Solar modulation of Little Ice Age climate in the tropical Andes

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The underlying causes of late-Holocene climate variability in the tropics are incompletely understood. Here we report a 1,500-year reconstruction of climate history and glaciation in the Venezuelan Andes using lake sediments. Four glacial advances occurred between anno Domini (A.D.) 1250 and 1810, coincident with solar-activity minima. Temperature declines of $-3.2 \pm 1.4$°C and precipitation increases of $\approx 20\%$ are required to produce the observed glacial responses. These results highlight the sensitivity of high-altitude tropical regions to relatively small changes in radiative forcing, implying even greater probable responses to future anthropogenic forcing.

During the past millennium, significant climatic fluctuations have occurred. Prominent among these is the Little Ice Age (LIA), recognized in historical records (e.g., ref. 1) and documented in proxy climate records from many locations (2). Although the LIA was a significant global event (3), its causes and regional differences in the timing and climatic response remain unclear (2, 4). This uncertainty is particularly true in the tropics, where well dated records with sufficient temporal resolution to resolve decadal changes in climate are sparse (2). Better knowledge of tropical climate during the LIA will help determine its causes and aid in the prediction of future climatic change.

It is hypothesized that variations in the sun’s energy output played a role in climatic change during the LIA (4). However, although the tropics receive 47% of the planetary insolation, their response to solar irradiance variability is uncertain. Here we present evidence that climatic change in the Venezuelan Andes is linked to changes in solar activity during the LIA. Venezuela is situated near the northern limit of the annual migration of the intertropical convergence zone (ITCZ) (Fig. 1). The annual migration of the ITCZ between hemispheres leads to pronounced seasonality in rainfall at the latitudinal extremes of this trajectory. Thus, Venezuela is particularly sensitive to changes in the position and strength of the ITCZ (5), which are expressed as changes in the amplitude of the annual cycle (6). The annual cycle is a function of the intensity and zonal migration of maximum solar insolation received at the earth’s surface. Therefore, variations in solar energy can be expected to cause changes in the strength of the ITCZ, leading to precipitation and temperature anomalies in Venezuela.

Tropical glaciers respond rapidly to precipitation and temperature variations and, hence, are faithful recorders of climatic variability (7–9). In this study we use glacier fluctuations and paleoclimatic records of precipitation and moisture balance to reconstruct Venezuelan climate during the past 1,500 yr. Prior studies in the Cordillera de Mérida have documented the extent of glaciers during the Last Glacial Maximum and their rapid retreat at the beginning of the Holocene (10, 11). During most of the past 10,000 yr, glaciers were absent from all but the highest peaks in the Cordillera de Mérida (11). Evidence for recent glacier advances comes from unweathered moraines and other glacial landforms. These features have been correlated with the LIA (12); however, they have not been dated, and thus the timing of recent advances remains unknown.

Here we present continuous decadal-scale lake-sediment records of glacier activity and moisture balance in the Venezuelan Andes during the past 1,500 yr. The continuous nature of the glacial record allows us to resolve multiple advances and determine the timing of these events. Because glaciers are sensitive to both temperature and precipitation changes, we present independent reconstructions of precipitation and moisture balance that allow a more accurate determination of the climate during the LIA. Mapping of the paleoglacier and modeling of the glacier response to precipitation and temperature variations provide a quantitative estimate of climatic change during the LIA. Comparison of these glacial and climatic records from Venezuela with regional and global proxy data as well as probable forcing variables allows us to infer potential causes for the glacier advances.

Study Sites

Sediment records from two watersheds were analyzed to reconstruct the timing of glacial advances and regional changes in climate.

Conflict of interest statement: No conflicts declared.

Abbreviations: AAR, accumulation-area ratio; A.D., anno Domini; ELA, equilibrium-line altitude; ITCZ, intertropical convergence zone; L. Laguna; LIA, Little Ice Age; MS, magnetic susceptibility; P/E, precipitation evaporation; TOC, total organic carbon.

