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Moisture transport and seasonal variations in the stable isotopic composition of rainfall in Central American and Andean Páramo during El Niño conditions (2015–2016)

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Abstract

High-elevation tropical grassland systems, called Páramo, provide essential ecosystem services such as water storage and supply for surrounding and lowland areas. Páramo systems are threatened by climate and land use changes. Rainfall generation processes and moisture transport pathways influencing precipitation in the Páramo are poorly understood but needed to estimate the impact of these changes, particularly during El Niño conditions, which largely affect hydrometeorological conditions in tropical regions. To fill this knowledge gap, we present a stable isotope analysis of rainfall samples collected on a daily to weekly basis between January 2015 and May 2016 during the strongest El Niño event recorded in history (2014–2016) in two Páramo regions of Central America (Chirripó, Costa Rica) and the northern Andes (Cajas, south Ecuador). Isotopic compositions were used to identify how rainfall generation processes (convective and orographic) change seasonally at each study site. Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) air mass back trajectory analysis was used to identify preferential moisture transport pathways to each Páramo site. Our results show the strong influence of north-east trade winds to transport moisture from the Caribbean Sea to Chirripó and the South American low-level jet to transport moisture from the Amazon forest to Cajas. These moisture contributions were also related to the formation of convective rainfall associated with the passage of the Intertropical Convergence Zone over Costa Rica and Ecuador during the wetter seasons and to orographic precipitation during the transition and drier seasons. Our findings provide essential baseline information for further research applications of water stable isotopes as tracers of rainfall generation processes and transport in the Páramo and other montane ecosystems in the tropics.

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KEYWORDS

El Niño–Southern Oscillation (ENSO), HYSPLIT, moisture recycling, precipitation, tropical Páramo, water stable isotopes

1 | INTRODUCTION

The Páramo is a high-elevation tropical grassland ecosystem situated above the tree line (~3,000 m asl) and below the perennial snow line (~4,500 m asl). It extends between 11°N and 8°S, covering roughly 35,000 km^2 along Central and South America (Buytaert et al., 2006). Although the Páramo is limited in its spatial extent, covering about 2% of the land area in tropical countries, it plays an important role in the regional water cycle. The Páramo is considered as the "water tower" (Beniston, 2000) of the tropical Andes (Madriñan, Cortés, & Richardson, 2013; Mosquera et al., 2016). The Páramo provides key ecosystem services such as water provisioning, energy production through hydropower, and climate regulation by carbon sequestration (Célleri & Feyen, 2009; Buytaert, Célleri, et al., 2006; Célleri et al., 2010; Crespo et al., 2011; Hofstede, Segarra, & Mena, 2003; Mosquera et al., 2016). These ecosystem services help to sustain the life and economic development of millions of people in surrounding and lowland regions. Because of the variety of ecosystem services provided by the Páramo, there is an increasing need to understand the hydrometeorological conditions influencing and maintaining its ecohydrological functioning. To date, however, crucial information such as the origin and factors controlling the inputs of atmospheric water to the Páramo remains limited. These knowledge gaps need to be urgently addressed to improve the assessment of the impacts of fast changes in climate that might affect the current water balance of this fragile ecosystem (Buytaert, Cuesta-Camacho, & Tobón, 2011; Mosquera, Célleri, et al., 2016; Ochoa-Tocachi et al., 2016).

Among the methodologies available to investigate rainfall generation processes, water stable isotopes (δ^2H and δ^{18}O) can provide valuable insights of hydrometeorological conditions in different ecosystems under varying environmental conditions. These isotope tracers have helped to understand local atmospheric conditions at different temporal scales (e.g., Araguás-Araguás, Froehlich, & Rozanski, 2000; Lachniet, Paterson, Burns, Asmerom, & Polyak, 2007; Mayr et al., 2007; Breitenbach et al., 2010; Windhorst, Timbe, Frede, & Breuer, 2013; Muller, Baker, Fairchild, Kidd, & Boomer, 2014; Sánchez-Murillo, Durán-Quesada, Birkel, Esquivel-Hernandez, & Boll, 2016; He, Goodkin, Jackish, Ong, & Samanta, 2018; He, Goodkin, Kurita, Wang, & Rubin, 2018). The global relationship between δ^2H and δ^{18}O in natural meteoric waters, the Global Meteoric Water Line (GMWL; Craig, 1961), is used as a reference to determine equilibrium and nonequilibrium fractionation processes affecting the isotopic composition of local precipitation. In addition, deuterium excess (hereafter referred as *d*-excess; Dansgaard, 1964) can provide insights about moisture recycling processes (e.g., reevaporation of water) affecting the isotope composition of precipitation (Frankenberg et al., 2013; Good, Noone, Kurita, Benetti, & Bowen, 2015; Jasechko et al., 2013; Pfahl & Sodemann, 2014). The *d*-excess has also helped to identify interannual rainfall variability due to changes in the oceanographic conditions across the Pacific Ocean such as El Niño/Southern Oscillation (ENSO; Conroy, Cobb, & Noone, 2013; Ichiyanagi & M.D., 2005; Sánchez-Murillo, Durán-Quesada, et al., 2016; Welker, 2012; Yoshimura, Kanamitsu, Noone, & Oki, 2008). In the Páramo of both Central America and the Andes, however, detailed isotopic characterizations of precipitation are scarce due to their remote locations.

