

Oxygen isotopes in tree rings are a good proxy for Amazon precipitation and El Niño-Southern Oscillation variability

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We present a unique proxy for the reconstruction of variation in precipitation over the Amazon: oxygen isotope ratios in annual rings in tropical cedar (*Cedrela odorata*). A century-long record from northern Bolivia shows that tree rings preserve the signal of oxygen isotopes in precipitation during the wet season, with weaker influences of temperature and vapor pressure. Tree ring $\delta^{18}\text{O}$ correlates strongly with $\delta^{18}\text{O}$ in precipitation from distant stations in the center and west of the basin, and with Andean ice core $\delta^{18}\text{O}$ showing that the signal is coherent over large areas. The signal correlates most strongly with basin-wide precipitation and Amazon river discharge. We attribute the strength of this (negative) correlation mainly to the cumulative rainout processes of oxygen isotopes (Rayleigh distillation) in air parcels during westward transport across the basin. We further find a clear signature of the El Niño-Southern Oscillation (ENSO) in the record, with strong ENSO influences over recent decades, but weaker influence from 1925 to 1975 indicating decadal scale variation in the controls on the hydrological cycle. The record exhibits a significant increase in $\delta^{18}\text{O}$ over the 20th century consistent with increases in Andean $\delta^{18}\text{O}$ ice core and lake records, which we tentatively attribute to increased water vapor transport into the basin. Taking these data together, our record reveals a fresh path to diagnose and improve our understanding of variation and trends of the hydrological cycle of the world's largest river catchment.

climate change | dendrochronology | plant physiology

The Amazon basin is a major center of atmospheric convection and precipitation (1), and at the same time the world's largest drainage basin. The Amazon's river discharge accounts for ~17% of the annual global discharge to the oceans (2); its hydrological cycle is tightly linked with the carbon cycle of the Amazon rainforest (3), which itself is one of the largest terrestrial biomass carbon pools. Changes in the hydrological cycle of the Amazon may therefore significantly affect atmospheric dynamics and global climate by changing atmospheric CO_2 concentration. Two particularly severe droughts occurred within the last decade (4), and long-term river records of the Amazon show a steady increase in discharge over the last century (5), indicating that the system may start to undergo some changes. It has been suggested that these changes are a result of anthropogenic warming, but they may also be part of longer-term, natural climatic variability. To clarify such a globally important issue, long-term, accurate records of the hydrological cycle of the Amazon basin are needed. However, meteorological data are only reliable for the last 50–60 y (6), and annually resolved long-term proxies for the hydrological cycle from within the Amazon basin itself are very scarce (7).

A commonly used diagnostic for strength and functioning of the water cycle is the isotopic composition of precipitation. Although variation of oxygen isotope ratios in precipitation in temperate to arctic regions is determined among other factors by the condensation temperature (8), the dominant contributing factors over tropical land are rather Rayleigh distillation [because of changes in the isotopic water vapor content of air when traveling inland caused by precipitation (9, 10)], recycling of rainwater (11), and local

precipitation intensity (cf. “amount effect,” refs. 8, 12, and 13). Observations of the isotopic composition of meteoric precipitation over South America show that isotopic composition is indeed closely associated with the amount of precipitation along the air parcel path (10), which suggests that oxygen isotopes in precipitation are predominantly a proxy for the large-scale atmospheric component of the basin-wide hydrological cycle (9, 14). However, the interpretation of results from paleoclimatic studies of oxygen isotopes in ice cores (15–17), lake sediments (18), and speleothems (19, 20) remains disputed, and proxies have been interpreted variously as indicators of temperature (17), basin-wide rainfall (18–21), or a combination of both (22). Despite numerous oxygen paleorecords from the Andes, there are no such proxies from within the Amazon basin itself.