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Laguna (L.) Mucubají (Fig. 1) is situated in a north-facing lake-sediment record of glacier activity. The Mucubají record indicates the presence of glaciers in the L. Mucubají watershed increased the catchment with a maximum elevation of 4,942 m (Pico Humboldt), and 4,883 m (Pico Bonpland). The only four remaining glaciated peaks in Venezuela have a vegetation and inactive were occupied during the LIA, increasing the supply of clastic sediment to the lake. The MS of the sediment record contains significant peaks at 227 and 125 yr in both the irradiance and MS records, closely matching the de Vries and Gleissberg oscillations identified from solar irradiance reconstructions. The LIA period in Mucubají occurs during an extended interval of low solar activity (23, 24), which likely promoted the growth of glaciers in the watershed. On the basis of the L. Mucubají sediment record, the establishment of an active glacier occurred at approximately A.D. 1150. The lack of sediment MS response to earlier irradiance minima at A.D. 750 and 1050 is attributable to the absence of a glacier in the watershed before approximately A.D. 1100 (Fig. 2).

Although the shielding effect of volcanic aerosols likely contributed to glacier growth, it is difficult to differentiate the effects of solar and volcanic forcing because they are correlated during the past 1,000 yr (4). However, solar and volcanic forcing are uncorrelated between A.D. 1520 and 1650, and the MS record follows the solar-irradiance reconstruction during this interval (Fig. 2F). This observation suggests that solar forcing is an important underlying cause of variations in glacier activity during the LIA.

**Sediment Record of Moisture Balance.** L. Blanca (Fig. 1) contains a nonglacial record of catchment erosion associated with increased P/E balance. Watershed streams that are currently vegetated and inactive were occupied during the LIA, increasing the supply of clastic sediment to the lake. The MS of the sediment record contains significant peaks at 227 and 125 yr in both the irradiance and MS records, closely matching the de Vries and Gleissberg oscillations identified from solar irradiance reconstructions. The LIA period in Mucubají occurs during an extended interval of low solar activity (23, 24), which likely promoted the growth of glaciers in the watershed. On the basis of the L. Mucubají sediment record, the establishment of an active glacier occurred at approximately A.D. 1150. The lack of sediment MS response to earlier irradiance minima at A.D. 750 and 1050 is attributable to the absence of a glacier in the watershed before approximately A.D. 1100 (Fig. 2).

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Mucubají. This conclusion is supported by higher abundances of Cyperaceae (sedge) pollen in the Piedras Blancas peat bog (Fig. 1) during the glacial period. Maxima of Cyperaceae occur during glacial advances (Fig. 2C and ref. 13) indicating a marshy environment, corroborating the L. Blanca MS record.

**Climatic Inferences from Glaciers.** The response of glaciers to both temperature and precipitation changes must be assessed to fully interpret the glacial record (8). This assessment is accomplished by reconstructing changes in glacial extent and then calculating the temperature and precipitation changes needed to support the new glacier size. Fig. 3 shows the modern and reconstructed LIA glacier extent. From these maps, cumulative area-elevation profiles for the LIA and modern glaciers were developed (Fig. 4A). We use the equilibrium-line altitude (ELA; the elevation of the dividing line between the glacier accumulation and ablation areas) as a climatically sensitive measure to document variations in glacier extent. If the glacier accumulation-area ratio (AAR; the ratio of accumulation area to total glacier area) is known, these profiles can be used to determine the ELA. The vertical difference between the LIA and modern ELA (ΔELA) as a function of the AAR value is shown in Fig. 4B. Theoretical AAR values for tropical glaciers are ~0.82 (26), whereas an average AAR from 78 modern tropical glaciers is 0.69 (27). The ΔELA does not change significantly with the AAR; thus, values of 0.69–0.82 give an estimated ΔELA of approximately ~300 m. However, modern glaciers on Pico Bolívar have been rapidly retreating since at least A.D. 1870 (12); thus, −300 m represents a minimum estimate of the ΔELA. Accelerated melting since A.D. 1972 has caused two glaciers to disappear completely (12), suggesting that late-20th-century ELAs are actually nearer to the elevation of Pico Bolívar (4,979 m), and the ΔELA may be as much as −500 m.

