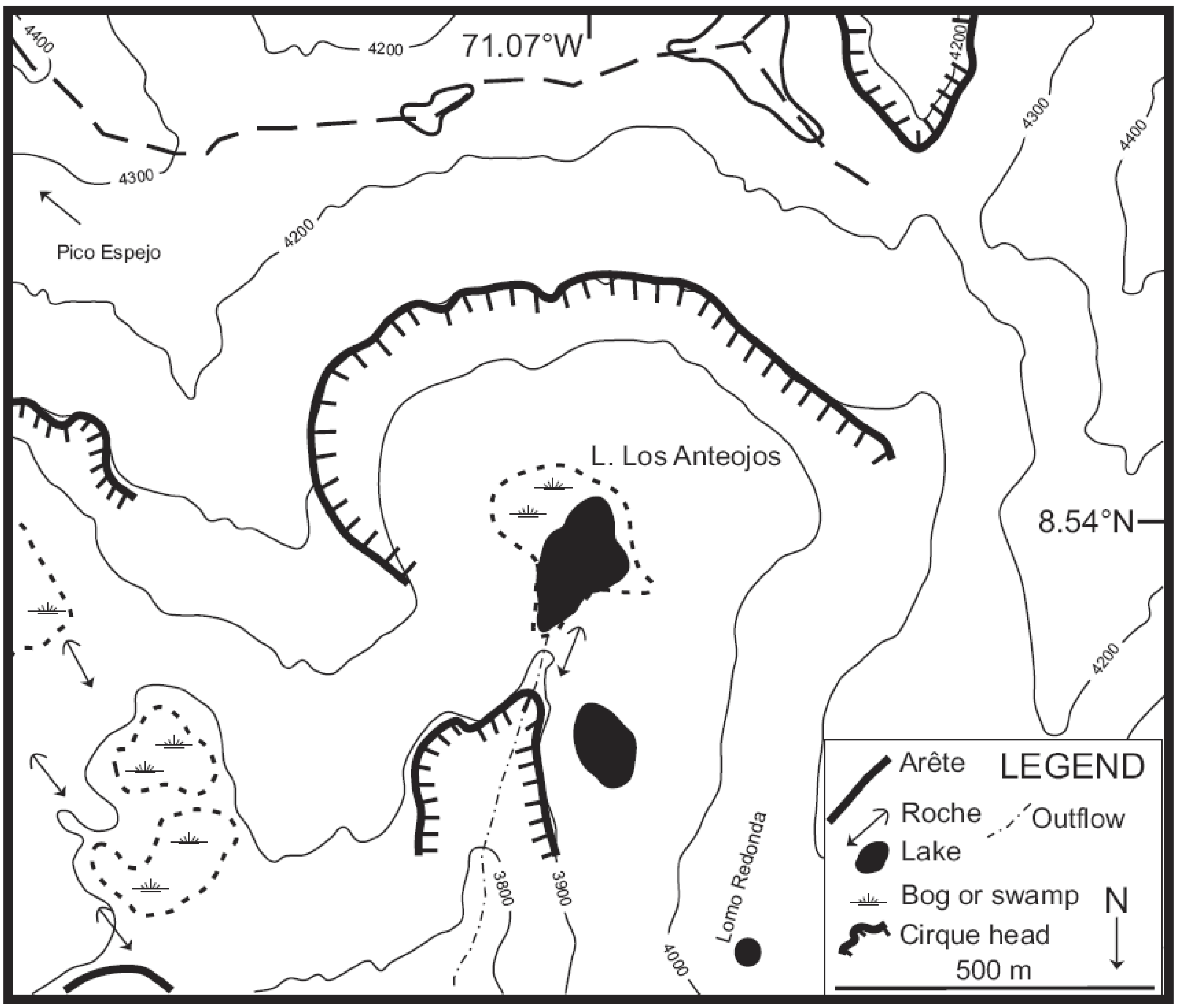

Figure 2.2. Location and glacial-geologic map of the Laguna Los Anteojos watershed. Modified after (Schubert, 1972).

2.2 METHODS

2.2.1. Sedimentology and geochemistry

A 425 cm-long piston core was taken from the depocenter of LA and recovered in a single polycarbonate tube. The lower 144 cm of sediment core representing the Bølling/Allerød (BA), YD and Holocene transition are discussed here (Fig. 2.3). Bulk density (BD) was measured every 1 cm after drying at 60°C. Total organic matter (Fig. 2.3) was then measured every 1 cm by loss-on-ignition (LOI) at 550°C (Dean Jr., 1974). There is no calcium carbonate in the sediments, based on LOI measurements made after burning at 1000°C. Bulk sediment geochemistry was measured every 1mm using an ITRAX scanning Xray fluorescence (XRF) instrument (Brown et al., 2007), and the values are presented in counts per second (CPS). Total carbon (C) and nitrogen (N) were measured every 2-5 cm at the University of Arizona stable isotope lab and are presented as atomic ratios.

There are two clear end-member sediment facies in the LA record. One end member facies is high in terrigenous (clastic) sediment with high Titanium (Ti) concentrations and dry bulk densities (>0.5 g/cm^3), low organic-matter content (<4%), and light gray (GLEY 8/1) coloration. In contrast, sections of the core without much clastic sediment content have low Ti concentrations and dry bulk densities (<0.5g/cm^3), high organic-matter content (>15%), and are dark brown (7.5YR 2.5/1). Low carbon-to-nitrogen (C:N) atomic ratios (11-13) of YD sediments indicate that the organic material is mostly of aquatic origin (Meyers and Ishiwatari, 1993) with limited input from soil eroded from the nearby headwall.

2.2.2. Clastic sediment flux

Percent of clastic detritus was determined by subtracting the measured organic matter and biogenic silica fractions from the residual (post 550°C LOI) values. Clastic flux was then calculated using the equation:

$$Flux_{clastic} = PC \times BD \times SR$$

in which PC is the percent clastics, BD is bulk density (gm cm^{-3}) and SR is sedimentation rate (cm yr^{-1}).

2.2.3. Biogenic silica flux

Biogenic silica concentration was determined by a combination of two methods. 1) Weight percentage biogenic silica was measured by time-dissolution procedures (DeMaster, 1979; Conley, 1998) at 2-5 cm intervals. 2) The XRF measurements for Si were normalized to Ti, which are a reliable measure of biogenic silica (Brown et al., 2007). The Si/Ti values were then calibrated and converted to weight percent biogenic silica using linear regression (r^2=0.44, p=.001) between the XRF and weight percent values. Biogenic silica flux was calculated using the equation:

$$Flux_{biogenic\ silica} = PB \times BD \times SR$$

where PB is the percent biogenic silica, BD is bulk density (gm cm^{-3}) and SR is sedimentation rate (cm yr^{-1}).

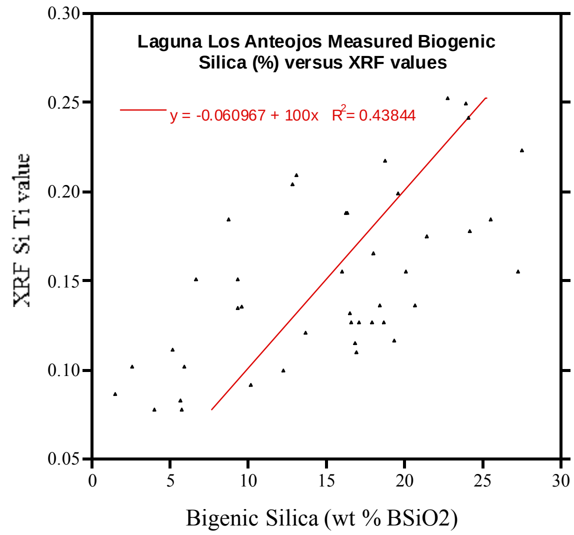

Figure 2.3. Scatter plot of percent (%) biogenic silica and measured XRF (Si/Ti) values.

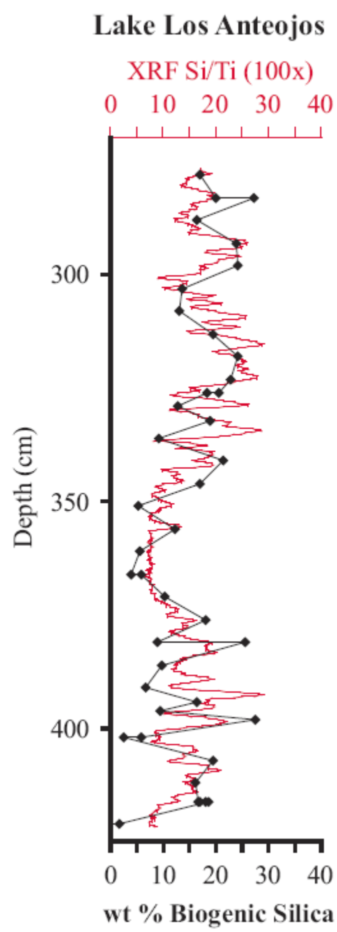

Figure 2.4. Lake Los Anteojos measured biogenic silica (black circles) and Si/Ti measurements by XRF (red).

2.2.4. Pollen

Volumetric samples (2 cm^3) were taken from the core every 2 to 5 cm for pollen analyses. A modern surface sample was taken, for comparison, in the same coring location. An additional modern sample from Laguna Negra (Mucubají), 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 (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 *Isoëtes*), and counting continued until a saturation of diversity was reached (Rull et al., 1987).

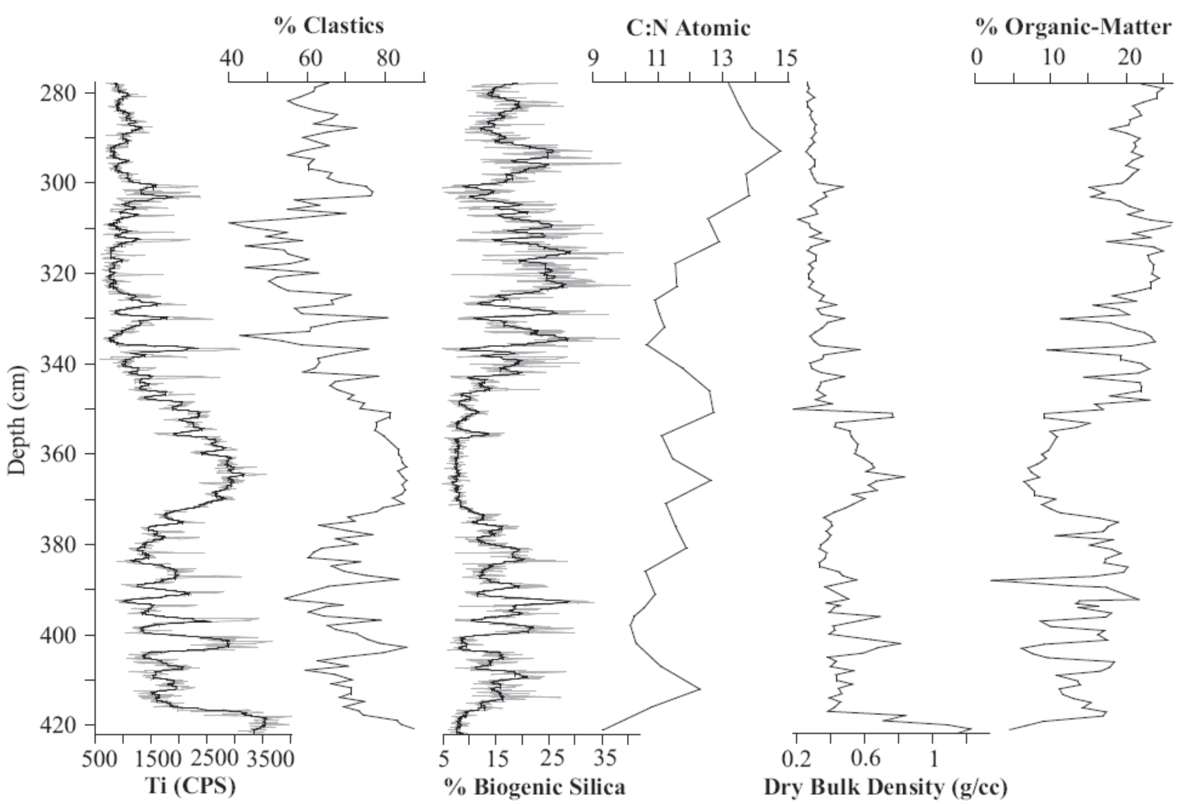

Figure 2.5. LA core data plotted versus depth.

2.2.5. Age model

Radiocarbon ages on 6 aquatic macrofossils (Table 2.1) were calibrated and converted to calibrated years before present (cal yr BP) using OxCal 4.0 (Bronk Ramsey, 2008) and the IntCal04 dataset (Reimer et al., 2004). There is no limestone in the watershed to produce a hard-water effect. An age-depth model (Fig. 2.4) was constructed using a 3rd order polynomial fit between median calibrated ages.

Table 2.1. Radiocarbon ages used in study. Calibrated ages represent the median and 2-sigma error range.

Lab #	Depth (cm)	^{14}C Age	±	Calibrated Age (Cal yr BP):
UCI-37537	231.6	6420	20	7291-(7365)-7421
UCI-37511	295.7	8850	20	9780-(10012)-10153
UCI-37538	341.6	10180	25	11760-(11889)-12025
UCI-37539	376.1	11060	30	12905-(12975)-13068
UCI-37540	395.1	11880	35	13656-(13749)-13833
UCI-37623	416.1	12430	80	14136-(14480)-14905

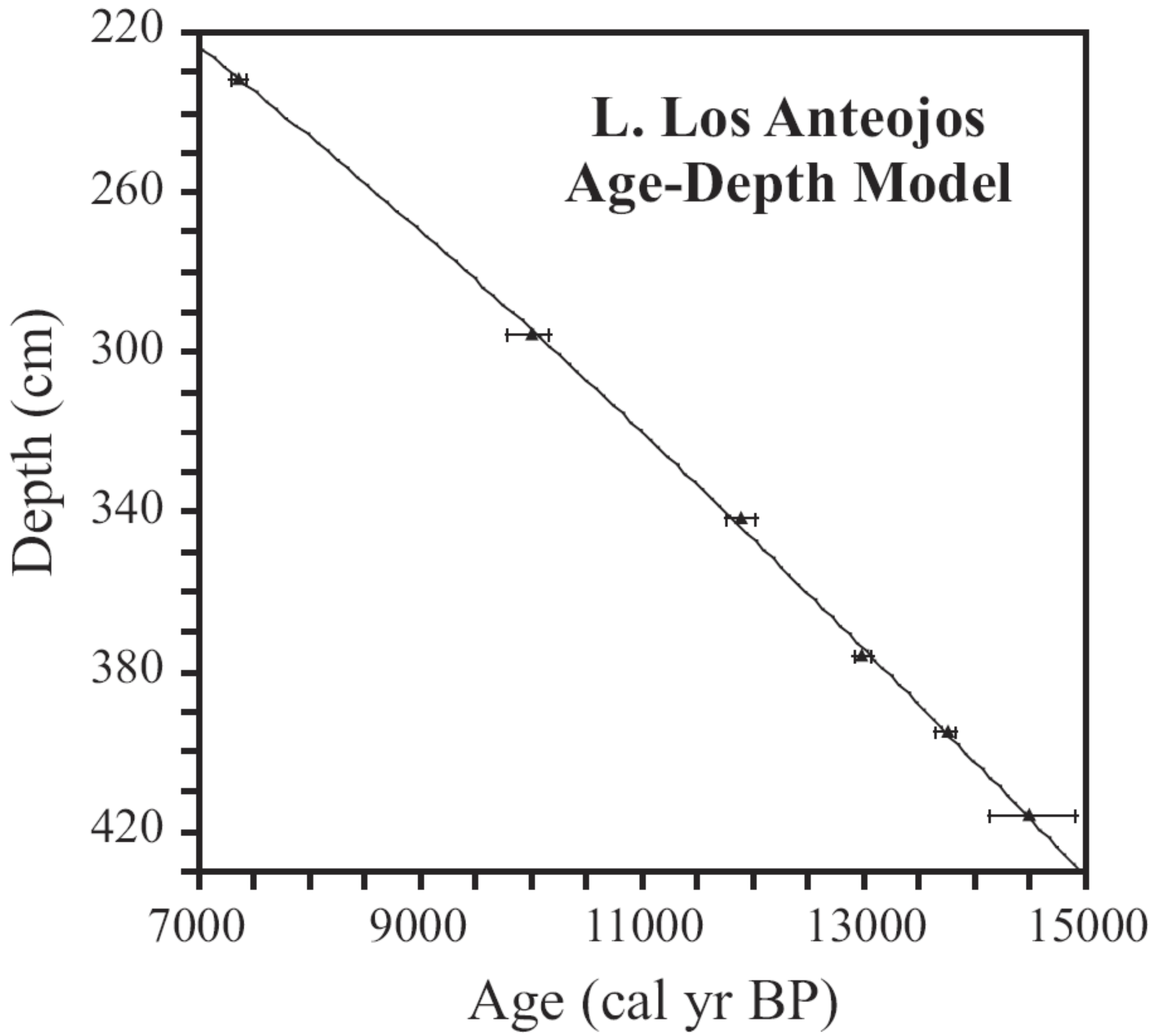

Figure 2.6. The LA age-depth model based on a 3rd order polynomial fit (r^2= 0.99) between 6 radiocarbon dated aquatic macrofossils (Table 2.1).

2.2.6. Paleo-temperature calculation

Modern and paleo-equilibrium line altitudes (ELAs) were determined using the terminus-headwall altitude ratio method (Porter, 2001) and a range of values from 0.2 to 0.4 (Porter, 2001). The modern and YD headwall values are assumed to be 4870 m. The modern lowest ice limit is ~4600 m (Polissar et al., 2006b), and the ELA is between 4650 and 4710 m. The lowest limit of YD ice in the nearby Pico Humboldt region was mapped at ~4000 m (Fig. 2.5)

(Mahaney et al., 2008). This yields YD ELA values of 4170 and 4350 m which correspond to changes in ELA (ΔELA) of -480 and -360 m, respectively.

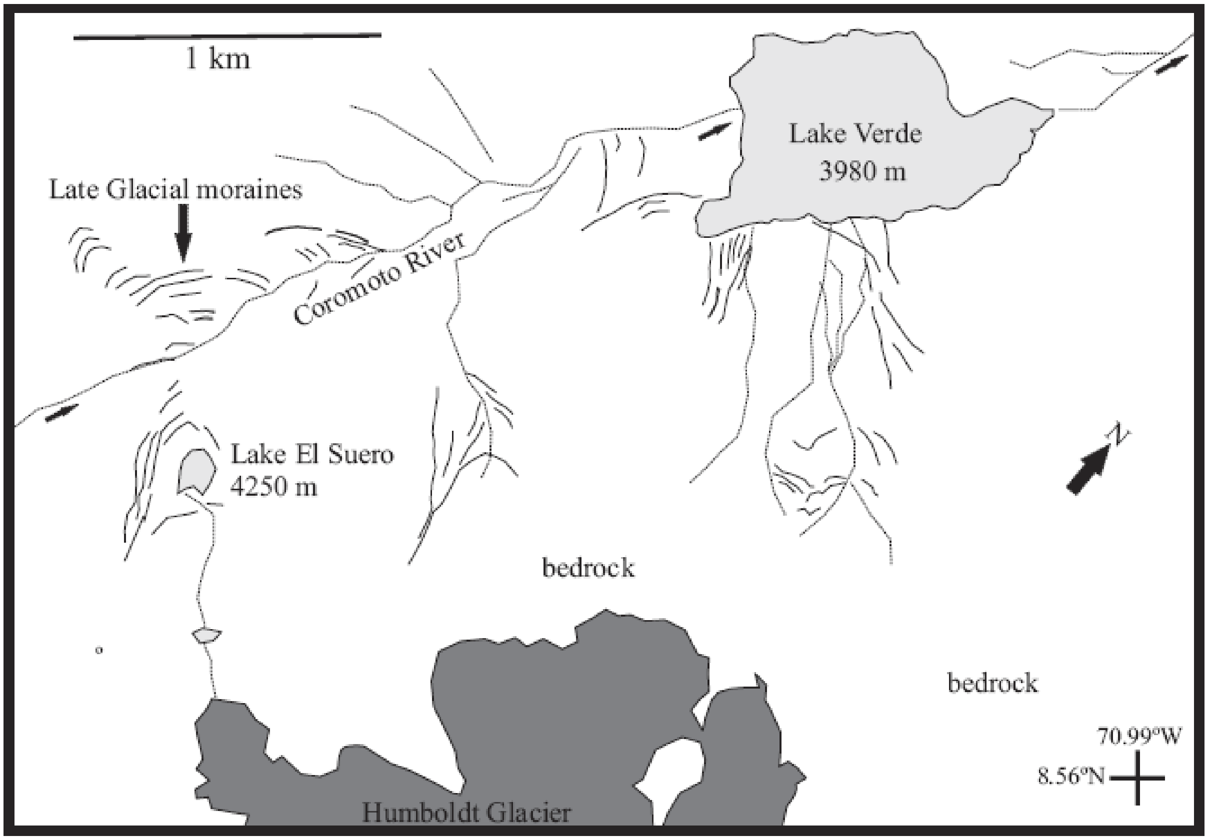

Figure 2.7. Location map of Younger Dryas moraines near Pico Humboldt. Modified from Mahaney et al. (2008).

Paleo-temperature estimates were calculated for the ΔELA values relative to modern. These should be viewed as minimum estimates because modern glaciers in the Venezuelan Andes are retreating rapidly. Today, ELA's are probably closer to ~4980 m, which requires an even greater cooling to explain the lower ice margins during the YD. Paleotemperatures for the YD were estimated using climate variables from (Monasterio and Reyes, 1980; Stansell et al., 2007), and by using an energy and mass-balance model (Seltzer, 1992):

$$\Delta T = \frac{L_m}{A_H}\left(\frac{\partial P}{\partial z}\Delta ELA + \Delta P\right) + \frac{1}{A_H}\left[\frac{L_m}{L_s} - 1\right]\left[A_s \frac{\partial p_{va}}{\partial z}\Delta ELA\right] - \frac{\partial T}{\partial z}\Delta ELA,$$

where L_m is the latent heat of melting, L_s is the latent heat of sublimation, A_H is the transfer coefficient for sensible heat, A_S is the transfer coefficient for latent heat, $\partial P / \partial z$ is the vertical precipitation gradient, $\partial p_{va} / \partial z$ is the vertical gradient in atmospheric absolute humidity, $\partial T_a / \partial z$ is the atmospheric lapse rate (6°C/km), and ΔELA is the change in ELA. ΔP is the change is precipitation and ± 50% the modern values were used in an analysis of sensitivity. A combined error estimate was then calculated by taking the square root of the sum of squared errors or uncertainties of each variable.