Although stable water isotopes can identify hydrometeorological processes, they do not provide accurate information regarding the provenance of moisture from which rainfall condensates. Lagrangian transport models have proven useful to identify pathways of water vapour transport from water vapour sources to rainout locations. Models of this type, such as HYSPLIT, offer air mass back trajectory analysis, which has been particularly useful to diagnose net changes in the specific moisture along air parcel trajectories (Stein et al., 2015). HYSPLIT was successfully applied in studies aiming at identifying sources of moisture in different regions of the world (e.g., Aravena et al., 1999; Bershaw, Penny, & Garzione, 2012; Yang et al., 2012; Windhorst et al., 2013; Drumond et al., 2014; Corrales, Sánchez-Murillo, Esquivel-Hernández, Herrera, & Boll, 2016; Sánchez-Murillo et al., 2016; Sánchez-Murillo, Durán-Quesada, et al., 2016; Cai, Tian, & Bowen, 2017; Durán-Quesada, Gimeno, & Amador, 2017; He, Goodkin, Jackish, et al., 2018).

Thus, the combination of back trajectory models with the analysis of the isotopic composition of rainfall is a promising way to study rainfall generation processes in understudied tropical montane ecosystems such as the Páramo. For this purpose, we present a unique dataset of the water stable isotopic composition of rainfall in the Páramo in Central America (Costa Rica) and the northern Andes (southern Ecuador) during the strongest El Niño event recorded to date (2014–2016). Using available rainfall isotope datasets at both locations, this paper addresses the following research questions: (a) What are the potential sources and transport pathways of rainfall reaching the Páramo of Central America and the northern Andes? (b) How do different rainfall generation processes (e.g., orographic vs. convective systems) influence the stable isotope composition of rainfall at these two sites? This information is necessary to improve water management strategies in the Páramo and assess the future impact of climate change on high-elevation tropical ecosystems, particularly during strong El Niño conditions, which largely influence hydrometeorological conditions in the tropics. It is also urgently needed to further validate general circulation models and improve reanalysis datasets, which are currently the only practical means to identify the origin and passage of incoming precipitation at larger scales (van der Ent & Tuinenburg, 2017).

2 | DATA AND METHODS

2.1 | Study areas

The study sites are the Chirripó National Park (hereafter referred to as Chirripó, Latitude: 9.46°N, Longitude: 83.49°W, Elevation: 3,400 m asl) located in the Talamanca range of Costa Rica, and the Cajas National Park (hereafter referred to as Cajas, Latitude: 3.07°S, Longitude: 79.23°W, Elevation: 3,900 m asl) located on the east slope of the Andes in southern Ecuador (Figure 1a). These sites were selected to investigate how potential water vapour sources from different origins (i.e., the possible influence of maritime and continental moisture sources in local rainfall) contributed to the atmospheric moisture reaching the Páramo. A description of the main climate, vegetation, and soil characteristics at each site is provided in Table 1.

In general, the climate of the Costa Rican Páramo is controlled by the north-east trade winds, the latitudinal migration of the Intertropical Convergence Zone (ITCZ), cold continental outbreaks (i.e., northerly winds), and the seasonal influence of Caribbean cyclones (Waylen, 1996). Wind direction during the dry season is controlled by a regional moisture transport mechanism, the Caribbean low-level jet, whereas during the wet season, an intensification in the genesis and development of deep convection systems on the Pacific coast of Costa Rica occurs; generally, this phenomenon is associated with the presence of the "Chorro del Occidente Colombiano" or CHOCO jet (Durán-Quesada, Gimeno, Amador, & Nieto, 2010). These circulation patterns produce two rainfall maxima on the Pacific slope, one in June and one in September, which are interrupted by a relative minimum between July and August, known as the midsummer drought, due to intensification of trade winds over the Caribbean Sea (Magaña, Amador, & Medina, 1999; Sánchez-Murillo, Birkel, et al., 2016). In Chirripó, the wettest season extends from May to November (contributing up to 89% of the annual precipitation), whereas the driest season is from December to April (Kappelle & Horn, 2016).

The climate of the Ecuadorian Páramo, in turn, is mainly influenced by the Continental air masses stemming from the Amazonian side of the Cordillera, and to a lesser extent by oscillations of the ITCZ and the Humboldt Current dry cool winds originating from the Pacific Ocean (Emck, 2007). Air masses travelling across the Amazonian region are linked with moisture transport flow through north-eastern South America, associated with the dynamics of the easterly trade winds from the Atlantic Ocean to the Andes, where they turn to the south-east to reach the La Plata River basin. This flow develops a core