A promising new method for the reconstruction of Amazon precipitation is oxygen isotopes in tree-ring cellulose ($\delta^{18}\text{O}_{\text{tr}}$). However, the conditions and degree to which tropical tree rings record variation in oxygen isotopes in precipitation, and thus indeed contain information about the hydrological cycle, remains poorly known (23). Oxygen isotopic values in tree rings are believed to mainly reflect isotopic composition of soil water and plant physiological effects, like leaf-water enrichment and oxygen isotope exchange reactions of photosynthates with water (24, 25). The degree to which these factors influence the signal of oxygen isotopes in tree rings may vary between sites and species (24). In the tropics, the number of oxygen isotope studies is small, although recently has been increasing. The few studies undertaken so far show that oxygen isotope signals in wood of lowland tropical trees are often dominated by a negative influence of precipitation amount (7, 23, 26), but correlations are often weak (7). Positive correlations with rainfall amount have also been found (26). Still, the number of long tree-ring isotope chronologies is small, and the factors controlling variation in tree-ring oxygen isotope ratios in lowland tropics remain poorly understood.

In this study, a unique annually resolved isotope record from well-dated tree rings of *Cedrela odorata* from the Amazon basin is presented. These trees are a prime candidate to record variation in precipitation $\delta^{18}\text{O}$ because *C. odorata* has a relatively superficial root-system and relies strongly on water from the topsoil layer (27). We first analyze the relation between variation in tree-ring oxygen isotopes and isotopic composition of soil water using records of oxygen isotopes in meteoric rainwater and from Andean glaciers. We then quantify the effect of climate on interannual variation in tree-ring oxygen isotopes by relating our records to local and basin-wide climate variables and to discharge data of the Amazon River

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at Obidos. Finally, we explore the influence of the associated large-scale climate drivers for the Amazon [e.g., influence of El Niños and Atlantic sea-surface temperatures (SSTs)], and discuss the wider importance of our findings.

Results and Discussion

What Controls Oxygen Isotopes in *Cedrela* Tree Rings? As tree roots take-up soil water without fractionation of the heavier $H_2^{18}O$ (24, 25), at least part of the isotopic signature in tree rings should reflect variation in precipitation $\delta^{18}O$. To test this hypothesis, we correlated $\delta^{18}O_{tr}$ with isotopic ratios in meteoric precipitation (data; Global Network of Isotopes in Precipitation; see *SI Appendix*), which shows indeed significant relations with various stations across the Amazon Basin (Fig. 1). Among the station records, the correlation is strongest with annual values of oxygen isotopes in precipitation ($\delta^{18}O_{prec}$) from Manaus ($r = 0.86, n = 15$). Generally variation in $\delta^{18}O_{tr}$ correlated most strongly with $\delta^{18}O$ in precipitation during the wet season (December–May), which corresponds to the main period of growth for this drought-deciduous species (*SI Appendix*, Fig. S3) (28).

Additional support for a dominant influence of the soil-water signal on $\delta^{18}O_{tr}$ comes from a comparison of the tree-ring record with $\delta^{18}O$ from Andean glaciers (15, 17), which have primarily been interpreted as indicators of $\delta^{18}O$ in atmospheric water vapor from the Amazon basin (21). We find a relatively strong correlation with the Quelccaya and Huascarán ice core records (Quelccaya, 1963–1984, $r = 0.77$; Huascarán, 1963–1992, $r = 0.68$), and somewhat lower correlation with the Sajama ice core record (1963–1997, $r = 0.44$).

Plant physiological models using $\delta^{18}O$ predict that tree-ring cellulose is not only influenced by soil water but also by evaporative enrichment of transpiring leaves (25). To explore to what degree the interannual variation in $\delta^{18}O$ in *Cedrela* tree rings contains such signals, we related $\delta^{18}O_{tr}$ to locally recorded climate variables and found statistically significant relationships of local precipitation, temperature, and vapor pressure (*SI Appendix*, Table S2). The effect of interannual variation in isotopic composition of precipitation is bigger however (correlations in

Fig. 1). Although we do not have additional ecophysiological data (e.g., daily leaf temperature and stomatal conductance) to detect the plant physiological influences, overall results indicate that plant physiological controls are relatively small (see *SI Appendix* for further details). This finding differs from Kahmen et al. (29), showing that leaf-to-air vapor pressure was the main control of plant $\delta^{18}O$ along an altitudinal gradient. For our species at this site, the dominant control of interannual variation in $\delta^{18}O_{tr}$ seems to be interannual variation in the isotopic composition of meteoric precipitation ($\delta^{18}O_{prec}$).

