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## Hydroclimate and ENSO Variability Recorded by Oxygen Isotopes from Tree Rings in the South American Altiplano

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## Key Points:

- Tree-ring stable oxygen isotopes of *Polylepis tarapacana* record austral summer precipitation variability in the South American Altiplano.
- El Niño - Southern Oscillation is imprinted in the tree-ring oxygen isotopes with a stronger signal towards the north of the studied area.

## Abstract

Hydroclimate variability in tropical South America is strongly regulated by the South American Summer Monsoon (SASM). However, past precipitation changes are poorly constrained due to limited observations and high-resolution paleoproxies. We found that summer precipitation and the El Niño - Southern Oscillation (ENSO) variability are well registered in tree-ring stable oxygen isotopes ( $\delta^{18}\text{O}_{\text{TR}}$ ) of *Polylepis tarapacana* in the Chilean and Bolivian Altiplano in the Central Andes (18-22°S, ~4500 m a.s.l.), with the northern forests having the strongest climate signal. More enriched  $\delta^{18}\text{O}_{\text{TR}}$  values were found at the southern sites, likely due to the increasing aridity towards the south-west of the Altiplano. The climate signal of *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  is the combined result of moisture transported from the Amazon Basin, modulated by the SASM, ENSO and local evaporation, and emerges as a novel tree-ring climate proxy for the southern tropical Andes.

## Plain Language Summary

Understanding past climatic changes in the Central Andes in tropical South America is of great importance to contextualize current hydroclimatic conditions. Here we present the first *P. tarapacana* tree-ring stable oxygen isotope ( $\delta^{18}\text{O}_{\text{TR}}$ ) chronologies and analyze their value as environmental records for this region. Locally known as queñoa, *P. tarapacana* grows in the South American Altiplano from 16°S to 23°S at very high elevations (up to 5,100 m a.s.l), making it the highest-elevation tree species worldwide. We analyze *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  from 1950 to present and find that it registers precipitation changes in the Altiplano and the El Niño - Southern Oscillation (ENSO). We suggest that  $\delta^{18}\text{O}_{\text{TR}}$  is likely affected by soil evaporation and

leaf transpiration, due to the high solar radiation and aridity in the Altiplano, leading to an enrichment in  $\delta^{18}\text{O}_{\text{TR}}$  values, with a more pronounced effect at the more arid sites. *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  reflects the atmospheric processes transporting moisture to the Altiplano and the influence of local evaporation. Our findings are relevant for generating robust hydroclimate reconstructions in the Central Andes to improve circulation models and provide better management of water resources in tropical South America.

## 1 Introduction

Droughts in the South American Altiplano, a semi-arid high-elevation plateau located in the Central Andes, affect millions of people and produce large economic losses across the Andes and the adjacent arid lowlands (Canedo-Rosso et al., 2021). Some studies (Minvielle and Garreaud, 2011; Neukom et al., 2015) have projected a future increase in drought over the Altiplano, although the assumptions on which these projections were based, have recently been questioned (Segura et al., 2020). Thus, understanding hydroclimatic changes in the Altiplano is of great importance to assess the vulnerability of natural habitats and human activities to water scarcity.

The South American Summer Monsoon (SASM) system dominates most of the South American seasonal hydroclimate (Marengo et al., 2010; Vuille et al., 2012). The build-up of the Bolivian High, an anticyclonic system situated over Bolivia, during the austral summer is a key atmospheric feature associated with the SASM. The Bolivian High blocks the atmospheric circulation from the west, allowing the mid- to upper-level easterly winds to entrain near-surface upslope flow and moisture transport from the Amazon basin toward the Altiplano (Garreaud et al., 2003). This moisture originates in the Atlantic Ocean, and is transported toward the Amazon Basin by easterly trade winds during the austral summer (Lenters and Cook, 1997). Moisture is recycled over the Amazon basin before being transported toward the Altiplano (Garreaud, 1999; Segura et al., 2020). Thus, most precipitation (i.e. 75-90%) in the Altiplano falls during the austral summer (December to March; Garreaud et al. 2003; Vuille and Keimig, 2004), coincident with the mature phase of SASM from December to February (Raia and Cavalcanti, 2008), although occasional winter snowfall sourced from the Pacific is possible (Vuille and Ammann, 1997). At interannual scales, this moisture transport to the Altiplano from the Amazon Basin is greatly influenced by sea surface temperatures (SST) in the tropical Pacific (Sulca et al., 2018), with below (above) normal precipitation during El Niño (La Niña) years (Vuille, 1999).