The temperature and precipitation changes associated with this ELA lowering can be estimated by combining equations for the mass and heat balances of a glacier. This method is more accurate than simply multiplying the atmospheric lapse rate by the change in ELA because the elevation gradients of precipitation and humidity cause changes in the sensible and latent heat transfers at the glacier surface and affect the magnitude of the estimated temperature depression. The relationship between temperature depression, precipitation, and ELA lowering was calculated with the combined energy-balance and mass-balance model of ref. 28 after ref. 29. Vertical gradients in temperature, atmospheric humidity, and precipitation were calculated from data in refs. 30, 31, and 32, respectively. Transfer coefficients for sensible and latent heat are from ref. 28. The uncertainty in the temperature estimate is largely related to uncertainty in the estimated ELA depression. This method suggests that an ELA lowering of −300 to −500 m is equivalent to a temperature depression of 2.6–4.3°C, using the modern annual precipitation of 950 mm (Fig. 5).

**Palynology and Biome Migration During the LIA.** Pollen evidence from two nearby sites (Piedras Blancas and L. Victoria; Fig. 1) documents the expansion of the superpa´ramo (alpine tundra) ecotone and a lowering of Andean biomes by several hundred meters coeval to the glacial advances in L. Mucubají. Quantitative estimates for this biome lowering [Δh_{biome} (15)] at the Piedras Blancas site (13) indicates a gradual decrease in Δh_{biome} during the LIA, with an average LIA value of approximately −220 m and a minimum of −460 m near the LIA termination (Fig. 2D). The temperature and precipitation change associated...
with $\Delta h_{\text{biome}}$ is calculated from the climatology at the modern forest–páramo and páramo–superpáramo biome transitions, and the corresponding vertical gradients of temperature and precipitation. Compared with the NW slopes of the Venezuelan Andes, the modern forest–páramo and páramo–superpáramo boundaries are higher on SE-facing slopes, with mean annual temperatures that are 2.9 and 2.0°C lower, respectively. This difference is primarily a function of the precipitation gradient between these aspects (+1,225 and +755 mm yr$^{-1}$, respectively) and provides a constraint on the effect precipitation has on the temperature of the forest–páramo and páramo–superpáramo boundaries ($k_{\text{avg}} = -0.0085^\circ$C mm$^{-1}$ yr). Thus, the temperature ($T$) and precipitation ($P$) combinations that define the modern and LIA forest–páramo boundary are

$$T_m - kP_m = T_{\text{LIA}} - kP_{\text{LIA}}.$$  \[1\]

This equation can be rewritten to include a change in the elevation of the biomes ($\Delta h_{\text{biome}}$) using the vertical gradients in $P$ and $T$ and solved for the LIA temperature change ($\Delta T = T_{\text{LIA}} - T_m$) as follows:

$$\Delta T_{\text{LIA}} = k\Delta P_{\text{LIA}} - \Delta h_{\text{biome}}(k\frac{\partial P}{\partial z} - \frac{\partial T}{\partial z}).$$  \[2\]

Eq. 2 gives the relationship between precipitation and temperature change when the elevation shift of biomes is known. Vertical gradients in temperature and precipitation were calculated from data in refs. 30 and 32, respectively, and used to determine the climatic changes associated with the lowering of biomes during the LIA.