2.3 RESULTS AND DISCUSSION

2.3.1. Clastic sediment flux and ice volume changes

The dominant first order control on clastic sediment flux to alpine lakes in glaciated tropical Andean catchments is the extent of ice cover (Rodbell et al., 2008; Rodbell et al., 2009). We interpret higher clastic sediment flux in LA to be principally a record of increased glaciation. Radiocarbon ages on aquatic macrofossils (Fig. 2.4) tightly constrain the timing of changes in clastic sediment flux in the LA record and periods of ice advance. Glaciers abruptly retreated just after ~14,600 cal yr BP with the onset of BA warming (Fig. 2.7). BA warming was interrupted by a brief, yet pronounced, return to colder conditions between 14,100 and 13,900 cal yr BP. Ice again advanced after ~13,000 cal yr and reached its maximum YD extent between ~12,800 and 12,500 cal yr BP. The latter half of the YD (12,300 to 11,800 cal yr BP) was characterized by warmer temperatures, and a dramatic decrease in glacier ice volume and clastic sediment flux.

2.3.2. Paleoecological record from LA

The closest modern analogue for YD pollen assemblages is the periglacial desert zone between 4400 and 4500 m (Rull, 2006). *Podocarpus* currently is found in the uppermost Andean forests (Berg and Suchi, 2001), and its pollen abundance decreased sharply during the YD (Fig. 2.6). Likewise, *Polylepis* has a modern upper boundary of ~4300 m altitude (Rull, 2006), and its pollen is nearly absent during the peak YD cooling. This distribution suggests that vegetation had shifted downward at least 480 to 580 m relative to today. Using the present-day lapse rate of -6.0ºC/km altitude, this corresponds to a temperature decrease of 2.9 to 3.5ºC.

The YD interval is characterized by a dramatic reduction in taxon that are sensitive to aridity. For example, *Huperzia* is a páramo fern that typically exists in relatively wet climates (Berg and Suchi, 2001), and *Isoëtes* is a common pteridophyte that lives in semi-aquatic environments (Rull, 2006). There is a scarcity of *Huperzia* and *Isoëtes,* as well as algae remains (mainly *Pediastrum* and *Botryococcus*) during the YD, which indicates this was a period of drier conditions. Trends in biogenic silica flux (Fig. 2.7) indicate a concomitant decrease in diatom abundance and lake productivity, and corroborate the pollen evidence of colder and drier conditions.

2.3.3. The LA record of climate change

The LA sediment record indicates that the northern tropical atmosphere reached peak YD cooling between ~12,800 and 12,500 cal yr BP. Minimum and maximum estimates of paleoglacier equilibrium line altitudes (ELA) were between 360 m and 480 m lower than today, respectively. These values of ELA depression correspond with a temperature lowering of between 3.3 and 4.4°C (±1.0°C). The reduction of temperature is slightly more than the palynology-based estimates of a 2.9 to 3.5ºC cooling, but the ELA-based temperature estimates account for multiple climate variables and are probably better indicators of YD conditions.

Major, clearly shown, YD sedimentological and ecological changes in LA cores are well dated with bracketing AMS radiocarbon ages. The LA watershed is too steep for moraine preservation, however glacial-geomorphic features dated to the YD (Mahaney et al., 2008) have been identified in the same mountain range, near Pico Humboldt. Likewise, paleoecological evidence from Venezuelan Andes suggests that a cold reversal took place after 13,800 cal yr BP (Salgado-Labouriau, 1989), and evidence from the Colombian Andes indicates a YD cooling of 1.0 to 3.0ºC (Veer et al., 2000). Marine records off the coast of northern South America indicate that the YD was a period of intense windiness and aridity (Haug et al., 2001), and temperatures were 3.2º ± 0.5ºC colder (Lea et al., 2003). The well-dated multi-proxy LA record, presented here, combined with other independently dated regional records, provides strong coherent evidence of colder and drier conditions in the northern tropical atmosphere during the YD.

Other paleoclimate records from the southern tropics of South America likewise indicate increased aridity in most regions during the YD. For example, mountain glaciers in the Peruvian Andes retreated due to decreased precipitation (Rodbell and Seltzer, 2000), and lake sediment records indicate increased evaporative enrichment of authogenic calcium carbonate and therefore drier conditions (Seltzer et al., 2000; Rowe et al., 2002). Low elevations in the southern tropics also experienced decreased precipitation (Wang et al., 2004), and Amazon River discharge was low (Maslin and Burns, 2000). In contrast, ice cores from Huascaran and Sajama suggest that the YD in the southern tropics was cold and wet (Thompson et al., 1998), but these records are not definitive because of dating uncertainties, and there are multiple influences on the $\delta^{18}O$ composition of tropical precipitation that could lead to alternative explanations (Pierrehumbert, 1999).

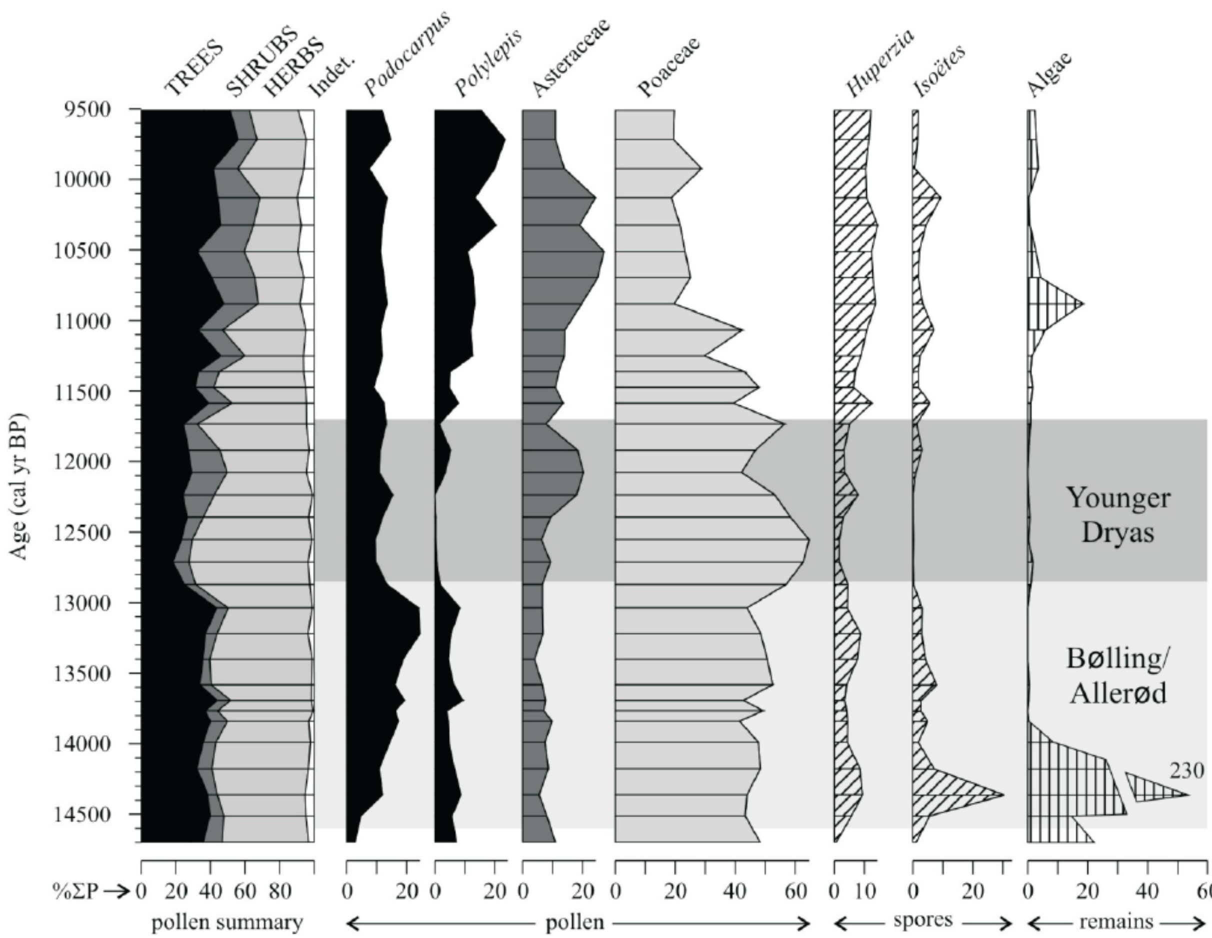

Figure 2.8. Diagram of the main LA palynological trends expressed in percentage of the pollen sum (ΣP). The column at the left is a summary of all pollen taxa subdivided into three categories representing forest (trees) and páramo (shrubs and herbs) communities. The more sensitive pollen types are depicted individually. Forest elements (*Podocarpus, Polylepis*) experienced a pronounced lowering, while páramo types (Asteraceae, Poaceae) increased during the YD, which is consistent with a downward shift in vegetation zones. Fern and allied spores also decrease and algae remains (including *Pediastrum, Botryococcus, Debarya, Mougeotia, Spirogyra and Zygnema*) reach a minimum in the YD indicating drier conditions.

Paleoclimate records from the Colombian (VM28-122) (Schmidt et al., 2004) and Cariaco basins are independently dated and closely covary with the northern tropical mountain records of paleoenvironmental changes during the YD. For example, the Ti record of continental runoff from the Cariaco Basin (Haug et al., 2001), and the evidence presented here from the Andes, indicate that northern South America experienced abruptly drier conditions at the onset of the YD. Likewise, the cooling at ~13,000 cal yr BP in the mountain records took place at a time of increased aridity and salinity in the Caribbean (Fig. 2.7), indicating that northern tropical surface marine and atmospheric conditions were tightly coupled. The transition to lower SSTs was similarly abrupt in the Cariaco Basin (Lea et al., 2003), which is consistent with the northern tropical pattern of atmospheric cooling during the YD (Wan et al., 2009).

The Greenland ice cores record abrupt temperature shifts at the beginning of the YD (Rasmussen et al., 2006). Likewise, paleoclimate records from the northern tropics show cold and dry conditions during this time (Fig. 2.7). The coupled low and high latitude cooling at the onset of the YD indicates a link between tropical and Arctic ocean-atmosphere cooling dynamics. At the onset of cooling, Northern Hemisphere winter insolation minima likely led to increased North Atlantic sea-ice extent, and colder Arctic winter conditions, which may have caused a southern displacement of the Atlantic Intertropical Convergence Zone (ITCZ) and monsoonal belts over the tropical Americas (Vellinga and Wood, 2002). The shift in the ITCZ and the resulting decrease in northern tropical atmospheric humidity would both have contributed to higher surface wind speeds over the oceans and cooler sea surface temperatures (Seager et al., 2000). A decrease in humidity would also probably have resulted in steeper adiabatic lapse rates, which could have led to cooling in the alpine environments and contributed to the observed northern tropical glaciation. Alterations of thermohaline circulation during the

YD probably contributed to cooler conditions in the Northern Hemisphere as well (Tarasov and Peltier, 2005). This mechanism requires that deepening of the thermocline in the tropical oceans,

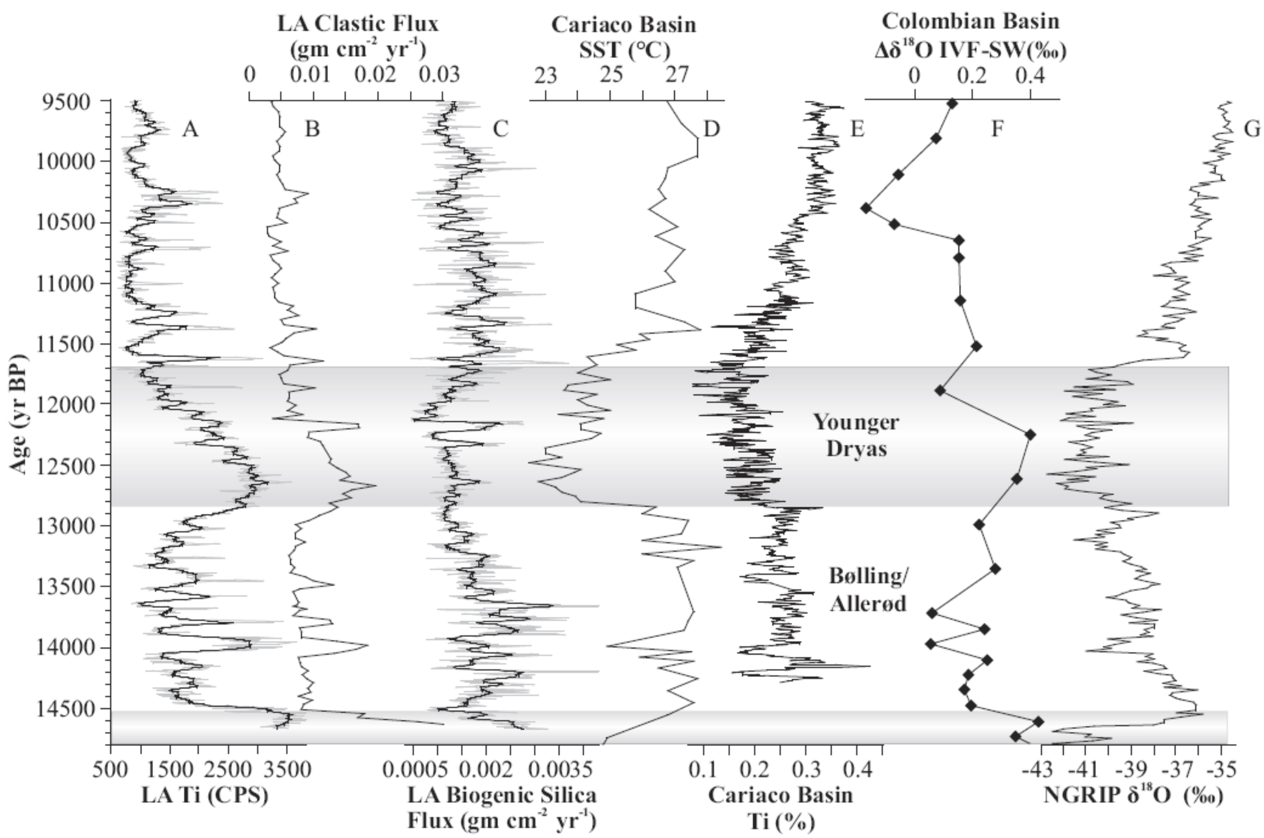

Figure 2.9. Comparison of LA data plotted versus age (A-C), with data from the Cariaco and Colombian Basins. Titanium (A) is plotted in raw counts per second (CPS, gray line) and was smoothed using a Lowess function (0.01 loading, black line). Clastic Flux (B) co-varies with Ti, and both are proxies for watershed erosion and ice margin fluctuations. Biogenic silica flux (C, gray line) is an indicator of lake productivity and was smoothed using a Lowess function (0.01 loading, black line). Glaciers retreated abruptly at ~14,600 cal yr BP, during the onset of BA warming. The YD is recorded in the LA sedimentology as a period of increased clastic sediment flux and decreased biogenic silica flux. Increased clastic sediment flux in LA during the start of the YD took place at a time of colder and drier conditions in the Cariaco Basin (D,E)(Haug et al., 2001; Lea et al., 2003), increased Caribbean salinity (F) (Schmidt et al., 2004), and lower temperatures recorded in the NGRIP oxygen isotope record (G) ((Rasmussen et al., 2006). Temperatures were higher, and salinity decreased in the northern tropical marine records during the latter half of the YD, at a time of glacial retreat in the Andes.

and/or heat transport to the Southern Ocean (Blunier and Brook, 2001) took place in order to explain the synchronous cooling in the low and high northern latitudes, and to balance the global heat budget. Sub-surface waters in the tropical Atlantic and Caribbean were indeed warming during most of the YD (Flower et al., 2004; Schmidt et al., 2004), which may have been a sink for heat as atmospheric conditions became colder. Changes in salinity and heat export in the tropical oceans may have contributed to climate change in the North Atlantic region (Schmidt et al., 2004). Tropical marine salinity decreased during the latter half of the YD, at a time that glaciers were retreating in the northern Andes and palynological records indicate warming conditions in Venezuela (Fig. 2.6). Cariaco Basin SST's became 0.9º ± 0.4ºC higher after ~12,300 cal yr BP (Lea et al., 2003), which was likely a response to changing atmospheric conditions (Wan et al., 2009). In summary, a return to interglacial-like atmospheric conditions in the northern tropics, and increased export of warm, salty water from the Caribbean (Schmidt et al., 2004) occurred before the abrupt warming in Greenland at ~11,700 cal yr BP (Rasmussen et al., 2006).

2.4. CONCLUSIONS

The cause of the YD remains elusive, but mounting evidence indicates that a cascade of events must have taken place to produce such widespread changes. The synchronicity of both cooling and aridity in the high and low northern latitudes during the YD emphasizes the role of the tropical atmosphere and oceans in transmitting and modulating abrupt climate change. Temperature in the northern tropical atmosphere reached its peak cooling of 3.3 to 4.4°C within 300 to 500 years after the onset of the YD. The early warming and salinity changes in the tropics that followed (Schmidt et al., 2004) indicate that the low-latitude climate system may have provided a trigger for the return to interglacial conditions in the Northern Hemisphere

(Steffensen et al., 2008), through a combination of changes to the global radiation budget, ocean and atmosphere circulation, and the hydrologic cycle (Clement and Peterson, 2008).

3. THE LATE-GLACIAL INTERVAL IN THE NORTHERN TROPICAL ANDES

3.1. INTRODUCTION

Knowledge of the modern climate system and the ability to predict future changes requires highly resolved paleoclimate records documenting how the low latitude ocean-atmosphere system has varied on millennial time scales in the past. Study of the Late-Glacial (LG) interval (~17,500 to 11,650 cal yr BP), marked by warming and cooling events that lasted for nearly a millennia or more (Blunier et al., 1998), may provide useful insight into climatic processes. Understanding these abrupt events is ultimately the key to predicting how the oceans and atmosphere will reorganize in response to future abrupt climate change (Alley et al., 2003).

Here, a record of LG atmospheric changes is presented from the climatically sensitive Venezuelan Andes. These records indicate that the northern tropical Andes were mostly in phase with high northern latitude abrupt cooling and warming events, and were out of phase with conditions in the high southern latitudes. The Andean record of climate change also suggests that conditions in the northern tropical atmosphere were relatively dry during cold northern hemisphere events, and wet during warmer periods. These records emphasize that tropical humidity played a major role in abrupt climate change during the LG through feedbacks related to changes in the global hydrologic cycle.

Records from multiple ice cores indicate that Greenland and Antarctica maintained a generally asymmetric pattern of temperature changes during the LG interval (Blunier et al., 1998), but the global pattern of climate change outside the high latitudes is less clear. It is particularly important to understand how the tropical ocean and atmosphere systems varied during this interval because the low latitude hydrologic cycle likely contributed to abrupt global temperature shifts through the transfer of energy from the low to high latitudes.

Within the LG, the Younger Dryas (YD) cold reversal (12,850 to 11,650 cal yr BP) (Rasmussen et al., 2006), is one of the best studied and debated climate anomalies of the past. The rapid and large increase in temperature at the onset of Bølling warming (~14,600 cal yr BP) was arguably as impressive as the YD climate reversal, and its cause is similarly unclear. The low latitude record of the Bølling is largely unknown because records spanning the LG are difficult to obtain, contain dating uncertainties, are poorly resolved and have ambiguous interpretations (Pierrehumbert, 1999).

3.1.1. Study site and local controls on glacier mass-balance

The tropical Andes are well situated to study the terrestrial low latitude manifestation of atmospheric variability because they span the equator, and have glacially-carved lake basins and paleo-glaciers for study in both the northern and southern tropics. Tropical circulation must have contributed to LG climate change because rapid temperature shifts occurred synchronously in both the low and high latitudes (Lea et al., 2003). Likewise, marine records indicate that humidity changes took place that were synchronous with changes in Northern Hemisphere temperature (Hughen et al., 1998; Peterson et al., 2000; Haug et al., 2001; Schmidt et al., 2004).

Lake Los Anteojos (hereafter LA) in the Venezuelan Andes (3920 m a.s.l.) (Fig. 3.1) is well situated to capture LG glacial variability because its headwall was glaciated multiple times during this period. Although the watershed is currently ice free, it is situated just below the modern ice limit of 4860 m (Polissar et al., 2006b), and even a slight cooling would be sufficient to initiate glacier formation in the highest reaches of the basin. The climate of the Mérida Andes is cold and humid throughout the year (Azocar and Monasterio, 1980). Precipitation amount is controlled by the position and intensity of the ITCZ, which is linked to the seasonal cycle of solar declination, and is probably sensitive to shifts in Northern Hemisphere sea ice extent as well. Rainfall data from Loma Redonda (4045 m) and Pico Espejo (4765) are in the LA watershed and record 1550 and 1173 mm yr^{-1} of precipitation, respectively (Azocar and Monasterio, 1980).

Temperature in the Cordillera de Mérida is typical of the low latitudes and shows little seasonal variability, but a substantial diurnal freeze-thaw cycle. Daily temperatures vary as much as 20°C (Schubert and Clapperton, 1990) and greatly exceed the total annual variation. Diurnal temperature variations are large because conditions in the Mérida Andes are strongly controlled by net irradiance, and short-term temperature changes are largely independent of sea-surface conditions (Snow, 1976). National Center for Environmental Prediction (NCEP) temperature data indicate that the free-atmosphere lapse rate is ~0.55°C/100 m for this region of the Andes (Kalnay and co-authors, 1996). Environmental lapse rates based on local station data range from 0.40 to 0.70°C/100 m with an average of 0.60°C/100 m (Salgado-Labouriau, 1979). In the 1970's the regional freezing height (0ºC isotherm) was near 4700 m (Monasterio and Reyes, 1980; Schubert, 1992), but this has risen considerably in recent years to approximately 4860 m due to warming temperatures (Polissar et al., 2006b).

Figure 3.1. Location map of sites mentioned in text. Shaded areas represent elevations in South America that are higher than ~3000 m.