There are few instrumental records of climate in tropical South America prior to 1950, especially in the high Andes including the Altiplano. This is further compounded by the high interannual and spatial precipitation variability in the region, due to its complex topography and the multitude of climate drivers (Vuille and Keimig, 2004). Long-term high-resolution climate proxies are therefore of great importance to extend climate information into the past and to evaluate the present climate dynamics in multicentennial time scales. Tree rings are high resolution (annual to sub-annual) climate proxies with proven value for climate reconstructions. For more than a decade a great effort has been made to expand the South American tree-ring network to the tropical Andes, with special emphasis on the semiarid western Altiplano where *Polylepis tarapacana* grows (16°-23°S) (Argollo et al., 2004; Soliz et al., 2009; Christie et al., 2009; Morales et al., 2012; Morales et al., 2020). This species forms the world's highest elevation forests (4,000-5,100 m a.s.l.; Braun, 1997) and given the quality of its ring-width climate signal and its longevity of up to 750 years, represents the most valuable paleoclimate archive to develop tree-ring based reconstructions in the tropical Andes. However, very little research has been done to evaluate the climate signal in the stable oxygen isotopes contained in *P. tarapacana* (Ballantyne et al., 2011; Rodriguez-Caton et al., 2021).

Previous studies have shown that the degree of moisture recycling and rainout upstream over the Amazon Basin largely control  $\delta^{18}\text{O}$  in precipitation over the tropical and Central Andes and the Bolivian lowlands (Hoffmann et al., 2003; Vuille and Werner, 2005; Vimeux et al., 2005; Vimeux et al., 2011; Vuille et al., 2012; Kanner et al., 2013; Baker et al., 2015). These studies were based on models and natural archives mostly located north of 19° S, thus less is known about the driest and most distal part of the SASM domain located at the southwestern margin of the Altiplano adjacent to the Atacama Desert (Galewsky and Samuels-Crow, 2015).

The development of a network of *P. tarapacana* oxygen isotope chronologies emerges as a valuable tool to complement the present collection of stable oxygen isotope records from the tropical Andes (Vuille et al., 2012), mainly from ice cores, lake sediments and speleothems, to infer the local and large-scale climate variability and changes in the region during the last millennium. Stable oxygen isotopes in tree rings ( $\delta^{18}\text{O}_{\text{TR}}$ ) reflect the  $\delta^{18}\text{O}$  signal of the water absorbed by the roots, but also other processes such as soil evaporation and leaf transpiration. While water absorption by roots is a non-fractionating process (e.g. Bariac et al., 1990; Dawson

and Ehleringer, 1993), soil evaporation and leaf transpiration (the process of plant water evaporation through leaf stomata) can result in enriched  $\delta^{18}\text{O}_{\text{TR}}$  signatures due to preferential evaporation of the lighter isotope ( $^{16}\text{O}$ ). Finally, during cellulose synthesis oxygen atoms can be exchanged between phloem carbohydrates and xylem water contributing to a higher imprint of source water (Sternberg et al., 1986; Gessler et al., 2009; Cheesman and Cernusak, 2017).

Here we used four  $\delta^{18}\text{O}_{\text{TR}}$  site chronologies of *P. tarapacana* spanning from 1950-2015 along a latitudinal-aridity gradient from 18°S to 22°S in the South American Altiplano, to investigate the potential of this network to develop a precipitation reconstruction for the southern tropical Andes. Since  $\delta^{18}\text{O}_{\text{TR}}$  carries a strong signal of the water used by the trees, we hypothesize that our  $\delta^{18}\text{O}_{\text{TR}}$  records reflect hydroclimate and thus register the SASM and ENSO variability in this region.

## 2 Data and Methods

### 2.1 Stable oxygen isotope tree-ring records

Annually-resolved *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  site chronologies: Guallatire (GUA), Frente Sabaya (FSA), Irruputuncu (IRR) and Uturunco (UTU), span from 1950 to 2007-2015 and are located at ~4500 m a.s.l. along a latitudinal-aridity gradient (Fig. 1a, Table S1). Site conditions and methods to develop the  $\delta^{18}\text{O}_{\text{TR}}$  site-chronologies can be found in the Supporting Information (Notes S1) and Rodriguez-Caton et al. (2021). High correlations between the four sites (Fig. S1) justify merging the  $\delta^{18}\text{O}_{\text{TR}}$  chronologies and obtaining a composite *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  chronology by computing a robust mean of the four site chronologies. This composite chronology is almost identical to the first principal component of the four chronologies (Fig. S2b), which explains 79% of the total variance.

We analyzed other  $\delta^{18}\text{O}$  paleoclimate proxy records based on from the Altiplano and surrounding areas, as well as observed and reanalysis-based precipitation amounts and precipitation  $\delta^{18}\text{O}$  (Fig. 1, Table S2). The records include ice cores (Thompson et al., 1984, 1998; Hoffmann et al., 2003; Vimeux et al., 2009),  $\delta^{18}\text{O}_{\text{TR}}$  from an individual *P. tarapacana* tree in Argentina (Ballantyne et al., 2011), and *Cedrela odorata*  $\delta^{18}\text{O}_{\text{TR}}$  from tropical lowlands (Brienen et al., 2012; Baker et al., 2015). We calculated average  $\delta^{18}\text{O}$  for 1954-1984, the common period between these proxies. Observed  $\delta^{18}\text{O}$  in precipitation was obtained from the International

Atomic Energy Agency-Global Network of Isotopes in Precipitation (IAEA-GNIP) from five stations closest to the study area (Fig. 1, Table S3). We also used 2.5° grid resolution IsoGSM precipitation and precipitation  $\delta^{18}\text{O}$  for the period 1979-2018 (Yoshimura et al., 2008). This isotope-enabled reanalysis product realistically portrays the  $\delta^{18}\text{O}$  seasonal cycle and interannual variability in this region (Hurley et al., 2019).

