

A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes

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Decadal and centennial mean state changes in South American summer monsoon (SASM) precipitation during the last 2,300 years are detailed using an annually resolved authigenic calcite record of precipitation $\delta^{18}\text{O}$ from a varved lake in the Central Peruvian Andes. This unique sediment record shows that $\delta^{18}\text{O}$ peaked during the Medieval Climate Anomaly (MCA) from A.D. 900 to 1100, providing evidence that the SASM weakened considerably during this period. Minimum $\delta^{18}\text{O}$ values occurred during the Little Ice Age (LIA) between A.D. 1400 and 1820, reflecting a prolonged intensification of the SASM that was regionally synchronous. After the LIA, $\delta^{18}\text{O}$ increased rapidly, particularly during the current warm period (CWP; A.D. 1900 to present), indicating a return to reduced SASM precipitation that was more abrupt and sustained than the onset of the MCA. Diminished SASM precipitation during the MCA and CWP tracks reconstructed Northern Hemisphere and North Atlantic warming and a northward displacement of the Intertropical Convergence Zone (ITCZ) over the Atlantic, and likely the Pacific. Intensified SASM precipitation during the LIA follows reconstructed Northern Hemisphere and North Atlantic cooling, El Niño-like warming in the Pacific, and a southward displacement of the ITCZ over both oceans. These results suggest that SASM mean state changes are sensitive to ITCZ variability as mediated by Western Hemisphere tropical sea surface temperatures, particularly in the Atlantic. Continued Northern Hemisphere and North Atlantic warming may therefore help perpetuate the recent reductions in SASM precipitation that characterize the last 100 years, which would negatively impact Andean water resources.

oxygen isotopes | varves | tropical hydroclimate

Recent work documenting the timing and geographic patterns of sub-centennial-scale Asian (1) and African (2) monsoon variability has advanced our understanding of late Holocene Northern Hemisphere (NH) monsoon systems; however, our knowledge of Southern Hemisphere monsoon variability remains limited. This is particularly true for the South American summer monsoon (SASM), the largest monsoon system in the Southern Hemisphere. Documenting the timing, direction, and magnitude of decadal to centennial changes in the SASM in the past will help determine the causes and relative importance of factors that influence monsoons and ultimately improve our knowledge of the climate system.

Previous paleoclimate studies in tropical South America show that over millennial time scales orbitally driven latitudinal changes in the Intertropical Convergence Zone (ITCZ), tropical continental convection and North Atlantic sea surface temperatures (SST) play important roles in driving SASM fluctuations (3, 4). However, the paucity of high-resolution Holocene hydroclimate records from tropical South America has hindered an evaluation of the role of these processes on SASM variability at decadal to centennial time scales. Here, we present an annually resolved reconstruction of the isotopic composition of tropical

South American precipitation as preserved in authigenic sedimentary calcite from Laguna Pumacocha, a varved alpine lake in the central Peruvian Andes. This unique archive documents subdecadal to centennial-scale variations in SASM precipitation over the last 2,300 years and provides insight into how this system responded to abrupt climate change during the late Holocene.

Study Site

Laguna Pumacocha is a small, high-altitude lake in the eastern Peruvian Andes set in a cirque basin at 4,300 m above sea level (asl) (10.70°S, 76.06°W) whose geological, morphological and limnological characteristics make it well-suited for archiving SASM variability in its sedimentary record (Fig. 1 and Fig. S1). The relatively small watershed has an area of only 1.7 km² and is surrounded by headwalls that rise to nearly 4,600 m asl. Jurassic marine limestones of the Chambará Fm. comprise the underlying bedrock and supply significant quantities of dissolved HCO₃⁻ and Ca²⁺ to the lake, maintaining a surface pH of approximately 8, an average alkalinity of 161 mg/L HCO₃⁻ and saturation with respect to calcite throughout the year. Authigenic calcite comprises between 22 and 38% of the sediment by weight and is likely formed when enhanced biological productivity draws down dissolved CO₂, increasing the lake's alkalinity and pH and initiating calcite precipitation. Scanning electron microscope images of the Pumacocha sediments show that the calcite crystals are euhedral with no apparent contamination by detrital limestone (Fig. S2). This is likely because the lake is flanked on all sides by a broad marshy zone that acts as a natural sediment trap for allochthonous material that might otherwise be washed into the lake during storm events (Fig. S1).