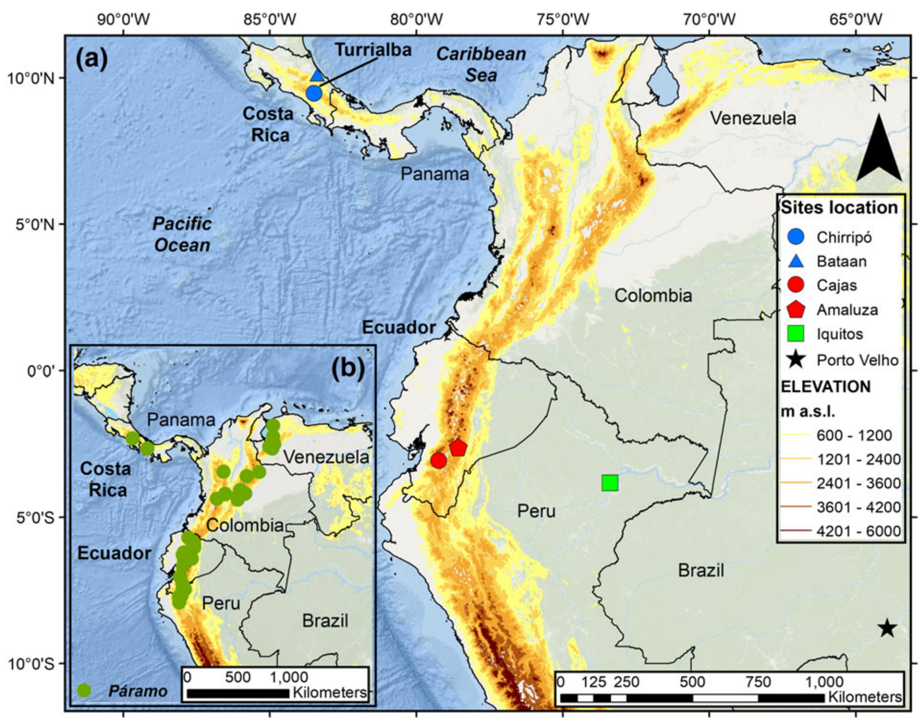

FIGURE 1 (a) Location of the Chirripó National Park (3,820 m asl) in Costa Rica and the Cajas National Park (3,900 m asl) in southern Ecuador. The map shows the monitoring stations Bataan and Turrialba (located ~35 km south-west from Bataan) on the eastern slope of Chirripó, and Amaluza, Iquitos, and Porto Velho located in the Amazon region east of Cajas. Additional stations shown are used to estimate the lapse rates of $\delta^{18}O$ and *d*-excess at Chirripó and Cajas, respectively. (b) Map of distribution of Páramo vegetation in Central America and the northern Andes. Dots show the geographic location of Páramo research sites reported by Aparecido et al., 2018

TABLE 1 Summary of major climate elements, vegetation, and soil characteristics of the Central American Páramo in the Chirripó National Park in Costa Rica and the Andean Páramo of the Cajas National Park in southern Ecuador

	Páramo site		
Characteristic	Chirripó	Cajas	References
Precipitation	1,000–2,000 mm/yr. The wettest season extends from May to November (contributing up to 89% of the annual precipitation), whereas the driest season is from December to April.	800–1,500 mm/yr. It is characterized by long duration events of low intensity (e.g., drizzle), with a relatively low year-round seasonality. It follows a bimodal pattern with a first peak in March–May and a second one in October.	Kappelle & Horn, 2016[a] Kappelle & Horn, 2005[a] Vuille et al., 2000[b] Muñoz et al., 2016[b] Padrón et al., 2015[b] Carrillo-Rojas et al., 2016[b]
Mean annual temperature	8.5 °C	5.4 °C with commonly abrupt diurnal changes	Kappelle & Horn, 2016[a] Muñoz et al., 2016[b]
Climate controls	North-east trade winds, the latitudinal migration of the Intertropical Convergence Zone (ITCZ), cold continental outbreaks (i.e., northerly winds), and the seasonal influence of Caribbean cyclones.	Continental air masses from the Amazon side of the Cordillera, linked with moisture transport flow through north-eastern South America (South American low-level jet [SALLJ]), the oscillations of the ITCZ, and the Humboldt Current dry cool winds originating from the Pacific Ocean.	Waylen, 1996[a] Magaña et al., 1999[a] Emck, 2007[b] Chaves & Takahashi, 2017[b]; Poveda et al., 2014[b]
Vegetation	0.5 to 2.5 m tall bamboo-dominated (*Chusquea subtessellata*) grasslands, covering up to 60% of the land. At drier spots, these grasslands are replaced by tussock grasses (e.g., *Calamagrostis*, *Festuca*, and *Muhlenbergia*).	Tussock grasses (commonly in the genera *Calamagrostis*, *Festuca*, *Stipa*, and various species of the Cyperaceae family, covering more than 70% of the land) and cushion plants (such as *Plantago rigida* (Kunth), *Xenophyllum humile* (Kunth) V.A. Kunk, and *Azorella* spp.)	Cleef & Chaverri, 1992[a] Kappelle, 1996, 2016[a] Ramsay & Oxley, 1997[b] Sklenar & Jorgensen, 1999[b] Mosquera, Lazo, Celleri, Wilcox, & Crespo, 2015[b] Pesántez, Mosquera, Crespo, Breuer, & Windhorst, 2018[b]
Soils	Histosols, Entisols, Inceptisols, and Andisols. Most Histosols are poorly drained, organic, shallow soils with a thin iron pan typical of soils derived from volcanic ash; Entisols are young, stony, mineral soils with little development and a lack of distinct horizons.	Histosols and Andisols, characterized by high-organic matter content and porous structures with low bulk densities as well as high-water storage capacities of up to 90% by volume.	Kappelle & Horn, 2005[a] Otárola & Alvarado, 1976[a] Buytaert, Wyseure, De Bievre, & Deckers, 2005[b] Buytaert, Deckers, & Wyseure, 2006[b]

[a]References referring to the Páramo of Chirripó.

[b]References referring to the Páramo of Cajas.

of particularly high-speed transport, called the South American low-level jet (SALLJ; Chaves & Takahashi, 2017; Poveda, Jaramillo, & Vallejo, 2014). In Cajas, and on the eastern slope of the Andes, precipitation varies between 800 and 1,500 mm/yr (Vuille, Bradley, & Keimig, 2000). Precipitation is characterized by long duration events of low intensity (Muñoz, Célleri, & Feyen, 2016), mainly corresponding to drizzle, and with a relatively low year-round seasonality (Padrón, Wilcox, Crespo, & Célleri, 2015). It follows a bimodal pattern with a first peak in March–May and a second one in October (Carrillo-Rojas, Silva, Córdova, Célleri, & Bendix, 2016).