## 2.2 Climate data

We used Climatic Research Unit 0.5° grid resolution precipitation dataset version 4.04 (CRU TS v.4.04; Harris et al., 2020), and CHIRPS precipitation data (Funk et al., 2015) based on remote sensing and meteorological stations for the period 1981-2020 with a spatial resolution of 0.05°x 0.05°. Monthly regional precipitation anomalies for 1950-2008 were also developed by averaging precipitation data from 32 meteorological stations located in the study region (Table S4; Rodriguez-Caton et al., 2021). We used 1° grid resolution ERA5 reanalysis temperature data (Dee et al., 2011) with a time span of 1979-2018 and global SST from version 3 of the NOAA NCDC Extended Reconstructed SST (ERSST version 3b) with 2.0°x 2.0° grid resolution from 1854 to present (Smith et al., 2008).

## 2.3 Relationships between climate and $\delta^{18}\text{O}$ tree-ring records

We performed Pearson correlations between *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  chronologies and monthly precipitation anomalies for the common period 1950-2007 from August of the previous tree-growing season to May of the current growing season using the R package *treeclim* (Zang and Biondi, 2015; R Core Team, 2020). The significance of the correlation coefficients was assessed by stationary bootstrapped confidence intervals (Biondi and Waikul, 2004).

Based on the results from monthly correlations we used January, February and March (JFM) precipitation for both CHIRPS ( $\text{PP}_{\text{CHIRPS}}$ ) and CRU ( $\text{PP}_{\text{CRU}}$ ) to develop spatial correlations with individual-site and composite- *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  chronologies using Spearman rank. Field correlations were also computed for JFM precipitation ( $\text{PP}_{\text{IsoGSM}}$ ) versus precipitation  $\delta^{18}\text{O}$  ( $\text{PP}_{\delta^{18}\text{O}_{\text{IsoGSM}}}$ ) from the isotope-enabled IsoGSM reanalysis dataset, averaged over the location of our four study sites (three grid cells, since two locations shared a grid point).

To assess the influence of ENSO on  $\delta^{18}\text{O}_{\text{TR}}$ , we calculated spatial correlations between the  $\delta^{18}\text{O}_{\text{TR}}$  chronologies and JFM global SST. Singular Spectral Analysis (Vautard and Ghil 1989;



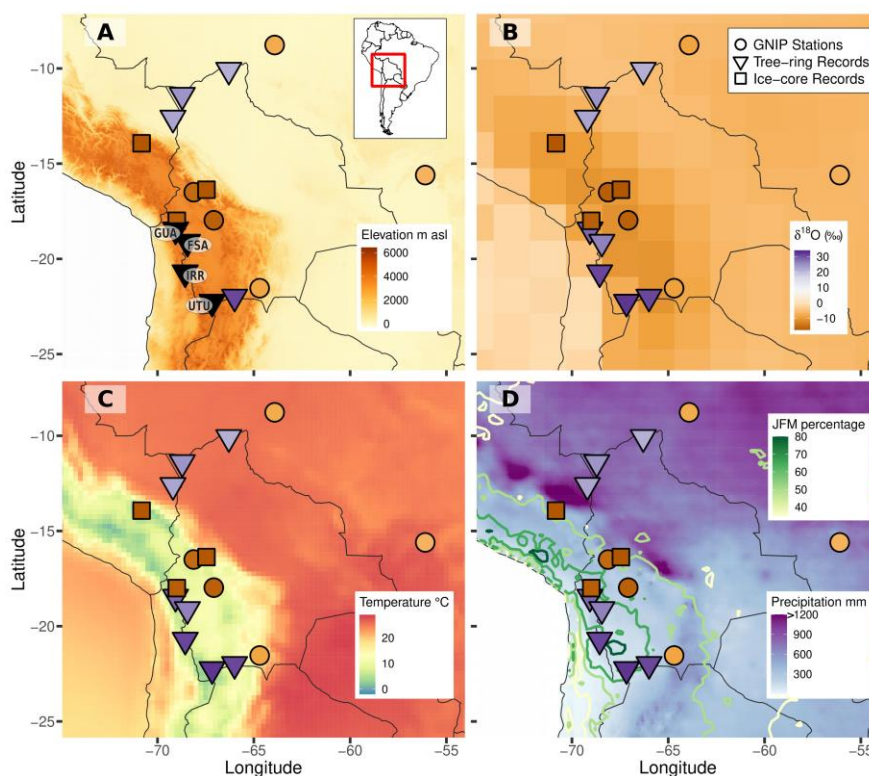
Vautard 1995) was performed to determine the dominant, non-stationary modes of variability of the frequency domains of the composite  $\delta^{18}\text{O}_{\text{TR}}$  chronology and JFM SSTs for the Niño 3.4 region (5°N-5°S, 170°W-120°W). We grouped the dominant modes of variability when they oscillated in similar frequencies (Notes S2). We also calculated probability density functions for  $\delta^{18}\text{O}_{\text{TR}}$  and precipitation at each study site, during El Niño/La Niña years and tested for significant differences according to the Mann-Whitney test using the R functions *density* and *wilcox.test* (R Core Team, 2020) (Fig. S3, Table S5).