The 23.5-m deep Pumacocha lake basin has a large volume (1.37 × 10⁶ m³) despite its small surface area (0.09 km²) and is characterized by steeply sloping sides that drop off rapidly to a flat bottom (Fig. S1). These features contribute to water column stability, which results in permanent stratification and anoxic conditions below 8–12-m water depth. Persistent deepwater anoxia has resulted in the near perfect preservation of millimeter-scale couplets in the upper 176.2 cm of the 579.0-cm Holocene-length record (Fig. S2). These couplets are composed of sub-millimeter-scale laminations of authigenic calcite and diatom-rich organic

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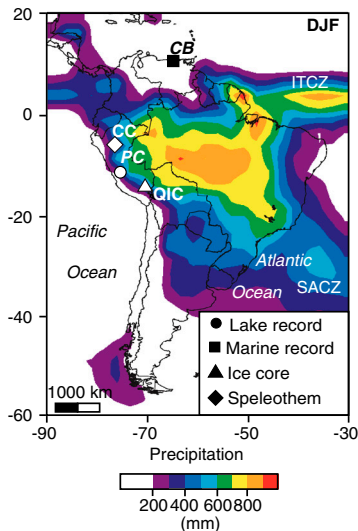


Fig. 1. Map of South America showing the locations of records discussed in the text (CB, Cariaco Basin; CC, Cascayunga Cave; PC, Pumacocha; QIC, Quelcayca Ice 557 Cap). Regions with precipitation >200 mm during the austral summer (December–February) are colored. Precipitation maxima over the oceans are related to low-level convergence within the ITCZ and the South Atlantic Convergence Zone (SACZ). Those over South America are associated with the SASM.

matter and were identified as varves based on the agreement between couplet counts, ^{137}Cs and accelerator mass spectrometry (AMS) ^{14}C ages (Fig. 2 and Tables S1 and S2). The varves extend uninterrupted from A.D. 840 to 2007, providing strong temporal constraints on the Medieval Climate Anomaly (MCA), Little Ice Age (LIA), and current warm period (CWP) in the Pumacocha record and allowing comparison with other high-resolution paleoclimate reconstructions.

Results and Discussion

The following discussion documents the close relationship between oxygen isotope values in precipitation ($\delta^{18}\text{O}_{\text{precip}}$) and lake water ($\delta^{18}\text{O}_{\text{lw}}$) and sedimentary calcite ($\delta^{18}\text{O}_{\text{cal}}$) from Pumacocha. We show that Pumacocha $\delta^{18}\text{O}_{\text{lw}}$ reflects variability in $\delta^{18}\text{O}_{\text{precip}}$ and that this variability is recorded by the $\delta^{18}\text{O}_{\text{cal}}$ of authigenic calcite that is precipitated from the lake's water column each year, forming an annually resolved sedimentary archive of SASM intensity. When compared with regional and global paleoclimate records, the Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record provides insight into SASM precipitation variability on subdecadal to

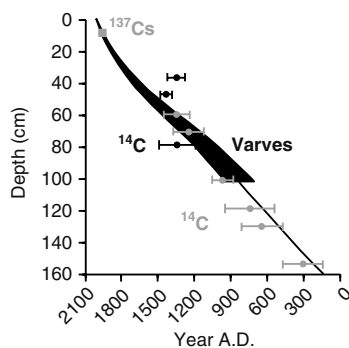


Fig. 2. Age–depth relationships for the Pumacocha record over the last 2,300 years. The gray box demarcates the A.D. 1963 ^{137}Cs peak. Varve ages are shown in black with the 1% cumulative error. AMS ^{14}C ages are represented by gray circles with error bars. Radiocarbon ages that were reversed and excluded from the age model are shown with black circles and error bars. The age–depth model is based on the equation of a 4th order polynomial fit to the AMS ^{14}C ages and anchored to the varve ages.

centennial time scales and during abrupt late Holocene climate events, including the MCA, which is not well documented by the currently available paleoclimate records.