Climatic Signals in Tree-Ring Oxygen Isotopes at Interannual to Decadal Time Scales. Our record provides an annually resolved reconstruction of oxygen isotopes for the last 100 y, and thus allows for an analysis of climatic controls on oxygen isotopes in tree rings, and thereby precipitation over the entire Amazon basin has the strongest correlations with $\delta^{18}O_{tr}$ (Fig. 2). There are also significant correlations with temperature and vapor pressure, but these are weaker and decrease or disappear entirely when controlling for the influence of (basin-wide, wet season) precipitation (*SI Appendix*, Table S3). This finding suggests that the amount of basin-wide precipitation during the wet season exerts the strongest influence on $\delta^{18}O_{tr}$. Consequently, we also find a remarkably strong correlation with the Amazon discharge measured at Obidos at interannual to decadal scales (Fig. 2). The correlations with river discharge, calculated for different time periods over the 20th century, remained relatively high for the entire record (varying between -0.80 over recent decades to -0.53 at the start of the century) (*SI Appendix*, Table S4), but the strength of the correlation with the precipitation record decreased more strongly (i.e., from -0.85 to -0.33) (*SI Appendix*, Table S3). This finding indicates that the influence of the amount of basin-wide precipitation on oxygen isotopic composition is stationary over longer time scales and that decreasing correlations with precipitation data further back in time are likely because of poor quality and low spatial resolution of the precipitation dataset at the start of the century (6). Known extreme dry years are clearly visible in the oxygen isotope record (Fig. 2). Notably, the driest year over the last

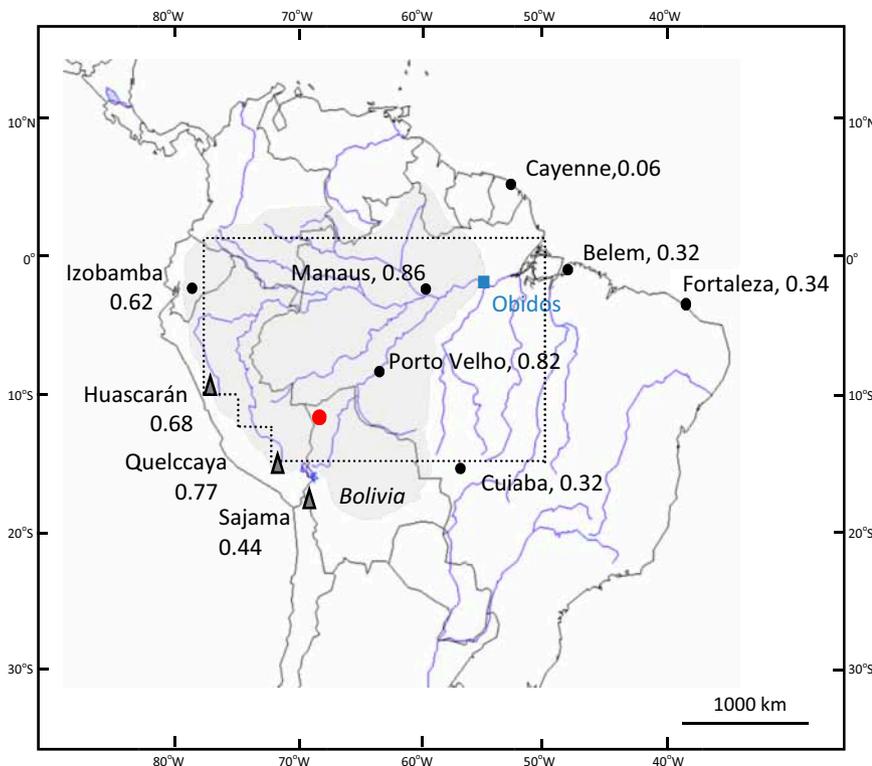


Fig. 1. Map of the Amazon indicating the study site (red dot), stations with records of $\delta^{18}O$ in meteoric precipitation (black dots), Andean glaciers with records of $\delta^{18}O$ (triangles), and the location of the Amazon River discharge records at Obidos (blue square). The shaded area shows the area of the catchment of the Amazon River that discharges at Obidos, an area encompassing 77% of the entire basin, or 4.68 million km^2 (5). The broken line indicates area from which climate data for the whole basin were extracted. Values next to the station names and glaciers indicate the correlation coefficients between $\delta^{18}O_{tr}$ and $\delta^{18}O$ measured in precipitation or ice cores at those sites. For details on data sources for $\delta^{18}O$ records, see *SI Appendix*.

