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Oxygen isotopes in tree rings record variation in precipitation δ^{18}O and amount effects in the south of Mexico

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[1] Natural archives of oxygen isotopes in precipitation may be used to study changes in the hydrological cycle in the tropics, but their interpretation is not straightforward. We studied to which degree tree rings of *Mimosa acantholoba* from southern Mexico record variation in isotopic composition of precipitation and which climatic processes influence oxygen isotopes in tree rings ($\delta^{18}O_{tr}$). Interannual variation in $\delta^{18}O_{tr}$ was highly synchronized between trees and closely related to isotopic composition of rain measured at San Salvador, 710 km to the southwest. Correlations with δ^{13}C, growth, or local climate variables (temperature, cloud cover, vapor pressure deficit (VPD)) were relatively low, indicating weak plant physiological influences. Interannual variation in $\delta^{18}O_{tr}$ correlated negatively with local rainfall amount and intensity. Correlations with the amount of precipitation extended along a 1000 km long stretch of the Pacific Central American coast, probably as a result of organized storm systems uniformly affecting rainfall in the region and its isotope signal; episodic heavy precipitation events, of which some are related to cyclones, deposit strongly ^{18}O-depleted rain in the region and seem to have affected the $\delta^{18}O_{tr}$ signal. Large-scale controls on the isotope signature include variation in sea surface temperatures of tropical north Atlantic and Pacific Ocean. In conclusion, we show that $\delta^{18}O_{tr}$ of *M. acantholoba* can be used as a proxy for source water δ^{18}O and that interannual variation in $\delta^{18}O_{prec}$ is caused by a regional amount effect. This contrasts with δ^{18}O signatures at continental sites where cumulative rainout processes dominate and thus provide a proxy for precipitation integrated over a much larger scale. Our results confirm that processes influencing climate-isotope relations differ between sites located, e.g., in the western Amazon versus coastal Mexico, and that tree ring isotope records can help in disentangling the processes influencing precipitation δ^{18}O.

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1. Introduction

[2] Oxygen isotopes in precipitation are a powerful tracer for changes in the climate system due to differences in the condensation and evaporation rates of light and heavy isotopes while they move through the hydrological cycle. Therefore, isotope ratios of precipitation that are recorded in natural archives like ice cores [*Thompson et al.*, 2006], speleothems [*Frappier et al.*, 2007b; *Kennett et al.*, 2012; *Lachniet*, 2009], lake sediments [*Bird et al.*, 2011], or tree rings [*Anchukaitis and Evans*, 2010; *Brienen et al.*, 2012; *Miller et al.*, 2006] have been used to elucidate climatic changes in the past over different time scales. While the use of such natural archives is potentially a very powerful way of recording natural climatic variability and understanding its drivers, multiple factors influence variation of δ^{18}O in precipitation and interpretation of the isotope records can be a bit of a puzzle. Precipitation δ^{18}O is influenced by its source region, by temperature, by cloud physics, and by the condensation history of atmospheric water vapor (i.e., Rayleigh rainout processes) [*Araguás-Araguás et al.*, 1998; *Sturm et al.*, 2007; *Villacis et al.*, 2008]. Currently, annually resolved records of precipitation δ^{18}O that can be related to variation in climate over a sufficiently long period to study the relative influences of each of these factors are scarce.

[3] In temperate regions the composition of δ^{18}O in precipitation shows generally strong dependence on the condensation temperature, while in the tropics the most well-known feature is the so-called "amount effect," an anticorrelation

Additional supporting information may be found in the online version of this article.

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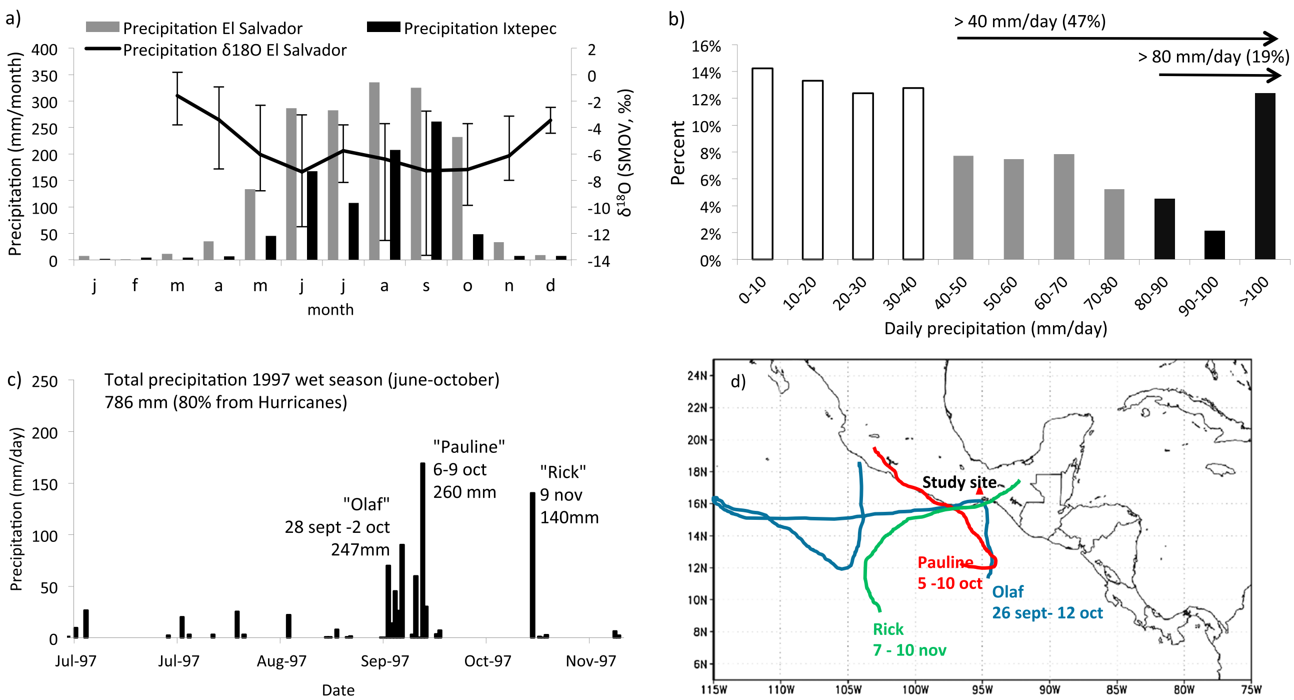

Figure 1. Climate of the study region (a) monthly mean precipitation (bars) of Ixtepec and San Salvador and monthly mean values of $\delta^{18}O_{prec}$ for San Salvador (lines with error bars indicating the minimum and maximum values, data from: GNIP, IAEA, number of years varies from 3 to 15), (b) the contribution of days with different precipitation intensities to total annual precipitation for Ixtepec (Mexico). (c) Daily precipitation records for the 1997 wet season (June to November), showing three episodic heavy rainfall events associated with different hurricanes. Hurricane Pauline also contributed to extreme precipitation (400 mm/d) near Acapulco, north of the study site (cf. Jauregui 2003). (d) Map of the storm trajectories of the three East Pacific hurricanes in 1997 that hit the study site (tracks redrawn from data of National Hurricane Centre, NOAA: http://www.nhc.noaa.gov/pastall.shtml#tracks_all). Dates indicate official start and end dates of hurricanes.

