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Supporting Information for

Variability and controls on $\delta^{18}O$, d-excess, and $\Delta'^{17}O$ in southern Peruvian precipitation

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Introduction

This file includes supplementary figures that support the moisture flux ratio analysis and triple oxygen isotope discussion in the main text. This file also contains a figure similar to Figure 1 in the main text that includes the stations from which we do not report isotopic data, additional information about the precipitation stations, tables with new precipitation isotope data, and extended results of the regression modeling to support the main text.

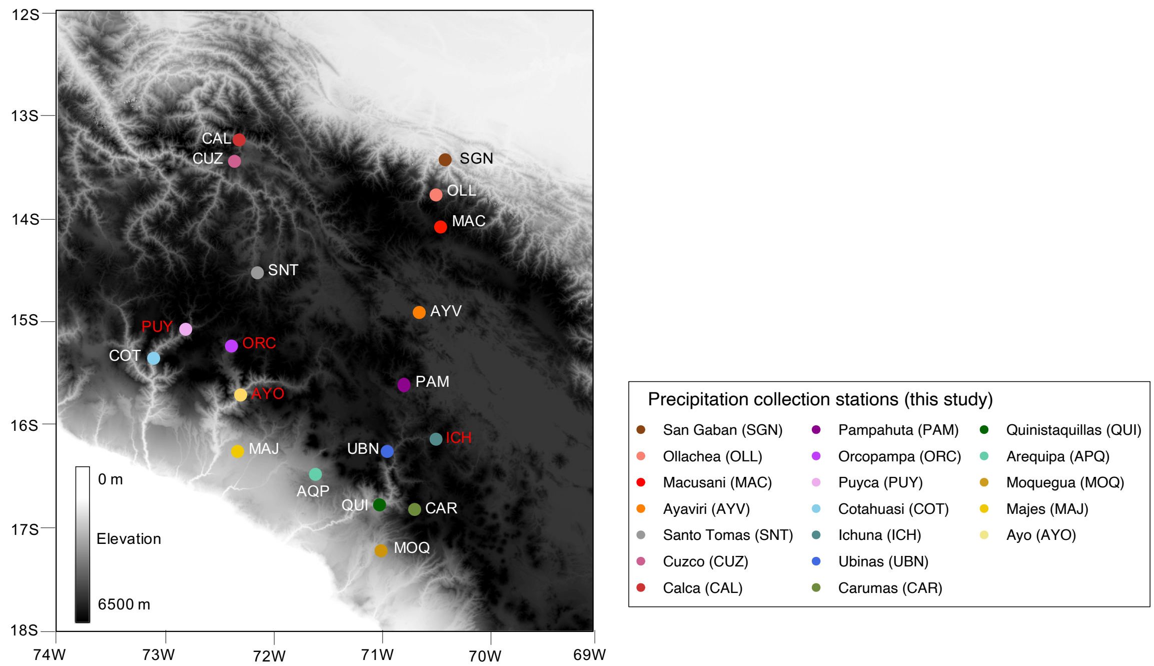
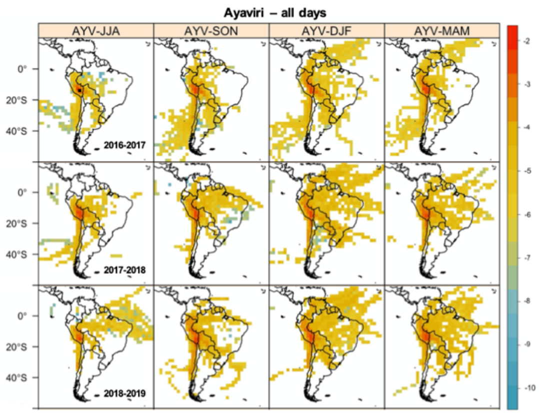
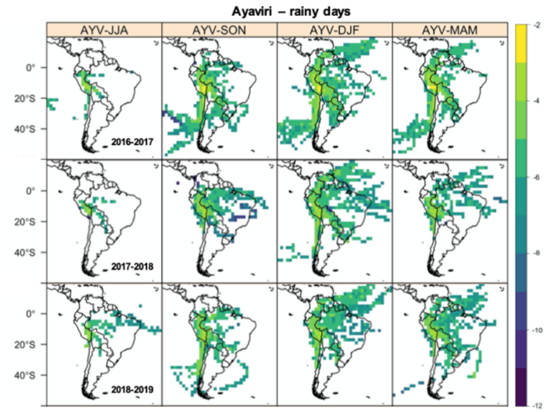
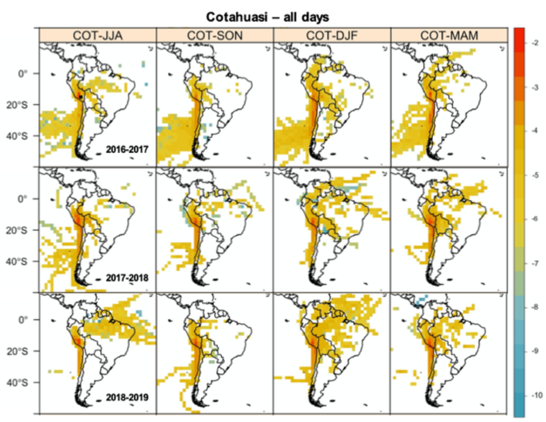
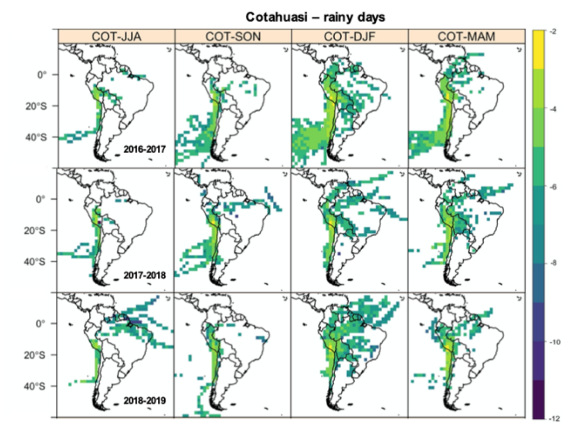


