Synchronous interhemispheric Holocene climate trends in the tropical Andes

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Holocene variations of tropical moisture balance have been ascribed to orbitally forced changes in solar insolation. If this model is correct, millennial-scale climate evolution should be antiphased between the northern and southern hemispheres, producing humid intervals in one hemisphere matched to aridity in the other. Here we show that Holocene climate trends were largely synchronous and in the same direction in the northern and southern hemisphere outer-tropical Andes, providing little support for the dominant role of insolation forcing in these regions. Today, sea-surface temperatures in the equatorial Pacific Ocean modulate rainfall variability in the outer tropical Andes of both hemispheres, and we suggest that this mechanism was pervasive throughout the Holocene. Our findings imply that oceanic forcing plays a larger role in regional South American climate than previously suspected, and that Pacific sea-surface temperatures have the capacity to induce abrupt and sustained shifts in Andean climate.

Venezuela | Bolivia | Caribbean | El Niño-Southern Oscillation | Milankovitch

Variations in solar insolation driven by the precession of the equinoxes have been invoked as the determinant factor modulating tropical climate on millennial timescales (1–5). Humid conditions prevail in the hemisphere where perihelion (minimum earth–sun distance) coincides with the summer wet season (June–August in the northern hemisphere, December–February in the southern hemisphere), whereas the opposite hemisphere experiences a drier climate. The proposed mechanism calls for enhanced solar heating, convection, and rainfall during the wet season when it coincides with perihelion. This mechanism is supported by a number of South American Holocene paleoclimate records in the southern hemisphere. Runoff from the Amazon Basin (1), evaporation in Peruvian lakes (2), speleothem $\delta^{18}O$ (3, 6, 7), ice cores (4, 8), and lake sediment records (5) all suggest these regions became wetter as summer insolation increased during the Holocene. Additional support for this mechanism comes from reduced precipitation in regions that are dynamically linked to convection in the southern hemisphere tropics, such as the Nordeste of Brazil (9).

In contrast to the southern hemisphere, evidence for precessional forcing of Holocene climate in northern South America remains equivocal, and there appear to be more complex spatial patterns of climate evolution that are not consistent between available marine and terrestrial paleoclimate records. Marine sediments off the Venezuelan coast (10–11 °N) indicate a decrease of terrigenous (continental) sedimentation during the Holocene, providing evidence for reduced precipitation with decreasing northern hemisphere summer insolation (10). However, terrestrial Holocene paleorecords from low-altitude Andean sites do not support a direct insolation forcing mechanism. For example, results from Lake Valencia in northern Venezuela [10° 11′ N, 67° 43′ W, 402 m above sea level (a.s.l.)] indicate arid conditions during the early Holocene, a humid interval during the middle Holocene, and a return to arid conditions in the late Holocene (11, 12). This arid–humid–arid sequence is at odds with the marine evidence for precessional forcing of climate, suggesting either a sharp climatic boundary between coastal and inland Venezuela, or perhaps a more complex control over terrigenous geochemical indicators in the marine record (13, 14) (*SI Text* and Fig. S1).

Here we present a unique multiproxy record of Holocene climate from Laguna Blanca in the Venezuelan Andes, which is strategically located to test whether precessional forcing resulted in antiphased climate changes in the northern and southern hemispheres of the Cordillera, and resolve the discrepancy between terrestrial and marine climate histories. Laguna Blanca (8° 20′ N, 71° 47′ W, 1,620 m a.s.l.; Fig. 1 and Fig. S2) is a small shallow lake in an unglaciated watershed where sediment lithology and geochemistry offer first-order proxies for changes in lake level and hence regional moisture balance. We use sediment organic content, dry density, and magnetic susceptibility (MS) to characterize sediment lithology, constrained by a robust chronological framework based on 11 calibrated accelerator-mass spectrometric (AMS) radiocarbon ages from terrestrial macrofossils and bulk sediment (*SI Text* and Fig. S3). Carbon/nitrogen (C/N) molar ratios distinguish terrestrial (C/N > ~30) from aquatic (C/N < ~15) organic matter. Previous results documented that a humid period with overflowing lake levels coincided with glacier advances in the Venezuelan Andes during the Little Ice Age (15). Here we extend this record back to 11,000 y before present (BP) to document shifts in lake level that reflect millennial-scale patterns of Andean climate evolution.