The mass-balance profiles of glaciers reflect ice thickness, which is controlled by rates of accumulation and ablation that vary depending upon geographic setting. For instance, glaciers in the tropics are differentiated from temperate ones because they are affected by the annual migration of the ITCZ and experience greater diurnal than annual temperature variation (Kaser, 1995; Kaser and Noggler, 1996). Furthermore, inner tropical glaciers receive precipitation year-round and are more sensitive to changes in temperature (Kaser, 2001). Outer tropical glaciers experience nearly constant temperature year-round but precipitation is strongly seasonal. Therefore, outer tropical glaciers have an annual mass-balance that is seasonal and sensitive to variations in both precipitation and temperature (Kaser and Georges, 1999).

The climate conditions of the Venezuelan Andes is intermediate between the inner and the outer tropics because this region has a pronounced wet and dry season combined with high humidity throughout the year (Azocar and Monasterio, 1980). These conditions play an important role in the mass-balance process, because humid air inhibits latent heat loss through sublimation and promotes melting. Melting is a faster and more efficient ablation process than sublimation, because it requires less energy. High ablation rates reduce the overall glacier surface area below the equilibrium-line that is needed to balance accumulation. As a result, humid tropical glaciers have a mass-balance that is mostly sensitive to temperature changes.

3.1.2. Clastic sediment flux, glacier variability and temperature change

The northern tropics presently receive abundant precipitation and experience humid conditions year-round, and glacier mass-balance in most sensitive to changes in temperature (Kaser and Osmaston, 2002; Polissar et al., 2006b; Stansell et al., 2007). Therefore, periods of increased clastic flux in proglacial lakes in the Venezuelan Andes correspond to times of colder conditions and increased up-valley ice cover (Rodbell et al., 2008). The Ti record of clastic flux (Fig. 3.3) from LA (Stansell et al., 2009) may be used to assess the LG record of climate change in the Venezuelan Andes. The record of biogenic silica flux and palynological data from LA also provide indicators of paleo-moisture changes and supporting evidence of temperature variability (Fig. 3.2).

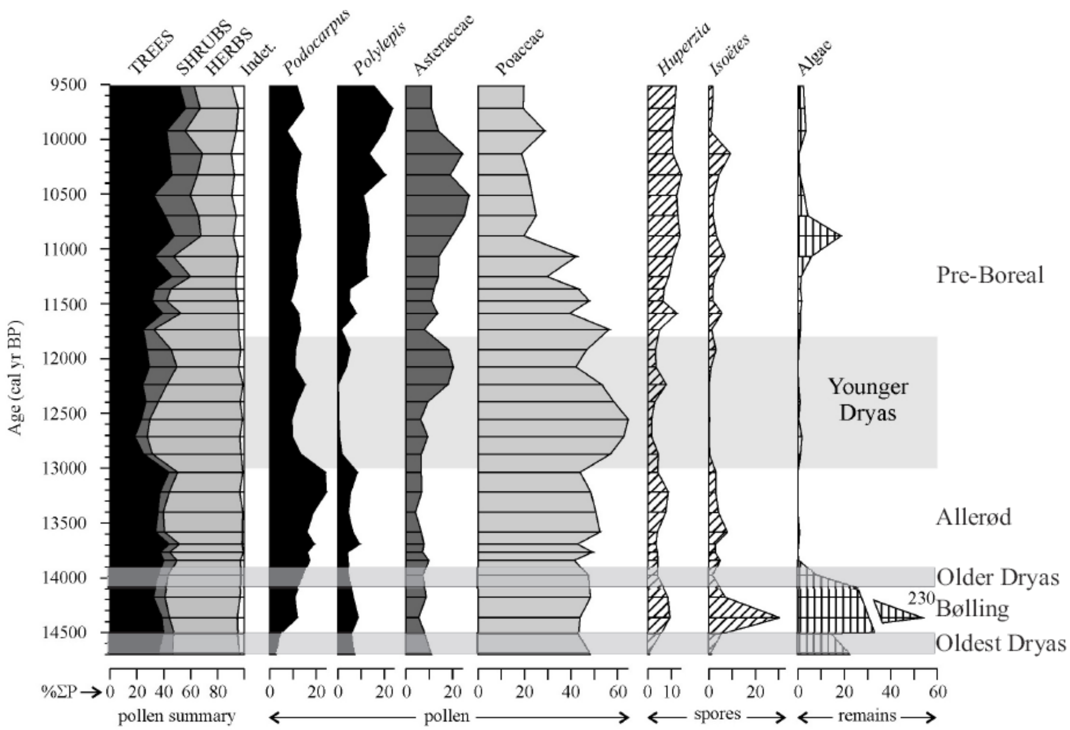

Figure 3.2. Diagram that shows pollen abundance expressed in percentage of the pollen sum (ΣP) versus time. The column at the left is a summary of all pollen taxa subdivided into three categories representing forests (trees) and páramo (shrubs and herbs) communities. The more sensitive pollen types are depicted individually. Forest trees (*Podocarpus, Polylepis*) experience a pronounced lowering, while páramo elements (Asteraceae, Poaceae) notably increase during the colder periods, consistent with a downward vegetation shift. Fern and allied spores also decrease and algae remains (including *Pediastrum, Botryococcus, Debarya, Mougeotia, Spirogyra and Zygnema*) show their minima during low lake levels, suggesting drier periods.

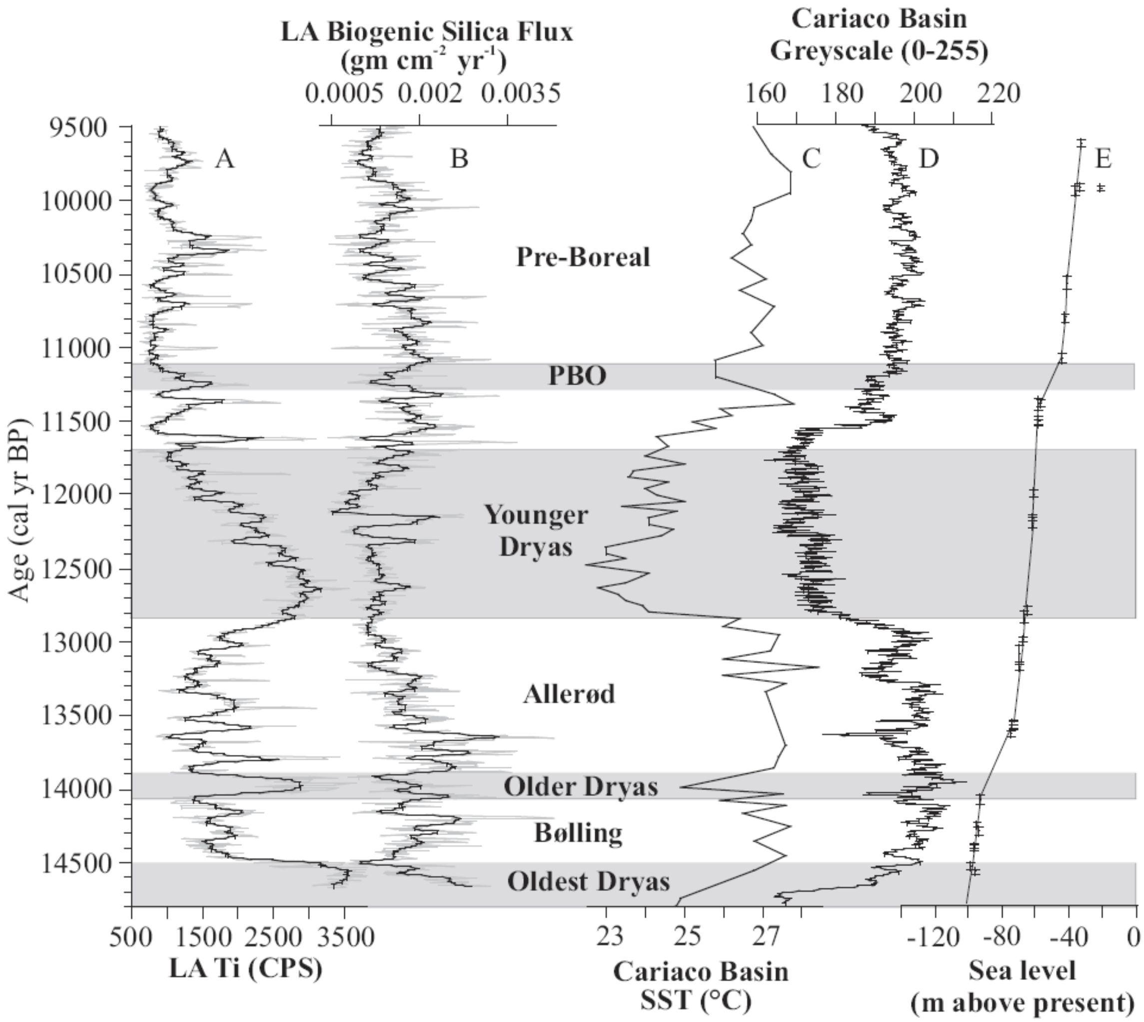

Figure 3.3. A diagram that shows a comparison of various types of data from LA (A,B), the Cariaco Basin (C-D) and sea-level changes (E) (Peltier and Fairbanks, 2006). The data are plotted versus age. Titanium (A) is shown in raw counts per second (CPS, gray line) and was smoothed using a Lowess function (0.01 loading, black line). Ti represents clastic flux where increased values correspond to lower ice margins and colder conditions (Stansell et al., in review). Biogenic silica flux (B, gray line) was smoothed using a Lowess function (0.01 loading, black line).

3.2. SUMMARY OF EVIDENCE

Below is a summary of the available evidence from South America, Greenland and Antarctica during the LG interval. It is written mostly from the northern tropical Andean perspective, but includes proxy data from ice cores, marine records and mountain glacier evidence from locations throughout the low and high latitudes. The LG interval includes the

Oldest Dryas, Bølling, Older Dryas, Allerød, Younger Dryas and PreBoreal time periods, and I discuss each separately in the following sections.

3.2.1. The Oldest Dryas (~17,500 to ~14,600 cal yr BP)

Existing proxy records from the Mérida Andes provide limited information on the climatic conditions during the Oldest Dryas (OD) in the Venezuelan Andes, because ice margins were advanced and most lake basins were covered just prior to ~15,000 cal yr BP (Stansell et al., 2005). There are hints in the geologic record of fluctuating ice margins and climatic conditions around ~15,700 cal yr BP (Stansell et al., 2005), and again starting at around 14,880 cal yr BP (Salgado-Labouriau et al., 1977). Outside of the Andes, the Cariaco Basin marine record suggests that there may have been a brief cold period in the northern tropics during the Heinrich 1 (H1) event (17,500 to 17,000 cal yr BP), but overall sea-surface temperatures (SST's) near Venezuela were probably no warmer during the entire OD than the average LG conditions (Lea et al., 2003).

Beyond the Cariaco Basin, tropical marine records indicate that temperature changes took place that are inconsistent with the pattern of cooling recorded in Greenland during the OD. For example, the tropical and subtropical Atlantic records indicate that sea-surface temperatures were warmer than conditions at the onset of Bølling warming (Rühlemann et al., 1999; Weldeab et al., 2006), whereas tropical Pacific surface waters experienced a minor cooling trend (Rosenthal et al., 2003; Kienast et al., 2006). Temperature records from the Caribbean indicate that these warmer conditions in the tropical Atlantic were associated with a reduction in North Atlantic deep water (NADW) formation (Schmidt et al., 2004), and played a major role in North Atlantic climate conditions.

Warmer temperatures in the Caribbean during the LG generally correspond to periods of increased salinity and more arid conditions (Schmidt et al., 2004). Terrestrial records are in good agreement with surface water records from marine sites that also indicate conditions were more arid during the OD. For example, the Yucatan Peninsula (Hodell et al., 2008) and the northern tropics off the coast of western Africa (ODP 658C) (deMenocal et al., 2000) were relatively dry during the OD.

The southern tropical terrestrial records show a different pattern of arid than the northern tropics. For example, the Huascaran and Illimani ice core records (Fig. 3.4) indicate that the southern tropical Andes may have been cold and dry during most of the OD (Thompson et al., 1995; Ramirez et al., 2003), while data from Sajama suggest that conditions were cold and wet in the southern sub-tropics (Thompson et al., 1998). Likewise, conditions were wetter at Lake Titicaca (Rowe et al., 2002), and lake levels in the Altiplano were high, indicating that the period from 18,100 to 14,100 cal yr BP was locally the wettest of the last ~120,000 years (Placzek et al., 2003). The Sajama accumulation record was also high during the OD (Thompson et al., 1998), and cave records from 10°S in coastal Brazil also suggest that regions south of the modern ITCZ limit were wetter (Wang et al., 2004). In summary, during the OD, most paleoclimate records suggest that the northern and southern tropical atmosphere was generally cold and dry, and the southern sub-tropics were cold and wet. This pattern of temperature and aridity during the OD suggests that the ITCZ was situated south of its modern average position, and a strengthened South American summer monsoon in the Southern Hemisphere.

3.2.2. Bølling warming (~14,600 to 14,100 cal yr BP)

The abrupt shift from mostly clastic sediments to organic-matter-rich sediments at ~14,500 cal yr BP is the most pronounced change in the LA sediment record. Likewise, basal radiocarbon ages from lakes in the nearby Piedras Blancas region mark an abrupt transition from glacio-lacustrine to organic-rich sediments at ~15,000 cal yr BP (Stansell et al., 2005; Polissar et al., 2006a). Algal remains, *Isoëtes*, and biogenic silica (Figs 3.2 and 3.3) in the LA record during the Bølling reach nearly the highest values of the entire LG sequence and suggest wetter and warmer conditions. The palynology data supports this interpretation and indicate that treeline was higher and forest pollen dominated the Bølling interval in Venezuela, while temperatures in Colombia were higher (Thouret et al., 1997).

The onset of Bølling warming at the end of the Oldest Dryas was abrupt in multiple proxy records, and temperatures increased in both the low (Lea et al., 2003) and high northern latitudes (Severinghaus and Brook, 1999). Ice core oxygen isotope data from Huascaran and Illimani in the southern tropics also suggest warmer conditions during this interval (Thompson et al., 1998; Ramirez et al., 2003). Decreased accumulation combined with increased dustiness and higher oxygen isotopes in the Sajama ice core record (Thompson et al., 1998) suggest that the southern sub-tropics were more arid during the Bølling (Fig. 3.4). Likewise, records from Lake Titicaca on the Altiplano suggest that conditions were more arid during this interval (Rowe et al., 2003). Combined, the mountain glacier records, lake level records and paleoecological evidence indicate that the northern tropics and sub-tropics were relatively warm and wet.

The southern tropical records indicate that locally conditions were warmer and more arid during the OD. For example, ice core oxygen isotope values from Huascaran and Illimani in the southern tropics were higher, suggesting warmer conditions (Thompson et al., 1998; Ramirez et al., 2003). Decreased accumulation combined with increased dustiness and higher oxygen isotopes in the Sajama ice core record (Thompson et al., 1998) suggest that the southern sub-tropics were more arid during the Bølling (Fig. 3.4). Likewise, records from Lake Titicaca on the Altiplano suggest that conditions were more arid during this interval (Rowe et al., 2003).

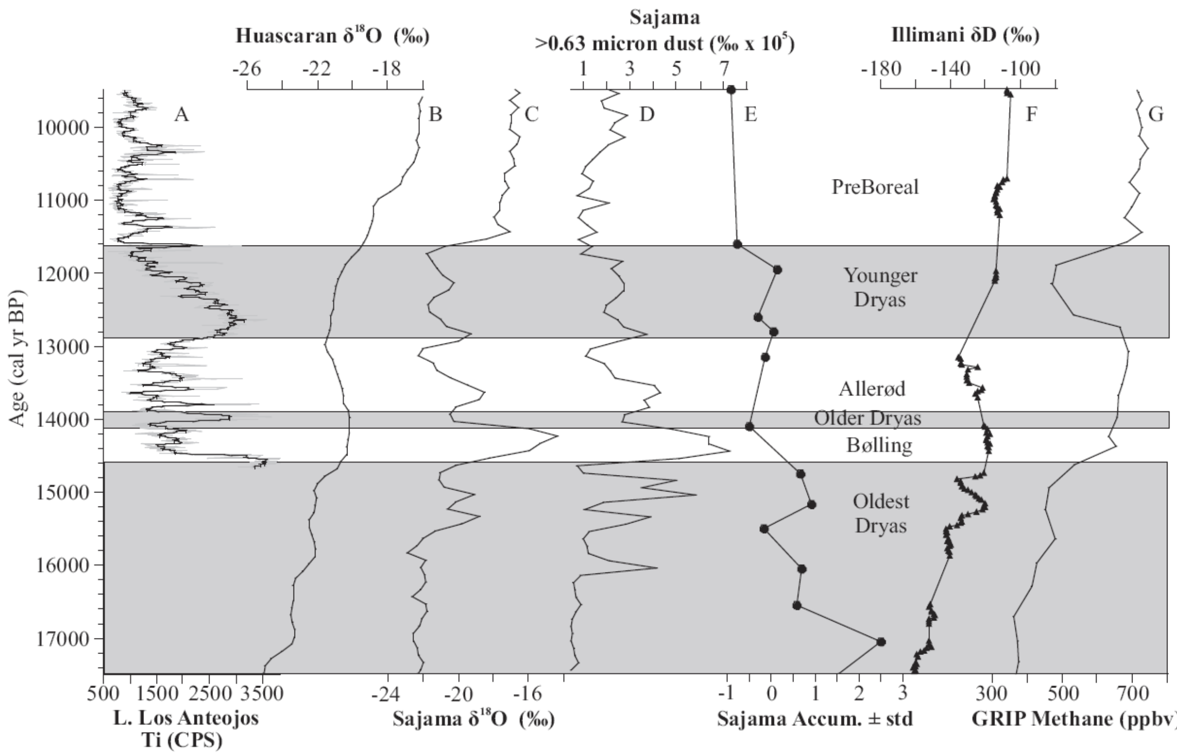

Figure 3.4. LA Ti (A), Huascaran $\delta^{18}O$ (Thompson et al., 1995) (B), Sajama $\delta^{18}O$ (C), Sajama dust (D), Sajama Accumulation (E) (Thompson et al., 1998), Illimani δD (Ramirez et al., 2003) and GRIP methane (D) (Blunier et al., 1998). Cold and dry periods in the northern tropics during the Late Glacial correspond to generally cold and wetter conditions in the southern tropics. The Oldest Dryas was cold and dry in the northern tropics and the southern tropics were generally cold and wet. The Bølling was a period of abruptly warmer and wetter conditions in the Venezuelan Andes that was followed by a brief glacial advance during the Older Dryas. The Younger Dryas was cold and wet in the northern tropics and ice core evidence from Peru and Bolivia suggests that the southern hemisphere as also cold and wet.

Atmospheric methane (Fig. 3.4) rose substantially during the Bølling (Blunier et al., 1995). Atmospheric methane is sourced mostly from wetlands in the northern hemisphere and tropics. Increased atmospheric methane levels during the Bølling suggests that the Northern Hemisphere was wetter and a more rigorous hydrologic cycle was operating in the tropics (Sowers, 2006). Combined with the ice core evidence, atmospheric evidence indicates that the ITCZ was biased further north during the Bølling, with warm and wet conditions in the tropics and northern sub-tropics, and drier conditions in the southern subtropics. This interval also marks the start of the Antarctic Cold Reversal (ACR) in the high southern latitudes, which may have influenced the position of maximum moisture convergence in the tropics.

3.2.3. Older Dryas cold reversal (~14,100 to 13,900 cal yr BP)

The oxygen isotope record from Greenland indicates that temperature dropped in the Northern Hemisphere during the Older Dryas (Rasmussen et al., 2006). Coincident increases in clastic sediment supply to LA suggests that glaciers advanced in the Venezuelan Andes during this interval (Fig. 3.3). Paleoecological evidence (Fig. 3.2) suggests conditions were becoming drier in the northern tropics during the Bølling and through the period bracketing MWP-1A and the Older Dryas. An abrupt and short-term (~200 yr) shift to drier conditions in the Yucatan also took place after ~14,000 cal yr BP (Hodell et al., 2008). A brief return to colder conditions during the Older Dryas is also apparent in the Cariaco (Lea et al., 2003) and Colombia (Schmidt et al., 2004) basin records, and indicate that the temperature changes taking place in Greenland and the northern Andes also occurred in tropical marine locations. To summarize, the northern tropics were relatively cold and dry during the Older Dryas, and the southern tropics were colder and possibly slightly wetter. The Sajama ice core records indicate that the southern tropics were slightly colder and there was a minor increase in ice accumulation (Thompson et al., 1998), suggesting that the southern sub-tropics were generally wetter.

3.2.4. Allerød warming (~13,900 to 12,850 cal yr BP)

The Allerød was a warm interval that followed the brief Older Dryas cooling event. The Allerød section in the LA record is characterized by low clastic and biogenic silica fluxes. A concomitant decrease in the accumulation of aquatic markers, algal remains and *Isoëtes* at LA indicates that the northern Andes were markedly drier during the Allerød than the earlier Bølling interval (Fig. 3.2). The northern sub-tropics do not show the same trend, and indicate abruptly wetter conditions at the onset of the Allerød (Hodell et al., 2008). Likewise, the Cariaco Basin records suggest that northern South America was experiencing a period of increased continental runoff (Haug et al., 2001). This pattern of increased moisture in the lowlands and more arid conditions in the northern Andes suggests that precipitation was preferentially falling out in lower elevations while the high altitudes became drier.

The upper ~300 years of the Allerød sequence (13,300 to 13,000 cal yr BP) in the LA record shows slightly increased clastic flux and decreased biogenic silica flux (Fig. 3.3), at a time of briefly colder conditions in the Northern Hemisphere (Rasmussen et al., 2006). The late Allerød therefore marks a transition in the northern tropical Andes from the warm and wet Bølling to cold and dry conditions at the start of the YD (Stansell et al., 2009).

The southern sub-tropics generally show the opposite pattern of climate change during the Allerød, with relatively colder and slightly wetter conditions leading up to the onset of the Younger Dryas (Thompson et al., 1998). The Huascaran record also suggests that the southern tropics were cooling during Allerød (Thompson et al., 1995). In the lowland tropics, Amazon River discharge was decreasing during the Allerød, indicating a shift to drier conditions at the onset of the Younger Dryas (Maslin and Burns, 2000). The Altiplano (Placzek et al., 2003) and Lake Cardiel in southern South America were dry during the Allerød, just prior to the YD (Ackert Jr. et al., 2008). The pattern of Allerød climate change suggests that the northern sub-tropics were wet while the northern tropics and southern sub-tropics experienced lower lake levels and drier conditions.