Our sampling period (2015–2016) coincided with large sea surface temperature (SST) anomalies in the eastern Pacific Ocean. A maximum anomaly was recorded in September–October–November 2015 (average increment: 2.3°C using a combined El Niño 3.4/Southern Oscillation Index (SOI) index; Sánchez-Murillo, Durán-Quesada, et al., 2016), whereas in the El Niño, 1.2 region the SST anomalies in this period were reported with an average increment of 2.4°C. During El Niño, easterlies intensification decreases the moisture transport from the eastern Pacific Ocean and increases the transport of moisture from the Caribbean and northern South America to Central America, whereas the SALLJ is also more active, and there is an intensification of the trade winds blowing from the North tropical Atlantic to South America (Durán-Quesada et al., 2017; Silva & Ambrizzi, 2006).

2.2 | Data collection

At Chirripó, daily rainfall samples (N = 93) were collected for stable water isotope analyses between April 2015 and May 2016. At Cajas, weekly rainfall samples (N = 62) were collected between January 2015 and May 2016. At Chirripó, samples were collected using a passive collector (Palmex Ltd., Croatia; Gröning et al., 2012), whereas samples at Cajas were collected using a custom-built passive rainfall sampler. The rainfall samplers at Cajas consisted of a circular funnel and 1.5-L glass bottles isolated with foam and covered with aluminium foil. Evaporation in those samplers was prevented by placing a plastic sphere (4 cm diameter) in the funnel and a layer of 0.5 cm mineral oil inside the bottle. Samples at both sites were filtered using 0.45 μm polytetrafluorethylene (PTFE) syringe membranes and stored at dark and cool conditions (5°C) until analysis. Samples were stored in 30 ml high-density polyethylene (HDPE) bottles in Costa Rica and 2 ml amber glass vials in Ecuador. Daily precipitation amounts at Chirripó were measured using a RGR126 rain gauge with a resolution of 1 mm (Oregon Scientific Inc., USA). Daily precipitation amounts at Cajas were measured using a tipping-bucket rain gauge (Texas Instruments Inc., USA) with a resolution of 0.1 mm. Precipitation rain gauges were installed within 5–10 m from the collectors at both sites.

2.3 | Laboratory analysis

The isotopic composition of the samples was determined using a cavity ring-down spectroscopy water isotope analyser L2120-i (Picarro, USA) for samples from Costa Rica and L1102-i analyser (Picarro, USA) for samples from Ecuador. Stable isotope compositions are presented in delta notation δ (per mil [‰]) relative to the Vienna Standard Mean Ocean Water (Craig, 1961). Both instruments had an analytical long-term uncertainty of ±0.5‰ (1σ) for δ^2H and ±0.1‰ (1σ) for $\delta^{18}O$. Calibration was done using secondary standards with the following isotopic compositions: δ^2H = −131.4‰, $\delta^{18}O$ = −17.0‰ (tap water), δ^2H = −1.7‰, $\delta^{18}O$ = −0.2‰ (deep ocean water), and δ^2H = −64.3‰, $\delta^{18}O$ = −8.3‰ (Commercial Bottled Water). The Commercial Bottled Water standard was used as a quality control and drift control standard. The isotopic composition of samples collected in passive collectors with mineral oil was screened using the ChemCorrect software (Picarro, Inc.) to identify organic contamination. Samples that did not pass the organic contamination screening were removed from the analyses of the isotopic compositions.

2.4 | HYSPLIT air mass back trajectory analysis

Air mass back trajectory analyses were conducted using the HYSPLIT Lagrangian model (Stein et al., 2015) developed by the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (NOAA, USA). The model was used to identify the preferential transport pathways followed by the air masses that arrived at Chirripó and Cajas. Air mass separation (i.e., classification of air masses based on the preferential pathway followed from their origin to each study site) was used to identify the influence of different moisture transport patterns on the isotopic composition of precipitation at the study sites. Each trajectory was calculated using NOAA's meteorological data files (global data assimilation system: 2006 to present; 0.5° resolution; Su, Yuan, Fung, & Lau, 2015) as input for the HYSPLIT model. At both sites, back trajectories were estimated for periods of 240 hr at 6-hr intervals. For each day when rain was sampled at Chirripó and for each weekly composite sample collected at Cajas, an air mass back trajectory was calculated. This analysis resulted in 93 and 62 trajectories obtained for Chirripó and Cajas, respectively. These air mass trajectories were then combined to calculate composite spatial patterns of air mass trajectory pathways, which are presented in the form of averaged trajectory contour plots (Caves et al., 2016; Lechler & Galewsky, 2013). Overall, the calculation time was in agreement with the estimated residence time of water in the atmosphere, ranging from around 4 to 10 days (van der Ent & Tuinenburg, 2017). In accordance with the likely height of the cloud base (typically between 850 and 700 mb), where precipitation is generally formed, the ending elevations of the trajectories were set to 3,400 m asl at Chirripó and 3,900 m asl at Cajas. Trajectory analyses ending times at Chirripó and Cajas were set to 12:00 Coordinated Universal Time (UTC), which corresponds to a local time of 06:00 a.m. in Costa Rica and 07:00 a.m. in Ecuador, respectively. The ending dates for the trajectory analysis at Chirripó and Cajas were set according to the date when samples were collected.