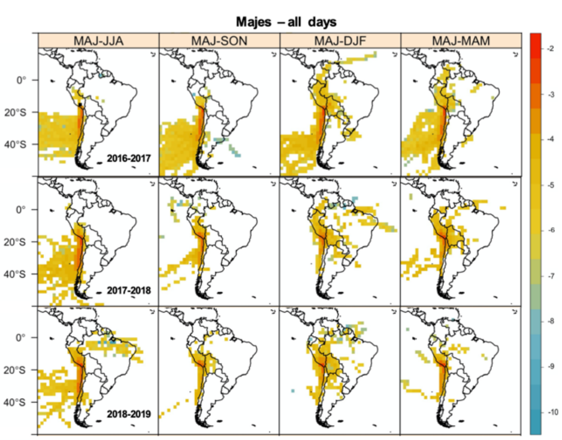
Figure S1. Same as Figure 1 in the main text, but with the four stations (red text) from which we do not report any isotope data. Samples from Puyca, Orcopampa, and Ichuña are excluded because the samples were likely collected from a tap or a surface water source; no data are reported from Ayo because it did not rain enough at that site to collect any samples during the study period.

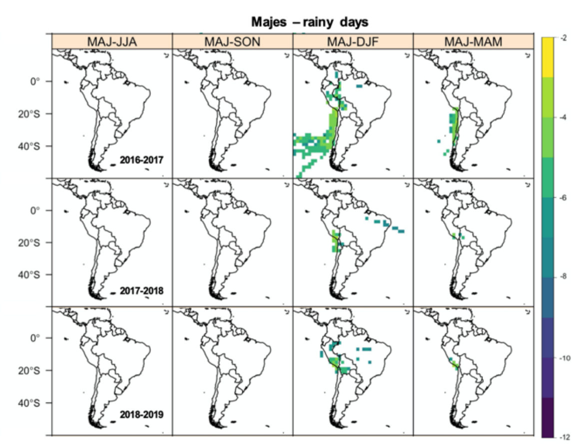

Ayaviri – all days
AYV-JJA
AYV-SON
AYV-DJF
AYV-MAM
2016-2017
2017-2018
2018-2019
0°
20°S
40°S

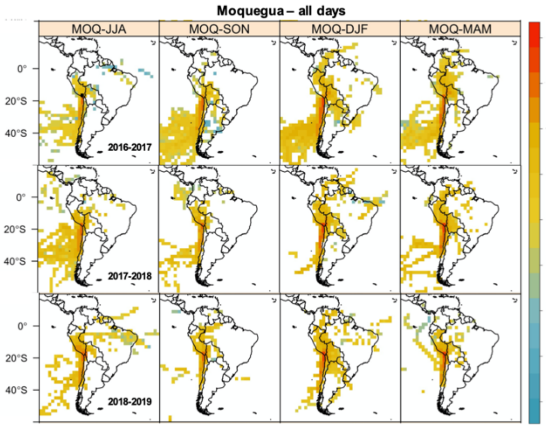

Ayaviri – rainy days
AYV-JJA
AYV-SON
AYV-DJF
AYV-MAM
2016-2017
2017-2018
2018-2019
0°
20°S
40°S