The magnitude of climate changes during the LIA depends on the exact values of $\Delta E_{\text{LA}}$ and $\Delta h_{\text{biome}}$, used in the reconstruction. $\Delta h_{\text{biome}}$ provides a continuous measure of climate change because there is very little lag between climate shifts and plant pollen production [on the order of decades (33)]. In contrast, $\Delta E_{\text{LA}}$ provides an estimate of the climate during maximum glacial extent. We reconcile these differences by using a value for $\Delta E_{\text{LA}}$ intermediate between the $-300$- and $-500$-m minimum and maximum estimates and a $\Delta h_{\text{biome}}$ average ($-308$ m) of the maximum $\Delta h_{\text{biome}}$ from each glacial advance. The intersection of the ELA and pollen estimates indicate that during the LIA the Venezuelan Andes were both cooler ($-3.2^\circ$C) and wetter ($+208$ mm yr$^{-1}$, +22%) than present (Fig. 5). Propagation of the uncertainty in $\Delta E_{\text{LA}}$ ($\pm 100$ m estimated from the minimum and maximum $\Delta E_{\text{LA}}$ values) and $\Delta h_{\text{biome}}$ [we use the larger uncertainty of $\pm 250$ m in the $\Delta h_{\text{biome}}$ calculation (15)] rather than the

±100-m range around the $-308$ m average] provides uncertainties of $\pm 1.4^\circ$C and $\pm 590$ mm yr$^{-1}$ in these $T$ and $P$ estimates.

**Discussion of LIA Climatic Change.** The reconstructed LIA temperature depression in the high altitudes of the Venezuelan Andes is greater than that inferred for Caribbean sea-surface temperatures (SSTs) ($\approx 2^\circ$C (34–36)). This result is likely a consequence of changes in adiabatic lapse rates due to cooling. Cooler tropical SSTs would reduce the absolute humidity of the lower troposphere and steepen the slope of the moist adiabat above the condensation level. This effect would lead to cooling at 4,500 m above sea level, which was $\approx 1.5$ times that at sea-level (Fig. 6), in agreement with our glacier- and pollen-temperature estimates.

Both the L. Blanca and Piedras Blancas P/E records support the increased precipitation inferred from the ELA-pollen reconstruction. However, the wetter conditions indicated by the L. Blanca and Piedras Blancas records also could be the result of decreased evaporation due to lower temperatures. A $3^\circ$C decrease in air and lakewater temperatures would reduce evaporation by approximately $-20\%$ (37), although decreased atmospheric water vapor due to cooling would likely decrease precipitation amounts (approximately $-20\%$ if precipitation is proportional to the partial pressure of water vapor) and offset the reduced evaporation. Accordingly, the P/E change documented in the Venezuelan Andes for the LIA strongly suggests but does not require an increase in precipitation.

Intuitively, it would seem that cooler temperatures and lower absolute humidity would lead to less precipitation in the Venezuelan Andes during the LIA. However, this view may be reconciled with the paleoclimate data for increased precipitation at the study sites by recognizing that it is the transport of moisture to high elevations that most likely controls the precipitation amount, as has been clearly documented for the Bolivian/Peruvian Andes (38). During the LIA, a steeper latitudinal temperature gradient induced stronger easterly trade winds (20), which may have actually enhanced the transport of moisture to the Venezuelan Andes. Thus, greater moisture flux may have more than compensated for the reduced atmospheric water-vapor concentration.

Paleoclimate records from other tropical sites support our interpretation of the glacier and sedimentary records in Ve-
implying that profound climatic impacts can be predicted for years surpass that of solar forcing in previous centuries (45), anthropogenic greenhouse-gas radiative forcing for the next 50 sensitivity of tropical climate to small changes in radiative forcing ance in many cases (12, 42–44). Our data suggest considerable tropical glaciers, leading to accelerated ablation and disappear-

20th-century temperature increases have raised the ELAs of altitude tropical montane regions (41). Supporting this concern, raises concern that global warming will adversely affect high-
effects of warming trends, irrespective of their origin, which It is likely that this mechanism also may serve to amplify the feedbacks involving water vapor, ultimately depressing temper-

Maracaibo or drain to the Orinoco River.