Results and Discussion

During the early Holocene, finely laminated lacustrine sediments accumulated in Laguna Blanca, dominated by autochthonous organic matter and minerogenic influxes from the catchment, together resulting in high sediment accumulation rates (Fig. 2). This style of deposition results from humid conditions that prevailed between 11,000 and 8,200 y BP. However, an intense drought punctuated this interval between ~9,100 and 8,500 BP, as indicated by a hiatus in sediment accumulation. This arid interval is also preserved in nearby Laguna Brava (8° 19′ N, 71° 50′ W, 2,380 m a.s.l.; Fig. 1), indicating a period of sustained regional drought. The calibrated radiocarbon age of lacustrine sediments from Laguna Brava immediately overlying the desiccation surface (Table S1) dates the return to wetter conditions at 8,410 y BP. The cause of this drought remains uncertain, as it predates the 8,200-y event identified in many tropical and high latitude records (16).

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EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

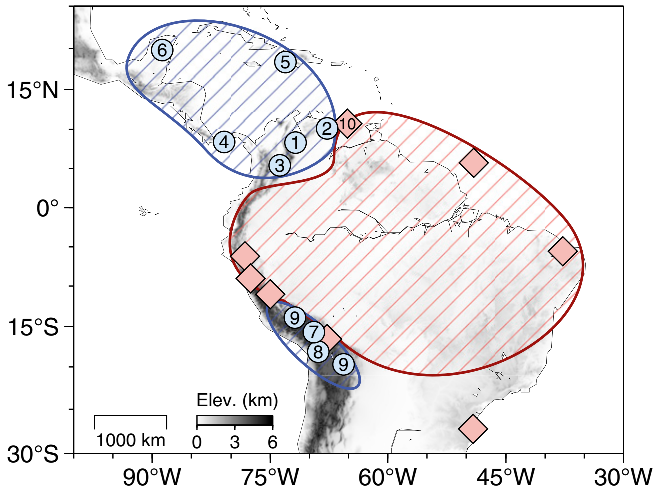

Fig. 1. South American topography and the location of paleoclimate records discussed in the text: 1, Laguna Blanca, Venezuela; 2, Lake Valencia, Venezuela; 3, Lake Fuquene, Colombia; 4, Lake La Yeguada, Panama; 5, Lake Miragoane, Haiti; 6, Lake Chichancanab, Yucatan Mexico; 7, Lake Titicaca, Peru/Bolivia; 8, Nevado Sajama, Bolivia; 9, small lakes in the Cordillera Réal, Bolivia; 10, Cariaco Basin. Blue circled sites and patterned areas are in-phase with Laguna Blanca while red-diamond sites and patterned areas are more coherent with solar insolation.

Lake levels dropped markedly in Laguna Blanca during the middle Holocene (8,200–2,000 y BP), as evidenced by decreased rates of sediment accumulation, elevated organic carbon content, abundant subfossil littoral macrophytes, and a marked decline in mineral sedimentation. Mire accumulation peaked between 7,000 and 4,000 y BP, as indicated by high organic carbon concentrations and correspondingly terrestrial C/N ratios. Bracketing this interval are periods of more variable lake levels that mark transitions into and out of the most arid intervals of the middle Holocene (8,000–7,000 and 4,000–2,000 y BP). Higher lake levels stabilized around 2,000 y BP, when increased mineral content and aquatic organic matter signify a return to lacustrine sedimentation. High lake levels culminated in the wettest conditions of the Holocene during the Little Ice Age (700–130 BP), when mineral sedimentation peaked in the lake system (15).

The timing and abruptness of Holocene moisture balance changes in Laguna Blanca differs fundamentally from that predicted by orbital insolation forcing. During the early Holocene, stronger seasonality from enhanced summer and reduced winter insolation in the northern tropics (Fig. S4) are thought to have enhanced the summer wet season by shifting precipitation patterns northward (10). In this scenario, the decreasing seasonality of insolation in the middle and late Holocene would have weakened this mechanism, ultimately leading to progressively more arid conditions. Although the early Holocene wet period and middle Holocene arid intervals inferred from Laguna Blanca are broadly consistent with northern hemisphere insolation forcing, the abrupt character of climate transitions coupled with the increased moisture balance during the late Holocene call into question the dominant role of insolation in modulating Holocene climate variability (Fig. 3, *SI Text*).

