

Supplementary Material

Climate Analysis

Precipitation data in the Mantaro basin are obtained from *in situ* stations at Huayao and Marcapomacochas. The Huayao station contains a continuous record of all climate variables considered. The Marcapomacocha station, however, lacks this information for the isotopic monitoring period, being available only for the period 2016 - 2020. Therefore, the information from the ERA5-Land monthly averaged dataset (DOI: 10.24381/cds.68d2bb30) at 0.1° spatial resolution was used to determine the mean air temperature for the considered period (2006 - 2012). In addition, relative humidity was obtained from ERA5 hourly data on pressure level (DOI: 10.24381/cds.bd0915c6) at 0.25° spatial resolution for the same study period as temperature.

To evaluate how adequate the use of monthly averaged ERA5 reanalysis (Hersbach et al., 2020) for representing local climate conditions is, Pearson's correlation between *in situ* and reanalysis data was applied to the common period (2016 - 2020). Results are presented in Figure S1, where 44 pairs of data are evaluated for the variable temperature, with a highly significant correlation ($r = 0.95$, p -value < 0.01). For relative humidity, the evaluated 46 pairs of data also show a strong correlation ($r = 0.64$, p -value < 0.01). Based on these results we consider ERA-5 data sufficiently reliable and its use for the analysis developed in the main manuscript appropriate.

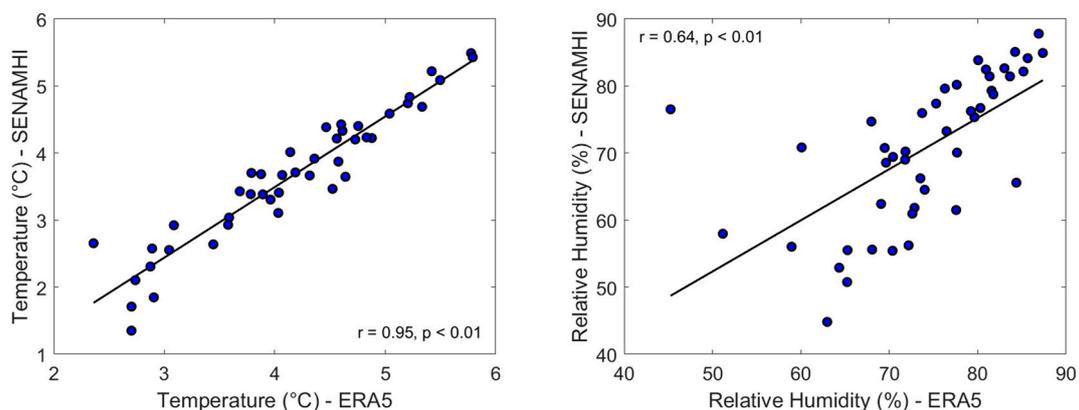


Figure S1. Pearson correlations between *in situ* data at Marcapomacocha Station and ERA5 reanalysis information during the 2016 - 2020 period. Panel A represents the linear regression for temperature and Panel B for relative humidity.

To highlight the importance of the two case studies analysed in the main manuscript (years 2010 and 2017), we demonstrate the contrasting atmospheric circulation, supporting our discussion related to the differing isotopic signature.

Atmospheric circulation anomalies at 500 hPa were calculated to highlight the circulation differences. Figure S2 clearly documents the contrasting conditions over South America and the Andean region during the two astral summer seasons.

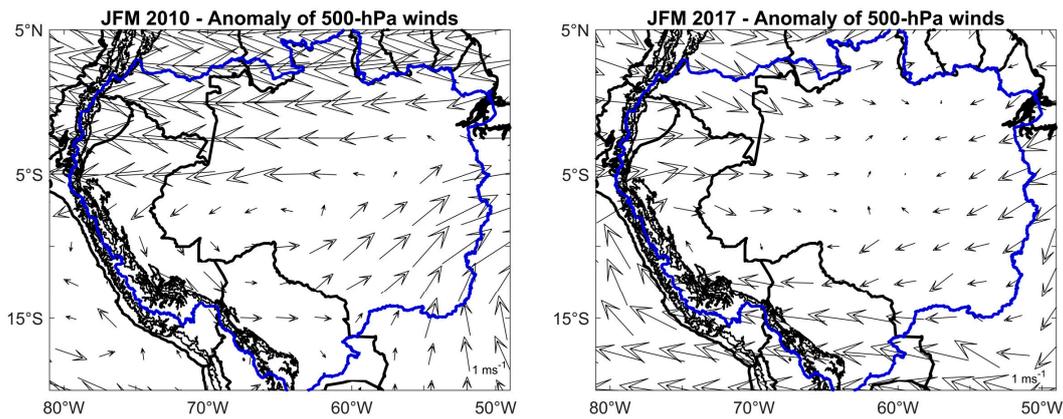


Figure S2: Wind anomalies at 500 hPa for South America featuring the two case studies: 2010 (Left panel) and 2017 (Right panel).