between local precipitation intensity and the isotope ratio [*Araguás-Araguás et al.*, 1998; *Dansgaard*, 1964; *Lee and Fung*, 2008; *Risi et al.*, 2008]. In addition to this local amount effect, isotopic signals are influenced by the origin of the water source [*Araguás-Araguás et al.*, 1998] and the history of cloud condensation and evapotranspiration of air masses from the source to the site of deposition [*Vuille and Werner*, 2005]. The degree to which instantaneous amount effects versus large-scale effects (origin and history of air masses) influence the isotope record may vary strongly from site to site. Observational studies have shown that the isotopic signature of continental precipitation such as in the western part of the Amazon [*Brienen et al.*, 2012; *Villacis et al.*, 2008; *Vuille and Werner*, 2005] or continental stations in Asia [*Araguás-Araguás et al.*, 1998] is only very weakly related to the local amount of precipitation and mainly determined by the total (or “integrated”) amount of precipitation upstream along the water vapor trajectory. In contrast, maritime sites often show more pronounced relations with local or regional rainfall amounts [*Kurita et al.*, 2009]. Hence, the relative importance of local versus large-scale effects is likely to vary from site to site [*Araguás-Araguás et al.*, 1998; *Kurita et al.*, 2009]. An improved understanding of the processes that govern the isotope-climate relation will help in understanding the climate system and may be used to calibrate climate models and improve interpretation of paleoclimatic proxies.

[4] The use of tree rings as natural archives for variation in $\delta^{18}O$ in precipitation is of particular interest for several reasons. Trees are widely distributed, and the use of trees as proxy archives is thus not limited to a few sites, like speleothems or ice cores. In addition, trees can provide data at an annual to subannual resolution [*Anchukaitis and Evans*, 2010; *Li et al.*, 2011] and may become several millennia old. However, the degree to which trees record variation in precipitation $\delta^{18}O$ is debated. Some trees may use deep groundwater which contains a precipitation $\delta^{18}O$ signal that is integrated over several years and which may be enriched by soil evapotranspiration [*Lawrence*, 1998; *Tang and Feng*, 2001]. Also, in addition to the source water signal, tree ring $\delta^{18}O$ is to some degree altered by plant physiological responses to climate, specifically by leaf water enrichment during evapotranspiration [*Roden et al.*, 2000; *Sternberg*, 2009]. In all, it is not so clear if source water or evapotranspiration has a stronger imprint on cellulose $\delta^{18}O$. Some studies suggest strong influences [*Kahmen et al.*, 2011] and others less [*Anchukaitis and Evans*, 2010] or no (measurable) influence of leaf water enrichment [*Brienen et al.*, 2012], and the relative importance may vary between species and soil structure.

[5] Here we reconstruct the interannual variation in $\delta^{18}O$ in tree rings for a tropical dry forest species, *Mimosa acantholoba*, from the Pacific coast of the Isthmus of Tehuantepec (South Mexico) and examine whether tree ring

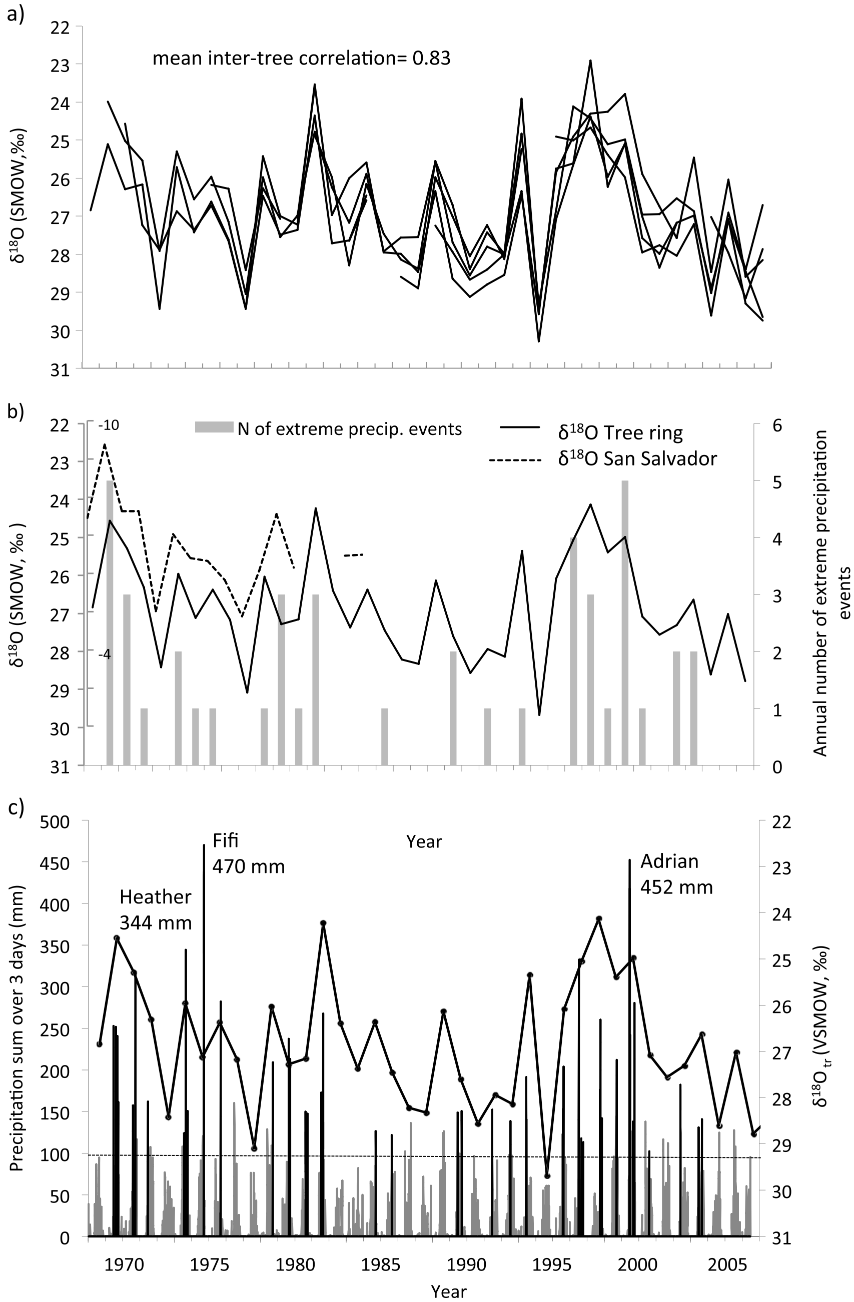

Figure 2. (a) Time trend of interannual variation of δ^{18}O in tree ring cellulose ($\delta^{18}O_{tr}$) for five trees of *Mimosa acantholoba* in southern Mexico (sample sizes vary from three trees at the start to five trees in 2007; note the inverted *y* axis), and (b) time trends of mean $\delta^{18}O_{tr}$ (solid line) and δ^{18}O in precipitation in San Salvador (broken line) and the number of extreme precipitation events per year (i.e., events exceeding a total of 100 mm of precipitation within a 3 day period, see section 2). (c) The time trend of $\delta^{18}O_{tr}$ and variation in precipitation summed over periods of 3 days (grey bars). Extreme precipitation events (i.e., higher than 100 mm over 3 days from precipitation > 40 mm/d, see section 2) are marked by black bars. For the three heaviest rainfall events between 1968 and 2006, corresponding hurricanes or tropical storms are indicated. The 10 heaviest precipitation events with names of tropical hurricanes or storms (if they could be matched) are shown in Table S1.