Venezuelan Andes may not directly influence the sedimentology of the Cariaco Basin. Alternately, catchments draining the Andean regions (40). This finding suggests the possibility that, precipitation anomalies have opposite signs in coastal and century Venezuelan climate records show that rainy-season

Conclusions

The data presented here suggest that solar activity has exerted a strong influence on century-scale tropical climate variability during the late Holocene, modulating both precipitation and temperature. Surface cooling is enhanced at high altitudes by feedbacks involving water vapor, ultimately depressing temper-

tatures in the Venezuelan Andes by $-3.2 \pm 1.4^\circ$C during the LIA. It is likely that this mechanism also may serve to amplify the effects of warming trends, irrespective of their origin, which raises concern that global warming will adversely affect high-

Materials and Methods

Sediment Chronology. In 1999, we recovered sediment cores from L. Mucubajı and L. Blanca with percussion and square-rod coring systems (46). Duplicate cores and undisturbed sediment/ water interface cores were retrieved from L. Mucubajı, and the interface core was extruded at 0.5-cm intervals in the field. A composite sediment record for L. Mucubajı was constructed from the two long cores and the interface core by matching visual stratigraphy and variations in volume MS, total organic carbon (TOC), total nitrogen (TN), $\delta^{13}$C$_{TOC}$, $\delta^{15}$N$_{TN}$, and C/N ratios. A composite sediment record for L. Blanca was developed by matching visual stratigraphy and variations of TOC, MS, and dry density between sediment sections.

Accelerator mass-spectrometry radiocarbon dates and excess $^{210}$Pb profiles constrained the age–depth relationship for the cores. Excess $^{210}$Pb profiles were converted to calendar ages with the constant rate of supply model (47) and the 1964 $^{137}$Cs nuclear testing peak. Radiocarbon ages were converted to calendar ages by using the CALIB 4.2 data set (Table 1; refs. 18 and 48). Age models (Fig. 7) were constructed with polynomial spline curves to interpolate ages between radiocarbon dates. A single radio-
carbon date at 72.5 cm in L. Mucubajı was excluded from the age–depth model because it produced sedimentation rates that were anomalous in the context of the complete 8,000-yr record.

Sediment Geochemistry. Clastic material represents the nonbiogenic component of sediments and can be used as an indicator of sediment supply from the catchment. In L. Mucubajı clastic sediment content was calculated as the total minus the sum of biogenic silica and organic matter content (no carbonates were present in

![Image](https://example.com/image.png)

**Table 1. Accelerator mass spectrometry radiocarbon ages on L. Mucubajı and L. Blanca sediments**

<table>
<thead>
<tr>
<th>Lab code*</th>
<th>Lake</th>
<th>Core</th>
<th>Material†</th>
<th>Composite depth, cm</th>
<th>$^{14}$C age, yr A.D.</th>
<th>1σ calibrated age ranges, A.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAMS-96809</td>
<td>L. Mucubajı</td>
<td>99 A</td>
<td>Wood</td>
<td>44.5</td>
<td>$1,620 \pm 40$</td>
<td>$1495–1500, 1508–1532, 1541–1600, 1614–1636$</td>
</tr>
<tr>
<td>AA-35204</td>
<td>L. Mucubajı</td>
<td>99 C</td>
<td>Aq macro</td>
<td>54.2</td>
<td>$1,315 \pm 45$</td>
<td>$1299–1325, 1349–1391$</td>
</tr>
<tr>
<td>CURL-4959</td>
<td>L. Mucubajı</td>
<td>99 C</td>
<td>Aq macro</td>
<td>66.2</td>
<td>$770 \pm 30$</td>
<td>$782–791, 809–845, 846–891$</td>
</tr>
<tr>
<td>CAMS-96810</td>
<td>L. Mucubajı</td>
<td>99 A</td>
<td>Aq macro</td>
<td>72.5</td>
<td>$585 \pm 30$</td>
<td>$645–685$</td>
</tr>
<tr>
<td>CURL-4960</td>
<td>L. Mucubajı</td>
<td>99 C</td>
<td>Aq macro</td>
<td>85.8</td>
<td>$-160 \pm 35$</td>
<td>$-194$ to $-193$, $-172$ to $-89$, $-74$ to $-59$</td>
</tr>
<tr>
<td>CURL-4973</td>
<td>L. Blanca</td>
<td>99 A</td>
<td>Wood</td>
<td>64.5</td>
<td>$1,820 \pm 35$</td>
<td>$1679–1708, 1719–1739, 1805–1822, 1827–1885, 1912–1935$</td>
</tr>
<tr>
<td>CURL-4974</td>
<td>L. Blanca</td>
<td>99 A</td>
<td>Leaf</td>
<td>103.5</td>
<td>$1,290 \pm 35$</td>
<td>$1290–1312, 1354–1387$</td>
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<tr>
<td>CAMS-73134</td>
<td>L. Blanca</td>
<td>99 A</td>
<td>Wood</td>
<td>123.5</td>
<td>$970 \pm 40$</td>
<td>$1002–1012, 1016–1045, 1088–1121$</td>
</tr>
<tr>
<td>CAMS-96802</td>
<td>L. Blanca</td>
<td>99 A</td>
<td>Wood</td>
<td>188.6</td>
<td>$-170 \pm 35$</td>
<td>$-197$ to $-187$, $-180$ to $-91$</td>
</tr>
</tbody>
</table>