Statistical Methods

To evaluate the isotopic variability at monthly timescales ($\delta^{18}\text{O}$, $\delta^2\text{H}$ and Dxs) boxplot analyses were developed for data from both Huayao and Marcapomacochas stations (Fig. S3). The boxplot figures reveal considerably enhanced variability year-to-year isotopic variability during the months of November and February. Maximum values for both stations were recorded in July and August and minimum values during March. The results are quite different regarding the Dxs variable where minimum values are observed during July and August and maximum values are recorded during July.

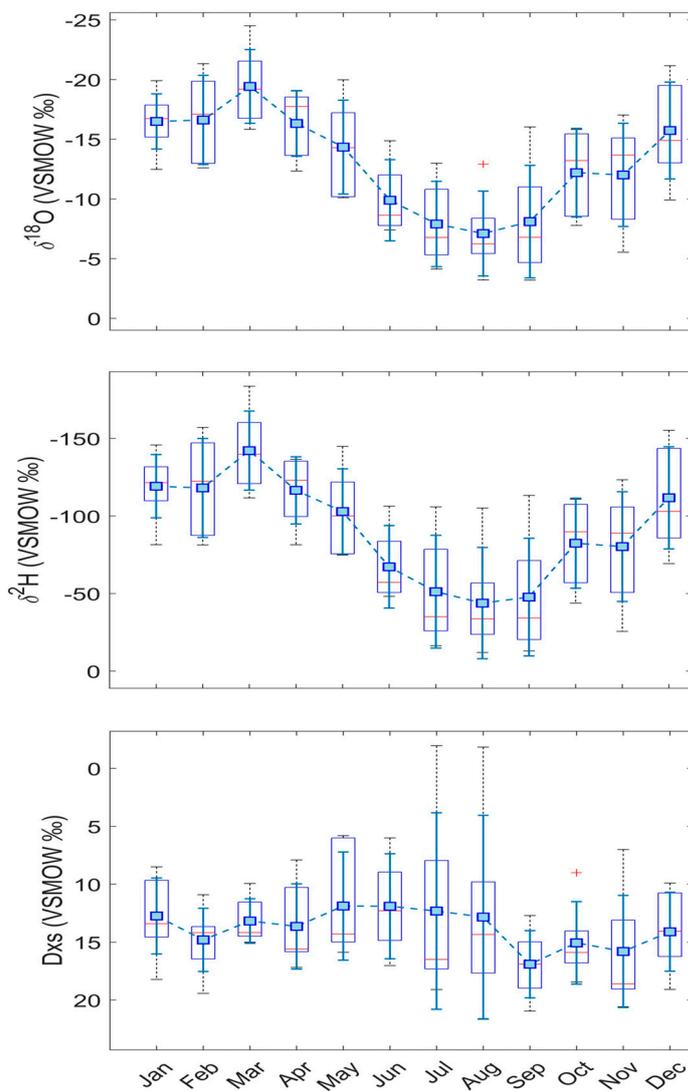


Figure S3: Temporal variability of monthly oxygen and hydrogen isotopes of precipitation ($\delta^{18}\text{O}$, $\delta^2\text{H}$ and Dxs) for both stations (Marcapomacha and Huayao) for the study period January 2006 – April 2018.

Table S1: Monthly average of the isotopic signals ($\delta^{18}\text{O}$, $\delta^2\text{H}$ and Dxs) with their respective standard deviations.