δ^{18}O of this species and site can be used as a recorder for precipitation δ^{18}O. We also establish what kind of climatic information is maintained in the record and over what spatial scales, and we unravel the large-scale controls. As precipitation in this region is influenced by tropical storms or cyclones [*Englehart and Douglas*, 2001; *García-Oliva et al.*, 1991; *Jauregui*, 2009], we further inquire whether tropical storms may have influenced the isotope signal. About half of annual precipitation in the study region falls in heavy events (Figure 1b) often related to tropical storms or cyclones

(Figures 1c and 2c). As precipitation generated by organized tropical storms or cyclones shows strongly depleted oxygen isotope ratios [*Gedzelman and Lawrence*, 1996; *Lawrence et al*., 2004] and as such precipitation events may drop very large amounts of rainfall in a short period (Figures 1 and 2c), they may substantially contribute to the signal observed in precipitation $\delta^{18}O$ and thus in proxy records. Several studies in Central America or the southern U.S. have demonstrated that oxygen isotopes can be used to identify cyclones in speleothems [*Frappier et al*., 2007a] or tree rings [*Lewis et al*., 2011; *Li et al*., 2011; *Miller et al*., 2006].

2. Methods

2.1. Study Area and Climate of the Region

[6] Our study area is located on the Pacific slope of the Isthmus of Tehuantepec, close to the village of Nizanda in the state of Oaxaca, South Mexico (16°39′N, 95°00′W). The landscape is dominated by low hills with an elevation varying around 250 masl, and the natural vegetation consists of tropical deciduous dry forest [*Perez-Garcia et al*., 2001]. As the Isthmus forms a very narrow landmass between the Gulf of Mexico and Pacific Ocean, we expect climate at the study site to be influenced by both oceans. Mean annual temperature is 26°C and annual rainfall is ~930 mm. Rainfall at the study site is highly seasonal with a pronounced dry season from November until May (<50 mm per month) and a wet season from June to October that accounts for 90% of total rainfall (Figure 1a). This seasonality is closely linked to meridional movements of the Intertropical Convergence Zone (ITCZ), with warmer sea surface temperature (SST) in the surrounding basins resulting in increased disturbances developing over the oceans leading to more rain. Interannual variation in rainfall is very high, showing a fivefold variation over the period 1968 to 2007 from a minimum of 380 to 1850 mm/yr. An important feature of the regional climate system responsible for the high variability of annual rainfall is the occurrence of deep convective systems during the wet season associated with warm SST of the surrounding oceans [*Magaña et al*., 1999] leading to organized mesoscale convective complexes such as tropical depressions, storms, and cyclones [*Englehart and Douglas*, 2001; *Jauregui*, 2009]. These storms and cyclones mostly originate in the tropical northeastern Pacific [*Maloney and Hartmann*, 2000] and drop large amounts of rainfall on the Pacific coast of Mexico and Central America, especially when making a landfall. *Larson et al*. [2005] showed that officially classified and named tropical cyclones passing within 5° of our site contribute to around 20% of total annual precipitation. The influence of precipitation extremes at the study site is evident from the distribution of daily precipitation (Figure 1b). Daily precipitation data from Ixtepec, the nearest climate station (14 km from research site), show that on average about half of the annual precipitation falls in less than 6 days (5.3 days on average days for 1968–2007) and is derived from episodic precipitation events that exceed 40 mm/d, while nearly a fifth of total annual precipitation comes from events exceeding 100 mm/d (Figure 1b). Such heavy precipitation events are often (but not always) related to tropical cyclones (varying in intensity from storms to category 5 hurricanes). For example, in 1997 each one of the episodic rainfall events with more than 100 mm/d was caused by cyclones passing over the study area and these three single events accounted for 80% of the precipitation for that year (cf. Figures 1c and 1d). Over the entire period, at least six of the top 10 most extreme precipitation events at the study site were related to named tropical cyclones most with origin in the eastern Pacific, although the top one precipitation event was related to a cyclone that originated in the Atlantic (see supporting information, Table S1).

2.2. Study Species, Tree Ring Sampling, and Isotope Analysis

[7] *Mimosa acantholoba* (Willd.) Poir. (Fabaceae) is a common dry forest pioneer tree that reaches up to 7 m in height, approximately 20 cm in diameter and has a maximum age of approximately 40 years. *M. acantholoba* forms distinct annual rings characterized by a higher density of vessels and larger vessel size at the beginning of each growth zone (i.e., semi-ring porous growth zones) [*Brienen et al*., 2009]. These rings are induced by cambial dormancy during the dry season, roughly from November–December to May–June, when the tree appears completely leafless.

[8] For this analysis, we selected five stem disks of trees between 28 and 40 years old. These disks were collected in February 2008 from three different forest stands that were abandoned between 40 and 64 years ago and used previously to study secondary forest succession [*Brienen et al*., 2009] and climate-growth relations of this species [*Brienen et al*., 2010]. Wood samples were isolated from exactly dated annual rings for each of the five trees. This was done manually along a small and thin section of each disk with a sharp knife. To avoid loss of material and possible cross contamination during grinding, samples were cut into fine pieces by hand with a sharp blade. Approximately 100 mg of each sample was placed in a 2 mL sealable plastic vial and treated first with 1 mL diglyme + 0.25 mL 10 M HCl and subsequently with 1.5 mL $NaClO_2$-acetic acid (5 g $NaClO_2$ dissolved in 500 mL of distilled water and 0.7 mL of glacial acetic acid) as detailed elsewhere [*Hietz et al*., 2005]. The resulting cellulose was homogenized with a UP200S ultrasonic homogenizer (HielscherUltrasonics, Teltow, Germany) and lyophilized [*Laumer et al*., 2009]. Samples (0.5 mg) were weighed in silver capsules, and the oxygen isotope ratio (^{18}O:^{16}O) was measured in carbon monoxide after sample pyrolysis at 1400°C by isotope ratio mass spectrometry. The continuous flow isotope ratio mass spectrometry (IRMS) system consisted of a high-temperature pyrolysis analyzer (TC/EA, Thermo Fisher, Waltham, MA, USA) coupled via a Con Flo III interface (Thermo Fisher) to the IRMS (Finnigan Delta V Advantage, Thermo Fisher). Standard deviation of repeated analyses of a lab standard (finely ground cellulose, International Atomic Energy Agency (IAEA) Cellulose C3) was 0.23‰ for $\delta^{18}O$. Isotopic values are expressed relative to the international standard for oxygen (Vienna standard mean ocean water):

$$\delta^{18}O = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right)$$

where R represents the ratio ^{18}O:^{16}O of sample and standard (in mol/mol), respectively. Calibration of the system was performed by analysis of certified reference materials from the International Atomic Energy Agency (IAEA, Vienna, Austria), i.e., benzoic acid (IAEA-601 and IAEA-602) and nitrates (USGS34 and USGS35).

2.3. Data Analysis

[9] To study the influence of source water $\delta^{18}O$ on the signal in tree rings, we retrieved data for $\delta^{18}O$ in precipitation from the Global Network of Isotopes in Precipitation (GNIP), accessed through the Water Isotope System for Data Analysis, Visualization and Electronic Retrieval, http://www-naweb.iaea.org/napc/ih/IHS_resources_isohis.html [*International Atomic Energy Agency/World Meteorological Organization*, 2006]. The two closest stations are Veracruz (Mexico, 19°11′N, 96°09′W, 16 masl, WMO code 7669200) and San Salvador (Ilopango, El Salvador, 13°42′N, 89°07′W, 615 masl, WMO code 7866399). We correlated tree ring $\delta^{18}O$ with wet season $\delta^{18}O$ precipitation data from these two stations. We filled in missing monthly $\delta^{18}O$ values using the multi-year monthly means, only if data were recorded at least for 4 out of 6 months during the wet season (May–October). Note that although average rainfall in May is $<$100 mm, we included May in the calculation of wet season precipitation $\delta^{18}O$, as some years showed relative high rainfall during this month ($>$100 mm), which may significantly affect the annual $\delta^{18}O$ values.