### 3 Results

#### 3.1. Precipitation $\delta^{18}\text{O}$ and proxy records in the Altiplano and surrounding areas

GNIP observations and ice-core proxy data show more negative  $\delta^{18}\text{O}$  values as elevation increases (Fig. 1a). This altitude effect likely reflects the first order isotopic Rayleigh distillation with decreasing temperature (Fig. 1c) and orographic precipitation (Fig. 1d) as air masses approach the Andes and are lifted along the eastern slopes. This depletion in heavy isotopes as air masses move from the lowlands in the Amazon basin toward the higher altitude environments in the Altiplano is consistent with the distribution of precipitation  $\delta^{18}\text{O}$  seen in IsoGSM (Fig. 1b). However, *Polylepis*  $\delta^{18}\text{O}_{\text{TR}}$  from the Altiplano have more positive  $\delta^{18}\text{O}$  signatures than  $\delta^{18}\text{O}_{\text{TR}}$  from *Cedrela* trees growing in lowland areas. This may be the result of increasing aridity and hence enhanced evaporation towards the south-west of the Andes (Fig. 1d). Within our *P. tarapacana* network an enrichment of  $\delta^{18}\text{O}_{\text{TR}}$  is also evident towards the southern and more arid sites (Table S1).





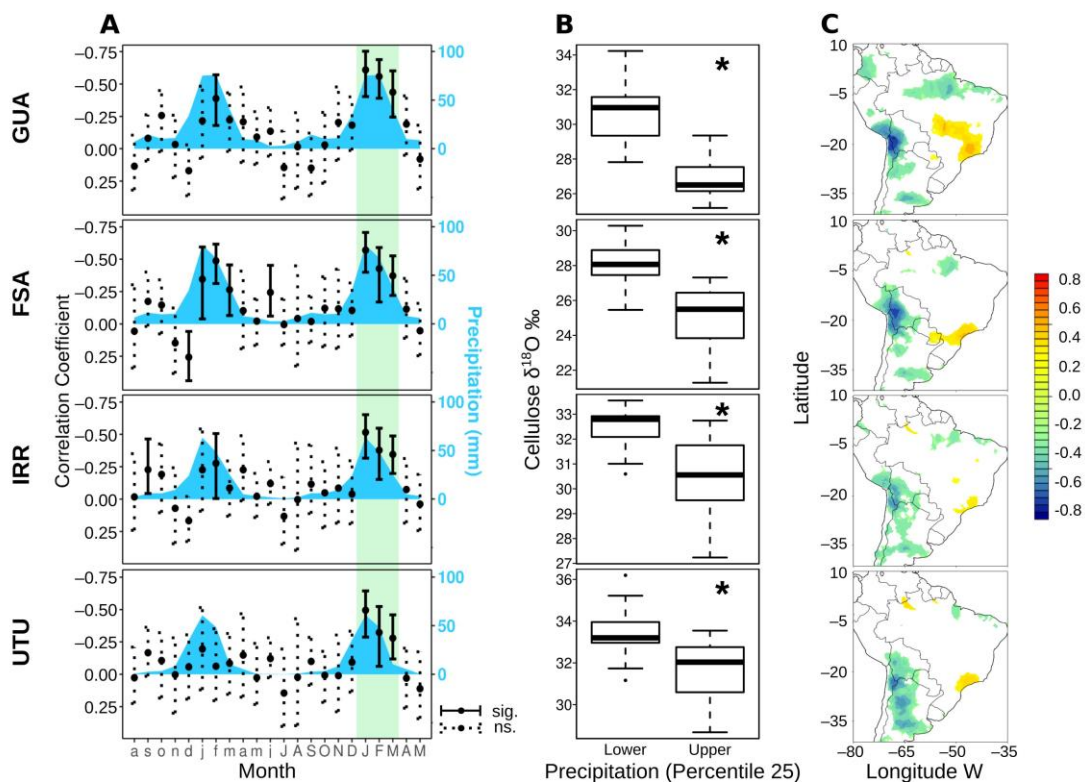
**Figure 1:** Topography, climate and  $\delta^{18}\text{O}$  observations and proxy records in the Altiplano. (A) Elevation in meters above sea level (m a.s.l.). Black triangles with labels (GUA, FSA, IRR, and UTU) represent our four *Polylepis tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  sites (Table S1). (B) IsoGSM mean precipitation  $\delta^{18}\text{O}$  for austral summer (JFM) for 1979-2018. (C) ERA5 mean summer temperature (JFM) for 1979-2018. (D) CHIRPS mean total summer precipitation (JFM) for 1981-2020. Contours represent the percentage of annual precipitation falling during JFM (contour interval is 15, contours <35 are omitted). Location of  $\delta^{18}\text{O}$  observations and proxy records (Table S2) are shown in all panels: mean JFM  $\delta^{18}\text{O}$  (‰) in precipitation for GNIP stations (circles) for the periods depicted in Table S3, and annual  $\delta^{18}\text{O}$  values for tree rings (triangles) and ice cores (squares) for the period 1950-1984. The symbols are colored according to the  $\delta^{18}\text{O}$  ratio (‰) following the color guide in (B).

