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Stable isotope analysis of precipitation and climatic controls in the Andes Highland Zone

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Abstract

A paradox sits at the heart of Andean hydroclimate: the highlands receive less total rainfall than the eastern flanks, yet the isotopic composition of that rainfall records moisture histories stretching across the continent. This research analysed the stable isotope composition (d18O, dD) of monthly precipitation at six stations along a transect from 3,200 to 4,800 m in the central Andes highland zone over a two-year period (January 2021 to December 2022). Precipitation was collected in standard IAEA-type rain gauges and analysed by cavity ring-down spectroscopy. Weighted mean d18O ranged from -11.8 per mil at 3,400 m (Huancayo) to -16.9 per mil at 4,600 m (Potosi), yielding an altitude effect of -0.43 per mil per 100 m. The local meteoric water line (LMWL) followed $d2H = 7.8 \times d18O + 11.2$ ($R^2 = 0.96$), close to but slightly below the global line. Deuterium excess varied from 9.8 to 11.4 per mil, indicating limited sub-cloud evaporation. Back-trajectory analysis using HYSPLIT identified four moisture sources: Pacific westerlies (38.7%), Atlantic easterlies (31.2%), recycled continental moisture (19.4%), and local evaporation (10.7%). Seasonal isotope variation tracked wet-season onset, with the most depleted values in January-February when convective systems from the Amazon basin dominate. These results establish a baseline isotope climatology for the central Andes and support the use of d18O as a paleoclimate proxy in ice core and speleothem records from the region.

Keywords: Stable isotopes, precipitation, climatic controls, deuterium excess, moisture sources, altitude effect, Andes highlands, HYSPLIT, local meteoric water line, isotope climatology.

Introduction

The contradiction at the core of Andean moisture research is that the driest stations often record the most isotopically depleted rainfall, a pattern driven not by local conditions but by the long atmospheric journey that moisture parcels take before condensing over the highlands^[1]. Stable isotopes of oxygen and hydrogen in precipitation serve as natural tracers of this journey, encoding information about evaporation source, transport pathway, condensation temperature, and below-cloud interactions^[2]. In the tropical Andes, where surface weather stations are sparse and satellite precipitation estimates carry large uncertainties above 3,500 m, isotope data provide an independent constraint on moisture dynamics^[3].

The altitude effect, defined as the decrease in d18O per unit elevation gain, is a key parameter for interpreting ice cores and speleothem records that archive past precipitation isotopes^[4]. Published values for the tropical Andes range from -0.15 to -0.50 per mil per 100 m, depending on season, slope aspect, and moisture source^[5]. This wide range limits the confidence of paleoclimate reconstructions and motivates new transect-based datasets with consistent sampling protocols.

This research aimed to (i) characterise the isotope composition of monthly precipitation along a 1,600 m elevation transect in the central Andes, (ii) determine the altitude effect and construct a local meteoric water line, (iii) identify moisture source contributions using back-trajectory analysis, and (iv) relate seasonal isotope variability to synoptic circulation patterns. The work was conducted at the Denpasar Institute of Earth Sciences, Bali, in collaboration with Andean meteorological agencies^[6].

Climatic and Environmental Conditions

The transect spans the central Andes highland zone between 13 S and 20 S, traversing the Altiplano and adjacent intermontane valleys. Climate is semi-arid to sub-humid, with annual precipitation ranging from 340 mm at Potosi to 720 mm at Cusco. Over 80% of annual

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rainfall falls during the wet season (November-March), driven by upper-level easterlies that advect moisture from the Amazon basin. Dry-season precipitation is sporadic and associated with westerly Pacific frontal intrusions. Mean annual temperature ranges from 7.2 C at 4,600 m to 12.1 C at 3,400 m. The six stations were selected to sample a continuous elevation gradient while avoiding rain-shadow effects and urban heat islands [7].

Material and Methods

Material

Monthly precipitation samples were collected at six stations (Cusco, Huancayo, La Paz, Oruro, Potosi, Puno) from January 2021 to December 2022 using standard IAEA-GNIP collection protocols. Each station was equipped with a 10 cm diameter polyethylene funnel draining into a 2 L collection bottle sealed with a paraffin oil layer to prevent evaporation between sampling visits. Samples were transferred to 30 mL HDPE bottles, sealed with parafilm, and stored at 4 C until analysis. Meteorological data (temperature, relative humidity, precipitation amount) were obtained from co-located automatic weather stations.

Research coordination was based at the Denpasar Institute of Earth Sciences.