*CAMs, Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory; AA, Accelerator Mass Spectrometry Laboratory, University of Arizona; CURL, National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole Oceanographic Institute.

†Aq macro, aquatic macrophyte.

‡Not included in age model.
these sediments). Biogenic silica was analyzed by time-dissolution experiments (49, 50) following the recommendations of ref. 51. Dissolved silica from the dissolution experiments was determined by inductively coupled plasma–atomic emission spectrometry (ICP–AES) (52). TOC was measured with a CHNS elemental analyzer (Model 252, Finnigan-MAT, San Jose, CA). Total organic matter (TOM) was calculated as 2.05 AES (52). Dissolved silica from the dissolution experiments was determined with a mass spectrometer (Model 252, Finnigan-MAT, San Jose, CA). Total organic matter (TOM) was calculated as 2.05 × TOC based on eight samples where TOM was measured by loss-on-ignition (53, 54) and compared with TOC values. In cores from both L. Blanca and L. Mucubají, MS was measured on split sediment cores with a Bartington Instruments MS2 magnetic susceptibility meter. The glacier centerline was defined by connecting the glacier topography and using the AAR method (55). Glacier topography was used to determine the ELA. For comparison with the Mucubají paleo-ELA, the ELA of modern glaciers in the Cordillera de Mérida was determined by constructing cumulative elevation profiles from the maps of ref. 25.

Glacier Reconstruction. The Mucubají valley paleoglacier ELA was calculated by reconstructing the glacier topography and applying the AAR method (55). Glacier topography was reconstructed by defining the glacial limits, calculating ice thickness along the glacier centerline, and contouring the glacier surface. Glacier limits were drawn from field data, visual observations of aerial photographs, and 1:24,000 topographic maps. The glacier centerline was defined by connecting the lowest points in topographic cross-sections of the glacier area. The surface slope along the glacier centerline was reconstructed with a basal shear stress ($\tau_b$) of 100 kPa (56). (Alternate constructions with $\tau_b = 50$ and 150 kPa did not alter the contours significantly.) The surface slope was integrated along the glacier centerline, starting at the glacier terminus, to give the ice elevation. The glacier surface was contoured by connecting reconstructed centerline elevations and bedrock contour lines at the glacier margin. A hypsometric curve of glacier area vs. elevation was developed from the contour plot and used to construct a normalized cumulative area vs. elevation profile. If the glacier AAR (the ratio of accumulation area to total glacier area) is known, these profiles can be used to determine the ELA. For comparison with the Mucubají paleo-ELA, the ELA of modern glaciers in the Cordillera de Mérida was determined by constructing cumulative elevation profiles from the maps of ref. 25.

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