### 3.2. Precipitation and ENSO signal in *Polylepis tarapacana* $\delta^{18}\text{O}_{\text{TR}}$

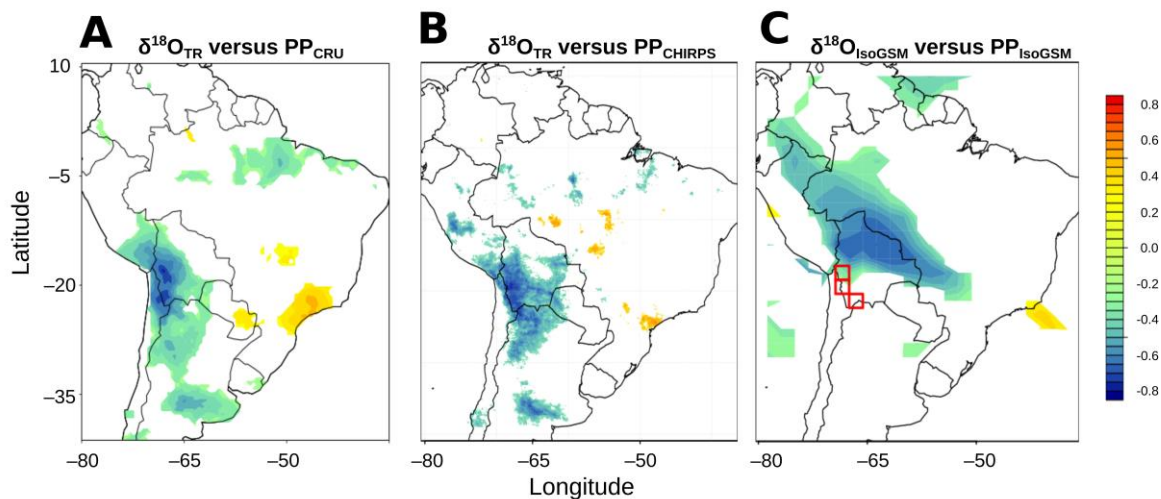
At all sites, the most significant correlations between  $\delta^{18}\text{O}_{\text{TR}}$  and monthly precipitation occurs during the concurrent growing season (Fig. 2a). The four *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  chronologies show a significant negative correlation with precipitation during the peak of the wet season (JFM), which coincides with the mature phase of SASM (Fig. 1d, Fig. 2a). The highest correlations between  $\delta^{18}\text{O}_{\text{TR}}$  and monthly precipitation occur in January, the rainiest month, with

correlations about -0.6 ( $\alpha < 0.05$ ) at the northernmost site GUA. Years with extremely low (high) precipitation, are characterized by significantly more positive (negative)  $\delta^{18}\text{O}_{\text{TR}}$  values (Fig. 2b). The spatial extent of the CRU precipitation signal embedded in the  $\delta^{18}\text{O}_{\text{TR}}$  records, covers much of the Altiplano, reaching correlation coefficients close to -0.8 ( $\alpha < 0.05$ ) at the northern sites of the study region (Fig. 2c). Significant negative correlations extend into the adjacent lowlands eastward from the Altiplano, indicating linkages to upstream rainout. When moving from north to south along the aridity gradient in the Altiplano, the precipitation signal in  $\delta^{18}\text{O}_{\text{TR}}$  weakens at both local (Fig. 2a) and regional (Fig. 2c) scales, but at the same time the signal starts to propagate to the southeast towards the La Plata basin (Fig. 2c site UTU). However, overall, there is high consistency in the pattern of spatial correlation among the four study sites, further supported by a 46, 43 and 42% of explained variance when using the composite  $\delta^{18}\text{O}_{\text{TR}}$  chronology as predictor for instrumental, CRU and CHIRPS precipitation, respectively (Fig. S4).