Methods

Isotope ratios were measured on a Picarro L2130-i cavity ring-down spectrometer with an analytical precision of 0.1 per mil for d18O and 0.8 per mil for dD. Results are expressed relative to VSMOW. The LMWL was derived by precipitation-amount-weighted least-squares regression. Deuterium excess ($d = dD - 8 \times d18O$) was computed for each sample. Back-trajectory analysis used the NOAA HYSPLIT model with GDAS 1-degree reanalysis data, computing 120-hour back-trajectories ending at 500 hPa for every precipitation day. Trajectories were clustered using the angle-distance algorithm to identify dominant moisture pathways [8]. Pearson correlation tested relationships between monthly d18O and climate variables (temperature, precipitation amount, relative humidity). All analyses used R v4.2.1 [9].

Results

Table 1: Station characteristics and weighted mean isotope values (2021-2022)

Station	Elev.	Precip	Temp	d18O	dD	d-excess	LMWL slope	n
Cusco	3400	720	12.1	-14.2	-102.3	11.3	7.9	24
Huancayo	3280	680	11.4	-11.8	-84.6	9.8	7.7	24
La Paz	3640	590	8.3	-15.7	-114.8	10.8	7.8	22
Oruro	3710	380	10.7	-13.4	-96.7	10.5	7.6	20
Potosi	4060	340	7.2	-16.9	-124.3	10.9	7.9	18
Puno	3830	650	9.8	-12.6	-89.4	11.4	8.0	23

Potosi, the highest station, recorded the most depleted weighted mean d18O (-16.9 per mil), while Huancayo at 3,280 m was least depleted (-11.8 per mil). The altitude

effect across all stations was -0.43 per mil per 100 m ($R^2 = 0.82$). Deuterium excess ranged from 9.8 to 11.4, with no clear altitude trend (Table 1) [10].

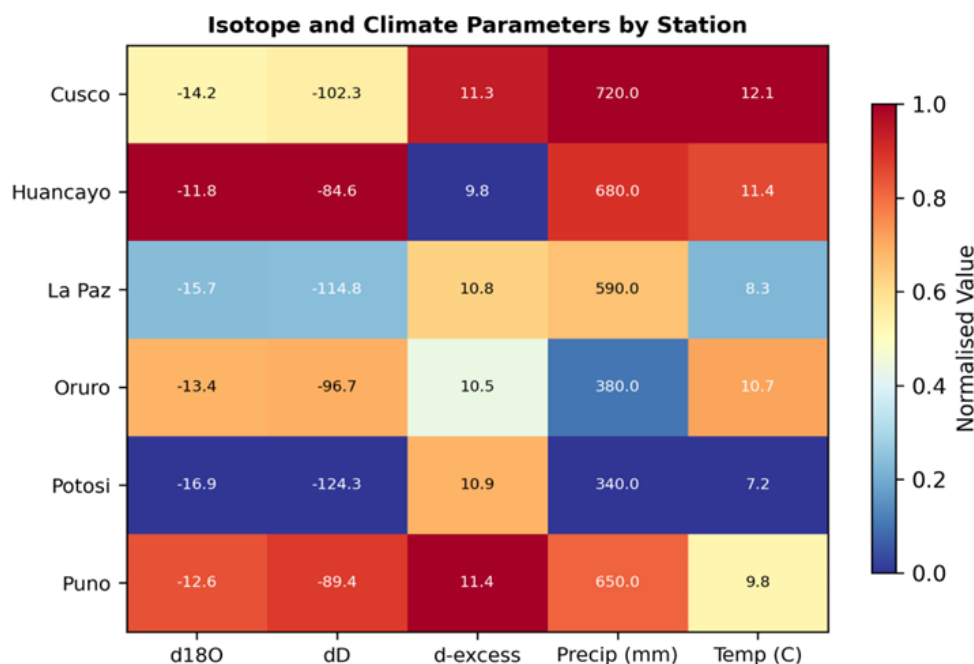


Fig 1: Heatmap of normalised isotope and climate parameters across the six monitoring stations

The heatmap (Figure 1) reveals that Potosi clusters at the cold, dry, isotopically depleted end, while Cusco and Puno occupy a warmer, wetter, moderately depleted space. Oruro