[10] To study to which degree $\delta^{18}O_{tr}$ was influenced by plant physiological responses, we also related $\delta^{18}O_{tr}$ with tree growth derived from averaged ring width measurements along two to three radii [*Brienen et al*., 2010] and with carbon isotope discrimination (Δ) or leaf internal CO_2 concentration(c_i) derived from $\delta^{13}C$ measurements on the same samples [cf. *Brienen et al*., 2011].

[11] To study the climate signal in the $\delta^{18}O_{tr}$ record, we correlated $\delta^{18}O_{tr}$ with local and regional climate data, and with global tropical sea surface temperature (SST) anomalies to explore large-scale controls. We did this for different seasons, including the preceding dry season (November–May), the wet season (June–October), and full year (November–October). Historical local climate data were obtained from several sources. Rainfall (1969–2006) and cloud cover data (1969–2003) from the nearest weather station of Ixtepec (16°33′N, 95°06′W, 14 km from research site) were obtained from the Comisión Nacional del Agua (CONAGUA 2003). As the Ixtepec temperature records showed irregularities, we used monthly gridded temperature anomaly data (1969–2007) from GISSTEMP [*Hansen et al*., 1999]. Average daily solar radiation data at Earth surface (kWh m^{-2} day^{-1}; 1983–2005) were also obtained from a gridded data set (NASA; http://eosweb.larc.nasa.gov). In addition to local climate, we correlated $\delta^{18}O_{tr}$ with gridded precipitation records of the Global Precipitation Climatology Centre (GPCC) [*Schneider et al*., 2011] to study the spatial extend of the correlation with rainfall. To study influences of global tropical SST and sea level pressure (SLP) gradients, we used the HadSST1 data set (http://www.metoffice.gov.uk/hadobs/hadisst/) [*Rayner et al*., 2003] and the HadlSLP2r data set (http://www.metoffice.gov.uk/hadobs/hadslp2/) [*Allan and Ansell*, 2006] and created spatial correlation maps using the climate explorer (http://climexp.knmi.nl/) [*van Oldenborgh and Burgers*, 2005].

[12] Finally, we also used a *t* test to test for the influence of El Niño events on the $\delta^{18}O_{tr}$ record using the definition of NOAA of El Niño years (cf. http://www.cgd.ucar.edu/cas/ENSO/enso.html).

[13] As there are no long-term relative humidity records at the study site to calculate leaf-to-air vapor pressure deficit (VPD), we used long-term air temperature and vapor pressure data (e_a) from the gridded data set CRUTS3.0 (University of East Anglia Climate Research Unit (2009)) to calculate air VPD. We calculate vapor pressure inside the stomata e_i according to *Allen et al*. [1998]; $e_i = 0.6108 * \exp((17.27\ T_l)/(T_l + 237.3))$, assuming saturated vapor pressure inside stomata. We also assumed leaf temperature T_l to be equal to air temperature because of the small leaflet size of *Mimosa* (width = 5 mm) and high wind speed in the area (mean 9.3 m s^{-1}), resulting in very high convective energy exchange between leaf and air [*Nobel*, 1991]. We checked this assumption using detailed climate data for 2007 and 2008 and the energy balance equations of *Nobel* [1991] and found that T_l rarely exceeded T_{air} by more than 0.5°C and never by more than 1°C [*Brienen et al*., 2011], even if leaves were not transpiring. We corrected for the offset between monthly VPD based on long-term gridded global data set and VPD during daylight hours (radiation 20 μmol m^{-2} s^{-1}) of the wet season (June–October), the period when carbon uptake can take place. To this end, we correlated daytime with gridded VPD for 2007 and used the regression to calculate long-term VPD trends over the wet season during daytime.

[14] Finally, to provide more detail of what rainfall processes influence the isotope signal in rainfall, we calculated the weighted mean intensity of daily precipitation (*PI*) using the daily Ixtepec data (CONAGUA). This was calculated as the daily precipitation rate (mm/d) weighted by the daily amount of rainfall, in analogue to *Dansgaard* [1964], i.e.,

$$\overline{PI}_{\text{daily}} = \sum_{i}^{n} P_i * \frac{P_i}{P_{\text{annual}}}$$

where P_i is the precipitation amount (in mm) for day i (only for days with any rain), P_{annual} the total annual precipitation, and n the number of days with rainfall in a given year. Given the strong role of cyclones on precipitation in the region, we also inquired how episodic heavy rainfall events that were possibly related to cyclones influenced the regional $\delta^{18}O_{tr}$ record. Episodic, heavy rainfall events were defined as a period of up to 4 days which in total received more than 100 mm of total rain from days with a precipitation rate $>$40 mm/d. This definition seemed to identify most extreme rainfall events of which some, but not all, could be related directly to named cyclones in the region. Using this definition, all three major cyclones in the year 1997 were detected (Figures 2c and 2d) and at least six of the top 10 precipitation extremes in the record for 1968–2006 could be related to named tropical storms or cyclones (Table 1). Still, some observed extremes could not be matched to named cyclones either because the convective complex was not strong enough to be classified as a tropical storm or because the precipitation was derived from faraway cyclone remnants. Cyclone remnants may generate rainfall far away from the eye of the cyclone, up to 550 km [*Englehart and Douglas*, 2001], while cyclone remnants travel potentially very far and may contribute significantly to local rainfall as far as the southwestern U.S. [*Larson et al*., 2005; *Ritchie et al*., 2010].

[15] To find further evidence for a signal of cyclones in the record, we tested whether there was a difference in $\delta^{18}O_{tr}$

Table 1. Correlations and Partial Correlations (*Italic*) Between $\delta^{18}O_{tr}$ and Local Climate Variables

	Dry Season[a]	Wet Season[b]	Annual[c]
Rain	−0.09	**−0.71*****	**−0.72*****
Controlled for $\delta^{18}O_{prec}$[d]	*−0.40*	*−0.49*	***−0.56****
Number of storms			**−0.68*****
Controlled for rainfall[e]			*−0.26*
Mean temperature	−0.06	**0.48****	0.20
Controlled for rainfall[e]	*0.05*	*0.10*	*0.08*
Controlled for $\delta^{18}O_{prec}$[d]	*−0.17*	*0.30*	*0.02*
Cloud cover	−0.22	**−0.46****	**−0.37***
Controlled for rainfall[e]	*−0.00*	*−0.31*	*−0.19*
Controlled for $\delta^{18}O_{prec}$[d]	*−0.04*	*−0.03*	*−0.04*
Solar insolation[f]	−0.26	**0.65***	0.41
Controlled for rainfall[e]	*0.09*	*0.43*	*0.37*
Controlled for $\delta^{18}O_{prec}$[d]	*0.13*	*0.39*	*0.35*
VPD	*−0.12*	***0.37****	***0.35****
Controlled for rainfall[e]	*−0.04*	*0.09*	*0.05*
Controlled for $\delta^{18}O_{prec}$[d]	*−0.13*	*0.24*	*−0.20*

Bold values correspond to significant correlations (*, p<0.05, **:;<0.01, ***p<0.001).
[a]Dry season = November–May.
[b]Wet season (>50 mm) = June–October.
[c]Annual = November–October.
[d]Partial correlation controlled for precipitation $\delta^{18}O$.
[e]Partial correlations controlled for the influence of wet season rainfall.
[f]Only for years 1984–2006.

between years with and without cyclones passing within 160 km of the study site. We used the climate explorer (http://climexp.knmi.nl/) [*van Oldenborgh and Burgers*, 2005] to extract presence or absence of data for cyclones from the Global tropical cyclone data (ftp://texmex.mit.edu/pub/emanuel/HURR/tracks_netcdf/).