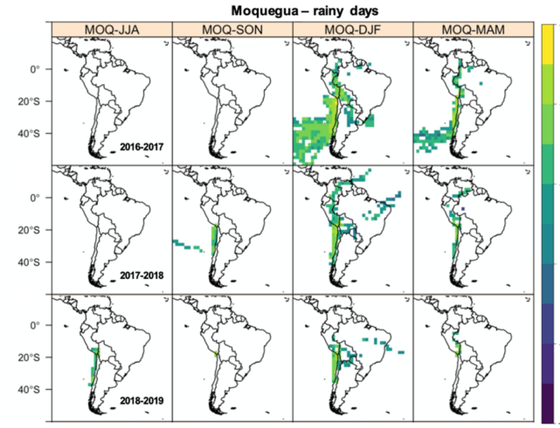

Cotahuasi – all days
COT-JJA
COT-SON
COT-DJF
COT-MAM
2016-2017
2017-2018
2018-2019
0°
20°S
40°S

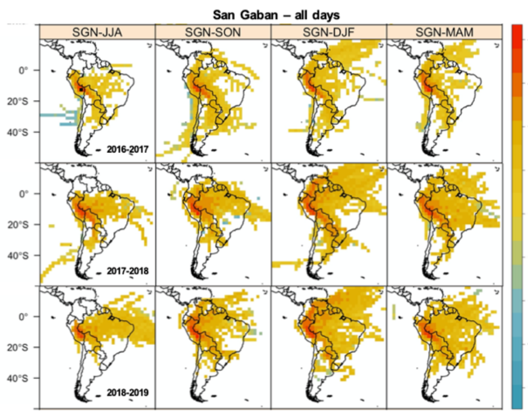

Cotahuasi – rainy days
COT-JJA
COT-SON
COT-DJF
COT-MAM
2016-2017
2017-2018
2018-2019
0°
20°S
40°S

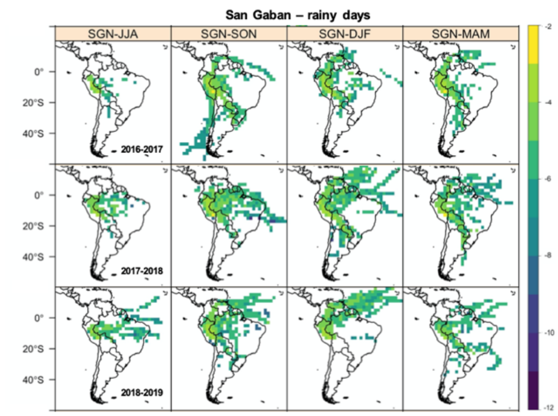

Majes – all days
MAJ-JJA
MAJ-SON
MAJ-DJF
MAJ-MAM
2016-2017
2017-2018
2018-2019
0°
20°S
40°S

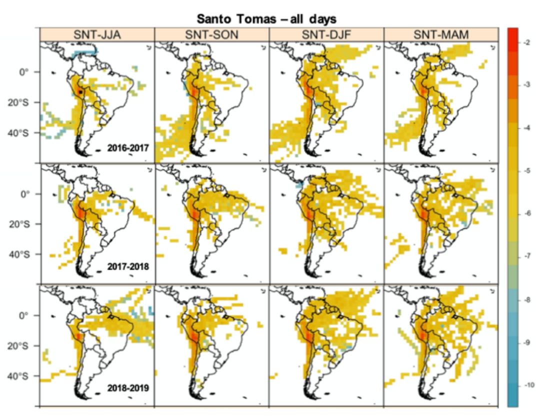

Majes – rainy days
MAJ-JJA
MAJ-SON
MAJ-DJF
MAJ-MAM
2016-2017
2017-2018
2018-2019
0°
20°S
40°S