2.5 | Isotopic characterization of rainfall

2.5.1 | Temporal variation analysis

The seasonal changes in the isotopic composition of daily and weekly rainfall samples (i.e., $\delta^{18}O$) and *d*-excess were used to identify how the origin of atmospheric vapour and the different rainfall generation processes influence the isotopic composition of precipitation at each study site. The *d*-excess is an isotope-derived parameter and was calculated as follows (Dansgaard, 1964):

$$d - excess = \delta^2 H - 8\,\delta^{18}O. \tag{1}$$

The GMWL has a mean *d*-excess value of ~10%, resulting from a single stage of evaporation from the oceans at an average relative humidity of 85% (Clark & Fritz, 1997; Rhodes, Guswa, & Newell, 2006). It is known that the *d*-excess is preserved in moisture when the water vapour condenses because when water initially evaporates from the ocean, the initial values of *d*-excess are fixed by the relative humidity of the air mass (Merlivat & Jouzel, 1979; Rhodes et al., 2006). Therefore, *d*-excess values greater than 10‰ indicate that rainfall contains water either recycled (e.g., reevaporated) from the land surface or condensed from vapour that formed when relative humidity was less than 85%. Additionally, in high-elevation mountain regions, such as the Páramo, the distance between cloud base and ground is relatively short, and the saturation deficit is low. Thus, subcloud evaporation into precipitation can be strongly reduced, and moisture recycling, depending on environmental conditions, can become the dominant process resulting in increased *d*-excess values (Salati et al., 1979; Froehlich et al., 2008; Cui et al., 2009; Guo, Feng, Wei, & Li, 2014; Li et al., 2016). Therefore, *d*-excess variations were used to identify the influence of water vapour recycling on rainfall reaching both sites.

Simple linear regression analysis was used to construct Local Meteoric Water Lines (LMWLs; i.e., the linear relationship between δ^2H and $\delta^{18}O$ in local precipitation) for Chirripó and Cajas (Craig, 1961). Histograms were constructed to describe the distribution of the isotopic values (i.e., $\delta^{18}O$) at each site. The slopes and intercepts of the LMWLs were used to identify the departure from equilibrium conditions and the effect of kinetic fractionation processes in the isotopic composition of precipitation at each site. We used a simple linear regression analysis to establish relationships between $\delta^{18}O$ and daily (for Chirripó) and weekly (for Cajas) precipitation amounts, as well as monthly precipitation amounts for both sites. At each site, rainfall amount weighted monthly average $\delta^{18}O$ values were used to indicate if the typical long-term relationship between rainfall amount and $\delta^{18}O$ (e.g., Dansgaard, 1964; Gonfiantini, Roche, Olivry, Fontes, & Zuppi, 2001) was valid for the Páramo.

2.5.2 | Isotopic lapse rates

The changes in the average isotopic composition (i.e., $\delta^{18}O$) and *d*-excess of precipitation with elevation were calculated independently for the Caribbean slope of Costa Rica at Chirripó and the Amazon Forest at Cajas, because our HYSPLIT results depicted that air masses originating from these regions contributed most of the precipitation at these two sites, respectively (see Section 3.1). For Costa Rica, the altitudinal relationship was estimated using additional isotopic data of sites located on the path of air masses (i.e., Bataan, 18 m asl, N = 127; and Turrialba, 1,115 m asl, N = 22) that travelled over the Caribbean Sea and ascended over the Talamanca range towards Chirripó. In Ecuador, we used additional isotopic data of sites situated on the trajectory of air masses (i.e., Porto Velho in Brazil, 105 m asl, N = 72; Iquitos in Peru, 98 m asl, N = 54; and Amaluza in Ecuador, 1,720 m asl, N = 27) originating from the Amazon region that climbed over the eastern side of the Andes to reach Cajas. Samples in Bataan and Turrialba were collected on a daily and weekly basis between January 2015 and March 2016, whereas for Porto Velho, Iquitos, and Amaluza, we used monthly isotope data from the Global Network of Isotopes in Precipitation (GNIP) network (GNIP/IAEA/WMO, 2017) collected in the periods 1965–1981 (Porto Velho), 2006–2012 (Iquitos), and 1992–1994 (Amaluza). These data were used to compare the first-estimated isotopic lapse rates for the Páramo of Chirripó and Cajas with other values reported for Central America and the Andes. Even though the GNIP data for the South American sites does not correspond to our study period, the consistency between our determined isotopic lapse rates (Section 3.4) and the results of our HYSPLIT analysis (Section 3.1) indicate that these data provide good approximations of the long-term isotopic conditions at these sites. The LMWLs of Bataan, Turrialba, Porto Velho, Iquitos, and Amaluza are included as Supporting Information (Figure S1).

3 | RESULTS AND DISCUSSION

3.1 | Preferential air mass trajectories

HYSPLIT back trajectory analyses identified that under the strong influence of El Niño during the study period, moisture reaching Chirripó was of maritime origin and predominantly came from the south-eastern Caribbean Sea coast of Costa Rica, whereas moisture reaching Cajas was of continental origin and predominantly came from the Amazon basin (Figure 2).