Hydrology and Hydrology and $\delta^{18}\text{O}_{\text{precip}}$. Pumacocha is the uppermost lake in a topographically isolated catchment with limited groundwater reserves and no fluvial input. As a result, the lake's hydrologic mass balance is dominated by precipitation. Data from the closest weather station in Cerro de Pasco (10.68°S, 76.25°W; 4330 m asl) show that regional precipitation averages 1,000 mm yr^{-1} with approximately 60% occurring between December and March during the monsoon season. From these data we estimate that precipitation over the Pumacocha watershed averages approximately $1.67 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. This is approximately 23% greater than the total lake volume ($1.36 \times 10^6 \text{ m}^3$), thereby maintaining hydrologically open conditions and a surface water residence time of less than a year. As a result, the influence of evaporation on the lake's hydrologic and isotopic mass balances is minimal, a point illustrated by $\delta^{18}\text{O}$ and δD measurements on 27 monthly lake water samples collected at Pumacocha between August 2006 and July 2008 (Fig. 3 and Fig. S3). These samples constrain a local meteoric water line (LMWL) that is offset from, but parallel to, the global meteoric water line (GMWL; Table S3). This indicates that the isotopic composition of the lake water reflects seasonal variation in $\delta^{18}\text{O}_{\text{precip}}$ free from the effects of evaporation. If Pumacocha surface waters were influenced by evaporation, they would plot along the local evaporation line (LEL), which is constrained by water samples from closed basin lakes in the region that are sensitive to evaporation (Fig. 3). This LEL is oblique to the GMWL and LMWL and intersects the LMWL at a $\delta^{18}\text{O}$ value of -13.6‰ . Additional support for the limited role of evaporation is provided by the close agreement between annual mean $\delta^{18}\text{O}_{\text{lw}}$ (-13.0‰) and modeled annual mean $\delta^{18}\text{O}_{\text{precip}}$ ($-12.9\text{‰} \pm 1.5$) at Pumacocha (Table S4; refs. 5, 6). These data support the contention that Pumacocha $\delta^{18}\text{O}_{\text{lw}}$ reflects $\delta^{18}\text{O}_{\text{precip}}$ and that other influences on $\delta^{18}\text{O}_{\text{lw}}$ are negligible. The monthly water samples also record a strong seasonal cycle,

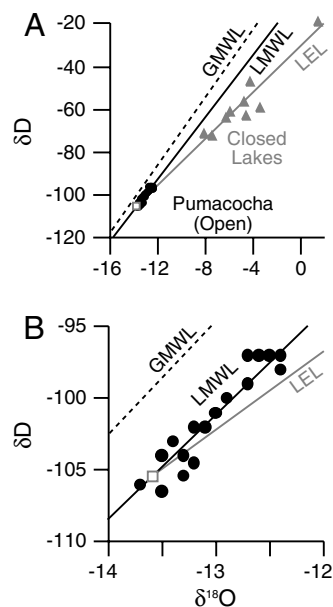


Fig. 3. (A) Surface water samples from Pumacocha (black circles) and regional hydrologically closed basin lakes (gray triangles). Pumacocha surface water samples plot along a LMWL (black line) that parallels the GMWL (dashed line). Regional lakes with closed basin hydrologies plot along a LEL (gray line), which is oblique to both the LMWL and the GMWL and intersects the LMWL at -13.6‰ $\delta^{18}\text{O}$ (VSMOW; gray square). (B) Same as in A but expanded to illustrate seasonal isotopic variability in the Pumacocha surface water.

indicating that $\delta^{18}\text{O}_{\text{lw}}$ responds rapidly to changes in $\delta^{18}\text{O}_{\text{precip}}$ and is sensitive to variations in $\delta^{18}\text{O}_{\text{precip}}$ (Fig. S3). No relationship was observed between $\delta^{18}\text{O}_{\text{lw}}$ and air, or lake-surface temperature, which is consistent with work that shows the amount of precipitation and rainout along the trajectory of an air mass are the primary factors that determine $\delta^{18}\text{O}_{\text{precip}}$ (7).

Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ and $\delta^{18}\text{O}_{\text{precip}}$. Modern limnological data from Pumacocha demonstrate a clear relationship among $\delta^{18}\text{O}_{\text{lw}}$, $\delta^{18}\text{O}_{\text{cal}}$, and $\delta^{18}\text{O}_{\text{precip}}$. Authigenic calcite was collected from littoral vegetation at Pumacocha in August 2006 and May 2008, and from deepwater sediment traps deployed between August 2006 and May 2007. When converted to Vienna standard mean ocean water (VSMOW) for comparison with $\delta^{18}\text{O}_{\text{lw}}$, the annual and three-year-average $\delta^{18}\text{O}_{\text{cal}}$ values are identical within error to measured mean annual $\delta^{18}\text{O}_{\text{lw}}$ (Table S4). This indicates that the calcite is precipitated in isotopic equilibrium with Pumacocha lake water and that $\delta^{18}\text{O}_{\text{cal}}$ measurements can be used to reconstruct past $\delta^{18}\text{O}_{\text{lw}}$ variability. Considering the evidence that $\delta^{18}\text{O}_{\text{lw}}$ tracks $\delta^{18}\text{O}_{\text{precip}}$, the correspondence between $\delta^{18}\text{O}_{\text{lw}}$ and $\delta^{18}\text{O}_{\text{cal}}$ supports using down-core $\delta^{18}\text{O}_{\text{cal}}$ measurements as a proxy for reconstructing $\delta^{18}\text{O}_{\text{precip}}$. Although we recognize that the links among $\delta^{18}\text{O}_{\text{cal}}$, $\delta^{18}\text{O}_{\text{lw}}$, and $\delta^{18}\text{O}_{\text{precip}}$ are empirical, the modern observational data support this working model as a reasonable first-order approximation.

Temperature Effect on Pumacocha $\delta^{18}\text{O}_{\text{cal}}$. Modern limnological and paleoclimate data suggest that temperature has a minor influence on the integrated $\delta^{18}\text{O}_{\text{cal}}$ signal at Pumacocha. Sediment trap $\delta^{18}\text{O}_{\text{cal}}$ averaged -12.8‰ and varied by 0.8‰ , which is about twice that attributable to temperature-controlled fractionation during calcite formation. On longer time scales, $\delta^{18}\text{O}_{\text{cal}}$ varied by up to 2‰ between the LIA and CWP (Fig. 4A). Accounting for temperature-controlled oxygen isotope fractionation during the formation of precipitation from water vapor ($+0.6\text{‰}\text{°C}^{-1}$; ref. 8) and calcite from lake water ($-0.22\text{‰}\text{°C}^{-1}$; ref. 9), a 2‰ shift requires a 5.5°C temperature change. This far exceeds

estimates of South American LIA cooling inferred from glacial equilibrium line altitude changes in Bolivia (1.1 to 1.2°C ; ref. 10) and lacustrine temperature reconstructions based on changes in lake productivity in central Chile (0.7 to 0.9°C ; ref. 11). Although a 0.7 to 1.2°C cooling could account for 0.3 to 0.5‰ (15 to 25%) of the Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ shift between the LIA and the CWP, the remaining variance is unexplained by temperature. These modern limnological and paleoclimate data suggest that temperature is, and has been, a minor influence on the integrated $\delta^{18}\text{O}_{\text{cal}}$ signal at Pumacocha and that $\delta^{18}\text{O}_{\text{cal}}$ variability is attributable to changes in the isotopic composition of precipitation.

SASM Variability and $\delta^{18}\text{O}_{\text{precip}}$. The principal control on $\delta^{18}\text{O}_{\text{precip}}$ over tropical South America is Raleigh-type fractionation during rainout (7). This is reflected by observations that show $\delta^{18}\text{O}_{\text{precip}}$ is more negative during the austral summer wet season, despite warmer temperatures, and more positive during the dry austral winter, when temperatures are generally cooler (12). There is, however, a slight offset of about 1–2 mo between the most intense precipitation and the most depleted $\delta^{18}\text{O}_{\text{precip}}$ at Pumacocha. Similar observations have been made in the Andes of Bolivia and attributed to rainout processes upstream over regions with slightly different precipitation seasonality (13). Hence $\delta^{18}\text{O}_{\text{precip}}$ is not simply a measure of precipitation amount at the site, but rather of the intensity of monsoon-related convective activity along the trajectory of an air mass (12–14). Year-to-year $\delta^{18}\text{O}_{\text{precip}}$ variability documented by observations, proxy data, and stable isotope-enabled global climate models show that $\delta^{18}\text{O}_{\text{precip}}$ is lower during intense monsoon seasons and vice versa (7). This isotopic response to monsoon variability is preserved and enhanced along an air mass trajectory, even if the precipitation signal at the site where stable isotopes are measured is not exactly the same as over the core region of convective activity, in this case the Amazon Basin (7). Hence the isotopic monsoon signal tends to be much more spatially coherent than monsoon precipitation, which is more strongly affected by microclimatic effects (14). This “isotopic memory” of an air mass and its influence on downstream $\delta^{18}\text{O}$ records like the one from Pumacocha means that local $\delta^{18}\text{O}_{\text{precip}}$ records reflect large-scale changes in the intensity of the SASM (7). We therefore interpret $\delta^{18}\text{O}_{\text{cal}}$ from Pumacocha as a proxy for the intensity of monsoon precipitation upstream.