Across the southern tropical Andes, the composite *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  chronology shows a clear and consistent spatial correlation pattern with CRU and CHIRPS precipitation data (Fig. 3a,b). These results are consistent with correlations between IsoGSM reanalysis precipitation (JFM  $\text{PP}_{\text{IsoGSM}}$ ) and reanalysis precipitation  $\delta^{18}\text{O}$  averaged across the four study sites ( $\text{PP } \delta^{18}\text{O}_{\text{IsoGSM}}$ ) (Fig. 3c). However, while the sign of the correlation is similar, the location of the most significant correlation between  $\text{PP}_{\text{IsoGSM}}$  and  $\text{PP } \delta^{18}\text{O}_{\text{IsoGSM}}$  is displaced upstream over the southwestern Amazon basin (Fig. 3c).



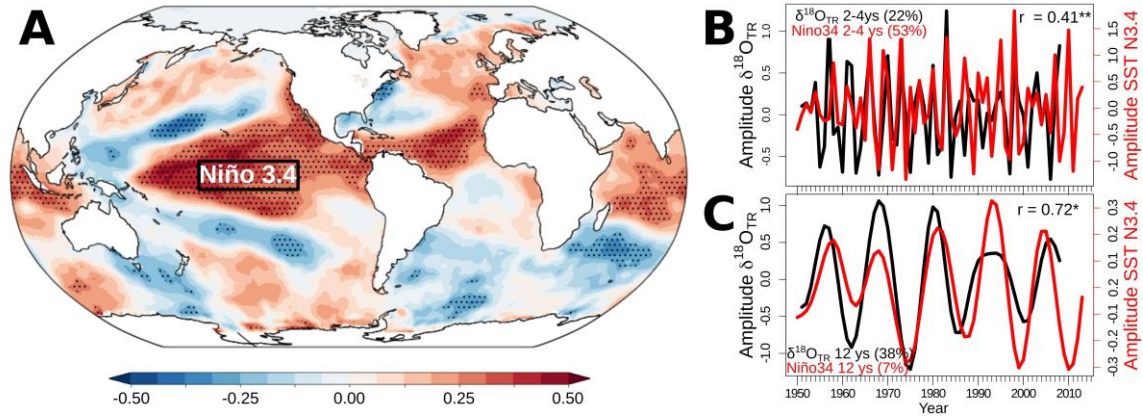
**Figure 2:** Relationships between *Polylepis tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  chronologies and precipitation. (A) Pearson correlation coefficients between  $\delta^{18}\text{O}_{\text{TR}}$  and monthly regional precipitation based on meteorological stations (note that left y axis is inverted), for August of the previous growing season (lowercase) to May of the current growing season (uppercase) for 1950-2007. Vertical solid (dashed) lines represent significant (non-significant) bootstrap monthly correlation coefficients ( $\alpha < 0.05$ ). Blue shading shows CHIRPS precipitation seasonality (1981-2020). Green vertical shading highlights current-year JFM. (B)  $\delta^{18}\text{O}_{\text{TR}}$  values during years of extreme (upper and lower percentiles (25%)) JFM precipitation. Asterisks indicate significant differences (Mann-Whitney,  $\alpha < 0.05$ ). (C) Field Spearman correlations between the  $\delta^{18}\text{O}_{\text{TR}}$  chronologies and JFM CRU precipitation; only significant values are shown ( $\alpha < 0.05$ ).



**Figure 3:** Spatial relationships between  $\delta^{18}\text{O}$  and precipitation over South America. Spearman correlation coefficients between  $\delta^{18}\text{O}_{\text{TR}}$  composite chronology and (A) JFM CRU precipitation for the period 1950-2007 and (B) JFM CHIRPS precipitation for 1981-2007. (C) Spearman correlation coefficients between  $\text{PP}$   $\delta^{18}\text{O}_{\text{IsoGSM}}$  averaged across the study sites and JFM  $\text{PP}_{\text{IsoGSM}}$  for the period 1979-2007. Red boxes represent the three grids where our four sites are located and from where  $\text{PP}$   $\delta^{18}\text{O}_{\text{IsoGSM}}$  data was extracted. Only grid cells with significant values ( $\alpha < 0.05$ ) are shown.

The composite  $\delta^{18}\text{O}_{\text{TR}}$  chronology shows strong correlations with SSTs over the Niño 3.4 region (Fig. 4a), in particular at interannual (Fig. 4b) and decadal (Fig. 4c) scales as evidenced by shared spectral properties (Notes S2). These results demonstrate the ENSO signal imprinted on the  $\delta^{18}\text{O}_{\text{TR}}$  of *P. tarapacana*.

Our results also show that precipitation amount is lower during El Niño than La Niña events along the aridity gradient, with significant differences at the wetter sites GUA and FSA (Fig. S3b, S5). Accordingly, the northernmost and wettest site GUA shows significantly more enriched  $\delta^{18}\text{O}_{\text{TR}}$  during El Niño *versus* La Niña major events (Fig. S3c), as well as stronger correlations with central and eastern equatorial SSTs compared with the rest of the sites (Fig. S3d).