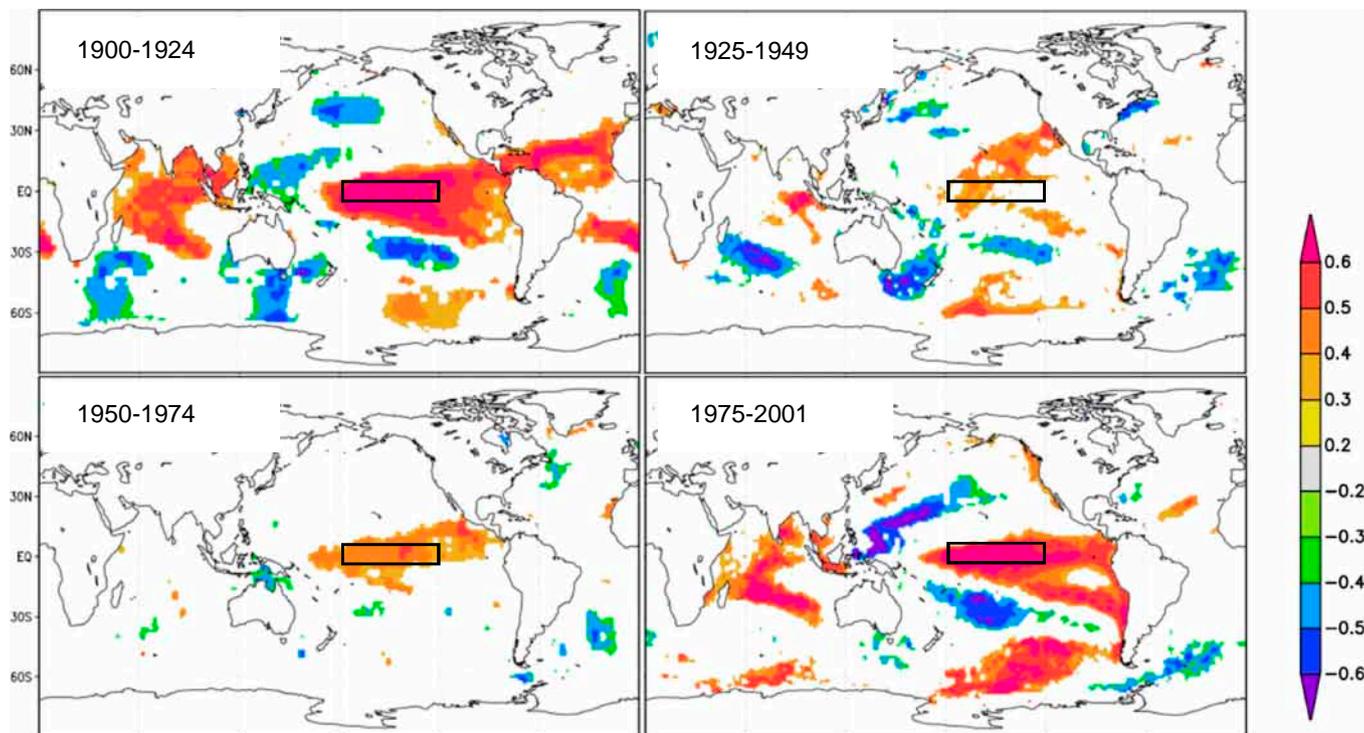


Fig. 3. Correlations between $\delta^{18}\text{O}_{\text{tr}}$ and gridded global SSTs (data:HadISST1) during the wet season (i.e., October to April) for different time periods of the last century. Values on the color scale correspond to correlation coefficients ($P < 0.01$). The square in the Pacific Ocean indicates the Niño3.4 region (5°S – 5°N , 120°W – 170°W).