Modern interannual variations in SASM intensity are caused by a number of factors. Pacific SST anomalies associated with El Niño–Southern Oscillation (ENSO) play a primary role in modulating SASM variability through changes in the Hadley and Walker circulation over tropical South America and the Pacific (15, 16). Changes in tropical Atlantic SSTs have also been linked to interannual variations in SASM activity and drought conditions over the Amazon Basin (15, 17). Soil moisture provides an important land surface feedback that has been shown to affect SASM precipitation patterns (18). All these factors lead to distinct variations in SASM activity, only loosely coupled to ITCZ variations over the tropical oceans on interannual time scales. Over the tropical Andes, summer precipitation is predominantly modulated by eastern equatorial Pacific SST (15). Cooling in the eastern equatorial Pacific (e.g., La Niña events) typically leads to reduced meridional baroclinicity and anomalous upper-level easterly flow over the Andes, which enhances near-surface moisture influx from the Amazon Basin, and vice versa. Therefore, although the SASM moisture supply lies almost exclusively in the tropical Atlantic, perturbations in atmospheric circulation caused by SST anomalies in the tropical Pacific play an important role mediating the intensity of the SASM in general and over the tropical Andes in particular (15).

SASM variability is less well understood on decadal and longer time scales because limited instrumental data in the tropics complicates investigations of long-term trends. Nonetheless, observa-

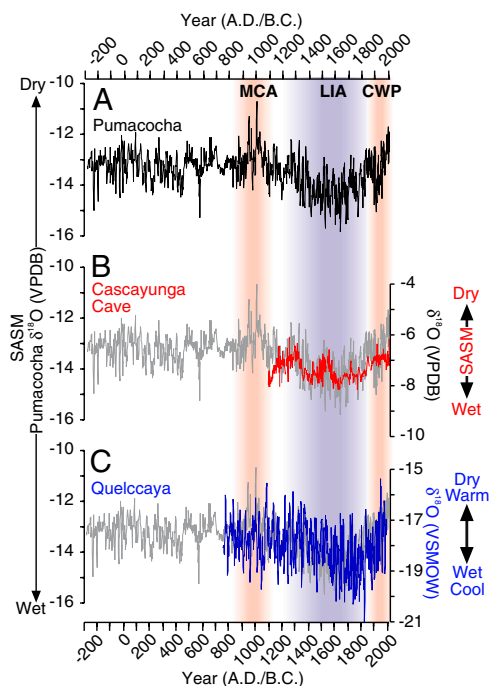


Fig. 4. (A) The Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record of SASM intensity. In B and C, the Pumacocha data are shown with a gray line for comparison with (B) $\delta^{18}\text{O}_{\text{cal}}$ from Cascayunga Cave, Peru, a record of lowland precipitation (22) and (C) $\delta^{18}\text{O}_{\text{ice}}$ from Quelccaya, Peru (23) smoothed with a 5-point moving average.

tions show that Atlantic SST variations play a significant role modulating SASM variability on multidecadal time scales (19). Paleoclimate studies similarly suggest that the tropical Atlantic may have been an important factor driving tropical South American rainfall variability on longer time scales and during past periods with different climatic boundary conditions (20, 21).

SASM Variability and Mean State Changes. Using the empirical relationships among Pumacocha $\delta^{18}\text{O}_{\text{lw}}$, $\delta^{18}\text{O}_{\text{cal}}$, and $\delta^{18}\text{O}_{\text{precip}}$, and the documented close relationship between SASM intensity and $\delta^{18}\text{O}_{\text{precip}}$ (7, 12), we interpret down-core variations in Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ as representative of the intensity of the SASM. Accordingly, high $\delta^{18}\text{O}_{\text{cal}}$ is taken to reflect a less intense SASM, whereas lower $\delta^{18}\text{O}_{\text{cal}}$ represents a more intense SASM.

The Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record is characterized by considerable decadal-scale variability with three pronounced century-scale mean state changes during the MCA, LIA, and CWP, indicating major changes in the strength of the SASM (Fig. 4A). During the MCA, $\delta^{18}\text{O}_{\text{cal}}$ increased between A.D. 900 and 1100 with two distinct decadal-scale peaks from A.D. 935 to 950 and A.D. 1000 to 1040, indicating considerable reductions in SASM intensity. Medieval aridity was followed by a prolonged decrease in $\delta^{18}\text{O}_{\text{cal}}$ during the LIA starting as early as A.D. 1300, with minimum values between A.D. 1400 and 1820. This trend signifies the most dramatic increase in the strength of the SASM identified in the 2,300-year-long Pumacocha record. After A.D. 1820, $\delta^{18}\text{O}_{\text{cal}}$ generally increased to the present, especially after A.D. 1900. Between A.D. 1908 and 2007, $\delta^{18}\text{O}_{\text{cal}}$ increased from -15.0‰ to -12.9‰ at an average rate of 0.02‰ per year, which is the steepest and most rapid $\delta^{18}\text{O}_{\text{cal}}$ rise in the 2,300-year-long Pumacocha record. This increase reflects a long-term reduction in the intensity of the SASM that is similar in magnitude to the MCA aridity, but with a more abrupt onset.

Comparison with other highly resolved paleoclimate records from tropical South America shows that SASM mean state changes captured by the Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record were regional in scale with similar timing, direction, and magnitude. Specifically, the Pumacocha record tracks the 900-year-long Cascayunga Cave $\delta^{18}\text{O}_{\text{cal}}$ record (6.09°S, 77.23°W, 930 m asl), which is interpreted as a record of South American rainfall (Fig. 4B; ref. 22). The correspondence between these $\delta^{18}\text{O}$ records during their common period from A.D. 1050 to 2006 is notable because Cascayunga Cave is 3,400 m lower than Pumacocha and over 600 km to the north. Interestingly, the timing of mean state changes in the two records is nearly identical, although both the degree and magnitude of $\delta^{18}\text{O}$ variability are more pronounced in the Pumacocha record. Their similarities, however, support our contention that the Pumacocha record reflects regional scale precipitation variability and provides supporting evidence that strengthening of the SASM during the LIA was not strictly an Andean response.

The Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record also shares many features with the annually resolved Quelccaya Ice Cap $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{ice}}$) record, which is approximately 500 km southwest of Pumacocha (13.93°S, 70.83°W; 5670 m asl; Fig. 4C; ref. 23). The timing and direction of mean state changes in these records are similar during the LIA and CWP, although the Quelccaya ice core shows greater variability and slightly later minimum $\delta^{18}\text{O}_{\text{ice}}$ values during the LIA. The MCA is less pronounced in the Quelccaya $\delta^{18}\text{O}_{\text{ice}}$ record than in the Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record, although $\delta^{18}\text{O}_{\text{ice}}$ increased between A.D. 980 and 1100 with two peaks centered on A.D. 990 and 1080. It is not clear why the MCA is less evident at Quelccaya because, although considerably lower resolution (100 years per sample), tropical Andean ice cores from Nevado Huascarán (24) and Sajama (25) have broadly elevated $\delta^{18}\text{O}_{\text{ice}}$ from A.D. 900 to 1300 and A.D. 900 to 1500, respectively. Notably, the Quelccaya $\delta^{18}\text{O}_{\text{ice}}$ record has historically been interpreted as a paleo-temperature record, although a number of authors have noted that precipitation amount likely plays a major

role driving $\delta^{18}\text{O}_{\text{ice}}$ variability (e.g., ref. 26). Because the Pumacocha and Cascayunga Cave records reflect SASM precipitation variations, their similarities with Quelccaya are consistent with the notion that Rayleigh distillation during rainout in the SASM region strongly influences isotopic records of tropical precipitation.