**Figure 4:** ENSO signal in  $\delta^{18}\text{O}_{\text{TR}}$ . (A) Field Spearman correlations between the *Polylepis tarapacana* composite  $\delta^{18}\text{O}_{\text{TR}}$  chronology and JFM SSTs for the period 1950-2007. Dotted areas indicate significant correlations ( $\alpha < 0.05$ ). Time series of (B) interannual and (C) decadal frequency components of the  $\delta^{18}\text{O}_{\text{TR}}$  and JFM SST. Variance explained by each frequency component is indicated between brackets,  $r$  indicates Pearson correlations coefficients between the components, and the stars indicate significance at  $\alpha < 0.1$  (\*) and  $\alpha < 0.05$  (\*\*) after accounting for the lower degrees of freedom due to the applied spectral filtering.

#### 4 Discussion and Conclusions

Our findings reveal that *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  can serve as a valuable proxy for recording precipitation variability over the South American Altiplano. All the study sites show negative correlations between  $\delta^{18}\text{O}_{\text{TR}}$  and precipitation (i.e. years with more rainfall correspond to more negative  $\delta^{18}\text{O}_{\text{TR}}$ ) during austral summer (JFM) of the tree's current growing season. The sensitivity of our four  $\delta^{18}\text{O}_{\text{TR}}$  records to summer precipitation agrees with the fact that most precipitation across this region falls during austral summer as a consequence of the SASM (Garreaud et al., 2003; Vuille et al., 2012). Indeed, the highest correlations occurs in January, which corresponds to the rainiest month in our region. Although precipitation is also important during December, correlations were not significant for this month. This might be related to the fact that  $\delta^{18}\text{O}_{\text{TR}}$  was measured from cellulose, which, depending on the species and area, can accumulate late in the growing season (Rathgeber et al., 2016).



The IsoGSM data indicate that precipitation  $\delta^{18}\text{O}$  over the Altiplano is related with precipitation upstream over the Bolivian lowlands and southwestern Brazil (Fig. 3c). This is consistent with previous studies showing that precipitation  $\delta^{18}\text{O}$  in the tropical Andes is dominated by Rayleigh-type fractionation during rainout over the Amazon basin (i.e. more negative precipitation  $\delta^{18}\text{O}$  results from enhanced convective activity upstream, resulting in depletion of the heavy isotopes in the remaining water vapor) (Vuille and Werner, 2005; Risi et al., 2008).

The influence of upstream processes over the Amazon basin on the precipitation  $\delta^{18}\text{O}$  has been observed in tree-rings (Brienen et al., 2012; Baker et al., 2016), as well as in models and observations (Vimeux et al., 2005; 2011) in the Bolivian lowlands, and other proxies in Peru (Vuille et al., 2012; Kanner et al., 2013; Hurley et al., 2019). While our  $\delta^{18}\text{O}_{\text{TR}}$  records also seem to capture this signal of upstream rainout, they show the highest correlations with precipitation over the Altiplano and surrounding areas (Fig. 3a,b). First, this increased signal of precipitation over the Altiplano can be the consequence of a local amount effect where more precipitation over this region results in more depleted precipitation  $\delta^{18}\text{O}$  (the heavier isotopologues,  $\text{H}_2^{18}\text{O}$ , tend to collect in the precipitation, leaving the vapour and subsequent precipitation isotopically lighter). Second, local evaporation covaries strongly with precipitation over the Altiplano (Vuille and Keimig, 2004). Cloudy and rainy conditions reduce solar radiation and temperature, hence evaporation is reduced and soil water is less enriched in heavy isotopes. This effect may contribute to the enhanced local precipitation signal seen in our  $\delta^{18}\text{O}_{\text{TR}}$  records. In addition, the  $\delta^{18}\text{O}_{\text{TR}}$  not only depends on source water  $\delta^{18}\text{O}$ , but can also reflect evaporative conditions at leaf level during plant transpiration, where drier conditions can result in enriched plant water  $\delta^{18}\text{O}$  due to preferential evaporation of the lighter isotope ( $^{16}\text{O}$ ) (Roden and Ehleringer, 1999; Barbour et al., 2004). Under increased aridity however, Pex (the fraction of carbonyl oxygen atoms that exchange at the cambium during biosynthesis) increases, inducing decreased  $\delta^{18}\text{O}_{\text{TR}}$  (Cheesman and Cernusak, 2017; Szejner et al., 2020) which may partly counter-balance the effect of leaf transpiration. Thus, we interpret the signal in our  $\delta^{18}\text{O}_{\text{TR}}$  records to be associated with (1) the local precipitation amount effect, (2) an effect of local evaporation on soil water in the Altiplano, (3) upstream rainout over the Amazon basin, and (4) potential physiological processes at the tree level (Rodriguez-Caton et al., 2021). This would result in  $\delta^{18}\text{O}_{\text{TR}}$  being a valuable proxy for

precipitation and evaporation over the Altiplano, sensitive to local precipitation, local evaporation and upstream rainout.