the $\delta^{18}\text{O}$ signal in the Amazon basin, and not a local amount effect (i.e., a negative correlation between the rate of precipitation and $\delta^{18}\text{O}$ in local precipitation) (12, 13), consistent with model predictions (14). Similar controls of ENSO on the isotopic signature in tree rings were observed in Costa Rica (40) and Asia (32, 41), and negative correlations were observed along the west coast of Peru, where warm-phase ENSO events result in increased precipitation and thus negative excursions in $\delta^{18}\text{O}$ (23). These tree-ring isotope studies show that ENSO affects interannual variation in plant $\delta^{18}\text{O}$ over large areas in the tropics. As the tropics are also regions with very high net primary productivity, this pan-tropically coherent ENSO signal in plant water $\delta^{18}\text{O}$ is passed on to oxygen isotope ratios in atmospheric CO_2 through biosphere-atmosphere gas exchange, and leads to higher $\delta^{18}\text{O}$ in atmospheric CO_2 several months after El Niño's occurred (42). In all, our results confirm the potential of tree ring $\delta^{18}\text{O}$ to elucidate historical influences of ENSO on precipitation in the tropics.

The influence of ENSO is not always equally dominant, showing a weaker influence on our isotope record during the middle of the century and stronger influence during the beginning and end of the last century (Fig. 3). The reduced influence of ENSO during the middle of the century coincides with periods of lower variance in the Southern Oscillation Index (the atmospheric branch of El Niño) (43), weaker correlations between ENSO and precipitation in the Amazon (1), and lower interannual variation in precipitation and Obidos records (5, 39) during 1920–1960. At decadal scales the oxygen isotope record also shows a big shift in the oxygen isotope record around the 1970s, probably related to an abrupt warming of the tropical Pacific and change in sign of the Pacific Decadal Oscillation (1).

Possible Mechanisms Underlying the Strong Precipitation Signal in $\delta^{18}\text{O}_{\text{tr}}$. It is quite remarkable that oxygen isotopes in tree rings of just eight trees from one single site are such a good proxy of precipitation in the whole Amazon catchment basin of approximately 5 million km^2 . What are the underlying mechanisms for this strong coherence? Variation in the isotope signal in precipitation is a mixture of local effects (e.g., local precipitation intensity) and

large-scale influences (e.g., changes in isotopic signature during water vapor transport into the basin). The lack of strong correlations of $\delta^{18}\text{O}_{\text{tr}}$ with local climate records and the strong decrease in correlations after controlling for the effect of basin-wide precipitation (*SI Appendix, Table S3*), suggest that the isotopic signature in precipitation at our site reflects primarily what happens during water-vapor transport to the site rather than local precipitation amount. During air-parcel transport, two processes affect the isotopic composition of its water-vapor content. First, heavy isotopes tend to condense more readily, and thus water vapor gets gradually more depleted during transport over land [i.e., water vapor loses relatively more of the heavier isotopes (H_2^{18}O) because of the classic Rayleigh distillation (8)]. The degree of total “rainout” of heavy isotopes depends on the fraction of water that is removed from a particular air parcel, and is thus generally larger during years with high amounts of precipitation along the air-parcel trajectory than during years with low precipitation. Therefore, this mechanism leads to more depleted water vapor (more negative $\delta^{18}\text{O}$) at the end of the trajectory during wet years compared with dry years. A second process that may affect the isotopic composition of water vapor is recycling of rainwater by vegetation (11). Tropical rainforest transpires large amounts of water through transpiration by stomata and direct evaporation of water from leaf surfaces during the day; it is estimated that up to 60% of the yearly precipitation is returned into the atmosphere, much of which will eventually condense again (11, 44). As evapotranspiration is approximately a nonfractionating process with respect to oxygen isotopes (i.e., water vapor leaving the leaf has the same isotopic signature as stem water), once a transpirational steady-state has been reached in the leaf (45), large amounts of water vapor with an isotopic signal similar to that of soil water are returned to the atmosphere. The isotopic signature of this recycled water from vegetation into the atmosphere will be relatively lighter (i.e., has a lower $\delta^{18}\text{O}$) during years with high precipitation, as the precipitation from which the vapor originates is lighter because of the amount effect (12, 13). Continuous recycling of water along the trajectory thus adds more and more water vapor to the airstream traveling westward, which carries an isotopic “memory” of the local amount effect. Because

recycling may contribute to more than half of the precipitation in the western part of the basin (estimates vary between 50% and 88%) (46, 47), isotopic signatures in these parts of the Amazon are therefore also expected to be partly a reflection of the accumulated local amount effects. We expect that these two mechanisms will enhance the differences in the isotopic signal between dry and wet years along the water-vapor trajectory, and thus exacerbate difference in isotopic signal in the western and eastern part of the basin.