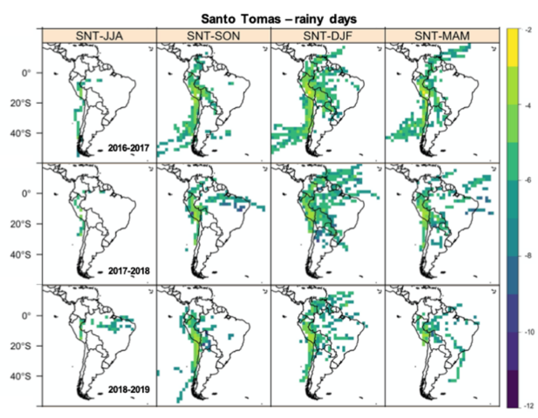

Moquegua – all days
MOQ-JJA
MOQ-SON
MOQ-DJF
MOQ-MAM
0°
20°S
40°S
2016-2017
2017-2018
2018-2019
-2
-3
-4
-5
-6
-7
-8
-9
-10


Moquegua – rainy days
MOQ-JJA
MOQ-SON
MOQ-DJF
MOQ-MAM
0°
20°S
40°S
2016-2017
2017-2018
2018-2019
-2
-4
-6
-8
-10
-12


San Gaban – all days
SGN-JJA
SGN-SON
SGN-DJF
SGN-MAM
0°
20°S
40°S
2016-2017
2017-2018
2018-2019
-2
-3
-4
-5
-6
-7
-8
-9
-10


San Gaban – rainy days
SGN-JJA
SGN-SON
SGN-DJF
SGN-MAM
0°
20°S
40°S
2016-2017
2017-2018
2018-2019
-2
-4
-6
-8
-10
-12


Santo Tomas – all days
SNT-JJA
SNT-SON
SNT-DJF
SNT-MAM
0°
20°S
40°S
2016-2017
2017-2018
2018-2019
-2
-3
-4
-5
-6
-7
-8
-9
-10


Santo Tomas – rainy days
SNT-JJA
SNT-SON
SNT-DJF
SNT-MAM
0°
20°S
40°S
2016-2017
2017-2018
2018-2019
-2
-4
-6
-8
-10
-12

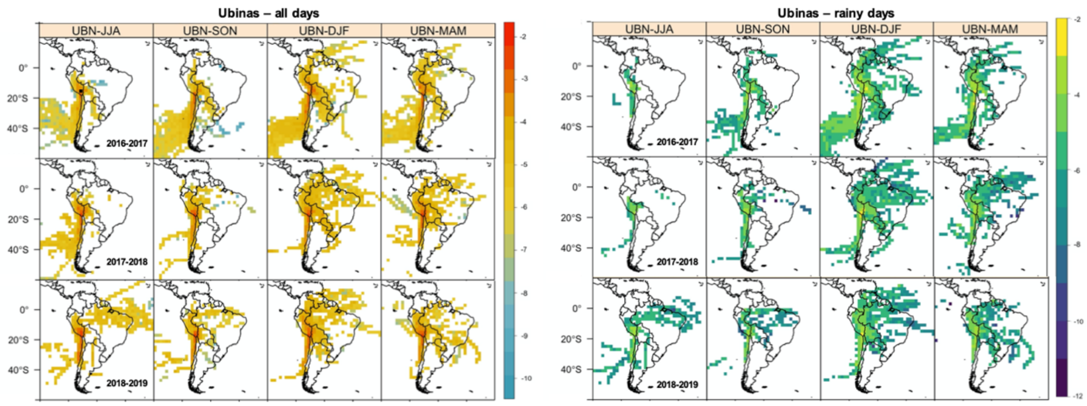


Figure S2. Quarterly seasonal moisture footprints from Ayaviri, Cotahuasi, Majes, Moquegua, San Gaban, Santo Tomas, and Ubinas. Site locations are noted with a 1 pixel black box in the top left panel in each set of site-specific figures. Color corresponds to the humidity contribution (g/kg/m^2) from each grid cell. For each site, the moisture footprint on the left was determined from all the trajectories initiated during the study period; the moisture footprint on the right was determined from the trajectories initiated only on days when rain fell as each site. In all figures, rows differentiate hydrologic years and columns separate seasons (JJA = June, July, August; SON = September, October, November; DJF = December, January, February; MAM = March, April, May). Hydrologic years are defined to keep the rainy season (DJF) intact. For example, the 2016-2017 trajectories show JJA16, SON16, D16JF17, and MAM17. Composite seasonal moisture flux ratios (Figure 8 in the main text) are derived from these moisture footprints.