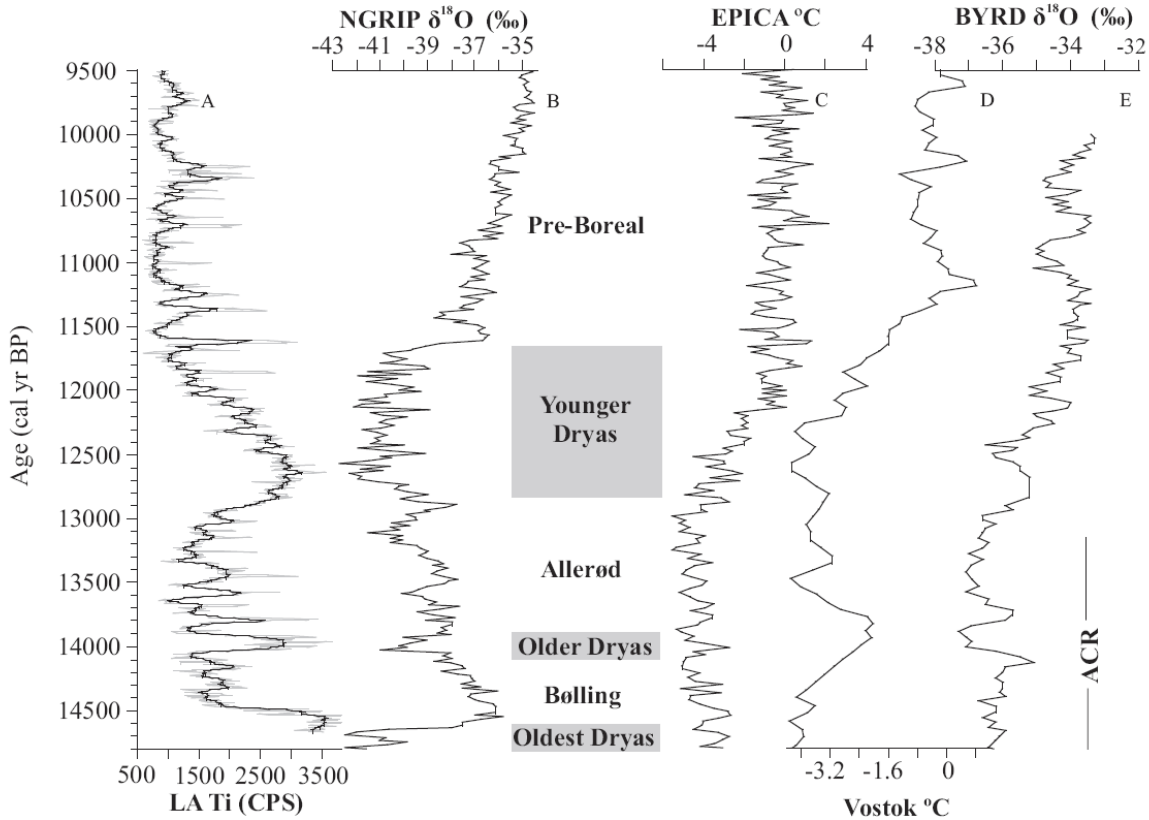

Figure 3.5. LA Ti record of Venezuela (A) is a record of glacial variability from the northern tropical Andes. The NGRIP oxygen isotope record ($\delta^{18}O$) is a record of temperature change from Greenland (B) (Rasmussen et al., 2006). The EPICA temperature record (C) from Antarctica (Jouzel et al., 2007) highlights the colder conditions of the ACR while conditions were warmer in the Northern Hemisphere. The Vostok temperature record (D) (Petit et al., 1999) represent the interior of Antarctica while the BYRD $\delta^{18}O$ record (E) (Blunier et al., 1998) is more intermediate to the coast. The Antarctica records of temperature change during the LG generally have the same pattern, and are out of phase with the northern tropics and Greenland.

3.2.5. Younger Dryas (~12,850 to 11,650 cal yr BP)

Mountain glacier and lake sediment paleoclimate records from the Venezuelan Andes indicate that the northern tropical atmosphere became abruptly colder and drier at the onset of the Younger Dryas (YD). Ice advanced at ~13,000 cal yr BP, reached its maximum extent between ~12,800 and 12,500 cal yr BP, and retreated thereafter (Stansell et al., 2009). Independent glaciological and pollen records indicate that temperature dropped 3.0 to 4.4°C

(±1.0°C) during the peak of this cooling. Biogenic silica (Fig. 3.3) and palynological data (Fig. 3.2) indicate that the YD in the Andes was cold and dry synchronously with lower sea-surface temperatures in the Cariaco Basin (Lea et al., 2003) and increased salinity in the Caribbean (Schmidt et al., 2004). Evidence from the Colombian Andes also indicates that conditions were relatively cold and dry in the northern tropics (Van der Hammen and Hooghiemstra, 1995).

Temperature trends in the northern and southern latitudes were asymmetrical during the YD. Greenland (Alley, 2000) and the northern tropics became abruptly cold, and Antarctica was relatively warm during the onset of the YD (Petit et al., 1999; Blunier and Brook, 2001). The northern tropical atmosphere then recovered from YD cooling by ~12,500 cal yr BP, several hundred years earlier than Greenland (Stansell et al., 2009). The Caribbean likewise experienced an early recovery from the YD by ~12,300 cal yr BP (Lea et al., 2003; Schmidt et al., 2004). This increased tropical aridity and high latitude atmospheric cooling during the YD may have been linked through changes in the hydrologic cycle that forced a temperature change (Charles et al., 1996; Lea et al., 2003).

The southern low latitude and equatorial record of YD climate change is less straightforward than the records from the northern tropics. However, the overall pattern suggests that rainfall was restricted to certain lowland tropical regions, and less precipitation was reaching the Andes, which in turn could have affected Amazon Basin discharge. Mountain glacier records indicate that ice margins were retreating during this period, as a result of decreased snow fall (Rodbell and Seltzer, 2000). Lake Titicaca water levels, on the Altiplano, were progressively lowering during the YD (Rowe et al., 2002), and Amazon River discharge was extremely low (Maslin and Burns, 2000). Conversely, it has been interpreted that Lake Titicaca water levels were rising during the YD (Baker et al., 2001), and the lake level high stand within the Copiasa basin on the

Altiplano has tentatively been dated to between ~13,000 and 12,000 cal yr BP (Placzek et al., 2003). Ice core evidence also suggests that the YD was cold and wet in the Central Andes (Thompson et al., 1998), which is corroborated by speleothem records (Fig. 3.1) from the Peruvian lowlands that indicate precipitation was higher (van Breukelen et al., 2008). Mountain records suggest that glaciers advanced in Ecuador (Clapperton et al., 1997), but this evidence is debatable (Heine, 1993; Rodbell and Seltzer, 2000). More records from the southern and equatorial tropics are clearly needed in order to determine which regions varied in precipitation during the YD.

3.2.6. Pre-Boreal cooling in the northern tropics (11,650 to 10,000 cal yr BP)

The onset of Pre-Boreal warming marks the end of YD cooling in the northern hemisphere and a slowing of warming in Antarctica (Jouzel et al., 2007). A Pre-Boreal Oscillation (PBO), or slight reversal in Northern Hemisphere temperature occurred between ~11,300 and 11,100 cal yr BP (Fisher et al., 2002), during a period of increased freshwater flux to the oceans (Peltier and Fairbanks, 2006). The LA record from Venezuela shows a possible PBO-related increase in clastic and decreased biogenic silica fluxes (Fig. 3.3), at a time of colder temperatures in the Cariaco Basin (Lea et al., 2003). Following the PBO, clastic flux in the LA record remained low, biogenic silica flux increased, and palynological proxies indicate a higher tree line and wetter conditions between ~11,100 to 10,500 cal yr BP.

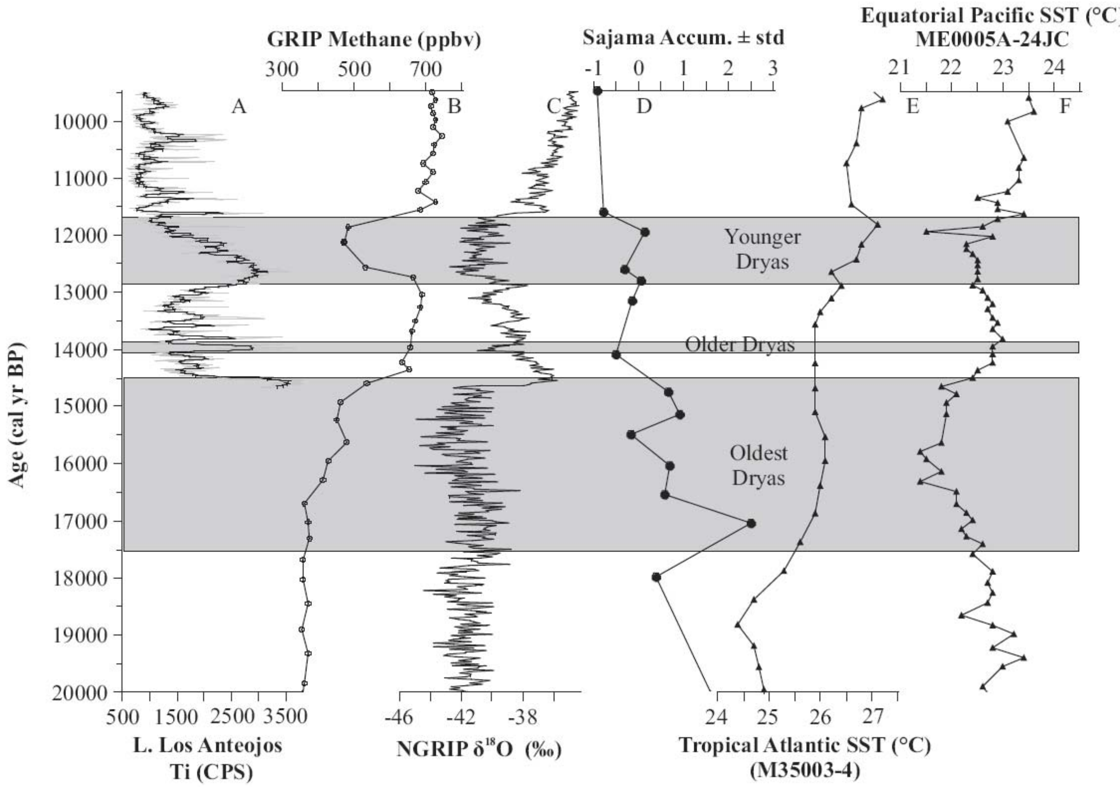

Figure 3.6. The LA titanium record of glaciation from the Venezuelan Andes (A). The GRIP methane (B) (Blunier et al., 1995) and NGRIP oxygen isotope records (C) (Rasmussen et al., 2006) from Greenland indicate that northern tropical humidity decreased and high northern latitude temperature cooled synchronously with lower temperature in the northern tropical Andes. The Sajama accumulation record (D) (Thompson et al., 1998) shows increased values at the beginning of the Oldest Dryas and the Younger Dryas. The tropical Atlantic (E) (Rühlemann et al., 1999) shows a warming trend during the Oldest Dryas, whereas the equatorial Pacific (F) (Kienast et al., 2006) was cooling. The tropical Atlantic and equatorial Pacific were warming during the Younger Dryas, while the northern tropical atmosphere was cooling.

The clastic record from LA suggests that glaciers advanced between ~10,500 and 10,200 cal yr BP. Elsewhere in the Venezuelan Andes, lake sediment records indicate an abrupt shift to non-glacial (ice-free) conditions in multiple watersheds at ~10,000 cal yr BP (Stansell et al., 2005). The highlands of Mexico (Vazquez-Selem and Heine, 2004) and Costa Rica (Orvis and Horn, 2000) also experienced a cold interval sometime after the YD and before the Holocene. In contrast, the southern hemisphere tropics were mostly ice free by ~13,000 cal yr BP (Seltzer et al., 2002), and with the exception of Vostok, the polar ice core records show no major climatological changes at a time of advancing ice margins in the northern tropics.

3.3. THE ROLE OF THE TROPICS IN ABRUPT LATE-GLACIAL CLIMATE CHANGE

Changes in the thermal contrast between the tropical Pacific and Atlantic oceans can influence the strength of the northeast trade winds that in turn affects low latitude circulation. Any perturbation that impacts low latitude atmospheric circulation has a rapid impact on tropical climate. Greater wind speed over the tropical ocean results in increased moisture transport from the Atlantic, cooler and wetter conditions in the tropical Pacific (Pahnke et al., 2007), and drier conditions in the Caribbean region. These changes in moisture transport are important for modulating salinity and density variations in the tropical Atlantic, which ultimately impact thermohaline circulation and temperatures in the high latitudes (Schmidt et al., 2004).

The position of the ITCZ generally follows the seasonal cycle of solar declination. On long time-scales, seasonality in the tropics is controlled largely by the precessional (~26,000 year) cycle. On shorter, millennial-scale time periods, the strength, position and intensity of the ITCZ is affected by SST and pressure gradients in the tropical Atlantic and Pacific oceans. Increased sea ice in the North Atlantic region during cold phases of the LG would likely have steepened the latitudinal SST gradient and caused the ITCZ to shift south or become less intense (Schiller et al., 1997; Vellinga and Wood, 2002). A more southerly ITCZ would likely cause the northern tropics to be drier and the southern subtropics would experience increased precipitation.

Changes in tropical water vapor content are closely related to temperature, and both act as positive feedbacks for one another. A high latitude, North Atlantic, mechanism may have caused a displacement of tropical moisture belts, and combined with low latitude feedbacks, may have had a major impact on global temperature changes during the LG. Mounting evidence suggests that the oceanic ‘bipolar see-saw’ mechanism was operating on millennial time-scales following the Last Glacial Maximum (Blunier and Brook, 2001). The associated transfer of heat back and forth to the poles would likely cause an increase of sea-ice in the respective cold regions, and have large impacts on the northern and southern tropics (Schiller et al., 1997). The mean position of monsoonal belts and the ITCZ in the tropics would shift north or south depending on the location of increased cooling (Vellinga and Wood, 2002). Changes in tropical water vapor content in the respective warmer continent would then amplify rising temperatures, and be recorded by glaciers in the Andes more directly than by marine sediments.

Strong evidence from marine records suggests that the Oldest Dryas was a period of increased sea ice in the North Atlantic during H1 (Bond et al., 1993). Overall, the northern tropical atmosphere was colder and drier during this period, while the southern subtropics experienced a sharp increase in precipitation (Placzek et al., 2003). These records fit the model of an overall southerly shift in the ITCZ during the Oldest Dryas. The equatorial Pacific (Fig. 3.6) generally co-varied with Greenland during this period, whereas the eastern tropical Atlantic was warming. No major temperature changes are shown in the Cariaco Basin climate records (Lea et al., 2003), which suggests that the high latitude variability operating during this interval did not have a major impact on Circum-Caribbean temperature. The reduction in North Atlantic deep water (NADW) formation during H1 and the Caribbean record of climate change, however, indicates that the tropical oceans played a major role in modulating global temperatures (Schmidt et al., 2004).

The warming in the northern hemisphere at the onset of the Bølling was too abrupt to be driven by astronomical forcing alone, which usually operates over much longer (greater than ~10,000 year time-scales). Glaciers retreated in the Venezuelan Andes, during a period of much wetter conditions in the northern tropics (Schmidt et al., 2004; Hodell et al., 2008). The Central Andes experienced decreased precipitation during this warm interval, which suggests that the ITCZ was situated further north, and the South American summer monsoon was weaker at this time. The Northern Hemisphere Bølling also coincided with colder conditions in the high southern latitudes (i.e. the ACR). Increased sea ice in the high southern latitudes during this cold phase could have forced a northward displacement of the ITCZ, which would enhance the northern hemisphere hydrologic cycle and atmospheric warming (Schmidt et al., 2006), and eventually export to the higher northern latitudes resulting in warmer and wetter conditions.

The abruptness of warming at the onset of the Bølling suggests that it may have been associated with a large fresh water discharge, and perhaps may have been coincident with the timing of meltwater pulse 1A (mwp-1A). It has been proposed that the source of this fresh water pulse originated in the Southern Hemisphere as a result of decaying Antarctic ice sheets (Weaver et al., 2003). Freshening of sea water could have resulted in perturbations in the Southern Ocean and NADW formation that subsequently triggered warming at the onset of the Bølling, and the ACR (Weaver et al., 2003). However, recent improvements in the chronology of sea level rise during the last deglacial, indicate that MWP-1A may have been a result of Bølling warming, and not its cause, because MWP-1A lagged by several hundred years (Peltier and Fairbanks, 2006; Stanford et al., 2006).

The specific timing of mwp-1A and LG sea-level rise are debated (Weaver et al., 2003), however, using the current ages from Peltier and Fairbanks (2006) (Fig. 3.3), mwp-1A (~14,100 to 13,900 cal yr BP) coincides with increased clastic flux and advancing ice margins in the Venezuelan Andes. Greenland, the Cariaco Basin and the Venezuelan Andes all experienced colder conditions (Fig. 3.3) while the lowland northern subtropics experienced decreased precipitation (Hodell et al., 2008). The southern tropical manifestation is less clear during this interval, but a slight increase in snow accumulation at Sajama (Thompson et al., 1998) suggests that colder Northern Hemisphere conditions during this ~200 year interval caused a southward shift in the ITCZ and monsoonal belts over the South American continent.

The record of aridity in the northern Andes during the Allerød does not follow the millennial-scale pattern of north-south aridity that is apparent during most of the earlier LG. The Allerød period in the northern tropical Andes marks a transition from warm and wet to colder and/or drier conditions just prior to the onset of the Younger Dryas. In contrast, the lowland northern tropical records indicate that conditions were locally wetter (Haug et al., 2001; Hodell et al., 2008). The high southern latitudes (Ackert Jr. et al., 2008) and the southern subtropics were relatively dry (Placzek et al., 2003) during this interval. The patterns of precipitation between the low and high altitudes were not always in phase, and increased moisture flux may have been restricted to the lowlands. It is also interesting that the end of Allerød warming in the Northern Hemisphere also marks the coldest period of the ACR in the Southern Hemisphere. This increase in sea ice in the high southern latitudes may have contributed to the pattern of increased aridity in the northern Andes, at a time of wetter conditions in the northern subtropics.

The Younger Dryas was a period of colder conditions and increased sea ice in the Northern Hemisphere (Bond and Lotti, 1995). The northern tropical lowlands (Haug et al., 2001; Hodell et al., 2008), northern Andes (Fig. 3.3) and the Amazon Basin (Maslin and Burns, 2000) were cold and dry during this interval. Mountain glacier records from Peru (Rodbell and Seltzer,

2000) and lake level records from the Altiplano (Rowe et al., 2003) suggest that conditions were drier in the southern tropics during the YD, even though ice core records (Thompson et al., 1998) and speleothem records from the nearby lowlands (van Breukelen et al., 2008) suggest wetter conditions. The high southern latitudes were also wet during the YD (Ackert Jr. et al., 2008). Thus, while there are some discrepancies between the mountain glacier and lake basin records from the southern Andes, overall conditions were likely wetter in the southern hemisphere lowlands and drier in the northern tropics and high southern Andes during the YD. The increased sea ice in the North Atlantic during the YD likely contributed to a southward displacement of the ITCZ, intensification of the easterlies and a shift in moisture convergence to a more southerly position.

The influence of high latitude sea-ice extent on tropical climate during the LG seems to diminish sometime during the YD. After ~12,500 cal yr BP, periods of advancing ice in the northern Andes do not correspond to any major change in either Antarctica or Greenland. Likewise, the tropical ice core records do not show major changes during the Pre-Boreal, and mountain glaciers in precipitation sensitive regions of Peru did not advance after ~13,000 cal yr BP until the early Holocene (Seltzer et al., 2002).

During most of the LG, moisture-balance records in the northern tropics were out of phase with the southern tropics, and were tightly coupled with climate changes in Greenland and Antarctica. After the YD, however, records of precipitation from the northern Andes seem to be more in phase with the Southern Hemisphere (Polissar et al., 2006a). It is also interesting that paleo-records from the northern subtropics do not show a pronounced reduction in moisture balance following the YD until the present (Lachniet et al., 2004; Hodell et al., 2008), which is what would be expected if orbital variations were the dominant controls of moisture convergence following the LG (Hodell et al., 1991; Haug et al., 2001). The north Atlantic probably still played a major role in Pre-Boreal and Holocene climate change (Broecker, 2000), but the influences of the sun in ocean-atmospheric processes may have become more dominant in the Holocene when the influence of the large ice sheets were reduced or absent (Bond et al., 2001).

3.4. CONCLUSIONS

The northern tropical marine and alpine records from Venezuela were in phase with Greenland during most of the LG, and low latitude ocean-atmosphere heat, salinity and water vapor changes probably played a major role in the observed abrupt climate changes. The origin of millennial-scale climate variability is still debatable, but the clear linkage between low and high latitude systems emphasizes the role of tropical atmospheric processes in modulating global temperature and moisture-balance during these periods. Improved age control for the timing and patterns of precipitation in the tropics are still needed, especially for the YD, however, the abrupt temperature shifts at the beginning and end of LG events further emphasizes the role of the atmosphere in abrupt climate change (Steffensen et al., 2008).

4. NEOGLACIATION AND CLIMATE CHANGE IN THE CORDILLERA RAURA, PERU

4.1. INTRODUCTION

Accumulating information about mountain glacier advances and retreats indicates that the southern hemisphere experienced multiple abrupt glacial advances during the Holocene (Denton and Karlen, 1973; Gellatly et al., 1988; Bradley et al., 2003; Glasser et al., 2004; Mayewski et al., 2004). The causes of such events are not clear, however, because glaciers have a complex energy balance that is affected by changes in albedo, temperature and precipitation (Francou et al., 2003; Favier et al., 2004). Furthermore, individual glaciers are affected not only by global-scale forcing, but also by regional and local climate dynamics, making it difficult to determine the specific variables responsible for mass-balance variability (Oerlemans, 2001). These complications coupled with dating uncertainties and the inherently discontinuous nature of the moraine record, make it difficult to precisely determine the causes and patterns of Holocene climate change based on the existing alpine records.