	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Dxs
JANUARY	-16.49 ± 2.31	-119.19 ± 20.4	12.74 ± 3.28
FEBRUARY	-16.61 ± 3.73	-118.07 ± 31.91	14.8 ± 2.73
MARCH	-19.42 ± 3.09	-142.15 ± 25.48	13.17 ± 1.92
APRIL	-16.32 ± 2.75	-116.52 ± 21.64	13.64 ± 11.88
MAY	-14.34 ± 3.93	-102.87 ± 27.55	11.88 ± 4.67
JUNE	-9.89 ± 3.40	-67.22 ± 26.59	11.9 ± 4.53
JULY	-7.9 ± 3.57	-51.17 ± 36.34	12.31 ± 8.48
AUGUST	-7.1 ± 3.55	-43.82 ± 35.86	12.83 ± 8.78
SEPTEMBER	-8.1 ± 4.71	-47.73 ± 37.92	16.9 ± 2.9
OCTOBER	-12.2 ± 3.71	-82.45 ± 29.02	15.06 ± 3.56
NOVEMBER	-12.01 ± 4.32	-80.26 ± 35.37	15.8 ± 4.84
DECEMBER	-15.73 ± 4.06	-111.73 ± 32.93	14.1 ± 3.41

Since there is clear evidence that precipitation at the local station is representative of precipitation distributed over the watershed, the mean precipitation integrated over the Mantaro basin was calculated using IMERG data for the period 2006 - 2018. The linear relationship between isotopes and rainfall over the Mantaro basin is consistent with those obtained at a single local station ($r = -0.63$, $p\text{-value} < 0.01$). This result indicates that it is possible to use such isotopic information to infer hydrological processes at the basin scale.

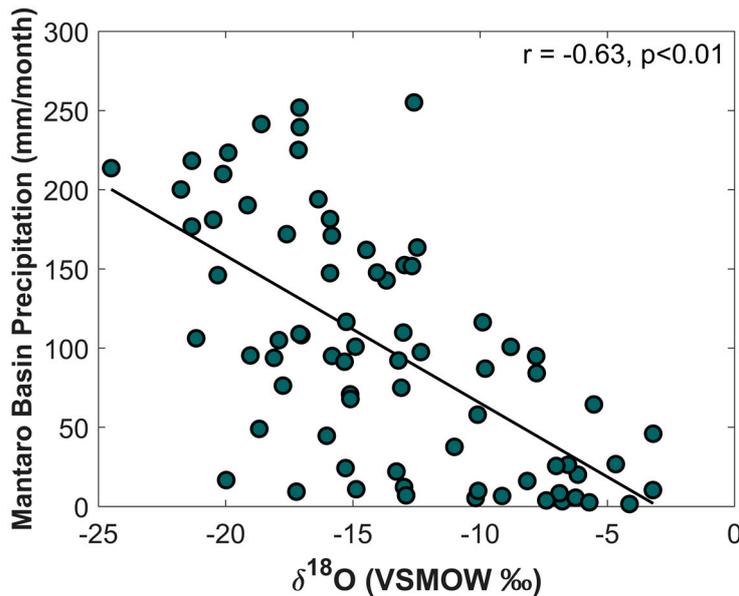


Figure S4: Correlation between monthly precipitation averaged over the Mantaro Basin and isotopic data collected at Huayao and Marcapomacochas stations.

Pearson correlations between the oxygen isotopic composition of precipitation at Huayao and Marcapomacochas stations with local environmental variables (precipitation, temperature and relative humidity) are presented in Figure S5. It is evident that similar a similar behavior and coefficients were obtained at different locations.