Interhemispheric Comparisons. Further evidence against a simple response to insolation in the outer tropics is provided by the coherence between additional Andean paleorecords from the northern and southern hemispheres. Paleolimnological results from Lake Titicaca (15° 45′ S, 69° 25′ W, 3,810 m a.s.l.) document a period of higher lake levels during the early Holocene that coincides with the wet interval in the Venezuelan Andes (Fig. 3). Lake Titicaca was fresh and overflowing 10,000–8,000 y BP (17), despite a minimum in insolation seasonality that should have decreased precipitation and increased evaporation. During

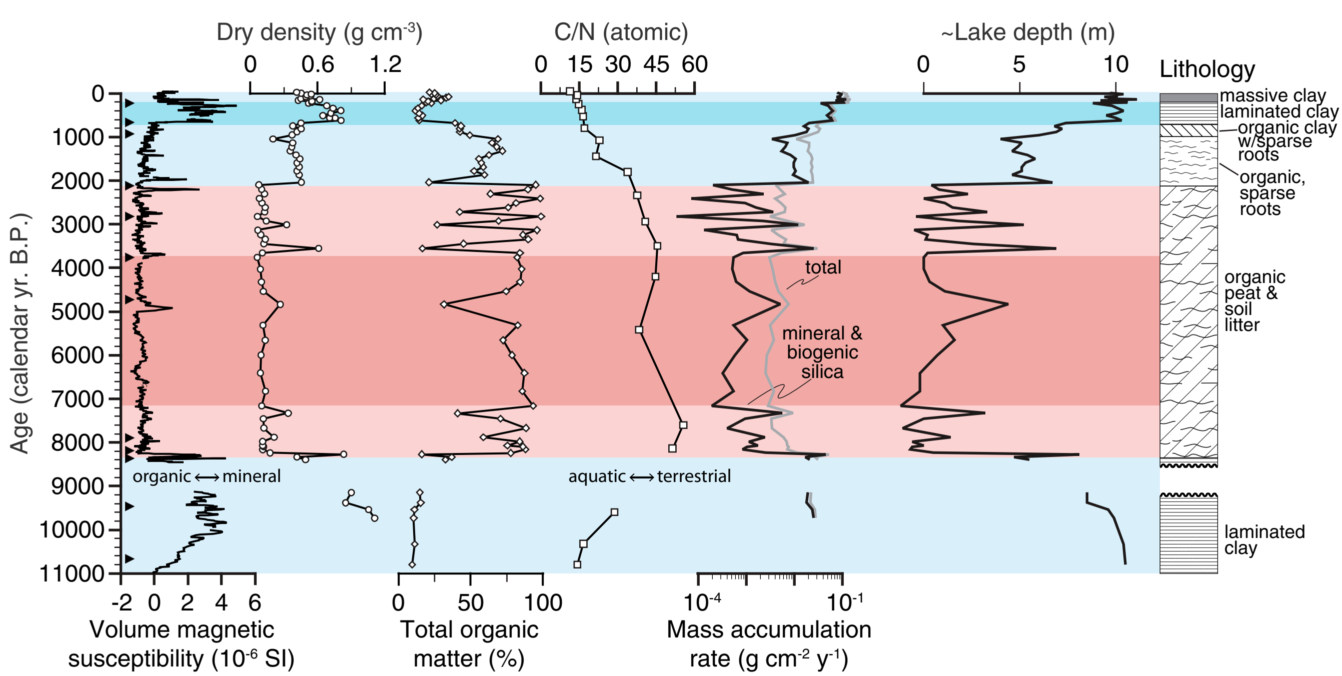

Fig. 2. Stratigraphy, sediment physical and geochemical properties, and lake-level reconstruction from Holocene sediments of Laguna Blanca. Triangles denote calibrated radiocarbon ages used for chronologic control (*SI Text*). Note log scale for accumulation rates. An approximate measure of lake depth was calculated from the sediment type determined by the first principle component of dry density, organic matter, C/N, and mineral accumulation scaled to the lake depth necessary for overflow (10 m), current lake depth (5 m), and the cutoff lake depth necessary for abundant soil litter accumulation (<1 m) (*SI Text* and Figs. S7 and S8). Blue and red shading indicates humid and arid intervals, respectively.