Solar forcing combined with ocean-atmospheric processes seems to be the dominant mechanisms for climate change during the Holocene (Mayewski et al., 2004), and particularly in driving glacier mass-balance changes in the Andes (Polissar et al., 2006b). It is not clear, however, how these systems are interrelated as observable environmental changes require an atmospheric response to external (solar) forcing (Haigh, 1996). Regardless of the initial forcing, alpine glaciers ultimately respond to atmospheric changes, and are therefore useful recorders of variations in past air temperature and precipitation.

Paleo-records of atmospheric changes from the tropical Andes are particularly important in climate studies because the low latitudes are especially sensitive to changes in temperature and the hydrologic cycle, that ultimately influence global climate. A growing body of data on tropical climate change is available from ice cores (Thompson et al., 2006), lake sediments (Seltzer et al., 2000), and glacier mass-balance studies (Francou et al., 2003; Vuille et al., 2008). However, atmospheric conditions and the response of tropical mountain glaciers to climate change during the Holocene are still poorly understood. Here we present a high resolution sedimentological record of neoglacial variability from the Cordillera Raura in Peru in order to further explore the causes and timing of Holocene climate change, and to better understand how temperature and moisture availability have varied in the southern tropical atmosphere during the neoglacial.

4.2. STUDY SITE

The Cordillera Raura and Lake Lutacocha (10.56°S, 76.73°W, 4320 m) are situated between the Cordillera Blanca and the Junin Plain in the Central Peruvian Andes (Fig. 4.1). This location is ideal for studying neoglacial climate variability because glaciers here are highly sensitive to temperature and precipitation changes (Ames and Hastenrath, 1996), and there are numerous proxy records from nearby lakes (Seltzer et al., 2000) and glaciers (Thompson et al., 1995) that are useful for comparison. Climate here is typical of the tropical Andes, with a diurnal temperature variation (~20ºC) that greatly exceeds the seasonal difference. Annual temperature variation is strongly dependent on Pacific sea-surface temperature (SST), humidity and cloud cover (Johnson, 1976). Temperature in this region of the Andes also appears to be affected, to a lesser degree, by Atlantic SST variability (Henderson et al., 1999). Moisture is derived primarily from evaporation in the Atlantic Ocean and Amazon Basin, and precipitation in the form of rain and snow eventually reaches the Andes via the easterlies. Precipitation variability is affected by a combination of continental as well as Pacific and Altantic SST anomalies that affect the pattern of moisture convergence (Vuille et al., 2000b). An average of ~1200 mm/yr of frozen precipitation falls on the existing glaciers in the Raura (Ames and Hastenrath, 1996). A negative precipitation gradient is present on the western slope of the Raura and only ~520 mm/yr of precipitation reaches a station in the town of Oyon, ~10 km southwest of Lutacocha.

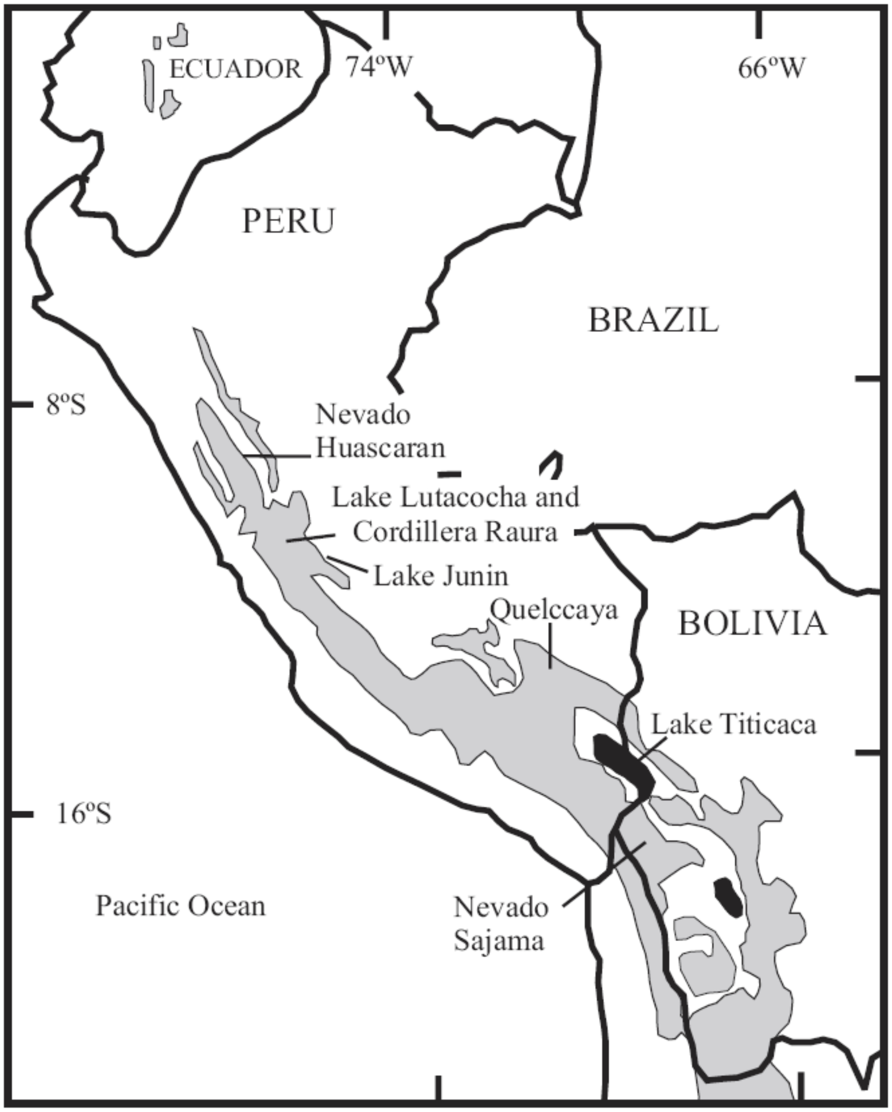

Figure 4.1. Location map of study site. Lake Lutacocha is in the Northern Peruvian Andes between Nevado Huascaran and Lake Junin. Shaded area is >4000 m in elevation. Lutacocha is on the western side of a prominent rain shadow with much higher precipitation on eastern slopes and high elevations in the mountains. Modern glaciers have been mapped as low as 4650 m in the watershed, with a modern ELA of 4900 m. The neoglacial maximum ice limit was mapped at 4350 m, with a corresponding ELA lowering of ~190 m.

4.3. METHODS

A 340 cm composite sediment core was taken from Lake Lutacocha in 2005 using a square-rod piston corer (Wright et al., 1984). In the laboratory, cores were split, digitally scanned to produce an optical image, analyzed using scanning electron microscopy (SEM), and described for major sedimentological features and Munsell Color. The upper 290 cm of finely laminated sediments were measured using an ITRAX scanning X-Ray Fluorescence (XRF) instrument every 1 mm. Calcium carbonate and organic carbon content were measured by coulometry every 3-5 cm. Radiocarbon ages were converted to calendar ages using CALIB version 5.0.2, and the Intcal 04 dataset (Reimer et al., 2004). An age-depth model (Fig. 4.4) was constructed using a 5^{th} order polynomial fit (R^2=.99) between 10 radiocarbon dated charcoal samples (Table 4.1).

Table 4.1. Lutacocha radiocarbon ages measured on charcoal (median ages in parentheses).

Lab #	Depth (cm)	Age ^{14}C (BP)	±	Calibrated age range (Cal yr BP)
UCI-22772	61	520	25	510 (530) 554
UCI-37625	76.5	205	40	135 (180) 226
UCI-37626	88.5	520	25	510 (530) 554
UCI-37627	108.5	930	30	782 (850) 925
UCI-37628	136.5	1260	30	1166 (1220) 1281
UCI-22773	182	2000	30	1879 (1940) 2003
UCI-37541	201.5	1935	20	1857 (1890) 1928
UCI-22850	226.5	2435	35	2353 (2450) 2545
UCI-25181	253.5	3030	30	3157 (3250) 3345
UCI-22851	291.5	4615	30	5374 (5420) 5462
				*Omitted
UCI-25180	131	370	20	427 (460) 500*
UCI-37629	362.25	740	45	642 (692) 741*

Three till matrix and 9 bedrock samples representing the exposed units in the field area were collected in 2006 in order to geochemically identify source materials for terrigenous lake sediments (Fig. 4.2). These samples were measured using ICP-AES and ICP-MS (Table 4.2). Bulk sediment geochemistry on 5 samples from the Lutacocha core was measured by ICP-AES and ICP-MS with near total digestion procedures (Table 4.2). Cation chemistry (Table 4.3) was also measured on modern water samples by ICP-AES.

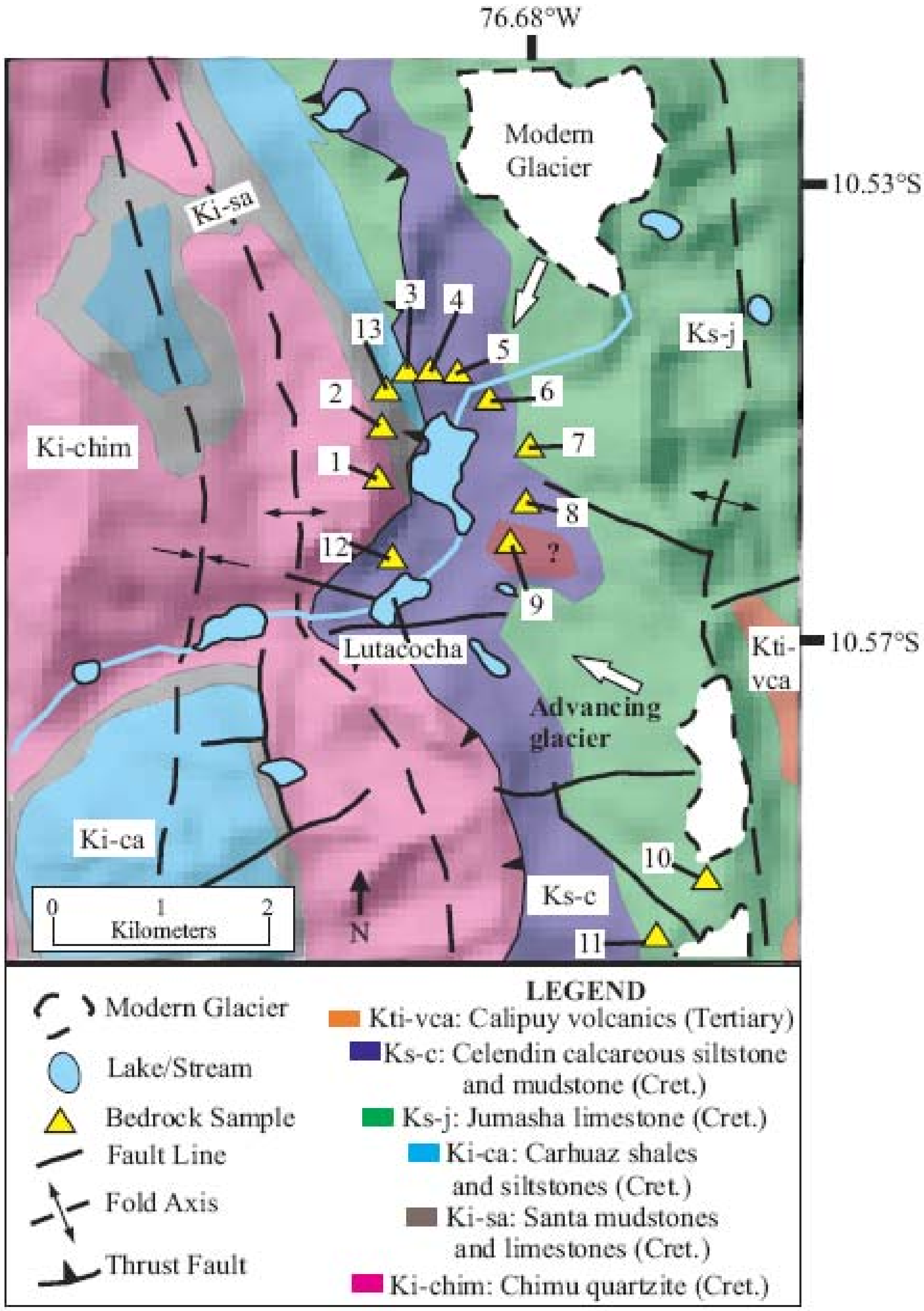

Figure 4.2. Sample locations and bedrock geologic map of the Lutacocha field area.

4.4. RESULTS

4.4.1. Sedimentology

The Lutacocha sediments are dominated by terrigenous mineral matter (>90%) as determined by both visual inspection and SEM imaging. The majority of the core is laminated at millimeter-scale with the exception of four gray-colored (Gley 5/1) units that are up to 10 cm thick (centered on depths 70, 86, 122 and 164 cm). The basal ~40 cm of the core are massive, dark gray, contain abundant plant macro-fossils, and are capped by a ~10 cm thick yellowish-brown and grayish brown sand layer. A composite of the digital image of the Lutacocha sediment core is presented in Fig. 4.3.

4.4.2. Geochemistry

Coulometry data (Fig. 4.3) indicate that the majority of the Lutacocha core has low (<10%) organic carbon content, and high (20-80%) calcium carbonate content. The most recent sediments are dominated by detrital calcium carbonate, and the modern water chemistry from Lutacocha likewise indicates high Ca (34.1 mg/L) and low Ti and Fe concentrations (0.004 and 0.003 mg/L, respectively). Bulk sediment elemental geochemistry data (Table 1) indicate down-core calcium values ranging from 10 to 27 percent.

Calcium carbonate is the dominant component of the sediments, but it is highly variable, and the scanning XRF data indicate sections of the core with low Ca become dominated by Fe, and to a lesser degree, Ti (Fig. 4.3). Sections of core with relatively high Ti and Fe occur between 25-110, 130-175 and 195-250 cm. Conversely the upper 25, 110-130, 175-195 and 250-290 cm are relatively high in Ca.

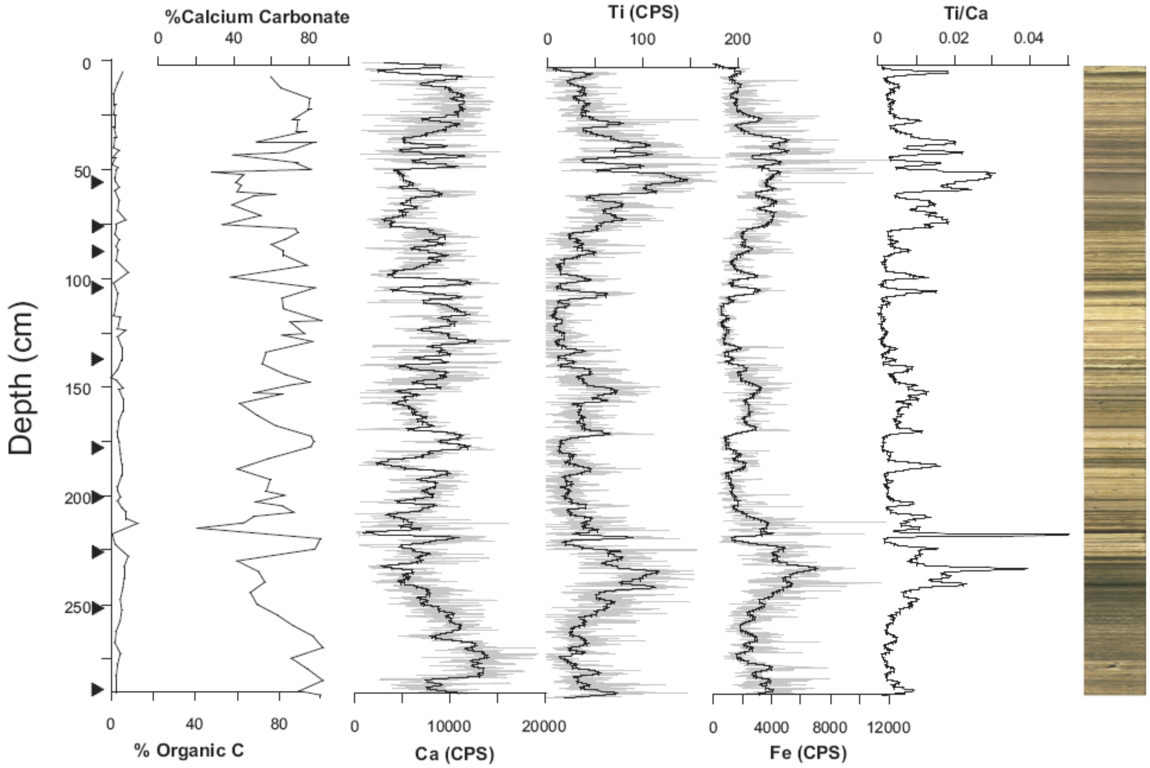

Figure 4.3. Top 290 cm of the Lutacocha core data and digital core scan. The percent organic carbon and percent $CaCO_3$ data were measured using coulometry. The Ca, Ti and Fe data were measured using an ITRAX scanning XRay Fluorescence instrument every 1mm. The XRF data were plotted as raw (gray) and smoothed using a Lowess filter with a 0.01 loading (black). The Ti data were normalized to Ca in order to highlight changes in source detritus. The Black triangles indicate locations of samples taken for radiocarbon dating.

During the 2006 field season, the glacier in the Lutacocha watershed was situated entirely on the Jumasha Limestone with high calcium (~33%), low Ti (~0.1%) and low Fe (~0.8%) concentrations. The till matrix sample collected near the margin of Lake Lutacocha has very low Ca (less than 1%), high Ti (~0.5%) and Fe (~5%). The other till matrix samples have Ca values that are up to 30%, but still have high Ti and Fe concentrations. In addition, a sample from an outcrop of felsic volcanic rocks has high Ti (~0.5%), high Fe (~3%), and very low Ca (~3%) relative to the carbonate samples. The other bedrock samples (Table 4.2) have variable chemical compositions, but in general all till deposits are lower in Ca and higher in Fe and Ti than most of the bedrock in the region.

Table 4.2. Bedrock and bulk sediment geochemical data measured using ICP-MS. Samples in bold represent end-member source material for the Lutacocha sediments. The present day glacier is situated on Jumasha limestone with high Ca, and low Ti and Fe. The volcanic rocks are below the present-day active glacier, have high Ti and Fe, and low Ca. The Ti and Fe values for the volcanic rocks closely match the chemistry of glacial till samples in the region, and were probably a primary source material for glacial detritus at times of glacial advances. The bulk sediment geochemistry confirms the scanning XRF data are accurately representing the sediment core geochemistry.

Bedrock Samples	**Sample #**	**Description:**	**Lat**	**Lon**	**Al (%)**	**Ca (%)**	**Fe (%)**	**K (%)**	**Mn (ppm)**	**Na (%)**	**S (%)**	**Ti (%)**	**Zn (ppm)**	**Zr (ppm)**
	1	Quartzite (Ki-chim*)	-10.55344	-76.72972	0.39	**0.14**	**1.14**	0.15	786.00	0.07	0.01	**0.05**	11.00	14.70
	2	Calcareous mudstone (Ki-sa*)	-10.54904	-76.72914	2.81	**29.20**	**1.23**	0.92	522.00	0.12	0.05	**0.12**	55.00	33.40
	3	Calcareous shale (Ki-ca*)	-10.54710	-76.72860	1.73	36.1	1.09	0.41	227	0.06	0.15	0.088	60	23.9
	4	Coarse-bedded limestone (Ks-c*)	-10.54790	-76.72852	0.86	**34.60**	**0.41**	0.32	149.00	0.09	0.11	**0.04**	20.00	14.00
	5	Calcareous mudstone (Ks-c*)	-10.54785	-76.72817	1.60	**32.40**	**0.92**	0.55	268.00	0.10	0.23	**0.08**	39.00	20.60
	6	Calcareous bedded mudstone (Ks-c*)	-10.54646	-76.72619	2.13	**30.90**	**1.00**	0.62	245.00	0.17	0.17	**0.10**	68.00	28.50
	7	Limestone (Ks-j*)	-10.55237	-76.72318	1.72	**30.80**	**1.00**	0.56	143.00	0.04	0.36	**0.08**	16.00	24.90
	8	Calcareous siltstone (Ks-c*)	-10.55393	-76.72351	1.74	**34.80**	**0.75**	0.56	198.00	0.09	0.23	**0.09**	44.00	20.00
	9	Felsic, fine-grained volcanic (Kti-vca*)	-10.55535	-76.72380	8.30	**3.37**	**3.19**	1.90	710.00	3.66	0.03	**0.45**	101.00	115.50
	10	Fossiliferous limestone bedrock (Ks-j*)	-10.58387	-76.71162	1.06	**35.60**	**0.67**	0.35	184.00	0.03	0.33	**0.05**	164.00	12.70
		*Ki-chim: Chimu quartzite	*Ki-sa: Santa mudstones and limestone					*Ks-c: Celendin calcareous siltstone and mudstone						
		*Ks-j: Jumasha limestone	*KTi-vca: Calipuy Tertiary volcanics					*Ks-ca: Carhuaz gray and brown shales and siltstones						
Till Matrix Samples	**Sample #**	**Description:**	**Lat**	**Lon**	**Al (%)**	**Ca (%)**	**Fe (%)**	**K (%)**	**Mn (ppm)**	**Na (%)**	**S (%)**	**Ti (%)**	**Zn (ppm)**	**Zr (ppm)**
	11	Breached moraine (unknown age), till matrix	-10.58452	-76.71149	2.22	**30.60**	**1.14**	0.77	281.00	0.05	0.18	**0.12**	56.00	29.00
	12	Late Glacial till matrix	-10.56102	-76.73164	8.49	**0.67**	**4.78**	2.44	620.00	0.38	0.18	**0.51**	187.00	3.80
	13	Late Glacial till matrix	-10.54815	-76.72911	2.67	**28.00**	**1.30**	0.81	318.00	0.13	0.04	**0.14**	74.00	36.00
Lutacocha Sediment		**Depth:**	**Lat**	**Lon**	**Al (%)**	**Ca (%)**	**Fe (%)**	**K (%)**	**Mn (ppm)**	**Na (%)**	**S (%)**	**Ti (%)**	**Zn (ppm)**	**Zr (ppm)**
Core Samples		52-53 cm (LIA glacial flour)	-10.55477	-76.71677	6.12	11	2.15	1.8	414	0.07	0.45	0.196	961	62
		114-114.5 cm (Carbonate-rich layers)	-10.55477	-76.71677	1.81	25.7	1.07	0.54	208	0.06	0.35	0.057	316	21.2
		211.5-212 cm	-10.55477	-76.71677	1.97	17.5	1.06	0.56	173	0.05	0.73	0.073	427	21.7
		233-233.5 cm	-10.55477	-76.71677	3.76	10.15	2.49	1.18	216	0.09	2.42	0.145	1835	40.5
		283.5-285.5 cm	-10.55477	-76.71677	1.42	26.9	0.99	0.43	515	0.06	0.91	0.049	704	14.6

Table 4.3. Lutacocha modern water cation concentration data.