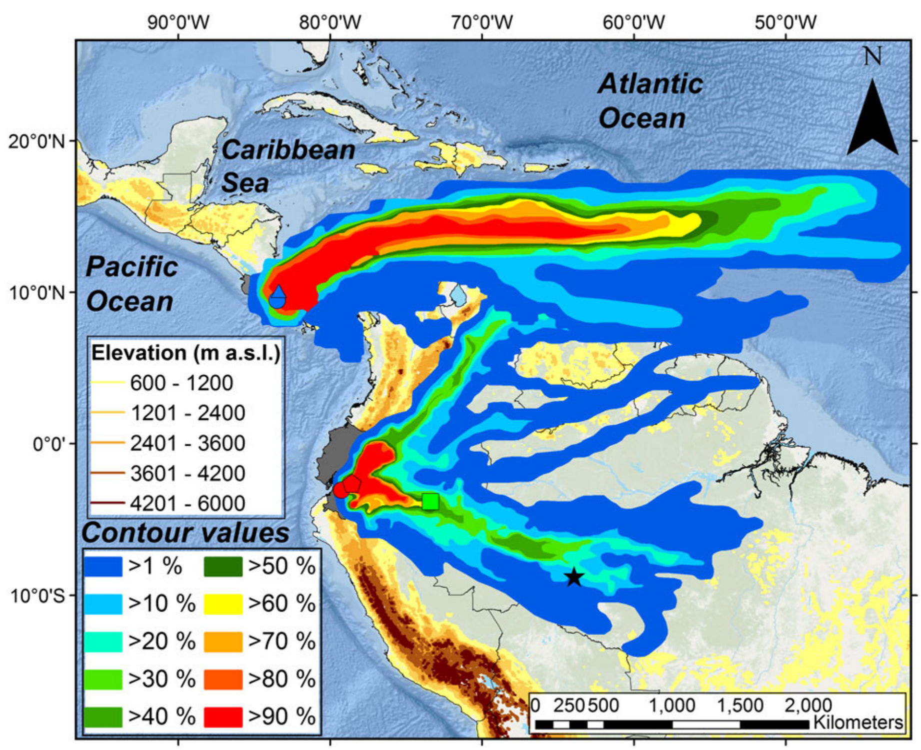

FIGURE 2 Composite HYSPLIT air mass back trajectories simulated for Chirripó (blue circle) and Cajas (red circle). The composite trajectories were calculated using 93 individual trajectories for Chirripó and 62 individual trajectories for Cajas using 240-hr time periods at 6-hr intervals. Contour values indicate how frequently the trajectory of an air parcel travelled above the Earth's surface towards each study site during the study period. The locations of Bataan (blue triangle), Amaluza (red pentagon), Iquitos (green square), and Porto Velho (black star) are also shown

For the Central American Páramo at Chirripó, the air masses originating from the Caribbean Sea contributed approximately 79.6% of the total rainfall recorded during the study period (1,146 mm between April 2015 and May 2016). Air masses arriving from the Caribbean Sea predominantly travelled over the central and southern Caribbean Sea basin (90% frequency; Figure 2). These air masses had little interaction with the surrounding landmasses, with the exception of air masses that travelled over northern South America (10% frequency). These trajectories most likely were influenced by the north-east trade winds in the region (Saénz and Quesada, 2015). Air masses coming from the Pacific Ocean contributed approximately 20.4% of the total rainfall recorded during the study period (294 mm between April 2015 and May 2016) and mainly originated from the Pacific coast of Costa Rica and Panamá.

For the Andean Páramo at Cajas, the air masses originating from the Amazonia contributed approximately 79.0% of the total precipitation recorded during the study period (1,278 mm between January 2015 and May 2016). These trajectories are most likely related to the strong influence of the SALLJ in the region (Chaves & Takahashi, 2017). Other air masses travelled over north-eastern Venezuela and Colombia and were deflected by the northern part of the Andes towards southern Ecuador. These air masses represented 17.7% of the total number of trajectories and contributed to 19.4% of the total rainfall (308 mm between January 2016 and May 2016). The influence of air masses stemming from the Pacific Ocean during the study period was very low (3.2%). In general, the most frequent pathway (90% frequency) came across the Amazon region of Ecuador and northern Peru (e.g., Iquitos; Figure 2). Moisture travelling across the central portion of the Amazonia (e.g., Manaus) to Cajas was less frequent (40% frequency).

Despite the strong influence of the El Niño conditions during the study period, our HYSPLIT analysis is still consistent with other Lagrangian models applied to track patterns of moisture transport from the Amazon Basin in South America, and from the Caribbean Sea and Pacific Ocean in Central America (Drumond et al., 2014; Durán-Quesada et al., 2010; Windhorst et al., 2013). Our findings are also supported by results of other investigations conducted at regional and global scales (e.g., Silva, Ambrizzi, & Marengo, 2009; Maldonado, Alfaro, Fallas-López, & Alvarado, 2013; van der Ent & Tuinenburg, 2017), providing confidence that the simulated composite air mass trajectories are representative of the annual distribution of incoming moisture under average conditions. In the following, these trajectories will be used in combination with the analyses of the isotopic composition of rainfall to investigate the prevailing transregional climate conditions that influence rainfall generation processes at each study site.

3.2 | Rainfall isotopic characterization

The $\delta^{18}O$ and δ^2H values of rainfall at Chirripó ranged from −22.4‰ to −3.07‰ and from −165.1‰ to −14.7‰, respectively (Table 2; Figures 3c). The LMWL for Chirripó is $\delta^2H = 8.07 \cdot \delta^{18}O + 10.9‰$ ($r^2 = 0.99$, $N = 93$, $p < 0.001$; Figure 3a). The slope and intercept parameters of the LMWL of Chirripó are consistent with those of the GMWL (slope = 8 and intercept = 10‰; Craig, 1961; Figure 3a). These compositions reflect equilibrium conditions in the rainout processes of local precipitation (Clark & Fritz, 1997). The parameters of the LMWL of Chirripó are in agreement with those of the LMWL calculated for the Caribbean region of Costa Rica ($\delta^2H = 8.26 \cdot \delta^{18}O + 12.3‰$; Sánchez-Murillo et al., 2013).