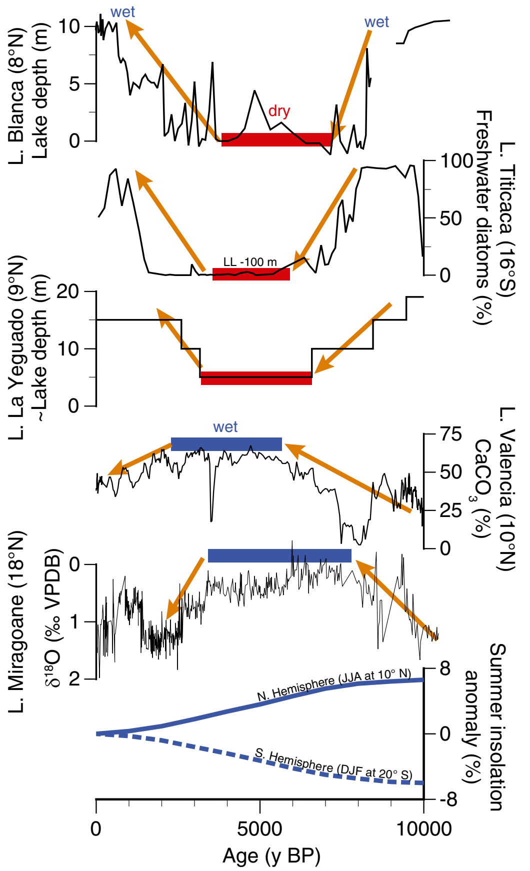

Fig. 3. Holocene paleoclimate records from the northern and southern Neotropics. Lake Titicaca freshwater diatoms reflect salinity (17), whereas a lowstand (red horizontal line) observed in sediment cores and inferred from seismic reflection surveys and sediment geochemistry (19, 20) indicates the driest interval. Lake La Yeguado water levels are inferred from the timing of sediment deposition in cores at different depths, the abundance of epiphytic diatoms that record flooding of a shallow shelf, and the influx of phytoliths that reflect allochthonous delivery to the lake (32). Lake Valencia authigenic carbonate reflects positive lake water balance as corroborated by diatom, pollen, and isotopic data (11, 12, 31). Lake Miragoane ostracode $\delta^{18}O$ reflects the evaporative enrichment of lake water (38, 39). None of these records track the summer wet season insolation (as % anomaly from the present) at their respective latitude.

the middle Holocene, Lake Titicaca lowered and became more saline by evaporative enrichment, in broad synchrony with the advent of mire sedimentation in Laguna Blanca. More specifically, the driest interval in Lake Titicaca, when water levels fell ∼100 m below modern levels and the Huinamarca basin was completely dry, occurred between 7,000 and 4,000 y BP (18–20). This coincides with the most arid interval inferred from Laguna Blanca. Lake Titicaca freshened and Laguna Blanca lake levels increased markedly after 2,000 y BP, producing conditions that have been sustained to the present. The spectacular Holocene moisture balance shifts recorded in Lake Titicaca are also registered by isotopic and sedimentological records from glacially fed headwater lakes in the Bolivian Andes (21). Alpine glaciers disappeared from high-elevation watersheds in the Cordillera Réal between 8,500 and 2,200 y BP, indicating sustained regional aridity over this protracted interval (22).

These comparisons reveal a pattern of Holocene paleohydrology in the outer tropics of South America that is broadly synchronous between the hemispheres, and thus cannot be mediated by precessional forcing alone. In-phase behavior across the equator is not predicted from insolation forcing because precession changes are 180° out of phase between the northern and southern hemispheres. Furthermore, Holocene insolation patterns evolve gradually over millennia, and are not anticipated to induce the sudden, threshold-type hydrological responses indicated here (Fig. 3). Therefore, different mechanisms are required to synchronize interhemispheric climatic and hydrologic variability between these regions.