Cation:	Mg	K	Mn	Sr	Ba	Zn	Al	Si	P	S	Na	Ca	Fe	Ti
concentration (mg/l)	7.890	0.909	0.000	0.365	0.014	0.023	0.168	1.029	0.072	8.810	1.466	34.140	0.004	0.003
stdev	0.121	0.112	0.001	0.002	0.000	0.000	0.042	0.027	0.004	0.094	0.344	0.865	0.005	0.002

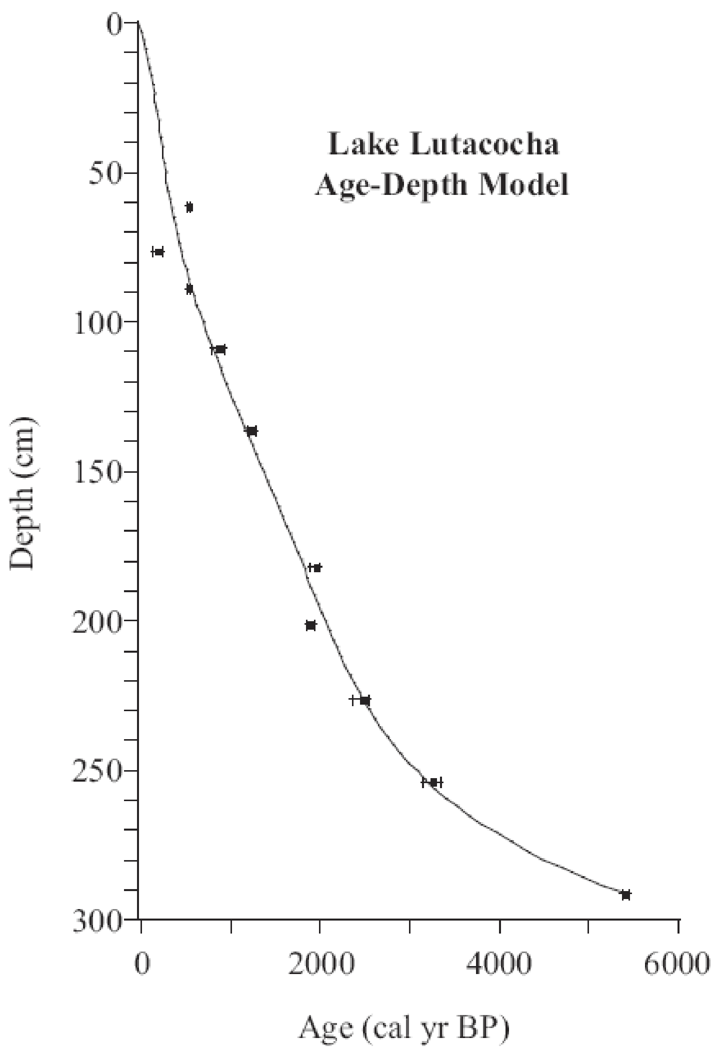

Figure 4.4. Lutacocha Age Model based on 10 charcoal samples. Radiocarbon ages were converted to calendar years before present (cal yr BP, where Present is 1950) using CALIB version 5.0.2. Error bars represent 2 sigma values.

4.5. DISCUSSION

4.5.1. The Lutacocha record of neoglacial variability

The periods of increased glacial surface area probably correspond to sections of the Lutacocha core that are relatively high in gray (Gley 5/1), low carbonate, inorganic sediments that are also high in Ti and Fe, and have a similar chemistry to the till matrix samples collected from the watershed. In contrast, the sections of the core that represent periods of decreased glacier extent are yellow (5Y, 8/2), high in calcium carbonate, and low in Ti and Fe. We chose these elements as robust proxies for changes in the source material of watershed erosion because they dominate the chemistry of the Lutacocha sediment core, and have sharply contrasting concentrations between watershed bedrock samples. Furthermore, Ti and Fe covary, which rules out redox changes as a major influence on Fe content in the Lutacocha sediments (Yarincik et al., 2000; Haug et al., 2001). Calcium (Ca) reflects calcium carbonate content (Fig. 4.2) and scanning electron microscopy confirms that most of the carbonate grains throughout the core are weathered and eroded, and therefore came from a terrigenous source. Likewise, organic carbon is low (usually less than 4%), confirming that the sediments are mostly inorganic.

The present-day glacier is situated almost entirely on calcium carbonate bedrock (Cobbing et al., 1981; Cobbing and Garayar, 1998). However, downvalley of the glacier's current position, the bedrock consists of calcium carbonate-rich shales and sandstones, quartzite and small outcrops of tertiary volcanic rocks. Thus, when the glacier advanced in the past these rock units were eroded and transported into the lake. Whole rock geochemistry confirms the present day glacier is eroding bedrock high in Ca, and low in Ti and Fe (Table 4.1). In contrast, the bedrock units beneath the current ice front, and till matrix samples, are relatively high in Ti and Fe, and low in Ca. Assuming that glacial processes dominate erosion in the Lutacocha watershed, changes in chemical composition of the detritus in the sediments over time reflect changes in glacier surface area. Specifically, as the glacier in the Lutococha watershed glacier advances, the proportion of detritus should shift from mostly limestone, as is the case today, to a more mixed lithology with higher Ti and Fe (advanced glacier).

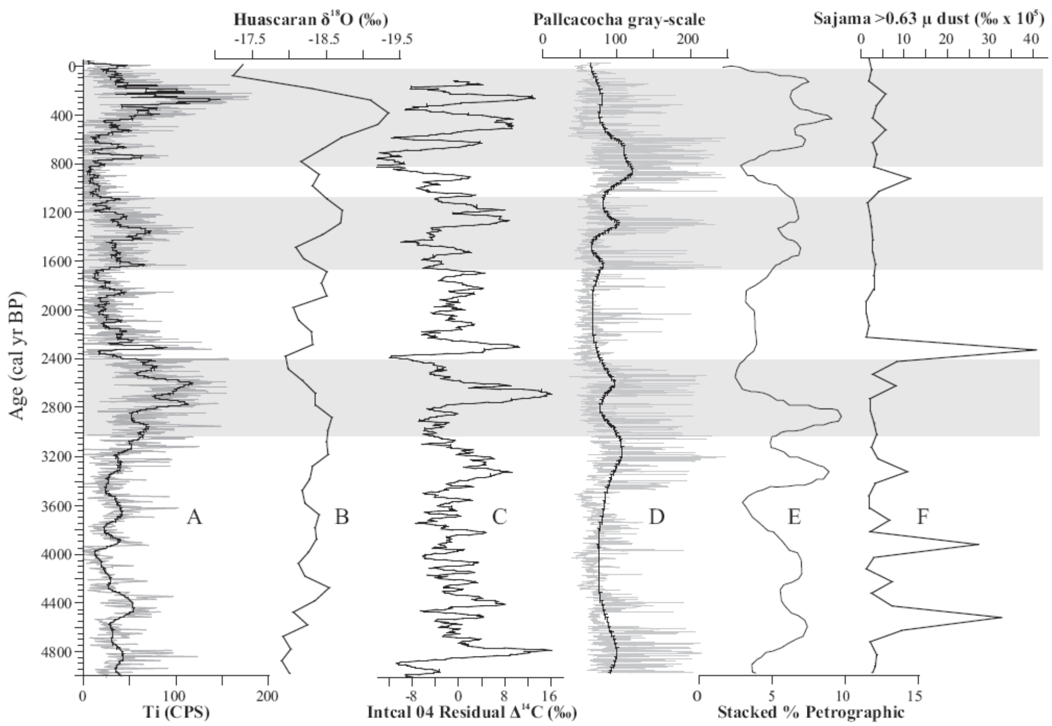

Figure 4.5. Lutacocha Ti (CPS) data (A) plotted versus regional records of climatic variability. Glaciers in the C. Raura were lower than today from 3100 to 2400, 1700 to 1100 and 800 to 150 cal yr BP. Huascaran (B) oxygen isotope data (Thompson et al., 1995) indicates conditions were generally colder and/or wetter during periods of advancing glaciers in the C. Raura. The Intcal 04 ^{14}C record (C) (Reimer et al., 2004) as a proxy for solar variability suggests that glaciers were advancing during periods of decreased solar activity. Pallcacocha, Ecudor gray-scale data (D) (Moy et al., 2002) with high values representing increased ENSO activity. Glaciers in the Late Holocene advanced during less frequent ENSO events. Bond et al. (2001) North Atlantic drift ice index (E). Sajama, Bolivia (F) dust accumulation record indicating higher values during periods of regional aridity.

Our model assumes changes in sedimentation were nearly synchronous with changes in glacierization, and the lag time for the release of glacial sediments trapped in ice was negligible.

Our reasoning is based on the observation that tropical glaciers are in a state of nearly constant flux, and respond rapidly to changing climate (Kaser, 2001; Kaser and Osmaston, 2002). Likewise, in this system, the rapid accumulation-ablation turnover rate of tropical glaciers (Francou et al., 2003) should result in nearly synchronous (sub-decadal) changes in glacial surface area, and thus the types of sediments being transported and deposited. We assume that sections of increased Ti and Fe in the Lutacocha record probably took place at or near the time glaciers were in an advanced state.

4.5.2. Cordillera Raura neo-glacial record and paleoclimatic significance

Based on our model of the results from lake sediment analyses, ice margins were lower than today in the Cordillera Raura from 3100 to 2400, 1700 to 1100 and 800 to 150 cal yr BP (Fig. 4.5). Interpreting Cordillera Raura glacier mass-balance changes in the context of regional climate variability requires careful consideration because of the lack of modern instrumental climate data. However, glaciers in the near-by Cordillera Blanca have been comparatively well-studied and behave in a similar fashion to glaciers in the Cordillera Raura (Ames and Hastenrath, 1996). Here we use data from the Cordillera Blanca as a framework for this discussion.

Glaciers in the Cordillera Raura are currently precipitation limited (Hastenrath, 1967a; Dornbusch, 1998). Vuille et al., (2008) suggest that on inter-annual timescales glacier mass-balance in this region appears to be more strongly related to moisture availability than temperature. Determining the exact contribution of specific climatic variables is complicated, however, because glaciers in these regions are ultimately affected the most by albedo changes (Favier et al., 2004), which results from a combination of precipitation (amount and type), cloud cover and radiation budget factors. Nevertheless, glaciers in the Cordillera Raura and Cordillera

Blanca behave similarly to Central Andean glaciers that have a mass-balance that is sensitive to changes in moisture availability, and to a lesser degree, temperature (Vuille et al., 2008).

Moisture availability and glacier mass-balance in the Central Andes on inter-annual timescales seems to be most affected by Pacific SST anomalies (Vuille et al., 2000a). On longer timescales spanning the Holocene, however, moisture seems to be more controlled by insolation forcing and feedbacks controlling the strength of wet-season convection (Abbott et al., 1997b; Martin et al., 1997). It seems reasonable, then, that the overall Holocene pattern of ice cover changes in the Central Andes is also affected largely by insolation-driven changes in moisture availability. Indeed, the timing of neoglaciation during the middle and late Holocene in the Central Andes generally follows the timing of higher lake levels in the region (Rowe et al., 2002; Abbott et al., 2003), and increased moisture availability that was gradually enhanced by precessional forcing of precipitation (Seltzer et al., 2000).

Temperature is not the main driver of glacier mass-balance variability, but it is still an important component of mass-balance in this region. Recent reports have highlighted the importance of rising temperatures (Oerlemans, 2005), and the added impact of ENSO on melting tropical glaciers (Francou et al., 2003). Unfortunately the glacial response to ENSO on longer (centennial and millennial) timescales is poorly understood even though ENSO has apparently varied substantially through the Holocene (Rodbell et al., 1999; Moy et al., 2002). ENSO dominates the modern system of inter-annual variability (Vuille et al., 2008), and the last ~1000 years of glacial variability in the Raura shows a trend toward increased ice volume during less frequent ENSO events (Fig. 4.5) (Moy et al., 2002). This tentatively may be explained by more frequent positive (warm) phases of ENSO causing glaciers to retreat because of increased temperatures, and decreased precipitation and cloud-cover in the Andes (Francou et al., 2003).

Less frequent ENSO events over certain sustained periods during the last ~1000 years may have allowed glaciers to advance as a result of lower temperatures, and increased precipitation and cloud cover. Stronger or more frequent ENSO events during shorter-scale events, such as the latter half of the LIA, may have contributed to decreased ice cover in the Andes.

The available marine records of ENSO do not always correspond to the Andean (Pallcacocha) record of precipitation changes, and glaciers in the Cordillera Raura may have retreated during periods of fewer El Niño events. For instance, a high resolution record of flooding from off the coast of Peru indicates that the Medieval Climate Anomaly (MCA) (1150 to 700 cal yr BP) was a period of severe drought and decreased precipitation (Rein et al., 2004). Glaciers in the Cordillera Raura retreated during the MCA, possibly as a result of increased aridity. The marine records off the coast of Peru indicate that following the MCA, El Niños became more frequent (Rein et al., 2005) while glaciers advanced anew in the Cordillera Raura. Therefore while the Andean record of ENSO suggests that glaciers in the Cordillera Raura retreated during periods of more frequent ENSO events, the marine records suggest that the opposite occurred, and glaciers retreated during periods of decreased precipitation and flooding on the Peruvian coast.

4.5.3. Comparison with regional records

The timing of increased neoglacial activity in the Raura coincides with a marked increase in regional moisture-balance (greater precipitation/evaporation or P/E) recorded in Lake Titicaca (Abbott et al., 1997a). Multiple records suggest that starting at ~5200 cal yr BP, the Central Andes became abruptly colder (Abbott et al., 2003; Thompson et al., 2006), but glacial sediments during the early neoglacial in the Raura remained low until ~3100 cal yr BP. Likewise, the $\delta^{18}O$ record of evaporative enrichment from Lake Junin (Seltzer et al., 2000), located near Lutacocha, shows an overall increase in P/E during the Holocene, and the onset of neoglaciation corresponds to the timing of increased regional moisture availability. It is also noteworthy that a decrease in the Lutacocha Ti record at ~2300 cal yr BP corresponds to an abrupt increase in the Sajama dust record of regional aridity (Thompson et al., 1998), a low-stand in Lake Titicaca (Abbott et al., 1997a; Rowe et al., 2002), and dessication in what is now a glacial fed lake in the Cordillera Real (Abbott et al., 1997b).

The Lutacocha neoglacial record generally covaries with the Huascaran $\delta^{18}O$ ice core record of climate change (Thompson et al., 1995). The Huascaran $\delta^{18}O$ record reflects local climatic changes as well as changes in Pacific sea surface temperatures which drive changes in the strength and intensity of monsoonal precipitation derived from the Atlantic (Vuille et al., 2000a; Bradley et al., 2003). Lower isotopic values in the ice cores probably indicate colder and/or wetter conditions in the tropics (Pierrehumbert, 1999; Bradley et al., 2003). Based on this first order interpretation, the Huascaran record provides supporting evidence that neoglacial advances took place during periods of slightly wetter and possibly colder conditions in the region.

4.5.4. Holocene glacial variability and climate change

The neoglacial record from the Cordillera Raura may be related to similarly timed increases in drift ice in the North Atlantic which has been linked to solar variability, and a coupled ocean-atmosphere response operating on millennial time-scales (Bond et al., 2001). Elsewhere it has been shown that mountain glaciers during the Holocene respond to a similar near-millennial scale forcing (Denton and Porter, 1970; Denton and Karlen, 1973; Rothlisberger, 1986; Reyes et al., 2006). A more positive glacier mass-balance in the Andes on near millennial time-scales may have resulted from cooling of the summer stratosphere (Haigh, 1996; Van Geel et al., 2000), and changes in convection and moisture availability that favored glacial expansion.

A convincing solar hypothesis has been proposed in order to explain Late Holocene glacial variability in the tropical Andes (Polissar et al., 2006b) on decadal and centennial timescales. Decreased solar irradiance could have led to cooler temperatures and variations in atmospheric circulation that promoted glacial expansion. Indeed the Late Holocene record of glacial variability from the Cordillera Raura does show similarity to the reconstructed irradiance record (Reimer et al., 2004) for the past ~1000 years (Fig. 4.6). Moreover, the highest peak in the

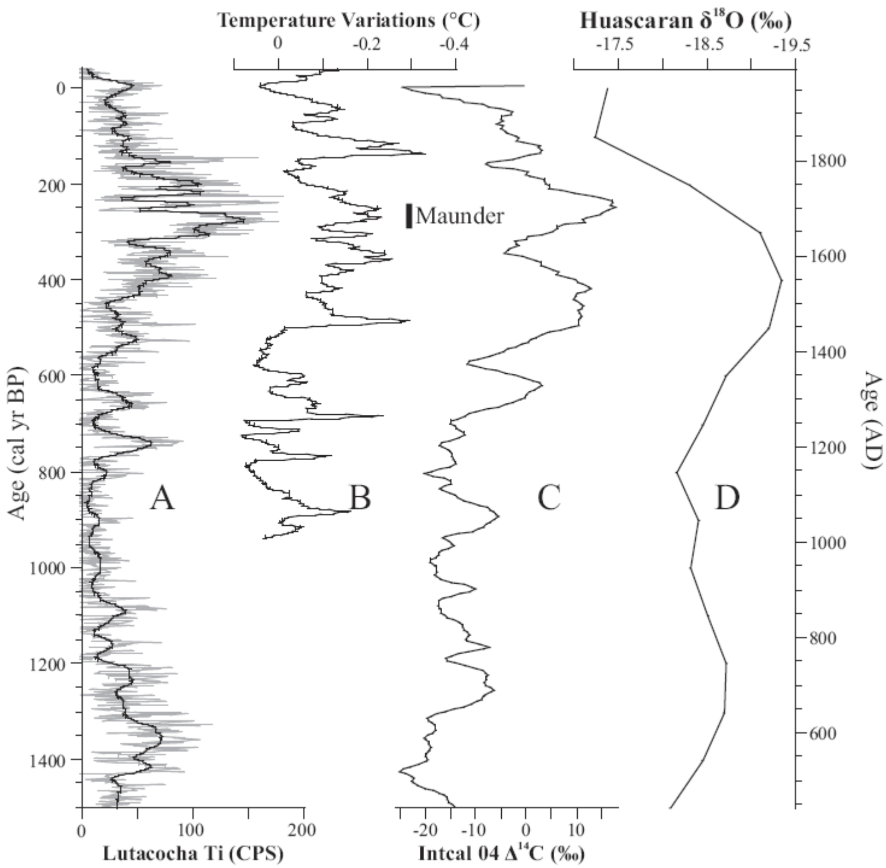

Figure 4.6. Lutacocha 1500 cal yr BP Ti record (A) of neoglacial variability (gray line are raw values, black line are smoothed data using a Lowess function and a 0.01 loading) plotted versus the Crowley (2000) combined record of temperature variations due to solar and volcanic forcings (B), the Intcal 04 (Reimer et al., 2004) $\Delta^{14}C$ record (C) and the Huascaran (Thompson et al. 1995) $\delta^{18}O$ ice core record of climate change (D). Increased glacial erosion in the Cordillera Raura corresponds to periods of decreased solar irradiance, lower global temperatures and generally colder and/or wetter conditions recorded at Nevado Huascaran. The peak of the LIA advance in the Cordillera Raura coincides with timing of the Maunder sunspot minimum.

~5000 yr Lutacocha Ti record corresponds to the Maunder sunspot minimum (305 to 235 cal yr BP). On longer timescales, the radiocarbon production record (Reimer et al., 2004), plotted versus the Lutacocha neoglacial record (Fig. 4.5), suggests decreased solar activity may correspond to isolated periods of increased glacial activity. Solar activity that is inferred from these proxies is especially low between 2800 and 2500 cal yr BP and over the last 700 years, which corresponds to periods of increased glacial flour content in the Lutacocha sediment core.

The combined effects of volcanic and troposphere aerosols, solar irradiance, geomagnetic variability and ocean-atmosphere mechanisms probably drove most of the observed sub-millennial-scale neoglacial variability in the southern hemisphere. However it is not clear of the net result of these combined forcing mechanisms during most of the neoglacial especially because it is difficult to separate out the influences of each specific mechanism in proxy records. Furthermore, a mathematical approach to the ultimate combined forcing of these mechanisms (e.g. Crowley et al., 2000) should be applied to improve our understanding of these impacts beyond the last ~1000 years. Nevertheless, it seems that insolation probably enhanced the overall pattern of Holocene mountain glacier variability and the short-term variability was probably driven by a combination of the aforementioned mechanisms.

4.5.5. The Little Ice Age in the Central Andes and the Cordillera Raura

Results from the Quelccaya ice cap indicate that the LIA in the Cental Andes experienced a cold and wet phase from 450 to 230 cal yr BP, followed by a cold and dry phase between 230 to 70 cal yr BP (Thompson et al., 1986; Liu et al., 2005). Evidence of a period of increased moisture availability is also supported by records from Lake Titicaca showing higher lake levels from ~500 cal yr BP to present (Baker et al., 2001; Rowe et al., 2002).

Glaciers reached a local LIA maximum at around 300 cal yr BP in the Central Andes, based on work in the Cordillera Real (Rabatel et al., 2005). Likewise, the finely laminated record from Lutacocha transitions to a ~10 cm think band of glacial sediments that dates to ~300 cal yr BP, and is bracketed by sediments high in glacial clay that span the period from 800 to 150 cal yr BP. Therefore, the peak of the LIA recorded in the Lutacocha sediments corresponds to the timing of colder and wetter conditions in the region. The Late Holocene chronology of neoglacial variability in the C. Raura also generally corresponds to dated moraines elsewhere in Peru (Rodbell, 1992; Solomina et al., 2007). Following ~250 cal yr BP, glaciers retreated in the Cordillera Raura at a time when it became drier overall in the Central Andes.