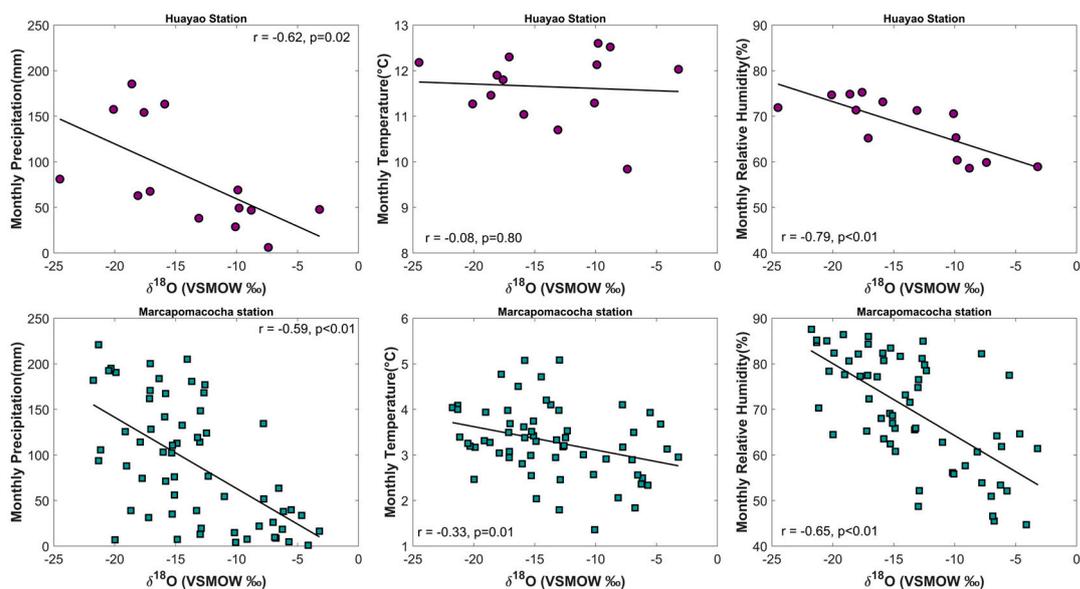


Figure S5: Linear Pearson's correlation between monthly local environmental parameters (precipitation, temperature and relative humidity) and the oxygen isotopic composition of rainfall ($\delta^{18}\text{O}$) for Huayao (top panel) and Marcapomacocha (bottom panel) stations.

Clusters analyzed in the main manuscript were determined based on changes in the Total Spatial Variance (TSV), which is an indicator, expressed in percent, of the variance explained by trajectories grouped in clusters. For Huayao station (Fig. S6A), the second significant increase in the TSV explained is for five clusters. For Marcapomacocha station (Fig S6B), the significant jump in TSV occurs with four clusters. However, the cluster means showed that clusters 3 and 5 (Fig S6C) merged into one group (FigS6D) despite having different directions. Therefore, we chose five sets of clusters for both stations, which is also helpful for the comparative analysis.

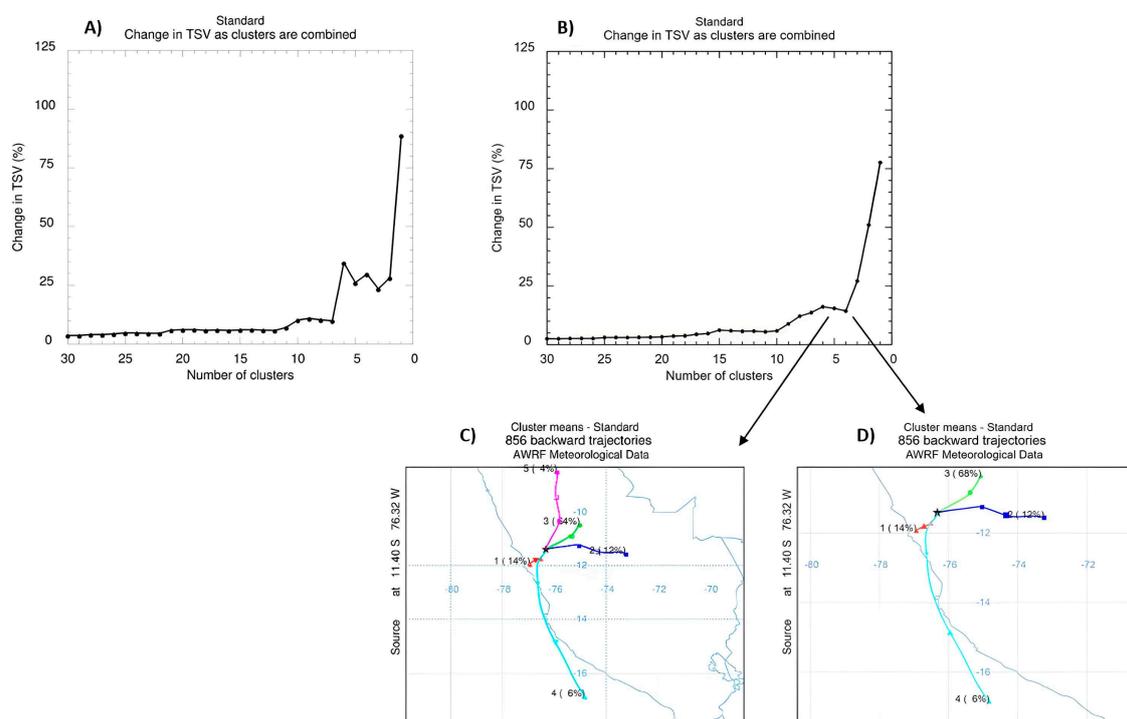


Figure S6. (A) and (B) represent the Total Spatial Variance (TSV) for Huayao and Marcapomacocha stations, respectively. (C) The cluster means considering five groups and (D) for four groups.