3. Results

3.1. Tree Ring-δ^{18}O Records and Correlations With Precipitation δ^{18}O

[16] Interannual variation in $\delta^{18}O_{tr}$ showed very strong synchronization with high mean intertree correlation ($r = 0.83$) between the five trees included in this study (Figure 2a). Intertree correlation was stronger for $\delta^{18}O_{tr}$ than for ring width ($r = 0.50$) or $\delta^{13}C$ ($r = 0.55$) for the same set of trees [*Brienen et al.*, 2010, 2011].

[17] The $\delta^{18}O_{tr}$ record correlated significantly with isotopic composition of wet season precipitation ($\delta^{18}O_{prec}$) of San Salvador ($r = 0.80$, $p < 0.01$, $n = 16$ years, period 1969–1984, see broken line Figure 2b). Correlations with $\delta^{18}O_{prec}$ for Veracruz (Mexico) are much lower ($r = 0.55$, $p = 0.06$, $n = 12$ years, 1971–1985). Veracruz is closer (330 km) to the study site than San Salvador (710 km) but located on the Mexican Gulf Coast, whereas Nizanda and San Salvador both are on the Pacific side.

3.2. Influence of Local Climate and Plant Physiology

[18] The $\delta^{18}O_{tr}$ record correlated significantly with precipitation during June to October, which is the growing season for this species and corresponds to the wet season (Figure 3a). Of the different tested climate variables, the $\delta^{18}O_{tr}$ record correlated best with the total annual amount of precipitation ($r = -0.72$, $p < 0.001$, Figure 3b). There were also significant correlations with temperature, cloud cover, solar radiation, and VPD, but these correlations disappeared in partial correlations that control for the influence of wet season rainfall (Table 1). This indicates that these correlations with variables other than rainfall probably only arise due to the high covariation between the various climate variables. For example, temperature and rainfall at the study site are strongly correlated [*Brienen et al.*, 2010], and dry years are usually also anomalously warm.

[19] To study to which degree these correlations between $\delta^{18}O_{tr}$ and climate are caused by source water effects (i.e., isotopic imprints in precipitation) versus plant physiological effects, we related $\delta^{18}O_{tr}$ with growth and carbon isotope discrimination, which indicate to some degree plant physiological responses to climate. This shows significant correlations between $\delta^{18}O_{tr}$ and the standardized growth indices of 28 trees from the same region from *Brienen et al.* [2009] ($r = -0.70$, $p < 0.001$) and with carbon isotope discrimination (Δ; $r = -0.67$, $p < 0.001$) or the internal CO_2 concentration (c_i, $r = -0.61$, $p < 0.001$) derived from carbon isotopes from the same set of trees [cf. *Brienen et al.*, 2011]. Again, there is a high covariation between rainfall and these variables, and once we control the effect of total rainfall, we find that there is only a very weak effect of intercellular (CO_2), c_i, derived from $\delta^{13}C$ ($r_{partial} = -0.28$, $p = 0.1$) or growth ($r_{partial} = -0.27$, $p = 0.1$) on $\delta^{18}O_{tr}$. In contrast, after controlling for the effect of growth, the effect of total rainfall on variation in $\delta^{18}O_{tr}$ remained significant ($r_{partial} = -0.45$, $p < 0.01$).

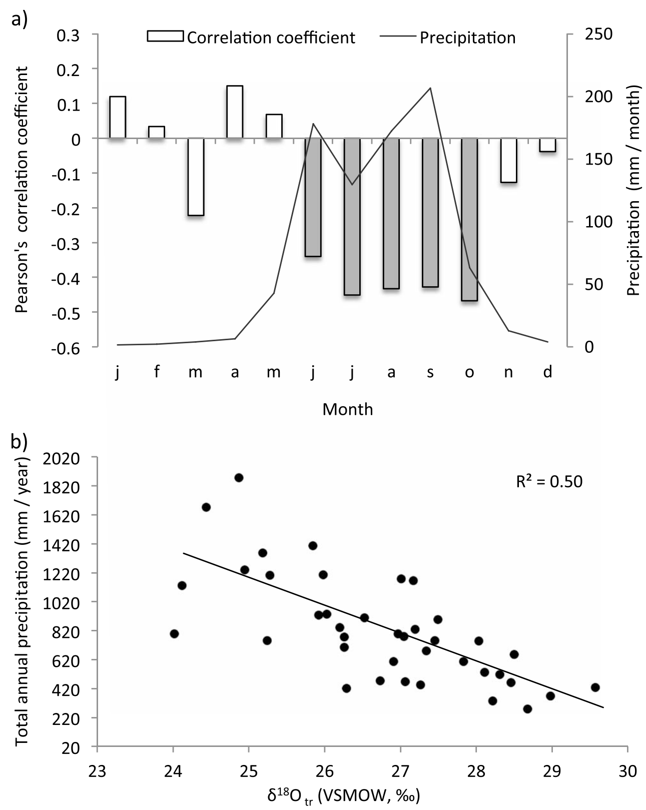

Figure 3. (a) The correlations of monthly rainfall with $\delta^{18}O_{tr}$. Filled bars indicate significant correlations ($p < 0.05$), and the line in Figure 3b indicates the monthly precipitation amount (mm/month). (b) Relationship between oxygen isotope ratios in tree rings ($\delta^{18}O_{tr}$) and total annual rainfall.