Glaciers in the Raura are more affected by precipitation changes than temperature, today, but temperature is still a major control of the equilibrium-line altitude (ELA), especially during periods when precipitation is abundant enough to maintain the ELA at or near the 0°C isotherm. The present ELA for glaciers on the west side of the Cordillera Raura is 4900 m using a conservative out-of-equilibrium estimate (Ames and Hastenrath, 1996). The highest glaciated peak in the Lutacocha watershed has an elevation of 5250 m, and in 2006 ice was as low as 4650 m. Therefore the toe-to-headwall ratio (THAR) is estimated at 0.40 (Porter, 2001). The lowest neoglacial maximum ice extent in the Lutacocha watershed was mapped at 4350 m (Clapperton, 1972). Assuming the LIA was the most extensive neoglacial advance and precipitation was abundant enough to maintain the ELA at or near the 0°C isotherm, the LIA ELA is estimated at 4710 m using the THAR method, which corresponds to a ΔELA of -190 m. A lapse-rate calculation method of 0.6 ±0.1ºC/100m requires a ~1.2 ±0.3ºC temperature reduction to explain an ELA lowering of 190 m (Porter, 2001). It should be noted that the THAR method, combined with a lapse rate temperature calculation, should only be viewed as a first estimate of LIA paleo-temperature because the exact timing and extent of neoglacial moraine limits are not well constrained, locally. Furthermore, the use of a more comprehensive glacial energy and mass-balance model (Seltzer, 1992) is beyond the scope of this study, but should be applied to more accurately determine the climate change associated with an ELA lowering in the Cordillera Raura.

4.6. CONCLUSIONS

Neoglaciation in the Cordillera Raura began after ~3100 cal yr BP, and ice margins were lower than today from 3100 to 2000, 1700 to 1100 and 800 to 150 cal yr BP. The peak neoglacial advance (300 cal yr BP) recorded in the Lake Lutacocha record corresponds to the LIA when conditions were wetter and colder than today. The record of neoglacial variability in the Cordillera Raura was generally synchronous with the long term, Holocene, pattern of moisture-balance changes that are recorded in other proxy records from the Central Andes. The combined short-term effects of volcanic, solar, and ocean-atmosphere phenomena probably drove most of the observed sub-millennial-scale Holocene glacial variability, but further work is needed in order to assess the relative role of these mechanisms in driving mountain glacier variability beyond the last ~1000 years. The neoglacial record from the Cordillera Raura emphasizes that southern tropical glaciers are highly sensitive to low latitude ocean and atmospheric circulation processes that are closely linked to abrupt global climate change.

5. STABLE ISOTOPIC RECORD OF LATE HOLOCENE CLIMATE CHANGE IN PACIFIC NICARAGUA

5.1. INTRODUCTION

Nicaragua, (Fig. 5.1) is located at an important global climatic border as the southern coast of Central America marks the current northern-most position of the Pacific Intertropical Convergence Zone (ITCZ) (Hastenrath, 1967b). Changes in the location, strength and intensity of the ITCZ are the dominant regional controls on precipitation, temperature and cloud cover. Records of Nicaraguan climate change can therefore indicate of past changes in ITCZ dynamics and the strength of the continental monsoon. Ultimately, this information can clarify our understanding of the linkages between low and high latitude ocean-atmosphere processes.

Oxygen isotope variations ($\delta^{18}O$) within lake sediment biological remains can be used as indicators of changes in regional P/E balance. Here we present a ~1500 year stable isotopic and sedimentological record from lake sediments in Nicaragua, supports the occurrence of widespread changes in northern tropical moisture balance during the late Holocene, and documents an abrupt shift to drier conditions beginning at ~700 cal yr BP. The tropical pattern of aridity during this interval suggests a southward displacement of moisture convergence resulting from a combination of solar, ocean and atmospheric processes.

The Holocene pattern of tropical climate change can elucidate low latitude hydrologic cycle interactions with the global climate system (Pierrehumbert, 2000; Seager et al., 2000). We need data records of the past changes in low latitude temperature and moisture balance to predict future global environmental and ecological changes. Rising temperatures due to anthropogenic greenshouse gas emissions and land use change are likely to have major socio-economic impacts in developing Latin American regions (Arnell, 1999; Vorosmarty et al., 2000). It is therefore vital to understand past climate change as we attempt to predict future variability and its impact on water resource availability in Central America.

The long-term Holocene patterns in the balance between precipitation and evaporation (P/E) at low latitudes seems to be linked, at least in part, to orbital (precessional) forcing (Hodell et al., 1991; Haug et al., 2001; Abbott et al., 2003). However, the causes of millennial-scale (and shorter) changes in Holocene P/E in these regions seem to be more dependent on solar forcing and coupled ocean-atmospheric processes (Bond et al., 2001; Mayewski et al., 2004). The precise interactions among these systems is not yet clear, and improved records of continental climate change from drought sensitive regions in the outer tropics can provide a better understanding of the timing and causes of abrupt shifts in moisture-balance.

5.1.1. Northern Hemisphere moisture balance during the Late Holocene

The Little Ice Age (LIA) was a period of colder and drier conditions that was first documented in the high latitude northern hemisphere (Kreutz et al., 1997). Previous studies have suggested that changes in the position and/or intensity of the ITCZ, linked to North Atlantic changes during the LIA, may have been the dominant cause of increased aridity in the northern tropical Americas (Hodell et al., 2005). In the circum-Caribbean region, the LIA was manifested as a 2-3°C reduction in temperatures (Winter et al., 2000; Watanabe et al., 2001), and increased aridity (Hodell et al., 2005). Records from the Cariaco Basin indicate that northern South America also experienced a decrease in continental runoff and more arid conditions (Haug et al., 2001; Haug et al., 2003). The extent of continental aridity is not clear, however, because the nearby northern tropical Andes were wetter during the LIA (Polissar et al., 2006b). The scattered records from Central and South America and inconsistencies between the lowlands and the mountain regions highlight the fact that sediment records from the tropics are underrepresented in the paleo-archive. New paleoclimate data from the Pacific region of Nicaragua should therefore improve our understanding of the role of ocean-atmosphere dynamics in Late Holocene rapid climate change (Clement and Peterson, 2008).

5.2. STUDY SITE

5.2.1. Modern climate

Climate dynamics within Central America are driven by complex interactions among the Pacific Ocean, Atlantic Ocean, Caribbean Sea and atmosphere. Temperature varies little throughout the year, and seasonality is exhibited largely by contrasts between wet and dry months. In general, precipitation patterns follow the annual migration of convective belts over the continent, with the wet season occurring during the Northern Hemisphere summer (May-October), and the dry season during the winter months. The wet season experiences a local minimum in precipitation during July and August, known as the mid-summer drought (Magaña et al., 1999). The mid-summer drought is related to a southward displacement of rainfall patterns leading to increased aridity that is particularly well pronounced along the Pacific coast (Hastenrath, 1967b).

Central American precipitation is derived mostly from Atlantic Ocean evaporation and Caribbean sources, and varies in response to changes in the Atlantic-Pacific pressure gradients that modulate trade wind strength. The influence of trade winds combined with orographic barriers, lead to enhanced precipitation on the Caribbean coast relative to the Pacific. On average, the Caribbean-side of Nicaragua receives as much as ~500 cm yr^{-1} of precipitation, whereas the immediate coastline of the Pacific side receives only ~160 cm yr^{-1} (Hastenrath, 1967b; INETER, 2001). The location of our study site is near the Pacific coast and receives between ~120 and 160 cm yr^{-1} of rainfall (INETER, 2001).

The Pacific ITCZ in Central America is situated mostly over the ocean and generally does not extend north to the Caribbean (Hastenrath, 1967b). Nevertheless, the position of the ITCZ over the Pacific is important because it modulates the strength and orientation of the trade winds transporting moisture over the Central American landmass. Typically, increased precipitation is associated with a more northerly position or intensification of the ITCZ. A less intense ITCZ is associated with decreased convection, lower temperatures, decreased cloud cover and decreased precipitation.

Central America and the Caribbean show a strong regional interannual variability correlated to El Niño and the Southern Oscillation (ENSO) and Pacific sea-surface temperatures (SSTs) (Enfield and Alfaro, 1999; Giannini et al., 2000). During ENSO, the axis of Central America generally separates regions with anomalously high (Caribbean) and low (Pacific) precipitation patterns. In general, ENSO results in decreased wet season precipitation along the Pacific coast of Nicaragua, and anomalously high precipitation along the Caribbean side (Diaz et al., 2001).

5.2.2. Location and description of coring site

Lago El Gancho (N11.9055°, W85.9177°) has a water depth of 1.1 m during the dry season. The lake (44 m a.s.l.) is situated on a peninsula that extends into Lake Nicaragua east of the city of Granada. The peninsula formed as a result of over-steepening, mass wasting and failure of the northeask flank of Volcán Mombacho (van Wyk de Vries and Francis, 1997; Shea et al., 2008). The lake itself formed in a shallow depression on top of block-rich porphyric andesite (Ui, 1972) and rhyolitic pumice-rich units (Shea et al., 2008). Volcán Mombacho is also composed of basaltic andesite and porphyritic basalt rocks (Ui, 1972) that provide the source sediments for

Lago El Gancho. In addition, this system is alkaline, and the sediments preserve calcium carbonate though the Late Holocene, which is rare for lakes in this region.

Lago El Gancho is perched ~10 m higher than Lago Nicaragua (34 m a.s.l.), and therefore direct hydrologic influence of the larger lake in minimal. Lago El Gancho is mostly precipitation fed. Strand lines on the shore ~1 m higher than water level at the time of fieldwork indicate sensitivity to evaporative enrichment. Our observations of other lakes in the region indicate that many lakes on the arid (Pacific) side of Nicaragua become desiccated in the dry season. Lago El Gancho is shallow (1.1 m), but interestingly there is no evidence in the sediments that it has completely dried since it filled.

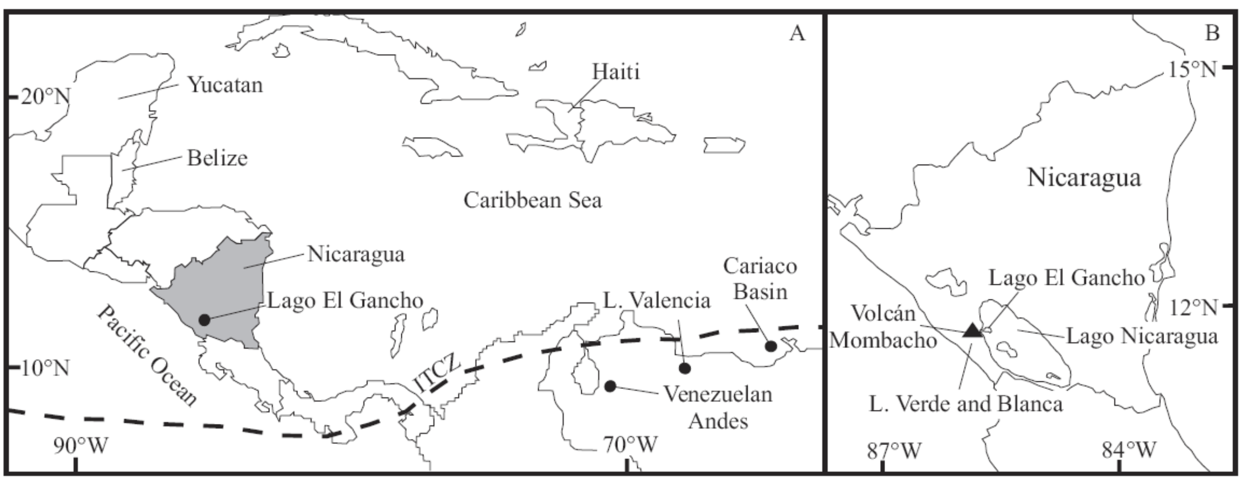

Figure 5.1. Location map of sites mentioned in text (A). Lago El Gancho is located on the Pacific side of Central America. The dashed line approximates the summer position of the ITCZ.

5.3. METHODS

5.3.1. Fieldwork

Lago El Gancho was sounded using a handheld depth sonar in June, 2004, and a 277 cm composite piston core (Wright et al., 1984) was retrieved from the depocenter of the lake.

Surface sediments were collected using a polycarbonate tube attached to a hammer corer. The upper 34 cm of the surface core were extruded in the field at 0.5 cm intervals. Square-rod piston core sections were extruded in the field, stored in PVC tubes, transported to the laboratory, and sampled at 0.5 cm intervals. Modern water samples from 11 sites were collected in 50 mL plastic bottles during the summers of 2003 and 2004 for modern oxygen and hydrogen isotope analyses (Table 5.1 and Fig. 5.3).

5.3.2. Analytical work

All cores were opened, split, and photographed in the laboratory, and were described for major sedimentological characteristics. Bulk density and loss-on-ignition (LOI) at 550°C and 1000°C were measured every 2 to 5 cm for organic matter and carbonate content (Dean Jr., 1974; Heiri et al., 2001; Boyle, 2004). Volume magnetic susceptibility (MS) was measured on split cores every 0.5 cm using a Tamiscan automated sediment track and a Bartington high-resolution surface-scanning sensor connected to a Bartington susceptibility meter.

Samples for isotope analyses were taken over 0.5 cm intervals every 1-2 cm. Samples were disaggregated with 7% H_2O_2 and then sieved at 63 μm. The >63 μm sediment was dried on filter paper at 60° C for 12 hours, and subsequently transferred to glass scintillation vials. Adult ostracod species of *Physocypria* were sieved and picked at 150 μm using a binocular microscope at 20x magnification. Picked ostracod valves were then soaked in 15% H_2O_2, cleaned ultrasonically in deionized water, rinsed with methanol and dried at 60°C for 12 hours. Aggregated samples of ~30 ostracod carapaces from each interval were reacted in 100% phosphoric acid at 90ºC, and measured using a dual-inlet GV Instruments, Ltd. IsoPrime™ stable isotope ratio mass spectrometer and MultiPrep^{Tm} inlet module at the University of Pittsburgh. Oxygen isotope results are expressed in conventional delta (δ) per mil (‰) deviation from the Vienna Peedee Belemnite standard (VPDB). Analytical uncertainties are within ±0.1‰.

Modern water sample hydrogen and oxygen isotope values were determined at the University of Arizona's Environmental Isotope Laboratory (Table 1). Isotope values were then plotted relative to the Global Meteoric Water Line (GMWL) to reflect relative degrees of evaporative enrichment. Cation chemistry was also measured on Lago El Gancho modern water samples using ICP-AES at the University of Pittsburgh.

Table 5.1. Modern water isotope data from Nicaragua.

Sample	Sample Date	Lat (°N)	Lon (°W)	$\delta^{18}O$	$\delta^{2}H$
Nejapa	May, 2003	12.00	86.32	3.0	4.9
Moyua	May, 2003	12.59	86.06	-5.4	-39.2
Verde	May, 2003	11.76	85.96	-0.3	-10.6
Blanca	May, 2003	11.77	85.96	-5.6	-39.3
Apoyo Center	May, 2003	11.94	86.05	2.4	8.2
Gancho	June, 2004	11.91	85.92	2.3	-6.0
La Prensa, Ometepe	June, 2004	11.49	85.55	-6.2	-38.9
Maderas	June, 2004	11.45	85.51	-6.6	-43.3
Charco Verde	June, 2004	11.48	85.63	-0.9	-14.2
Zapatera	June, 2004	11.91	85.92	0.6	-7.8
Apoyo	June, 2004	11.94	86.05	-1.4	-4.4

Table 5.2. Modern water cation concentration data.

Cation	Mg	K	Mn	Sr	Ba	Zn	Al	Si	P	S	Na	Ca	Fe	Ti
conc. (mg/l)	49.83	35.71	0.00	0.17	0.11	0.03	0.17	20.88	0.04	2.85	197.50	16.13	0.00	0.00
stdev	0.47	0.43	0.00	0.00	0.00	0.00	0.04	0.48	0.01	0.02	2.35	0.26	0.01	0.00

Radiocarbon ages were converted to calendar ages using CALIB version 5.0.2, and the Intcal 04 dataset (Reimer et al., 2004). The Lago El Gancho sediment core age-depth model (Fig. 5.2) was constructed using a 3rd order polynomial fit (R^2=.99) between 5 radiocarbon dated charcoal samples (Table 5.2).

Table 5.3. Lago El Gancho radiocarbon and calibrated ages measured on charcoal.

Laboratory Number	Depth (cm)	Radiocarbon Age (^{14}C BP)	cal yr BP 2-Sigma Age Range
UCI-19881	82.25	630 ± 35	551-601-663
UCI-19882	117.25	860 ± 35	690-768-802
UCI-19883	162.25	1100 ± 30	952-1006-1062
UCI-22766	212.75	1640 ± 40	1413-1537-1620
UCI-22767	226.25	1770 ± 30	1605-1682-1745
UCI-14575	228	675 ± 15	646-657-671

5.4. RESULTS

5.4.1. Radiocarbon ages

The base of the organic-rich sediment sequence from Lago El Gancho dates to ~1680 cal yr BP. No organic material was found to date in the lower ~40cm of the sediment profile. Given the highly clastic nature of this sediment, it probably represents a period of rapid sediment deposition as a result of the dry debris avalanche on the northeast flank of Vólcan Mombacho

(Shea et al., 2008). Therefore, an age-depth model was not applied to the lower ~40 cm of the record because it represents an instantaneous event.

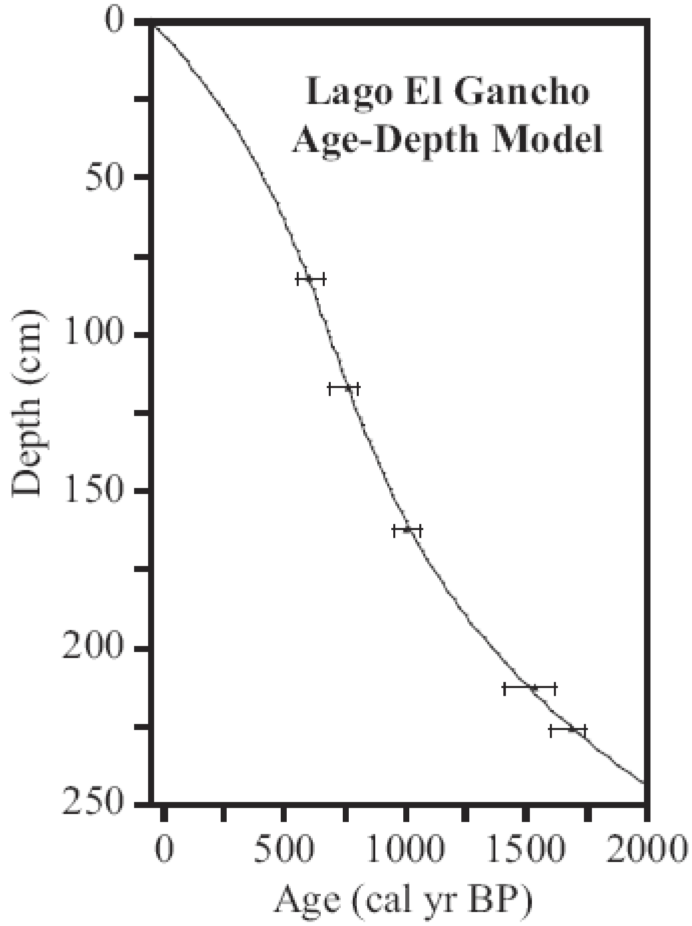

Figure 5.2. Age-depth model of radiocarbon dated charcoal samples from Lago El Gancho. Error bars represent 2-sigma age range.

5.4.2. Modern water chemistry

Lago El Gancho water isotope data plot the furthest distance off the GMWL (Fig. 5.3) indicating that it has the most enriched isotopic values of the lakes sampled in the region. The modern cation chemistry indicates Lago El Gancho is high in dissolved ions (Table 3), characteristic of oligosaline conditions, and highlights its sensitivity to evaporative enrichment.

In general, the crater lakes in the region, with the exception of Maderas, all show relative isotopic enrichment. Samples from Lakes Blanca and Moyua, a spring on Ometepe Island and precipitation collected from near Lake Apoyo have the lowest isotopic values of the study area.

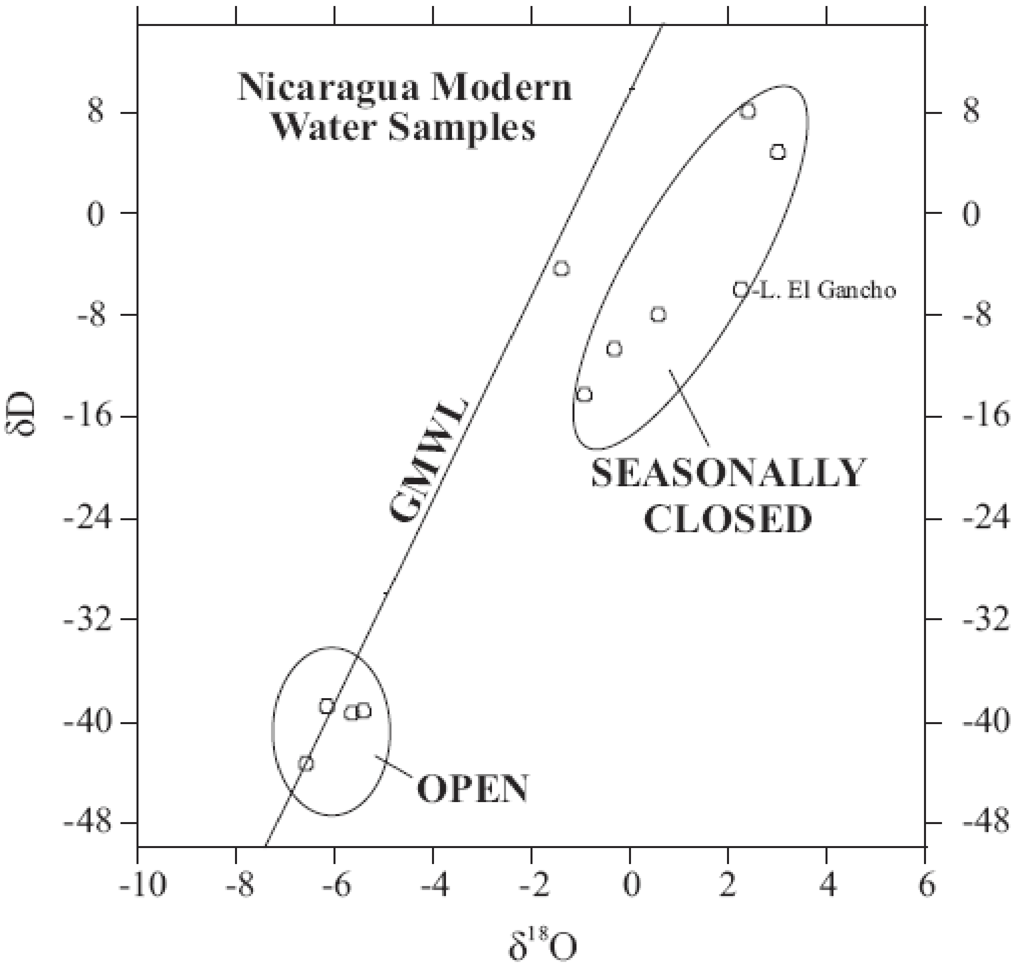

Figure 5.3. Nicaragua modern water samples plotted versus the global meteoric water line (GMWL).