Data Availability

Stable isotopes ($\delta^{18}\text{O}$, δD) in precipitation at the Huayao station were analyzed at the Centro de Pesquisas de Águas Subterrâneas at the University of São Paulo (USP) using an isotopic water analyzer - Picarro L2130i. Data were processed by LIMS for Lasers software. Values are reported with an analytical precision of 0.09‰ for $\delta^{18}\text{O}$ and 0.9‰ for δD relative to Vienna Standard Mean Ocean Water (VSMOW).

Table S2: Monthly rainfall amount-weighted isotopic composition at the Huayao station.

Date	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Dxs
1/12/2016	-17.1	-126.9	9.9
1/1/2017	-18.6	-139.77	9.03
1/2/2017	-20.1	-149.9	10.9
1/3/2017	-24.5	-183.7	12.3
1/4/2017	-18.1	-135.9	8.9
1/5/2017	-10.1	-74.8	6
1/6/2017	-7.4	-53.2	6
1/9/2017	-3.2	-12.9	12.7
1/10/2017	-8.8	-61.4	9
1/11/2017	-9.8	-71.4	7
1/12/2017	-9.9	-69.3	9.9
1/1/2018	-15.9	-118.7	8.5
1/3/2018	-17.6	-130.02	10.78
1/4/2018	-13.1	-96.9	7.9

Table S3: Monthly rainfall amount-weighted isotopic composition at the Marcapomacocha station and available at <https://nucleus.iaea.org/wiser>

Date	O	H	Dxs
1/1/2006	-17.14	-123.73	13.39
1/2/2006	-21.33	-157.13	13.51
1/3/2006	-21.76	-159.81	14.27
1/4/2006	-12.33	-81.46	17.18
1/5/2006	-10.18	-75.64	5.8
1/6/2006	-8.15	-48.18	17.02
1/7/2006	-6.77	-35.07	19.09
1/8/2006	-6.16	-27.62	21.66
1/9/2006	-11.01	-71.28	16.8
1/10/2006	-15.82	-110.85	15.71
1/11/2006	-17.03	-123.34	12.9
1/1/2007	-14.47	-100.99	14.77
1/2/2007	-13.02	-90.08	14.08
1/3/2007	-21.33	-160.71	9.93
1/4/2007	-19.03	-136.6	15.64
1/5/2007	-13.29	-92.13	14.19
1/7/2007	-10.08	-69.4	11.24
1/8/2007	-6.25	-33.66	16.34
1/9/2007	-6.55	-31.45	20.95
1/10/2007	-15.33	-106.39	16.25
1/11/2007	-15.11	-107.19	13.69
1/12/2007	-21.16	-155.23	14.05
1/1/2008	-19.9	-145.78	13.42

1/2/2008	-19.14	-138.94	14.18
1/3/2008	-17.91	-128.58	14.7
1/4/2008	-18.68	-133.85	15.59
1/5/2008	-19.98	-144.86	14.98
1/6/2008	-14.87	-106.29	12.67
1/7/2008	-5.71	-29.19	16.49
1/8/2008	-3.21	-12.01	13.67
1/9/2008	-7.01	-37.11	18.97
1/10/2008	-13.21	-89.79	15.89
1/11/2008	-5.53	-25.61	18.63
1/12/2008	-14.9	-102.97	16.23
1/11/2009	-13.68	-88.87	20.57
1/12/2009	-14.05	-96.17	16.23
1/1/2010	-16.36	-120.6	10.28
1/2/2010	-12.97	-86.63	17.13
1/3/2010	-15.83	-111.64	15
1/4/2010	-17.75	-123.02	18.98
1/5/2010	-17.22	-121.88	15.88
1/6/2010	-9.14	-61.22	11.9
1/7/2010	-4.13	-16.33	16.71
1/8/2010	-6.88	-40.7	14.34
1/9/2010	-4.67	-20.38	16.98
1/11/2010	-15.1	-101.62	19.18
1/12/2010	-20.31	-149.18	13.3
1/1/2011	-17.09	-122.39	14.33
1/2/2011	-17.1	-122.4	14.4
1/3/2011	-20.49	-149.64	14.28
1/4/2011	-15.26	-107.92	14.16
1/5/2011	-15.29	-107.92	14.4
1/7/2011	-12.99	-105.88	-1.96
1/8/2011	-12.91	-105.12	-1.84
1/9/2011	-16.03	-113.27	14.97
1/10/2011	-7.78	-43.81	18.43
1/11/2011	-7.8	-43.8	18.6
1/12/2011	-12.68	-82.36	19.08
1/1/2012	-12.47	-81.54	18.22
1/2/2012	-12.6	-81.38	19.42
1/3/2012	-15.9	-113.13	14.07