Today, sea-surface temperatures (SSTs) in the equatorial Pacific perturb atmospheric circulation patterns and cause coherent, in-phase interannual variability in both hemispheres (23, 24). We suggest that similar mechanisms have operated on millennial timescales, resulting in coherent interhemispheric moisture balance changes in the outer tropics of both hemispheres. Although SSTs in the Caribbean and tropical Atlantic may also influence climate in these regions, their effects are deemed secondary in the outer tropical Andes, as detailed below. While other factors may play a role locally, synchronization of climate in the outer tropics requires large-scale changes in atmospheric circulation that are coherent between hemispheres and persistent across both the boreal and austral seasons. We hypothesize that the evolution of variability of eastern equatorial Pacific SSTs provides such a mechanism. This is supported by (*i*) the modern relationship between equatorial Pacific SSTs and precipitation over these regions (25), (*ii*) records of tropical Pacific Holocene SST evolution, and (*iii*) the coherent fingerprints of Holocene climate evolution in the Neotropics.

Correlating South American Precipitation with SSTs. Modern climate data from the Venezuelan Andes demonstrate the pervasive influence of equatorial Pacific SSTs. Increased precipitation, the primary driver of Laguna Blanca water levels, occurs in the Venezuelan Andes when SSTs are below average in the eastern equatorial Pacific and tropical south Atlantic, and above average in the Caribbean (24). The correlation of precipitation anomalies with equatorial Pacific SST variability (Niño 3.4 index) is strongly negative over the Venezuelan Andes, indicating that higher lake levels would accompany cold SSTs and vice versa (Fig. 4). In support of this inference, available precipitation time series from meteorological stations in the Venezuelan Andes correlate with equatorial Pacific SSTs in a highly coherent pattern that is typical of El Niño-Southern Oscillation (ENSO) variability (26).

Historical water level records from Lake Titicaca also demonstrate a persistent influence of tropical Pacific SSTs on regional water balance. Hydrologic modeling indicates that Lake Titicaca's water balance is more strongly mediated by precipitation than net evaporation (27). Therefore, as with Laguna Blanca, Holocene lake-level histories primarily record changes in precipitation. Precipitation in the Titicaca watershed is strongly modulated by equatorial SSTs in the tropical Pacific (28, 29), through perturbations to easterly winds that deliver moisture to the high Andes. Cold SSTs in the eastern equatorial Pacific and stronger meridional SST gradients strengthen easterly flow over South America during the austral summer. These winds entrain boundary layer moisture from the Amazon basin and deliver it to the high Andes, enhancing precipitation. This mechanism operates on intraseasonal and longer timescales, as illustrated by the negative correlation between equatorial Pacific SSTs and precipitation in the Titicaca region (Fig. 3).

We evaluate the influence of various ocean regimes on South American climate by mapping correlations between gridded precipitation datasets and SST time series from the tropical Pacific, Atlantic, and Caribbean Oceans (Fig. 4 and *SI Text*). Mean annual SSTs from the Niño 3.4, Caribbean, north Atlantic, and south Atlantic sectors (Fig. S5) were assessed spatially in relation to South American gridded rainfall data (30). The results demonstrate that the geographic patterns in proxy records is best accounted for by Pacific Ocean SSTs (i.e., the Niño 3.4 index). The sign of these correlations is opposite between the