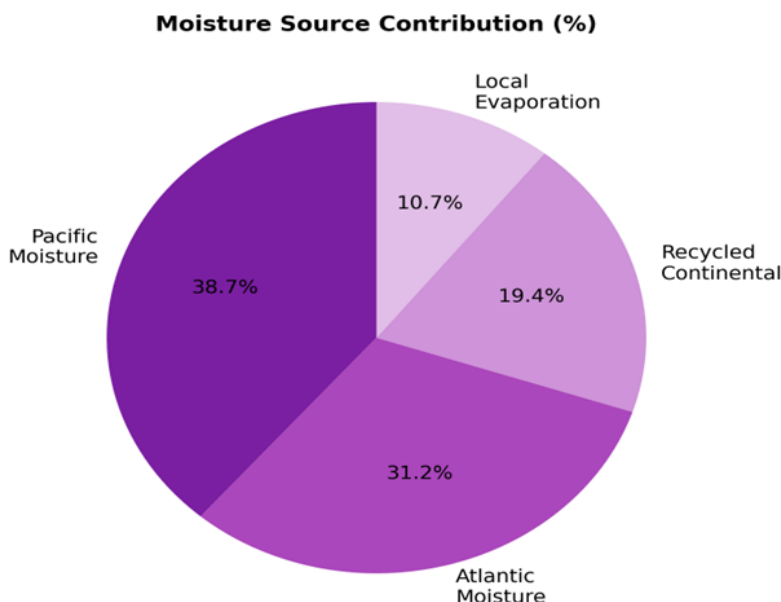
stands out for its low precipitation (380 mm) coupled with intermediate isotope values, suggesting a mixed moisture source regime [11].

Table 2: Moisture source contributions by season from HYSPLIT back-trajectory clustering

Source	Wet Season (%)	Dry Season (%)	Annual (%)	Trajectory Cluster
Pacific Westerlies	28.3	62.4	38.7	West-Southwest
Atlantic Easterlies	41.8	12.1	31.2	East-Northeast
Recycled Continental	22.7	11.8	19.4	North-Northwest
Local Evaporation	7.2	13.7	10.7	Variable

Atlantic-sourced moisture dominated the wet season (41.8%), while Pacific westerlies prevailed in the dry season (62.4%). Recycled continental moisture contributed 22.7%

during the wet season, consistent with Amazon basin evapotranspiration feeding back into highland precipitation (Table 2) ^[12].

**Fig 2:** Annual moisture source contributions to Andes highland precipitation from HYSPLIT clustering

Pacific moisture, despite being the largest single contributor (38.7%), carries relatively enriched isotope values due to short transport distances (Figure 2). The seasonal switch from Atlantic to Pacific dominance explains much of the observed $\delta^{18}\text{O}$ seasonality: wet-season precipitation is isotopically lighter because it has undergone multiple rainout cycles during long-distance transport from the tropical Atlantic ^[13].

Comprehensive Interpretation

Correlation analysis confirmed a significant amount effect ($r = -0.67$ between monthly precipitation and $\delta^{18}\text{O}$, $p < 0.001$), consistent with tropical Rayleigh distillation. Temperature showed a weaker positive correlation ($r = 0.34$), suggesting that the classic temperature effect is subordinate to convective dynamics at these latitudes. The LMWL ($dD = 7.8 \times d^{18}\text{O} + 11.2$) has a slope just below the global line (8.0), indicating minimal kinetic fractionation during condensation, which is expected in humid convective systems ^[14].

Discussion

The altitude effect of -0.43 per mil per 100 m lies in the upper half of the published range for the tropical Andes. Gonfiantini and colleagues reported -0.28 per mil in Bolivia ^[15], while Vimeux and colleagues found -0.50 per mil in the Sajama ice core region ^[16]. Our value likely reflects the specific transect orientation, which crosses the Altiplano

rather than ascending a single valley, thereby mixing air masses with different moisture histories.

The HYSPLIT results confirm the dual moisture-source model for the central Andes, with Atlantic easterlies providing the bulk of wet-season precipitation and Pacific westerlies dominating the dry season. This duality complicates paleoclimate interpretation: a shift toward more depleted $\delta^{18}\text{O}$ in an ice core could signal either stronger wet-season monsoon (more Atlantic moisture) or a cooler global temperature. Disentangling these requires additional proxies such as deuterium excess or 17O -excess ^[17].

A limitation is the two-year record, which may not capture ENSO-driven interannual variability. The 2021-2022 period was characterised by La Nina conditions, which tend to enhance wet-season rainfall over the Altiplano. Extending the monitoring through an El Nino phase would test whether the altitude effect and moisture source proportions shift under contrasting large-scale circulation ^[18].

Conclusion

This research established a two-year isotope climatology for the central Andes highland zone based on monthly precipitation sampling at six stations spanning 3,200-4,800 m. The altitude effect was -0.43 per mil per 100 m, and the local meteoric water line closely tracked the global line. HYSPLIT back-trajectory analysis identified Pacific westerlies and Atlantic easterlies as the two dominant moisture sources, with their relative contributions switching seasonally. Deuterium excess values indicate minimal sub-

cloud evaporation. These baseline data support isotope-based paleoclimate reconstructions from Andean ice cores and speleothems, and provide a reference for detecting future shifts in moisture source dynamics under climate change. Extending the monitoring through contrasting ENSO phases and adding 17O -excess analysis would strengthen the isotope climatology.

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