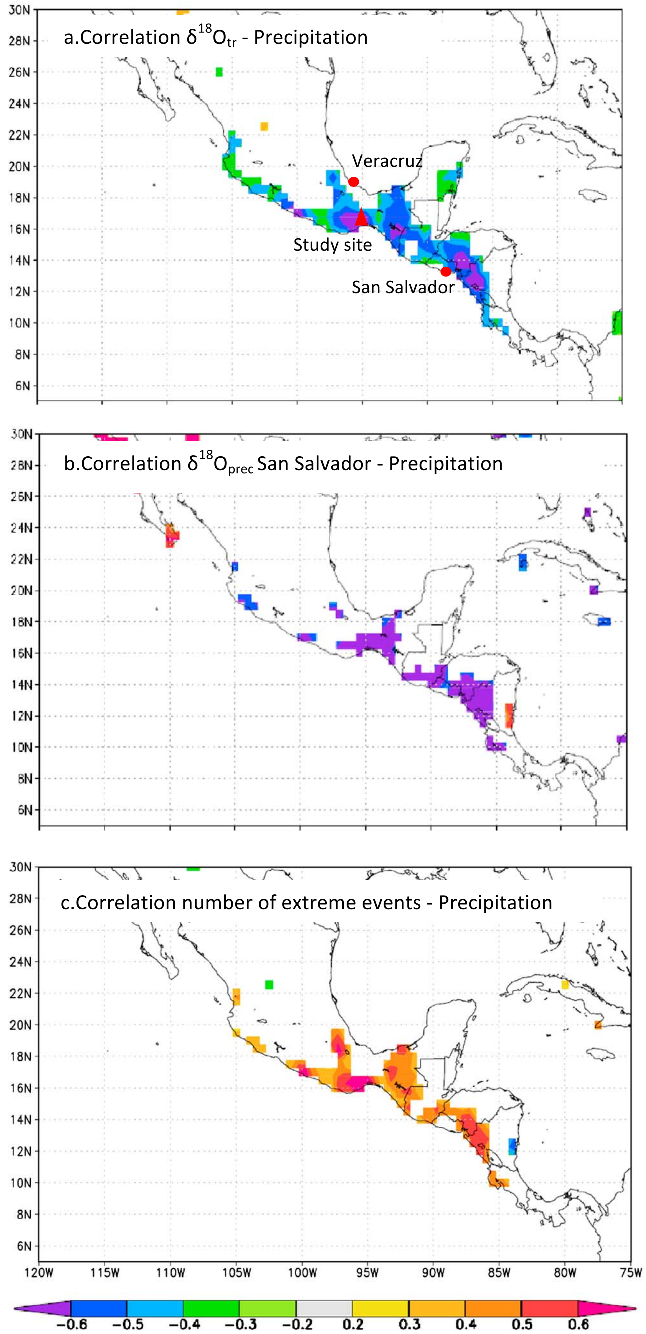

Figure 4. (a) Correlations between gridded precipitation data (GPCCv6, 0.5°) and $\delta^{18}O_{tr}$ for 1968–2007, (b) $\delta^{18}O_{prec}$ from San Salvador (data: GNIP) for 1968–1984, and (c) the number of extreme precipitation events observed at Ixtepec, the climate station nearest to the study site for 1968–2006 (see section 2 for definition used).

[20] There is a strong relation between the amount of rainfall at the study site and $\delta^{18}O_{prec}$ of San Salvador ($r = -0.89$, $p < 0.001$, $n = 14$). To determine whether the interannual variation in tree ring $\delta^{18}O$ is primarily an effect of variation in rainfall or is rather explained by variation in $\delta^{18}O_{prec}$ of San Salvador, we again use partial correlations. This shows that once we control for the effect of $\delta^{18}O_{prec}$ of San Salvador, there is no effect of local precipitation ($r = -0.28$, $p = 0.35$), while there still seems a small effect of $\delta^{18}O_{prec}$ of San Salvador after controlling for the effect of precipitation ($r = 0.40$, $p = 0.17$).

3.3. Influence of Cyclones, Regional Rainfall, and Tropical SST on $\delta^{18}O_{tr}$

[21] Interannual variation in $\delta^{18}O_{tr}$ is closely related to the number of extreme precipitation events at the local study site (Figure 2b, Spearman $P = -0.63$, $p < 0.001$), to other precipitation measures such as the proportion of precipitation derived from such extreme events ($r = -0.70$, $p < 0.001$), and to mean annual precipitation intensity ($r = -0.64$, p 0.001). Additionally, the $\delta^{18}O_{tr}$ record is closely related to annual precipitation peaks with lower $\delta^{18}O_{tr}$ values during years with high precipitation events such as those in 1973, 1974, and 1999, which were related to tropical cyclones (Figure 2c, note reverse *y* axis for $\delta^{18}O_{tr}$: and SI Table 1). Years with no or very few precipitation extremes clearly show higher $\delta^{18}O_{tr}$. The $\delta^{18}O_{prec}$ record for San Salvador also correlated strongly with the number of extreme precipitation events identified in precipitation at the local study site ($r = -0.88$, $p < 0.001$). This indicates that episodic heavy precipitation events leave a distinct imprint on the isotopic composition of precipitation in the region. The record showed a lower mean $\delta^{18}O_{tr}$ during years with tropical storms or cyclones within 160 km of the study site than during years without tropical storms (25.8 versus 27.3, $t = -4.03$, $p < 0.001$, $df = 24$).

[22] To assess the spatial extent of the relation between $\delta^{18}O_{tr}$ and precipitation, we correlated $\delta^{18}O_{tr}$ with gridded precipitation records for the region. We found significant correlations with precipitation along a large part of the Pacific coast of Central America (Figure 4a). The correlation was strongest toward the south of the coast and decreased toward the north. The spatial extent of these correlations is very similar to the correlation pattern of San Salvador $\delta^{18}O_{prec}$ with gridded precipitation data (Figure 4b) and also similar—but of opposite sign—to correlations of the number of extreme precipitation events observed in the precipitation record of the study site (Ixtepec) with regional precipitation data (Figure 4c). Correlations with mean precipitation indices of Central America from 105 different precipitation stations obtained by *Aguilar et al.* [2005] confirm these results, showing significant correlations of $\delta^{18}O_{tr}$ with total annual precipitation anomalies ($r = -0.65$, $p < 0.001$) and with the rain intensity index ($r = -0.65$, $p < 0.001$).

[23] Correlations of $\delta^{18}O_{tr}$ with gridded SST fields (HadSST) show differences in the influence of SST anomalies of the two basins during the dry and wet seasons (Figures 5a–5c). During the dry season (November–May), it is mainly the tropical North Atlantic SST anomalies that influence variation in tree ring $\delta^{18}O$, while during the wet season (June–October), there is a control of Pacific SST anomalies. Note that the tree ring $\delta^{18}O$ signal provides just one value for the entire year and does not distinguish between the different seasons shown in Figures 5a–5c.

[24] Dry season Atlantic SST indicates that a north-south SST gradient in the region between 30 to 60°W and 5 to 40°N influences the oxygen isotope signal. Correlations with Pacific SST anomalies indicate some influence of El Niño-Southern Oscillation (ENSO), given the