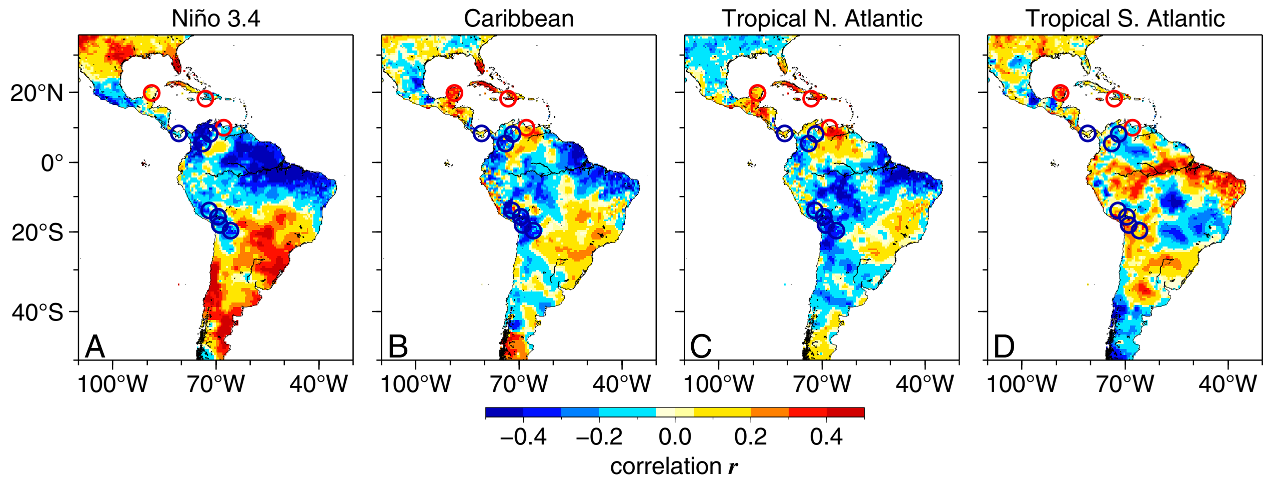

Fig. 4. Correlation between gridded precipitation over land (30) and SST time series for (*A*) the Niño 3.4 index, (*B*) the Caribbean, (*C*) the tropical north Atlantic, and (*D*) the tropical south Atlantic (regions defined in Fig. S5). Circles indicate paleorecords with a dry middle Holocene (blue) or wet middle Holocene (red). The Niño 3.4 spatial pattern is the most compatible with the compiled paleoclimate records, especially the coherence between northern and southern Andean sites and the site in central Panama. Although the Caribbean spatial pattern explains the similar response in lowland Venezuela and Haiti, it does not explain the phasing of the central Panamanian site. Additionally, the Caribbean pattern includes a significant component from the lagged effect of ENSO on Caribbean SSTs and precipitation (50) that is not accounted for in these instantaneous (lag 0) correlation maps. Both the tropical north and south Atlantic patterns fail to predict coherency between the southern Andes, northern Andes, and the Panamanian site.

northern and southern Andean sites for both the northern and southern tropical Atlantic sectors (Fig. 4). The correlation of precipitation with Caribbean SSTs is more similar to that for the Niño 3.4 region. However, the strength of the correlation is weaker in the Venezuelan Andes, and the sign of the correlation is opposite for the Panamanian site that is in-phase with the Venezuelan Andes over the Holocene, cases that are discussed below. Caribbean and Niño 3.4 SST time series are also significantly correlated ($r = 0.39$, $P = 0.004$) due to ENSO influences on the former, thus explaining a portion of the shared variance. When mapped, these correlations suggest that Caribbean and tropical Atlantic SSTs are unable to synchronize interhemispheric climate variability in the Andes, conferring the dominant role to equatorial Pacific SSTs.

Holocene Climate in the Neotropics. Coherent paleoclimate changes in a number of neotropical regions further supports the proposed role of equatorial Pacific forcing of South American climate. Holocene terrestrial records in Colombia, Venezuela, Panama, Mexico, and Bolivia are largely coherent with the Laguna Blanca record (11, 12, 21, 31–33). Moreover, the phasing of these Holocene records corresponds to the sign of their modern relationship with equatorial Pacific SSTs (Fig. 4) (24, 25, 28, 34, 35). For example, modern precipitation at Laguna Blanca and Lake Titicaca is negatively correlated with eastern equatorial Pacific SSTs and both lakes have the same, in-phase, Holocene lake-level history. Sites in-phase with Laguna Blanca (Fig. 3) include Lake La Yeguada (Panama) (32), Lake Fuquene (Colombian Andes) (33), and an array of lakes in the Bolivian Andes (17, 20, 21). Rainfall in all of these locations is negatively correlated with equatorial Pacific SSTs (Fig. 4) (24, 28, 34, 35). Sites that are antiphased with Laguna Blanca include Lake Valencia, Lake Cichancanab (Yucatan Peninsula, Mexico) (36, 37), and Lake Miragoane (Haiti) (38, 39). In each of these cases, precipitation correlates positively with equatorial Pacific SSTs, explaining their different responses relative to the Andean region. The relationship between modern precipitation variability and Holocene climate is evident even at the regional scale. For example, Lake Valencia and Laguna Blanca are less than 500 km from each other yet have opposite responses to ENSO (24, 25) and antiphased Holocene lake level histories (11, 12, 31)(Fig. 2).