We do find some evidence for this in our data as our tree-ring record correlated better with observational data of $\delta^{18}\text{O}$ in the western and center of the Amazon basin and with Andean ice cores, than with $\delta^{18}\text{O}_{\text{prec}}$ records at the east (see, for example, correlation coefficients in Fig. 1). This finding seems to confirm that the isotopic imprint in water vapor indeed changes from east to west. The specific location of our study site means that each air parcel has traveled at least 2,500 km from its origin in the tropical north Atlantic to the southwest of the basin (*SI Appendix*, Fig. S5), which probably played a major role in making the signal so particularly strong.

Long-Term Trends in Tree-Ring Oxygen Isotopes. In contrast to the tight correlation at interannual time scales, we find that the trends of $\delta^{18}\text{O}_{\text{tr}}$ and Amazon precipitation diverge over longer time scales. Obidos river discharge (5) and the Global Precipitation Climatology Centre precipitation dataset both show increases over the last century, but not Climatic Research Unit precipitation (*SI Appendix*, Fig. S7). If the $\delta^{18}\text{O}_{\text{tr}}$ records would have followed directly this river discharge and precipitation trend over the last century, we would expect a decrease in long-term $\delta^{18}\text{O}_{\text{tr}}$, but instead we find a significant increase of 0.5‰ in $\delta^{18}\text{O}_{\text{tr}}$ over the last century (*SI Appendix*, Fig. S2). A comparison with Andean ice core records (Fig. 2) (48), Andean lake sediments (18), and speleothems at the Andean foothills (20) reveal parallel increases in $\delta^{18}\text{O}$ since approximately 1850. We interpret this long-term increase in $\delta^{18}\text{O}_{\text{tr}}$ therefore as a result of increasing $\delta^{18}\text{O}$ in precipitation over the basin rather than because of plant physiological changes during ontogeny. Studies that specifically looked at physiological $\delta^{18}\text{O}$ trends in tree rings found a negative trend with age (49). Although this study was performed in a substantial different climatic zone, we argue that a strong ontogenetic (i.e., age- or size-related) -positive $\delta^{18}\text{O}$ trend is not very likely.

Previous studies have interpreted these recent increases in $\delta^{18}\text{O}$ differently. Thompson et al. (48) attributed the increases since 1850 to increases in air temperature, in line with interpretation of mid and high latitude $\delta^{18}\text{O}_{\text{prec}}$ data (50). Although the magnitude of increases in temperature over the Amazon basin (0.77 °C over 100 y) may explain the increase of 0.5‰ in our record, support for a temperature effect at tropical latitudes is scarce. In contrast, Bird et al. (18) explain recent increases in their lake record as an indication of a general weakening of South American wet season precipitation, but such a weakening of South American wet season precipitation is at odds with the observed (upward) trends in Obidos river discharge and precipitation over the last century. We briefly explore other mechanisms that may explain these long-term trends. One possible mechanism is related to a change in the water balance of the basin, such as changes in the net amount of water vapor transported into the basin. The observed increases in river run-off and satellite observations on water-vapor transport (51) indicate that water import into the basin may have increased. If such increases in influx of water vapor exceed the increase in rainout and loss via river run-off, the isotope ratios would increase. This is because for this scenario a lower fraction of the total water vapor traveling into the basin is rained out before reaching our site, and thus water vapor export out of the basin would have to increase as well. The strong, recent increases in summer precipitation and run-off in the La Plata basin (south west of Brazil) (52) indicates that export of water vapor toward the south of the Amazon Basin did indeed increase over the last decades (53). Other possible mechanisms that affect the isotope signal include changes in cloud cover and convection (54) and decreases in evapotranspiration rates because of increases in atmospheric CO_2 (55) and deforestation. Decreases in evapotranspiration do affect the isotope signal, but would rather lead to a decrease in

$\delta^{18}\text{O}$ over time at the west-end of the basin (56), and thus the opposite of what we observe. Although, we are not yet in a position to explain the observed trend, our results show that the upward trend in $\delta^{18}\text{O}$ is not because of drying of the Amazon (18), and that a temperature effect (48) also seems unlikely.