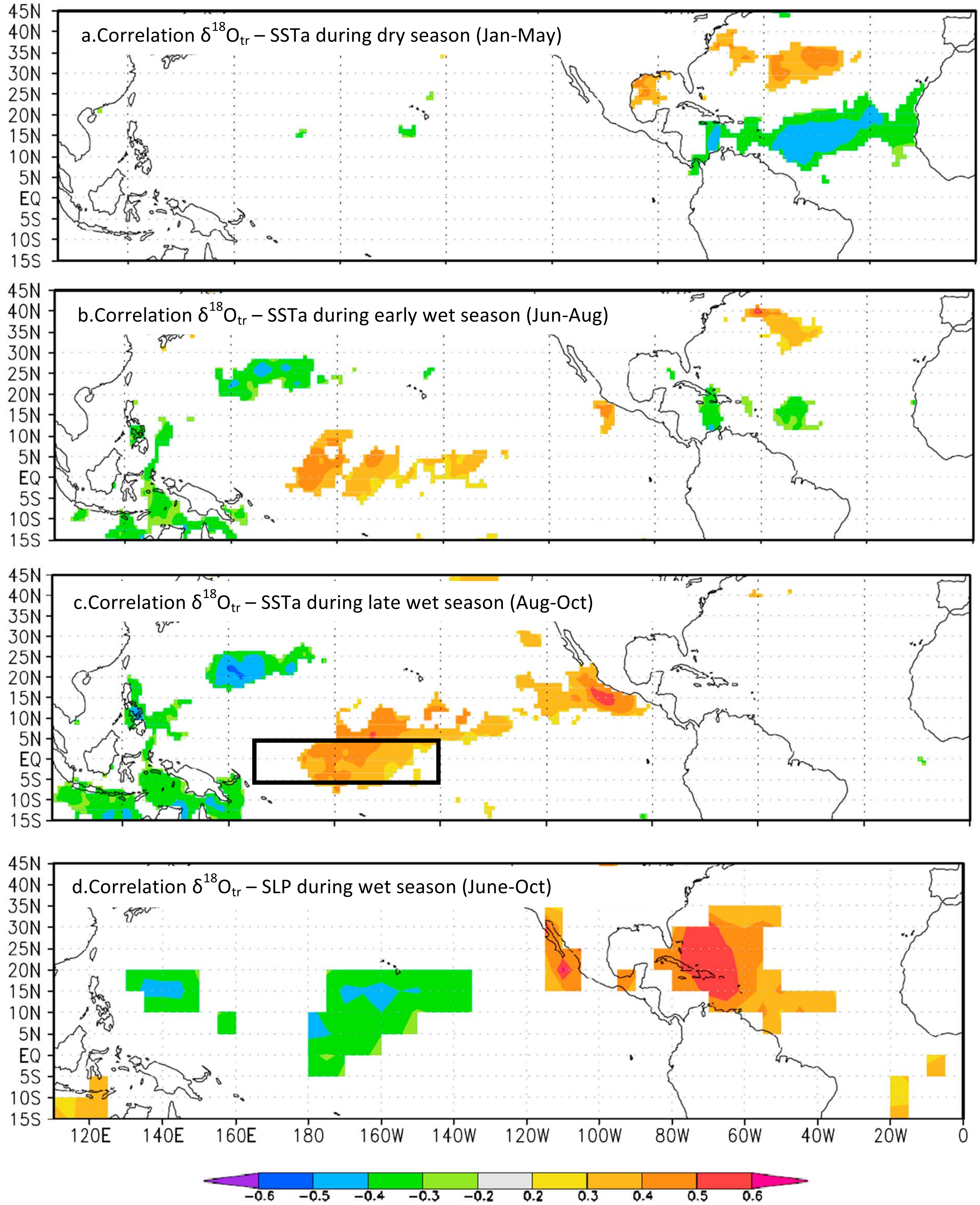

Figure 5. Correlations between $\delta^{18}O_{tr}$ and gridded tropical sea surface temperature anomalies (data set: HadlSTT1) for different periods; (a) dry season (January–May), (b) early wet season (June–August), and (c) late wet season (August–October). Squares in the Pacific Ocean indicate the Niño4 region (5°S–5°N, 160°E–150°W). (d) Correlations between $\delta^{18}O_{tr}$ and gridded sea level pressure anomalies (data set: HadlSLP2r) over the wet season (i.e., June–October).

zonal differences in correlations between east and west. Correlations with ∓ in the El Niño regions are highest for the Niño4 region in the central Pacific (5°S–5°N, 160°E–150°W) during August–October ($r = 0.39$, $p < 0.05$, Figure 5c). The $\delta^{18}O$ value in tree ring cellulose was significantly higher during El Niño years compared to non-Niño years (27.85 versus 26.52, t test, $t = -3.19$, $p < 0.01$, $df = 36$).

[25] Finally, relations of $\delta^{18}O_{tr}$ with interannual variations in sea level pressure show a distinct influence of a sea level pressure seesaw pattern between the tropical northwest Atlantic and central Pacific on variation in $\delta^{18}O$ (Figure 5d), which according to *Hastenrath* [1984] and *Giannini et al.* [2000] is correlated with El Niño-3 index.

4. Discussion

4.1. Local Controls on Variation in $\delta^{18}O_{tr}$

[26] The high intertree correlation between the five $\delta^{18}O_{tr}$ series indicates a strong common control on interannual variation in $\delta^{18}O_{tr}$. In comparison, intertree variation in growth or $\delta^{13}C$ for the same trees was noisier probably reflecting individual plant physiological responses to climate and differences between microsites, causing relatively bigger differences between trees in these records. This may reflect a relative large influence of a common source water or be due to spatially more coherent physiological controls on tree ring $\delta^{18}O$ compared to the controls on growth or $\delta^{13}C$. The correlation analysis showed that of all variables tested, isotopic composition in precipitation of San Salvador exhibited the strongest relation with tree ring $\delta^{18}O$, followed by the total amount of rainfall at the study site. Relations between tree ring $\delta^{18}O$ and carbon isotope discrimination or growth are lower and seem mainly due to the high covariation between these variables and annual rainfall amount at the study site. Together, these lines of evidence indicate a dominant role of source water and relatively minor plant physiological influences on interannual variation in tree ring oxygen isotopes for this site and species.

[27] Such a dominant source water influence is consistent with recent findings of *Brienen et al.* [2012] and confirms that $\delta^{18}O$ in tree rings in *Mimosa* at our study site is a powerful recorder of variation in precipitation $\delta^{18}O$, although relative importance of source water versus leaf enrichment may vary between species and sites. This suggests that tree ring $\delta^{18}O$ can only be interpreted confidently in terms of leaf physiological responses if the source water signal is known to be constant or its variation is known and accounted for [e.g., *Kahmen et al.*, 2011]. The strength of the signal also depends on the water source of the species. Isotopic composition of deeper groundwater is probably less variable between different years compared to rainwater [*Tang and Feng*, 2001]. As our species is a low-stature pioneer shrub with deciduous leaves, growing on arid, porous soils, we expect that it mainly uses precipitation water and has no access to deeper groundwater, explaining the high interannual variation in $\delta^{18}O_{tr}$. So far, only few annually dated, multitree oxygen isotope chronologies exist for the tropics [*Brienen et al.*, 2012; *Xu et al.*, 2011], and these show mixed results. *Xu et al.* [2011] find, for example, larger intertree variation than shown here (intertree correlation = 0.50), pointing toward stronger plant physiological influences and/or bigger differences between trees in their source water $\delta^{18}O$ in the mountainous area in Laos. Testing how oxygen isotope signals vary for a suite of different species using water from different depths and growing in different climatic conditions should provide more insight as to how common such a strong source water signal is.

[28] An additional advantage for using tree ring $\delta^{18}O$ in the tropics is that oxygen isotopic signals allow potentially for improved cross-dating techniques, which may be especially useful when trying to cross-date climate-insensitive trees (for example, in the wetter tropics) or to develop chronologies for problematic species with multiple cross-dating problems, not uncommon in the tropics [e.g., *Brienen and Zuidema*, 2005; *Stahle*, 1999]. In addition, as isotopic signals are maintained at the regional rather than local scale [*Kurita et al.*, 2009; *Xu et al.*, 2011] and show especially good coherence over large continents (e.g., 1500 km in Amazon Basin) [*Brienen et al.*, 2012], a single regional chronology could potentially be used to develop isotope chronologies for other species and sites and to confirm chronologies based on ring widths.