Paleorecords of equatorial Pacific SSTs support this mechanism. Coral proxies and individual foraminiferal $\delta^{18}O$ both suggest that ENSO variability was reduced in the middle Holocene (40, 41), which would decrease moisture balance in the outer tropical Andes (Fig. S6). A continuous record of individual foraminiferal $\delta^{18}O$ variability suggests ENSO was similar to present during the early Holocene, reduced in strength or frequency during the middle Holocene (6–4 ka BP), and was near-modern levels during the late Holocene (42). These data provide an oceanic record of early Holocene ENSO variability, in agreement with the independent synthesis of terrestrial neotropical paleoclimate records presented here.

We surmise that precipitation in the outer tropics—especially the high Andes—is limited by the amount of moisture available for precipitation. Whereas the inner tropics of South America have abundant water vapor year-round, the outer tropics rely upon seasonal changes in wind patterns that deliver water vapor necessary for precipitation. These wind patterns are the mechanistic link between equatorial Pacific SSTs and local precipitation (25, 28), and aptly explain why the outer tropics appear strongly influenced by Pacific Ocean forcing. In contrast, insolation anomalies have a larger effect on the inner tropics by increasing the energy and large-scale dynamics that promote deep convection. The stronger influence from insolation explains why lake, ice core, and speleothem records in the central Andes (Peru, Ecuador) and the Amazon basin all exhibit secular $\delta^{18}O$ declines since the early Holocene, interpreted as increasing Amazonian precipitation, decreasing evaporation, and enhanced discharge in the Amazon basin (1–8). The pattern of increasing rainout of Amazon moisture is expressed in isotopic records throughout the tropical Andes, although much of this signal is inherited from upstream rather than local climate events (5, 43).

Conclusion

Our findings suggest that the prediction of insolation-driven, antiphased, Holocene climate evolution between the hemispheres is insufficient to account for the paleoclimate trends observed across all regions of South and Central America, particularly in the northern tropics. Instead we conclude that the equatorial Pacific played a far greater role than previously identified in modulating Holocene climate in the outer tropical

Andes. The analysis of modern coupled ocean-atmosphere variability in the tropics, including the dynamics of ENSO, offers viable mechanisms that reconcile the apparent synchroneity of these interhemispheric climate trends. Furthermore, our analysis underscores the potential for far more rapid climate shifts driven by variability of the mean state of tropical Pacific SSTs than would be possible by insolation forcing alone. The large range of future projections for equatorial Pacific variability under global warming scenarios (44) highlights the utility and importance of understanding past variability, the rate of change, and teleconnections. Our findings suggest that any sustained shift in the SST field of this region may portend abrupt hydrological shifts in parts of the Americas—including severe droughts or pluvial events analogous to those witnessed in the Middle Holocene. Today the equatorial Pacific plays a major role in the variability of water resources in regions of Australia, Indonesia, India, southeast Asia, the Americas, and parts of Africa (45). Future hydrologic variability in these regions may also be tied to the ocean-atmosphere response of the tropical Pacific in a warming world with a nonlinear or threshold response that should be carefully evaluated.

Materials and Methods

Overlapping sediment cores were recovered from the deepest part of Laguna Blanca using a square-rod coring system (46). AMS radiocarbon dates on terrestrial macrofossils constrain the age–depth relationship for the cores. Radiocarbon ages were calibrated using the IntCal04 dataset (Table S1) (47, 48) and interpolated linearly to construct an age model (Fig. S3). Unless otherwise noted, all ages in the manuscript refer to calibrated or calendar ages before AD 1950 (BP).

Dry sediment density was determined on 1 cm^3 core samples that were subsequently heated at 500 °C to determine total organic matter by mass loss (49). Volume MS was measured at 0.25 cm intervals on split cores using a Tamiscan automated sediment track and a Bartington high-resolution surface-scanning sensor connected to a susceptibility meter (reported in 10^{-6} SI units). Total organic carbon, total nitrogen, and C/N molar ratios were measured on decarbonated sediments (acetic acid/acetate buffer at pH 4) with a Costech CHNS elemental analyzer. Principal components analysis and correlations with water depth were carried out in MATLAB (*SI Text*).

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