Outlook. Our proxy record shows that $\delta^{18}\text{O}$ in the Amazon is predominantly governed by large-scale variation in precipitation, but the relative importance of the different mechanisms that influence the signal remain elusive. One way of improving our understanding is by expanding the spatial and temporal coverage of $\delta^{18}\text{O}$ in tree rings or other proxies within the Amazon. Although our $\delta^{18}\text{O}_{\text{tr}}$ record covered only 100–150 y, *Cedrela* can become substantially older (i.e., > 300 y old) (28) and has a large geographic distribution (i.e., from 25°N to 25°S). Comparison of long-term trends at different extremes, or across different gradients in the Amazon basin could potentially reveal important insights as to what drives the long-term trends. For example, differences in long-term $\delta^{18}\text{O}$ trends along an east-west gradient may be indicative of long-term changes in water recycling, but differences in the north-south gradients may indicate changes in meridional positioning of the Intertropical Convergence Zone. An extension of the record in time may significantly improve our understanding of drivers over longer time scales, and allow testing of whether extreme events, like the droughts in 2005 and 2010, are increasing over time and are related to natural cycles or linked to global warming.

The coherence over large spatial scales of the isotopic signal in precipitation allows also, in theory, for a precise cross-dating of chronologies over long distances. For example, the interannual variation in oxygen isotopes in our site was similar to that of stations as far as 1300–1500 km to the north east and west of the basin (Fig. 1). Thus, as long as the trees use precipitation water in a similar way as *Cedrela*, and do not excessively use deeper groundwater, our isotope chronology could help assist the development of oxygen isotope chronologies from other sites and species, allowing more extensive sampling of the basin's hydrological history in time and space. Advantages of tree ring-based proxies are that records do not need to be limited to the Andes or location of caves, and that the records provide a much better resolution than, for example, speleothems or valve records.

Conclusions

We demonstrated that oxygen isotope ratios in tree rings in tropical *Cedrela* accurately record the isotopic composition of meteoric precipitation during the wet season ($\delta^{18}\text{O}_{\text{prec}}$) and show only weak controls by plant physiology. Isotope ratios in tree rings provide a very strong proxy for annual to decadal scale variation in the amount of precipitation over the entire Amazon basin and for basin-wide river discharge, and are only weakly correlated with temperature, vapor pressure, or local precipitation. The record shows significant correlations with $\delta^{18}\text{O}$ in precipitation in the central and western Amazon and ice cores in the Andes, indicating that the interannual variation in $\delta^{18}\text{O}$ of precipitation contains a spatially coherent signal over large parts of the Basin, consistent with model predictions. The most dominant large-scale control of variation in tree ring $\delta^{18}\text{O}$ at interannual scales is the ENSO, with a particularly strong influence over recent decades and a weakened influence during the middle of the last century. At longer time scales, the tree-ring oxygen isotope series showed a significantly increasing trend. These trends were previously interpreted as being a result of global warming or drying of the basin, but the true cause remains disputed. Our study shows that tree-ring oxygen isotopes can be used as a tracer for changes in meteoric $\delta^{18}\text{O}$ and is thus a highly promising tool for detecting long-term changes in the hydrological cycle of the basin.

Methods

Complete discs were collected from the bases of approximately 60 logged trees of *C. odorata* from undisturbed tropical moist lowland forest from Purissima, northern Bolivia (11°24'S, 68°43'W) (Fig. 1) in October 2002. Tree rings were measured and successfully cross-dated (28). For this study, we selected eight large

trees (>60 cm in diameter) and isolated wood from each individual ring along a single radius using sharp knives and razor blades. Procedures for cellulose extraction and homogenization are described in the *SI Appendix*. The samples were weighed and packed into silver capsules, and pyrolyzed at 1.080 °C in an element analyzer (Carlo Erba) coupled to an isotope spectrometer (OPTIMA; Micromass). Values are expressed relative to V-SMOW and have an analytic precision of 0.3‰. In all analysis we used the arithmetic mean isotope ratios of the different trees ($\delta^{18}\text{O}_t$). Details on the sources of climate, $\delta^{18}\text{O}_{\text{prec}}$ and $\delta^{18}\text{O}_{\text{ice}}$ records are provided in the *SI Appendix*.

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