[29] What climatic signal does the record exhibit? The main control on interannual variation in $\delta^{18}O_{tr}$ is the amount of rainfall. Other climatic variables were significantly related to $\delta^{18}O_{tr}$ but did not explain additional variation in the tree ring $\delta^{18}O$ record (i.e., disappeared once we controlled for the influence of rainfall). Thus, a regionally integrated amount effect [*Dansgaard*, 1964] dictates the interannual variation in tree ring $\delta^{18}O$ with a more strongly depleted isotope signal in precipitation during years with heavy rainfall. Correlations with precipitation amounts extended spatially to a wider region along the entire Pacific coast of Central America. This finding and the strong correlation between $\delta^{18}O_{tr}$ of our site and $\delta^{18}O_{prec}$ of San Salvador indicate the existence of a regional control on $\delta^{18}O_{prec}$. Such a regional control may arise either from strongly correlated precipitation regimes along the Pacific coast or from a spatially coherent imprint on the isotopic composition of water vapor in the region or a combination of these. Interesting in this regard is that we observed that $\delta^{18}O_{prec}$ of San Salvador (El Salvador, 600 masl) correlated with nearby coastal rainfall amounts (Zacatecoluca, El Salvador, 170 masl, $r = -0.75$) and with rainfall amounts at the nearest climate station (Ixtepec, Mexico, 750 km north, 75 masl, $r = -0.63$) but not with the local amount of rainfall for San Salvador ($r = -0.12$) suggesting a relative strong spatially coherent isotopic imprint on water vapor in the region. The lack of a local amount effect (at San Salvador) could be due to orographic effects and geography of the surrounding mountains altering the local pattern of interannual variation in rainfall there, but not affecting the "regional" isotopic signal in the water vapor. The origin for a strong regional control is most likely a spatially coherent imprint of large-scale organized storm systems in the regions like mesoscale convective complexes, tropical depressions and storms, or hurricanes on the isotopic composition of water vapor. Deep convection, tropical storms, and hurricanes produce vapor and rain with very low isotope ratios [*Gedzelman et al.*, 2003; *Gedzelman and Lawrence*, 1996]. Such low isotope ratios may persist in soil and surface waters for a few weeks [*Lawrence*, 1998] and are thus likely to be picked up by plants. This is also why tree ring studies from the southern U.S. found oxygen isotopes series to detect tropical cyclones [*Lewis et al.*, 2011; *Li et al.*, 2011; *Miller et al.*, 2006], although results are not unambiguous [*Lewis et al.*, 2011]. Our record showed some possible influence of cyclone activity, but it proved impossible to clearly attribute $\delta^{18}O$ variation in the record to individual cyclones using data at an annual resolution as we did. Recent advances in high-resolution isotope techniques on tree rings [*Evans and Schrag*, 2004; *Li et al.*, 2011; *Poussart et al.*, 2004] may allow reconstructions of

individual tropical cyclones in the past, in a similar way to high-resolution speleothem series [*Frappier et al.*, 2007a].

4.2. Large-Scale Controls on δ^{18}O Signals

[30] Precipitation in the study region is influenced by SST from both adjacent ocean pools: the Atlantic and the Pacific Ocean. Both basins are known to affect precipitation during different seasons, with a more pronounced influence of the Atlantic during the dry and early rainy season and a Pacific influence during the wet season [*Enfield and Alfaro*, 1999; *Taylor et al.*, 2002]. This bimodal pattern is reflected in the correlations between (annual values of) tree ring δ^{18}O and SST for these different seasons, with a dry season influence of the Atlantic and a significant influence of Pacific SST only during the late wet season. The observed meridional dipole pattern during the dry season with opposite correlations for the southern and northern portions of the tropical north Atlantic (i.e., across the Atlantic ITCZ) is consistent with a reported influence of this ocean pool on precipitation in central America: A warm tropical Atlantic Ocean between 0°N and 20°N is associated with increased early (May–June) rainy season rainfall [*Enfield and Alfaro*, 1999; *Giannini et al.*, 2000; *Taylor et al.*, 2002]. This influence is brought about by changes in atmospheric circulation but is possibly also related to a warm Atlantic, functioning as a trigger for the development of a late wet season La Niña [*Ham et al.*, 2013] further increasing rainfall in the study area. In either way, the negative relation between tree ring δ^{18}O and SSTa is due to increased rainfall amounts and thus more depleted ratios of oxygen isotopes in precipitation.

[31] Later in the wet season, influences of tropical SST shift to the Pacific Ocean with a weak, but characteristic, ENSO influence; during ENSO years when central Pacific SST is relatively warm, precipitation in the region is reduced [*Brienen et al.*, 2010] causing slightly higher values of δ^{18}O in tree rings. Another relevant feature of the climate system in the region that affects precipitation amounts is interannual variation in the interbasin sea level pressure (SLP) gradients. Several studies [*Giannini et al.*, 2000; *Muñoz et al.*, 2008] observed that a seesaw pattern with higher than average SLP in the Atlantic and lower SLP in the central to eastern Pacific leads to divergent atmospheric flow in the Caribbean and most of Central America, and hence a reduction in local precipitation. The observed anticorrelation between Atlantic and Pacific SLP influences on δ^{18}O is in accordance with this mechanism. High pressure in the tropical Atlantic corresponds to subsidence and divergent flow away from our region, which thus may affect the cyclone tracks.

[32] The ENSO influence observed here is relatively weak (see Figure 5c) compared with the influence of ENSO on δ^{18}O tree ring series from the Amazon Basin (north Bolivia) [cf. *Brienen et al.*, 2012]. The contrast with this study is especially interesting as the effect of ENSO on the interannual variation in local rainfall for the site in the Amazon is relatively weak, while the ENSO effect on local rainfall is much stronger in southern Mexico [*Brienen et al.*, 2010]. This is most likely because the δ^{18}O signal at the continental site is mainly controlled by cumulative rainout during water vapor transport across the entire Amazon Basin, which in turn is strongly influenced by ENSO [cf. *Brienen et al.*, 2012], as opposed to stronger regional controls on the δ^{18}O signal in the coastal site used in this study. Thus, records from different sites hold greatly different climatic information, depending on the water vapor source region and the air mass trajectories, which are controlled by regional and large-scale atmospheric circulation patterns. Continental inland sites are most likely to record Raleigh rainout processes over large scales, while coastal sites are likely a better proxy for local or regional convection [cf. *Araguás-Araguás et al.*, 1998]. Our record further shows that precipitation δ^{18}O in the tropics indeed contains essential climate information and is not just a result of a global isotopic imprint of, for example, El Niños on tropical precipitation δ^{18}O.

[33] The linking of annually resolved tree ring δ^{18}O records to regional and large-scale climate data as we have done here is a powerful way to explore to which degree precipitation δ^{18}O records local and large-scale climate variation. This will help identify sites that are of special interest to study the responses of the hydrological cycle to global warming, like changes in the positioning of the ITCZ or the Hadley cell widths [*Broccoli et al.*, 2006], changes in atmospheric water vapor content [*Santer et al.*, 2007], or changes in cyclone activity [*Vecchi and Soden*, 2007]. It will also help in the interpretation of paleoclimatic proxies such as speleothem [*Cruz et al.*, 2009; *Lachniet et al.*, 2004] and ice-core data [*Thompson et al.*, 2006], which themselves may not have the annual resolution to link records to recent variation in climate.

5. Conclusions

[34] Interannual variation in oxygen isotopes in tree rings from *Mimosa acantholoba* from southern Mexico is governed by variation in the isotopic composition of the plant source water. The effect of interannual variation in leaf evaporative enrichment on the tree ring isotope signal was very weak in comparison with the source water effect. Tree ring δ^{18}O correlated negatively with mean annual rainfall intensity and with the total amount of rainfall at the local study site due to the existence of a time-integrated amount effect on the isotopic composition of precipitation in the study region. Spatially, the correlation with precipitation extended along a stretch of approximately 1000 km of the Pacific Central American coast, which is probably associated with regional coordination of storm systems affecting the δ^{18}O signal of water vapor in a highly similar way. For example, heavy episodic precipitation events such as those associated with tropical storms and cyclones bring strongly ^{18}O-depleted precipitation to the wider region and may have influenced tree ring δ^{18}O. Large-scale controls on the isotopic signature include sea surface temperatures in the two surrounding oceans and a seesaw pattern of anticorrelated sea level pressures between the Atlantic and Pacific Ocean. Our study confirms that tree ring oxygen isotopes can be used to understand climate-isotope relationships and to discriminate between the processes influencing the isotope signal in precipitation.

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