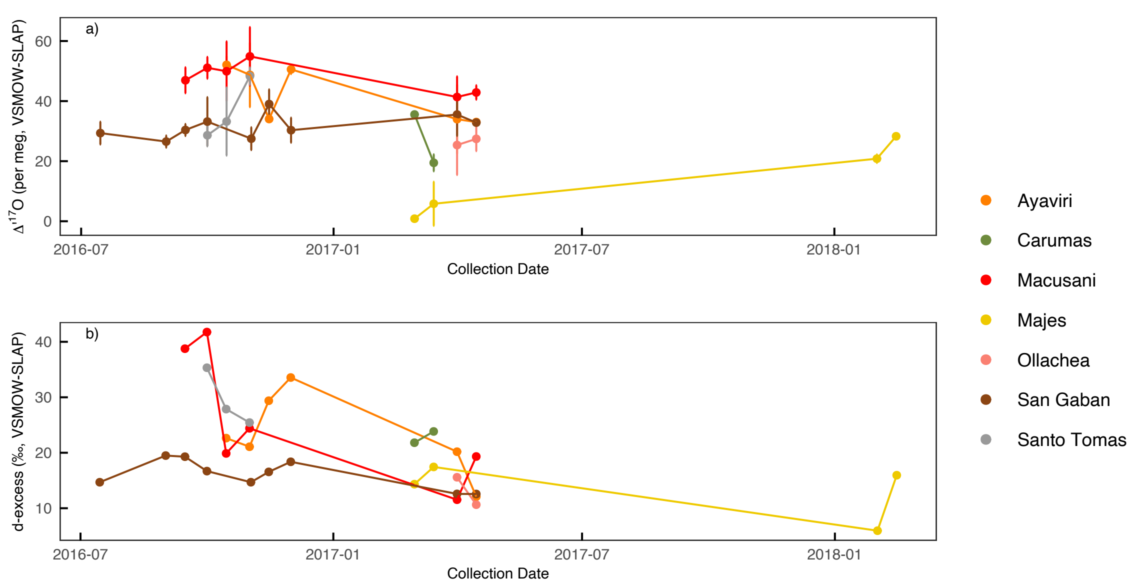


Figure S3. Timeseries of a) $\Delta'^{17}O_p$ and b) d-excess$_p$ from the 32 samples that were analyzed for triple oxygen isotopes. Color corresponds to the seven sites from which $\Delta'^{17}O_p$ data are reported.

Site	Elevation (m)	Latitude	Longitude	Start date	End date	n $\delta^{18}O$ and $\delta^{2}H$ analyses included (excluded)	n $\delta^{18}O$ and $\delta^{17}O$ analyses
San Gaban	657	-13.4518	-70.4091	6/15/16	5/15/19	71 (0)	9
Ollachea	2850	-13.7943	-70.4699	6/15/16	5/15/19	15 (28)	2
Macusani	4345	-14.0700	-70.4391	6/15/16	5/15/18	32 (0)	6
Ayaviri	3906	-14.8717	-70.5933	6/15/16	5/15/19	52 (0)	6
Cuzco	3263	-13.5400	-71.8964	11/15/17	5/15/18	5 (0)	0
Calca	2929	-13.3240	-71.9563	7/15/18	5/15/19	3 (0)	0
Santo Tomas	3658	-14.4503	-72.0959	6/15/16	5/15/19	38 (0)	3
Pampahuta	4400	-15.4853	-70.6758	11/15/17	5/15/19	27 (1)	0
Ubinas	3380	-16.3721	-70.8539	11/15/17	5/15/19	10 (1)	0
Carumas	2976	-16.8112	-70.69.51	6/15/16	5/15/19	9 (15)	2
Moquegua	1450	-17.1692	-70.9317	11/15/17	5/15/19	10 (1)	0
Quinistaquillas	1590	-16.7492	-70.8788	11/15/17	5/15/19	2 (1)	0
Arequipa	2200	-16.4582	-71.5758	11/15/17	5/15/19	10 (1)	0
Majes	1498	-16.3431	-72.1525	6/15/16	5/15/19	6 (1)	4
Cotahuasi	2683	-15.2113	-72.9833	11/15/17	5/15/19	19 (6)	0
Puyca	3661	-15.0605	-72.6923	11/15/17	5/15/19	0 (22)	0
Orcopampa	3779	-15.2659	-72.3478	6/15/16	5/15/19	9 (24)	0
Ichuña	3792	-16.1408	-70.5373	6/15/16	5/15/19	0 (41)	0
Ayo	1956	-15.6792	-72.2703	6/15/16	5/15/19	0 (0)	0