The $\delta^{18}O$ and δ^2H values of rainfall at Cajas varied from −20.8‰ to −2.16‰ and from −154.4‰ to −3.44‰, respectively (Table 2; Figure 3a,c). The LMWL for Cajas is $\delta^2H = 8.32 \cdot \delta^{18}O + 18.5‰$ ($r^2 = 0.99$, $N = 62$, $p < 0.001$; Figure 3a). The major difference between the LMWLs of Chirripó and Cajas was the larger intercept value of +18.5‰ at Cajas, a value that is also greater than the reference value (+10‰) of the GMWL. This value for Cajas is in agreement with the intercept of +18.0‰ reported by Mosquera, Segura, et al. (2016) at the Ecohydrological Observatory of the Zhurucay River, another Páramo site located on the western slope of the Atlantic–Pacific continental divide, 40 km south-west of Cajas. Windhorst et al. (2013) also found a value of +14.5‰ in the San Francisco Valley (eastern slope of the Andes), located in southern Ecuador. Two possible explanations for the shift of the Zhurucay Observatory LMWL intercept in relation to the GMWL were proposed by Mosquera, Segura, et al. (2016) on the basis of the possible origin and transport of water vapour masses towards the study site. These alternatives were that (a) water vapour originates from the Pacific ocean and undergoes enhanced strong nonequilibrium fractionation as it is transported from sea level at the coast of Ecuador, where high temperatures are dominant year-round (above 20°C), to colder regions as the vapour masses gain elevation in the Andes, or (b) water vapour originating from the Amazonian side of the Cordillera undergoes isotopic fractionation under nonequilibrium conditions due to reevaporation during its transport from the Amazon forest to the Páramo of Zhurucay. Nevertheless, based on the air mass pathways from our HYSPLYT analysis (Figure 3a), only a minimal contribution of moisture from Pacific Ocean was found at Cajas (~3%). Therefore, the shift in the LMWL can be attributed to precipitation evaporation and moisture recycling reaching the study area. Our stable isotopic observations indicate an increasing influence of moisture recycling with increase in δ^2H values

TABLE 2 Summary statistics of rainfall $\delta^{18}O$, δ^2H, and *d*-excess at the study sites

				$\delta^{18}O$ (‰)				δ^2H (‰)				*d*-excess (‰)			
Site	Lat–Lon	Elevation (m asl)	*N*	Mean	Max	Min	*SD*	Mean	Max	Min	*SD*	Mean	Max	Min	*SD*
Chirripó	9.46°N–83.49°W	3,400	93	−10.23	−3.07	−22.40	4.64	−71.75	−14.73	−165.05	37.63	10.08	17.18	−1.63	3.44
Cajas	3.07°S–79.23°W	3,900	62	−9.81	−2.16	−20.79	4.54	−63.08	3.44	−154.37	37.81	15.39	20.72	11.32	2.26

Note. Lat: latitude; Lon: longitude; *N*: number of samples collected; Max: maximum; Min: minimum; *SD*: standard deviation.