The close agreement in the timing, direction, and magnitude of mean state changes in $\delta^{18}\text{O}$ during the MCA, LIA, and CWP from lake sediment, speleothem, and ice core records supports the idea that a common large-scale mechanism influenced $\delta^{18}\text{O}$ reaching these central Andean sites spanning 11° latitude and 4,740 m of elevation. Based on the work presented here, the most likely cause of these documented shifts in $\delta^{18}\text{O}_{\text{precip}}$ is a change in SASM intensity as all three sites receive the majority of their annual precipitation during the monsoon season.

We compared the Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record to volcanic and solar radiative forcing (Fig. 5; e.g., 27, 28), reconstructed NH temperatures (29), variations in the latitude of the ITCZ (30, 31), and North Atlantic SST's (32, 33) to help identify the relevant factors that contributed to decadal variability and mean state changes in the SASM during the MCA, LIA, and CWP (Fig. 5). North Atlantic SST's are represented by the Mann et al. (32) reconstruction of SST from 60°N to the equator and 75.5° to 7.5°W and referred to generally as the North Atlantic. These variables were selected because numerous lines of evidence suggest that ocean-atmosphere processes, which are important drivers of modern SASM variability, contributed to past SASM changes

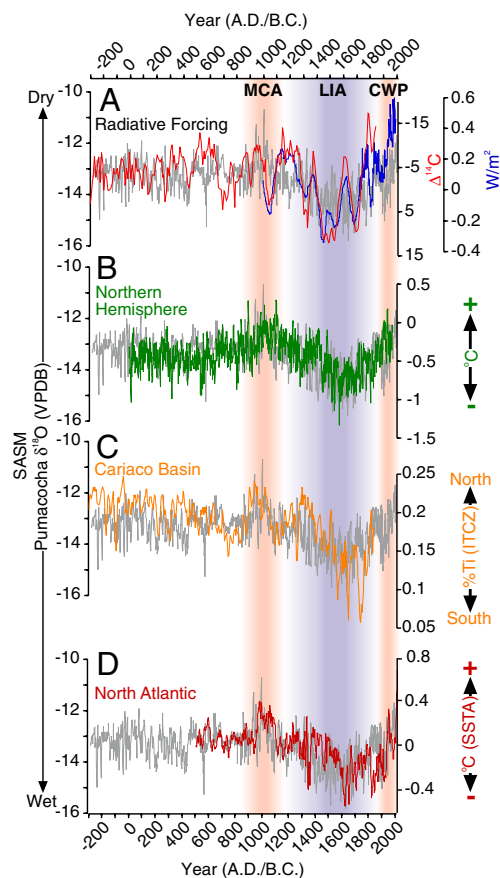


Fig. 5. (A) Reconstructed radiative forcing (blue) for the last 1,000 years from ref. 27 and residual ^{14}C for the last 2,300 years ($\Delta^{14}\text{C}$; a proxy for solar variability; red; ref. 28), (B) reconstructed Northern Hemisphere temperatures (29), (C) % Ti from the Cariaco Basin, Venezuela (30), interpreted as a proxy for the location of the ITCZ, and (D) reconstructed SST anomalies in the North Atlantic (32). The superimposed gray line in each of the graphs shows the Pumacocha $\delta^{18}\text{O}_{\text{cal}}$ record for comparison.

decrease in mean rainfall over the Amazon Basin during the instrumental period from A.D. 1975 to 2003 (41). Given the anticipated loss of many tropical Andean glaciers within the next 50 years (42), sustained reductions in SASM rainfall could negatively impact the availability of water resources in the Andes and along the arid Pacific coast.

Materials and Methods

The Pumacocha data are archived at the National Oceanic and Atmospheric Administration Paleoclimatology World Data Center: <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/southamerica/peru/pumacocha2011.txt>.

Sediment Core Recovery. Sediment cores were retrieved from Pumacocha using a piston corer in 23.5-m water depth in June 2005 and August 2006. The composite 579.0-cm Holocene-length sediment record is comprised of successive overlapping 1-m-long drives. A network of freeze cores collected from the lake between 2006 and 2008 captured the undisturbed sediment-water interface (Table S5).

Age Control. Samples for ^{210}Pb , ^{226}Ra , and ^{137}Cs were measured at approximately 1 cm intervals between 0.0 and 30.0 cm from freeze core D-08 by

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