Table S1. Information about the station location (elevation, latitude, and longitude), timing of bimonthly precipitation sample collection, and the number of samples collected from each site. Samples are excluded from Pampahuta, Ubinas, Moquegua, Quinistaquillas, Arequipa, Majes (n = 1 at each site), and Cotahuasi (n = 6) due to negative d-excess$_p$ values. Samples are excluded from Ollachea (n = 28, all samples collected after the 2017 water year), Carumas (n = 15, all samples collected after the 2017 water year), Orcopampa (n = 24, all collected samples), Ichuña (n = 41, all collected samples), and Puyca (n = 22, all collected samples) because we suspect these samples were collected from tap or surface water sources.

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Table S2. Raw triple oxygen isotope data of samples, international standards, and USGS reference waters

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Table S3. Bimonthly meteorologic data (temperature, relative humidity, and precipitation) and precipitation isotopes ($\delta^{18}O$ and $\delta^{2}H$) from 19 stations in southern Peru. $\delta^{18}O_p$ and $\delta^{2}H_p$ in yellow are likely tap or surface water. $\delta^{18}O_p$ and $\delta^{2}H_p$ in blue have negative d-excess$_p$ values. Meteorologic data are missing when no sample was recorded by SENAMHI observers or the meteorologic sensors were broken. Isotopic data are missing when rain did not fall during a collection period or the observer did not collect a sample.

Regression model parameters	AIC score
This study	
elevation + latitude + longitude + MAP	19.09
elevation + latitude + longitude	17.18
elevation + latitude	*15.47*
elevation	37.57
latitude	44.96
Fiorella et al., 2015	
elevation + latitude + MAP + longitude	8.68
elevation + latitude + MAP	7.36
elevation + latitude	6.85
elevation	*6.29*
latitude	20.96
Gonfiantini et al., 2001	
elevation + latitude + MAP + longitude	10.61
elevation + latitude + MAP	8.61
elevation + MAP	*6.66*
elevation	8.33
latitude	14.79

Table S4. Stepwise multiple linear regression model parameters and AIC scores. The model with the lowest AIC score from this study, Fiorella et al., (2015), and Gonfiantini et al., (2001) are in italics

	OLL	MAC	AYV	CUZ	SNT	PAM	COT	UBN	CAR	MOQ	AQP	QUI	MAJ
SGN	0.02	**0.65**	**0.67**	-0.04	**0.60**	0.29	0.23	0.09	0.18	0.48	0.44	-0.22	0.15
OLL		0.36	-0.07	NA	0.20	NA	NA	NA	-0.30	NA	NA	NA	-0.22
MAC			**0.68**	0.44	**0.63**	-0.08	0.09	NA	0.30	0.91	0.32	NA	-0.47
AYV				0.88	**0.62**	**0.61**	**0.49**	0.26	0.40	0.18	**0.60**	0.71	-0.43
CUZ					NA	0.36	0.35	NA	NA	NA	NA	NA	NA
SNT						0.24	0.37	0.17	0.80	-0.70	0.40	NA	0.10
PAM							**0.54**	0.51	NA	-0.23	0.25	0.19	-0.95
COT								0.27	NA	-0.29	**0.91**	0.96	0.73
UBN									NA	-0.25	0.73	NA	NA
CAR										NA	NA	NA	-0.80
MOQ											-0.07	NA	NA
AQP												0.97	NA
QUI													NA

Table S5. Correlation coefficient matrix between bimonthly $\delta^{18}O_p$ timeseries. Missing (NA) correlations occur when samples were not collected concurrently. Bolded values indicate a statistically significant ($p < 0.05$) relationship.

References

Fiorella, R.P., Poulsen, C.J., Zolá, R.S.P., Barnes, J.B., Tabor, C.R., & Ehlers, T.A. (2015). Spatiotemporal variability of modern precipitation $\delta^{18}O$ in the central Andes and implications for paleoclimate and paleoaltimetry estimates. *Journal of Geophysical Research: Atmospheres*. *120*, 1-27. https://doi.org/10.1002/2014JD022893

Gonfiantini, R., Roche, M.A., Olivry, J.C., Fontes, J.C., & Zuppi, G.M. (2001). The altitude effect on the isotopic composition of tropical rains. *Chemical Geology*. *181*, 147-167. https://doi.org/10.1016/S0009-2541(01)00279-0