The width of the rings of *P. tarapacana* is also a valuable proxy for precipitation and moisture changes in this area. However, tree-ring widths show opposite relationships with climate between consecutive growing seasons (e.g. Soliz et al., 2009), with the signal of the previous year being most useful for reconstructing precipitation (Morales et al., 2012). In contrast, the climate signal of *P. tarapacana*  $\delta^{18}\text{O}_{\text{TR}}$  is consistent across seasons and strongest for the current growing season (for a detailed analysis see Rodriguez-Caton et al. 2021). Although obtaining  $\delta^{18}\text{O}_{\text{TR}}$  can be expensive and time consuming,  $\delta^{18}\text{O}_{\text{TR}}$  represents complementary information to tree-ring width and has lower tree-to-tree variability (i.e. five trees are sufficient to capture the common variability in our *P. tarapacana* stands).

The depletion of heavy isotopes in precipitation  $\delta^{18}\text{O}$  and ice-core  $\delta^{18}\text{O}$  with elevation (Fig. 1) is consistent with prior observations on the isotopic composition of precipitation in the Bolivian and Chilean Altiplano (Aravena et al., 1999; Hardy et al., 2003; Fiorella et al., 2015; Valdivielso et al., 2020). In contrast,  $\delta^{18}\text{O}_{\text{TR}}$  seems to reflect the northeast-southwest aridity gradient across the region, with more negative values for *Cedrela odorata* east of the Andes in the wetter tropical lowlands of Peru and Bolivia (Brienen et al., 2012; Baker et al., 2015) and more positive values for semiarid high-elevation *P. tarapacana* (Ballentyne et al., 2011; Rodriguez-Caton et al., 2021). Similarly, the more enriched  $\delta^{18}\text{O}_{\text{TR}}$  signatures towards the southern and more arid sites of our network (Table S1) are likely due to reduced precipitation and therefore reduced cloudiness and higher solar radiation, driving higher soil-water evaporation and leaf transpiration.

Towards the southern portion of our study area, the  $\delta^{18}\text{O}_{\text{TR}}$  variability seems to be less influenced by SST changes in the tropical Pacific, and the precipitation signal is slightly weakened. In addition, the significant negative correlation between  $\delta^{18}\text{O}_{\text{TR}}$  and precipitation to the southeast of the Andes (i.e. north-central Argentina), most evident in the southern sites, suggests a possible influence of interannual variations in the intensity of the South American Low-Level Jet and extratropical cold air incursions (Garreaud, 2000; Vuille and Keimig, 2004). The southern sites (20-22°S) are located at the southern latitudinal limit of the SASM influence, in the transition zone between the tropics and the subtropics, where complex interactions between atmospheric processes in low and midlatitudes may affect the  $\delta^{18}\text{O}_{\text{TR}}$  precipitation



signal. How these multiple factors influence the  $\delta^{18}\text{O}_{\text{TR}}$  climate signal of the southern sites deserves an in-depth analysis and will be assessed in future work. Despite the differences along the gradient, the composite  $\delta^{18}\text{O}_{\text{TR}}$  chronology, explaining almost 80% of the  $\delta^{18}\text{O}_{\text{TR}}$  total variability, is strongly related with both summer precipitation and tropical Pacific SSTs. Stable oxygen isotopes in the tree rings of the long-lived species *P. tarapacana*, hold immense promise for reconstructing tropical South American hydroclimate of the past millennium. The strong and highly consistent precipitation signal embedded along the new network of  $\delta^{18}\text{O}_{\text{TR}}$  chronologies in the Altiplano, represents a new tool for evaluating year-to-year and multi-centennial precipitation variability in this region. Our findings are relevant for generating more reliable regional and local hydroclimate reconstructions in the Central Andes, as well as potentially contributing to reconstruct past ENSO variability, that will be useful for improving the circulation models and providing better management of water resources in this region.

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## 6 Open Research

The tree-ring stable oxygen isotopic data for the four sites and the regional instrumental precipitation data will be available at <https://www.ncei.noaa.gov/access/paleo-search/study/34812> upon acceptance.

IsoGSM data was retrieved from [https://data.giss.nasa.gov/swing2/swing2\\_mirror/isoGSMnew/](https://data.giss.nasa.gov/swing2/swing2_mirror/isoGSMnew/); GNIP data from <https://nucleus.iaea.org/wiser/index.aspx> and Ice core data from <https://www.ncdc.noaa.gov/data-access/paleoclimatology-data>. CRU data was downloaded from <https://crudata.uea.ac.uk/cru/data/hrg/>; CHIRPS from <https://www.chc.ucsb.edu/data/chirps>; ERA from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form> and SSTs from <https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v5#:~:text=The%20Extended%20Reconstructed%20Sea%20Surface,completeness%20enhanced%20using%20statistical%20methods.>

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