5.4.3. Lago El Gancho sedimentological record and stable isotope data

The residual (%) LOI values (Fig. 5.4) generally track changes in magnetic susceptibility (MS). For instance, the basal ~50cm of the core, with low organic matter and calcium carbonate, and high LOI residual values, also have the highest measured MS values of the core. The bottom ~30 cm of the core was not measured for LOI because the sediments were composed entirely of very coarse-grained, unconsolidated, terrigenous material. The LOI residual values show a sharp decrease from ~240 to 175 cm, followed by a trend toward slightly higher values through the modern sediments. The upper ~215 cm of the core shows little to no variability in magnetic susceptibility. We interpret that the high MS, clastic-rich sediments below ~215 cm are a debris avalanche deposit and do not discuss these sediments in the rest of this paper.

Oxygen isotope variations in the sediment generally track changes in calcium carbonate content. A progressive lowering of $\delta^{18}O$ values and increasing calcium carbonate content are present between ~215 and 100 cm. Above ~100 cm, and continuing through the modern sediments, $\delta^{18}O$ values become abruptly higher while calcium carbonate content decreases.

5.5. DISCUSSION

5.5.1. Stable isotopic evidence of Nicaragua Late Holocene moisture-balance changes

Ostracod-water oxygen isotope separation in simple systems is controlled mostly by water temperature, the isotope composition of the lake water from which the carapace is formed, and a constant vital offset (von Grafenstein et al., 1999). However, closed system lakes tend to have $\delta^{18}O$ values that are most affected by the balance between precipitation and evaporation (Leng and Barker, 2006). Assuming a lacustrine origin, interpretation of $\delta^{18}O_{ostracod}$ stratigraphies is reduced to distinguishing the degree of influence of: (1) the isotopic composition of input waters determined by surface and subsurface inflow and precipitation, and (2) hydrologic processes that can modify the isotopic composition of meteoric water, predominantly evaporation.

Lago El Gancho is a mostly closed system presently, based on the relatively enriched modern water isotope values, the lack of a major outflow and the absence of any obvious subsurface hydrologic influences. It is possible that the lake is groundwater fed, but based on the highly enriched modern isotope data, we assume that these influences were minimal during the Late Holocene. It is also assumed that temperature effects were minimal in Central America during the last 1500 years (Hodell et al., 2005), and the single-species ostracod record from Gancho therefore represent changes in lake water isotopic composition sensitive to changes in P/E. The oxygen isotopic composition of Lago El Gancho lake water and fossil ostracods ($\delta^{18}O_{ostracod}$) therefore likely reflects the composition of the total input (rainfall, surface flow and groundwater) minus the output (evaporation). We interpret that lower oxygen isotopic values represent wetter conditions or decreased evaporation (high P/E), and higher values indicate a drier climate or increased evaporation (low P/E).

The high sedimentation rate and fine resolution of our analyses produce a detailed profile of moisture balance changes during the late Holocene in Nicaragua, where no such records currently exist. Oxygen isotopes in the Lago El Gancho record became progressively lighter from ~1500 to 700 cal yr BP, indicating a relatively wetter climate or higher P/E. An abrupt shift marked by higher isotopic values and decreased P/E occurred at ~700 cal yr BP. Above this transition, there is a slight shift toward lower isotopic values between ~500 and 400 cal yr BP. Overall however, the sequence between ~700 cal yr BP and the present indicates relatively drier conditions and progressively increasing evaporative enrichment.

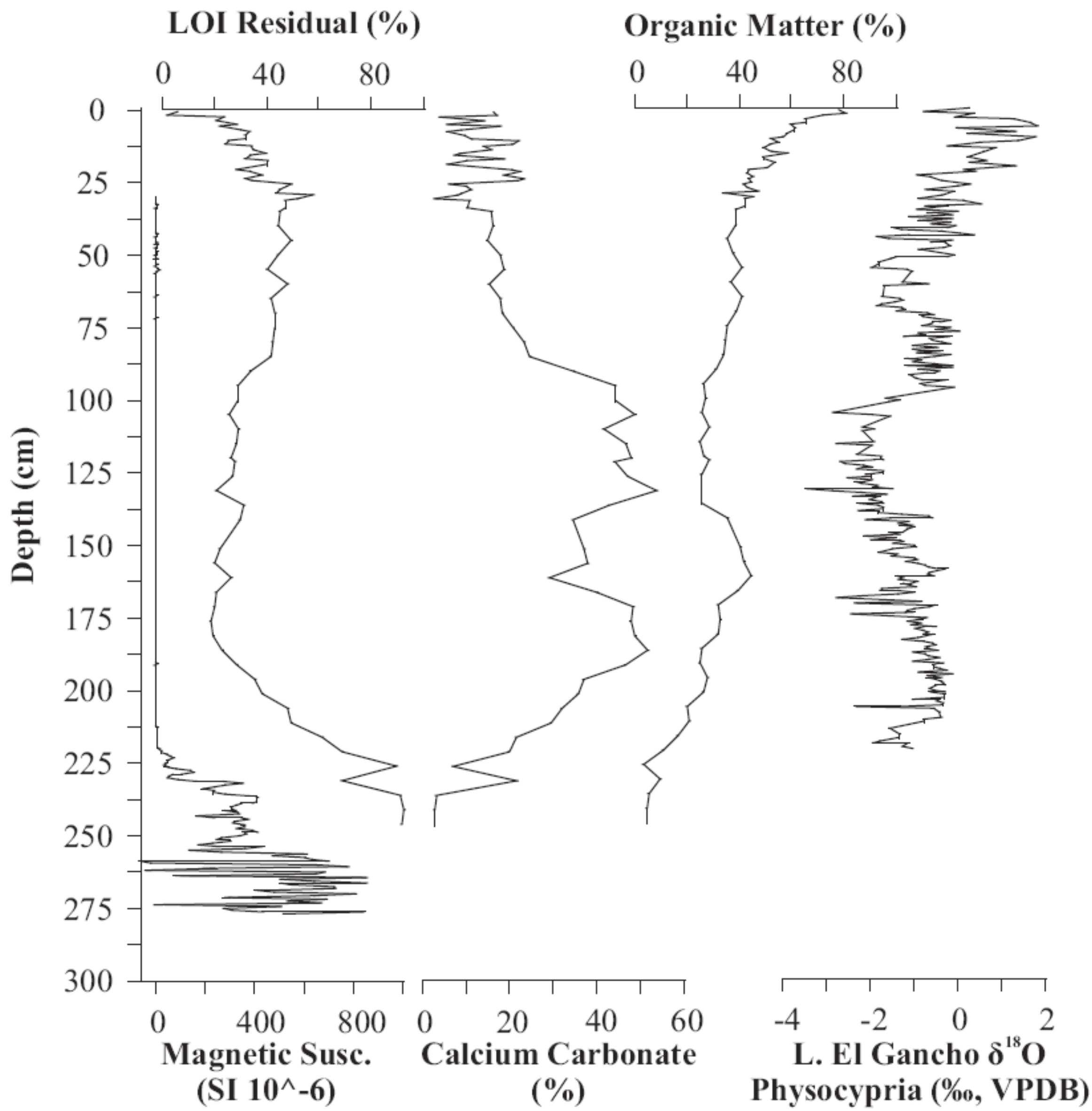

Figure 5.4. Lago El Gancho core data plotted versus depth. The section of the core below 225 cm is composed entirely of very coarse-grained material from the Las Isletas debris avalanche on the northeast flank of Vólcan Mombacho (Shea et al., 2008).

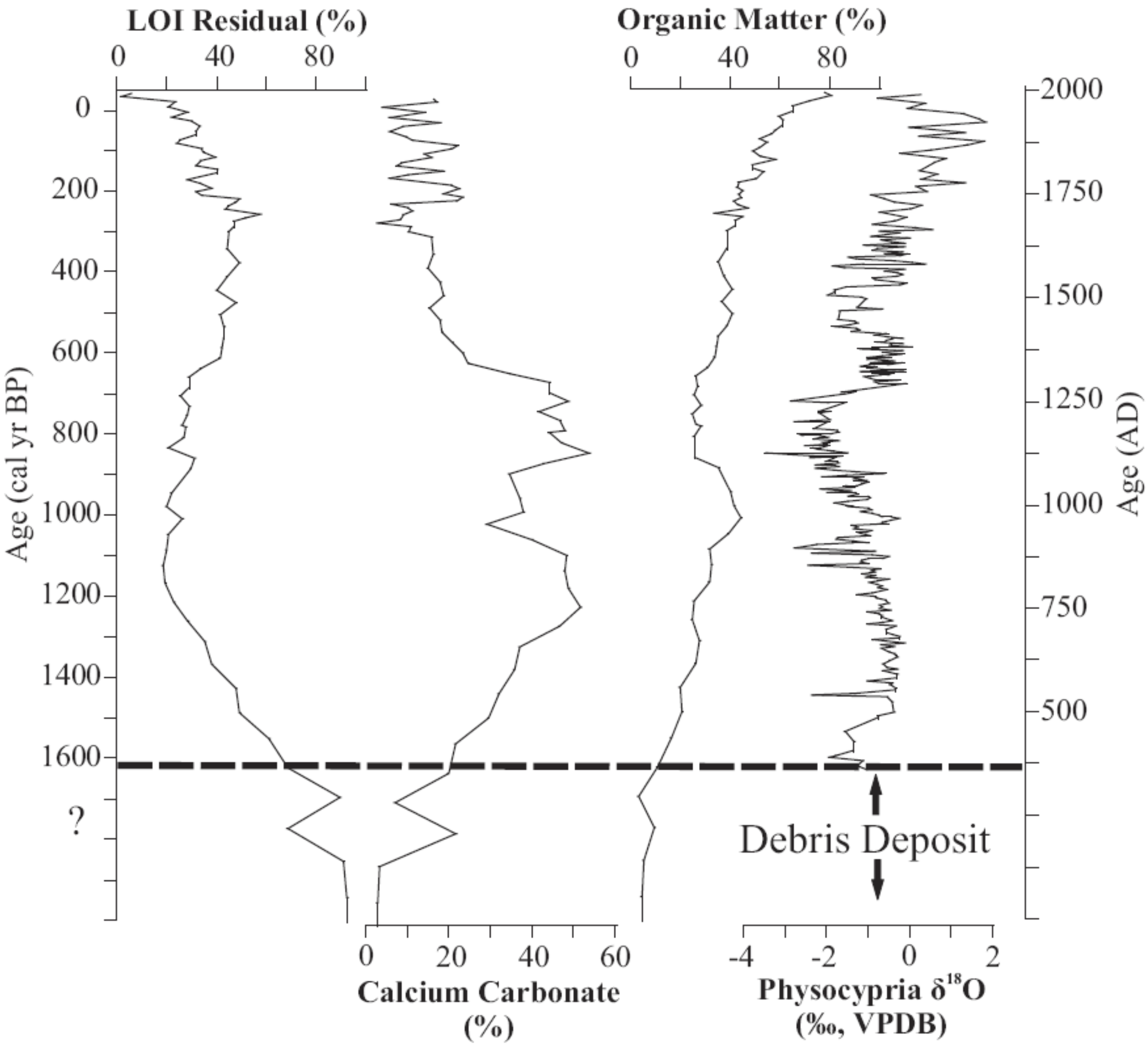

Figure 5.5. Lago El Gancho core data plotted versus age. The sediments below ~1600 cal yr BP represent an instantaneous mass wasting event.

5.5.2. Regional comparison

The major shift to drier conditions in Lago El Gancho sediments at ~700 cal yr BP (Fig. 5.6) is similar to the record of aridity from the Yucatan (Hodell et al., 2005) and the abrupt shift to more arid conditions at ~600 cal yr BP in the Gulf of Mexico (Richey et al., 2007). Additionally, continental record from Lake Valencia in Venezuela (Curtis et al., 1999) and speleothem records from Belize (Webster et al., 2007) both show a general trend toward drier conditions from 700 cal yr BP to the present. The Venezuelan Andes were cold and wet during the LIA (Polissar et al., 2006b), which seems to mark the physiographic boundary between the regions in the northern tropics that received increased versus decreased precipitation. The Lago El Gancho record shows a slight step-wise shift toward wetter conditions from ~500 to 400 cal yr BP, but the overall trend is toward drier conditions from 700 cal yr BP to the present.

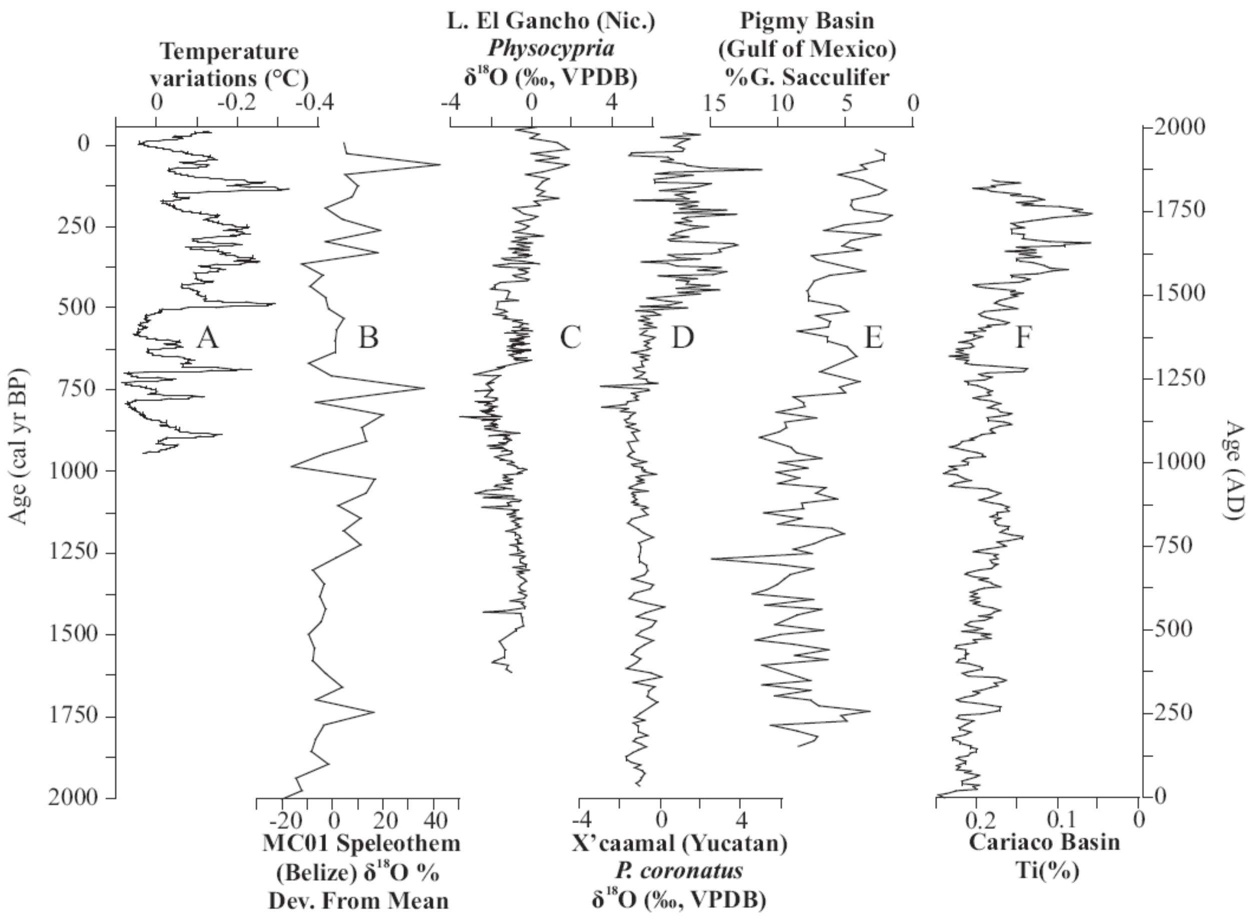

Figure 5.6. Combined effects of solar and volcanic forcings (A) (Crowley, 2000) based on scaling from (Bard et al., 1997), and regional records (B, D-F) plotted versus L. El Gancho data (C). Grey box marks an abrupt transition toward higher values in the Lago El Gancho record at ~700 cal yr BP which corresponds to a major change in the Cariaco Basin record (F) of northern tropical continental runoff (Haug et al., 2001). Paleoclimate records from Belize (B)(Webster et al., 2007), Nicaragua (C), the Yucatan (D) (Hodell et al., 2005) and the Gulf of Mexico (E) (Richey et al., 2007) all show a shift toward higher oxygen isotope values and drier conditions from ~500 cal yr BP to the modern.

5.5.3. The causes of LIA moisture-balance changes in the northern tropics

Colder conditions during the LIA has generally been considered to be driven by radiative forcing that resulted mostly from changes in solar irradiance (sunspots), and to a lesser degree, volcanic aerosol influences (Crowley, 2000; Polissar et al., 2006b). Decreased radiative forcing during the LIA probably caused a cooling in the northern hemisphere and increased sea-ice cover (Tarasov and Peltier, 2005). This would have steepened the latitudinal SST gradient, and caused the ITCZ to shift south or become less intense (Schiller et al., 1997; Vellinga and Wood, 2002). A more southerly ITCZ would have shifted the belt of convergence further south of the Central American continent, leading to drier and windier conditions in the northern tropics (Haug et al., 2001).

The climatology of Central America is driven by a complex interaction of Pacific and Atlantic ocean-atmosphere systems and processes from both oceans must have been linked in order to explain LIA aridity in Nicaragua. Colder conditions in the North Atlantic may have lead to intensified northeast trade winds that could have caused increased moisture transport from the Atlantic to the Pacific Ocean. Increased meridional SST gradients in the eastern tropical Pacific could then result in westerly anomalies in the upper troposheric winds over the Tropical Americas leading to lower precipitation during summer months (Pulwarty et al., 1992; Enfield, 1996; Pahnke et al., 2007).

The abrupt change toward drier conditions in the Lago El Gancho record at ~700 cal yr BP coincides with a major decrease in continental runoff recorded at the Cariaco Basin (Haug et al., 2001). The Pacific coast of Nicaragua becomes drier during more frequent El Niños events (Diaz et al., 2001) because the warm phase of ENSO causes a southward displacement of the ITCZ leading to decreased precipitation in this region of Central America (Dai and Wigley, 2000). Following ~700 cal yr BP, the Cariaco Basin sediments contain decreased Ti values which reach have been interpreted as coinciding with more frequent ENSO events and drier conditions in the northern tropics (Haug et al., 2001). This is also consistent with records of persistent drought and decreased El Niño events in the southern tropics during the Medieval Climate Anomaly from 1150 to 700 cal yr BP (Rein et al., 2004), and prolonged ENSO-related aridity in northern Europe from 1050 to 650 cal yr BP (Helama et al., 2009). Thus, the available evidence suggests that the trend toward drier conditions during the last ~700 years in Nicaragua may alternatively be driven by combined solar and ocean-atmosphere mechanisms that are linked more to Pacific than Atlantic Ocean-driven mechanisms.

5.6. CONCLUSIONS

The high resolution profile of stable isotopes measured on ostracods ($\delta^{18}O_{ostracod}$) from Lago El Gancho indicate progressively lighter values (wetter conditions) between ~1600 and 700 cal yr BP, followed by an abrupt shift toward heavier values and drier conditions. Following a brief recovery to wetter conditions, the region became progressively drier during the LIA, and through to the present. The available evidence to date suggests a North Atlantic trigger connected to a solar mechanism may have led to displaced convergence belts in Central America, leading to a more southerly ITCZ and overall decreased precipitation. Alternatively, climate change in the Tropical Pacific combined with solar and atmospheric changes can explain the patterns of aridity in the tropical Americas during the Late Holocene.

6. CONCLUDING REMARKS

My goal during my PhD research has been to highlight the importance of the tropical atmosphere and hydrologic cycle in rapid climate change events. A complex series of processes, including external (solar) and internal (ocean-atmosphere and feedbacks) are ultimately responsible for shifting temperature and precipitation patterns on large geographic scales. Determining the linkages between these processes, and how they ultimately combine to produce the global record of climate change, is a major challenge and goal for my future research.

Following my dissertation studies, I plan to continue working in the middle and low latitudes, and utilize GIS, remotely sensed datasets and quantitative glacial-geologic methods in order to model past ice volume fluctuations and the climate change associated with glacier mass-balance variability. I will also continue to utilize pro-glacial lake sediment geochemistry, stable isotopes and paleo-productivity indicators to further constrain the scope and pattern of climate change on very short (decadal) and longer (millennial) time-scales. This work strongly complements the on-going efforts of glaciologists and paleoclimatologists who are attempting to reconstruct the record of alpine climate change because my research provides the paired mountain glacier and lake sediment records of atmospheric variability.

My PhD research has produced sub-centennial-scale records of climate variability extending back to ~15 ka from the Peruvian and Venezuelan Andes. These records from proglacial lakes show intriguing hints of late-glacial and neoglacial climate variability, and the next step is to improve such records of temperature and hydrological variability in climatically-sensitive regions.

I am particularly interested in the potential climatological, ecological and socioeconomic changes that may be tied to human activity. My future research will continue to explore the interplay between atmospheric and hydrologic changes in Central and South America, and to use sedimentological data and stable isotopes as recorders of regional moisture-balance changes. Ultimately, I hope to collaborate with a diverse group of researchers that are interested in the human impact of climate change.

The role of tropical atmospheric dynamics in abrupt climate change since the end of the last glacial interval is a primary research topic in the study of climate change. I am therefore proposing collaborative research projects to continue reconstructing the climate history of the northern and southern Tropical Andes by applying an integrated methodology that combines elemental and isotopic geochemistry, sedimentology, paleo-productivity indicators, palynology, and quantitative glacial-geologic methods. I intend to continue testing hypotheses that abrupt climate change events in the tropics are synchronous with high latitude variability, and the low latitude ocean-atmosphere system is a major driver in global humidity and temperature changes.

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