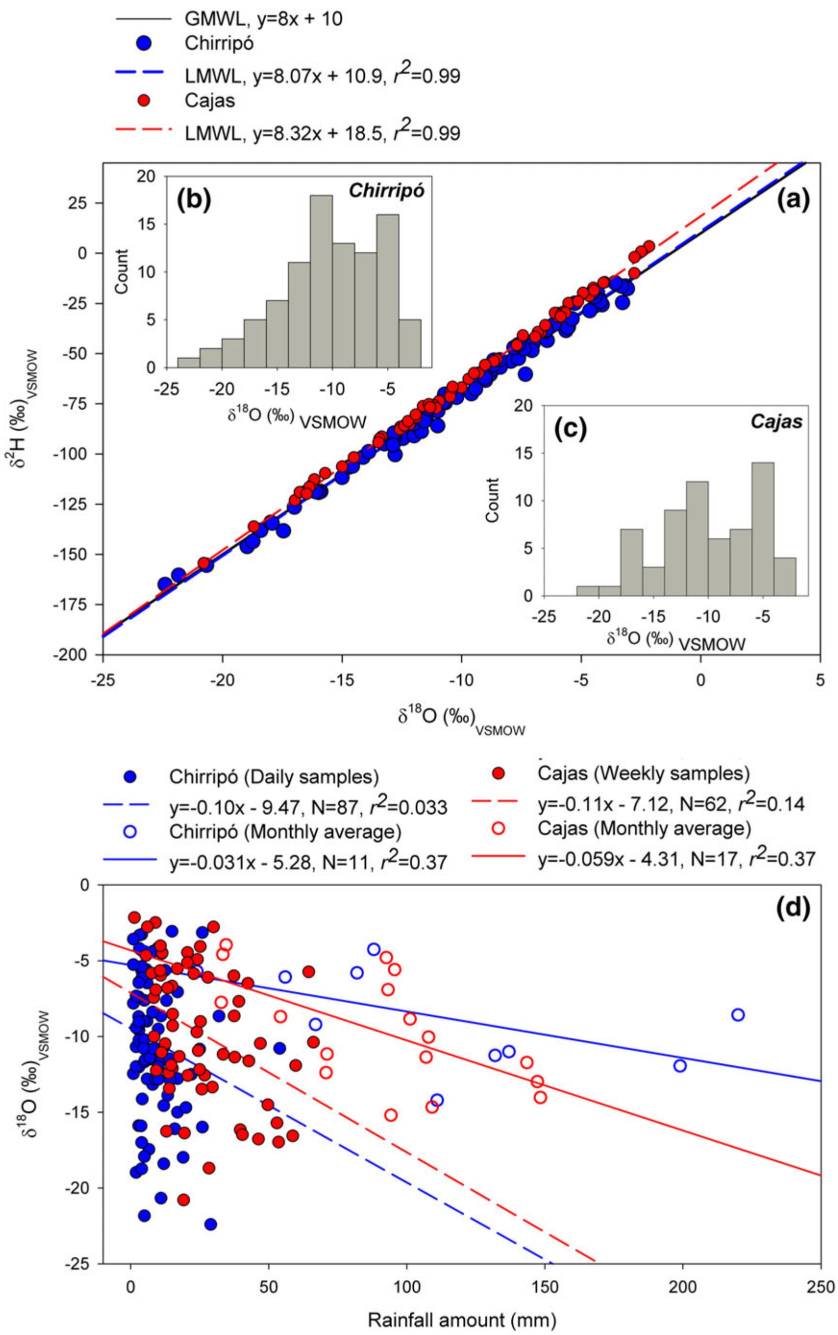

FIGURE 3 (a) Local Meteoric Water Lines (LMWLs) for Chirripó (dashed blue line) and Cajas (dashed red line) using samples collected between January 2015 and May 2016 (solid dots). The Global Meteoric Water Line (GMWL; black line; Craig, 1961) is plotted for reference. (b, c) Histograms showing the $\delta^{18}O$ isotopic composition for Chirripó and Cajas, respectively. In Figures 3b,c, "Count" refers to the number of observations within the shown $\delta^{18}O$ ranges. (d) Linear regressions between the $\delta^{18}O$ and rainfall amount for each site. Solid dots represent daily and weekly samples for Chirripó and Cajas, respectively. Open dots represent monthly average values for Chirripó and Cajas, respectively. VSMOW: Vienna Standard Mean Ocean Water

of rainfall arriving from the Amazonia or the South American continental region, as shown by the strong relationship between the δ^2H and *d*-excess in rainfall for Cajas ($r = 0.658$, $p < 0.001$; Figure S2). A similar effect was recently reported by Gastmans et al. (2017) in Brazil on the basis of the analysis of GNIP network stations (e.g., Belo Horizonte, Rio de Janeiro, Campo Grande, Carolina, Betânia, and Rio Claro). The LMWL intercepts at these stations varied between +12‰ and + 13‰, and this effect was attributed to vapour recirculation during the transportation of air masses arriving from the Amazonia. Therefore, based on the preferential air mass trajectories identified for Cajas, our results suggest that recycled water vapour arriving from this region likely lead to the shift of the LMWL at Cajas and Zhurucay in the Andean Páramo of southern Ecuador.

The relationship between rainfall amount and $\delta^{18}O$ (or the "amount effect," Dansgaard, 1964) occurs as a result of rainout processes of convective precipitation. The stronger the convective nature of a rainfall event, the greater the total precipitation amount, and thus, the lower the probability of moisture exchange during the travel time towards the surface (Sánchez-Murillo, Birkel, et al., 2016; Tharammal, Bala, & Noone, 2017). This "amount effect" appears to be stronger in the tropics when examined over longer time spans (e.g., months and years) than at shorter time scales (e.g., hours, days, and weeks; Risi, Bony, & Vimeux, 2008; Sánchez-Murillo, Birkel, et al., 2016). On daily and weekly time scales, we found that the relationship between rainfall amounts and $\delta^{18}O$ was very weak and not statistically significant at Chirripó ($r^2 = 0.033$, $p = 0.094$) and also very weak but statistically more significant at Cajas (r^2 = 0.14, p = 0.0027; Figure 3d). These low correlations suggest that the isotopic variations in high-elevation tropical ecosystems are likely controlled by the vertical air motion and microphysical processes governing the formation of orographic and convective precipitation, rather than the amount of precipitation at short time scales (Aggarwal et al., 2016; Scholl, Shanley, Zegarra, & Coplen, 2009). On the other hand, these relationships were stronger at the monthly time scale for Chirripó (r^2 = 0.37, p = 0.039) and Cajas (r^2 = 0.37, p = 0.0051). For these relations, the corresponding isotopic composition variations with rainfall amount showed a decrease of 3.1‰ per 100 mm at Chirripó and 5.9‰ per 100 mm at Cajas, respectively. In general, these isotopic rates are consistent with those reported by Sánchez-Murillo et al. (2016) for the intermountainous region of Costa Rica (2.8‰ per 100 mm, highest elevation ~3,400 m asl) and by Gonfiantini et al. (2001) for Bolivia (6.6‰ per 100 mm, Yungas–Altiplano, highest elevation ~5,200 m asl).

3.3 | Seasonal variations of δ^{18}O and *d*-excess

Seasonal δ^{18}O variations were clearly defined at Chirripó and Cajas. At Chirripó, the strongest depletion in ^{18}O occurred at the end of May and in June at the beginning of the wet season (δ^{18}O range: −4.29‰ to −22.40‰, mean value: −11.04‰; Figure 4a,c). In July and early August, during the midsummer drought (Magaña et al., 1999), the δ^{18}O values remained relatively stable and high (δ^{18}O range: −3.07‰ to −17.45‰, mean value: −7.62‰) in comparison with the rest of the year. Towards the end of the wet season (September–October), the δ^{18}O values also decreased (δ^{18}O range −4.32‰ to −20.67‰, mean value: −11.53‰; Figure 4a,c). During the beginning of the dry season in December–January, we observed an increase in the isotopic values (δ^{18}O range: −3.32‰ to −18.73‰, mean value: −9.70‰). Overall, the lower isotopic values observed after the beginning and at the end of the wet season (Figure 4c) are the result of the passage of the ITCZ over Costa Rica (Sánchez-Murillo et al., 2013; Sánchez-Murillo, Birkel, et al., 2016) and reflect convective rainfall arriving to Chirripó. During the midsummer drought and transition seasons (e.g., November–December), the NE trade winds intensified causing an increase in moisture transport from the Caribbean Sea. As a result, the prevailing influence of orographic rainfall was likely to bring isotopically enriched precipitation to Chirripó compared with convective rainfall. Although orographic clouds can experience rainout effects similar to those observed in convective precipitation, the high stable isotopic value is similar to cloud water because these air masses condense and rain near the mountain ranges (Guswa, Rhodes, & Newell, 2007; Rhodes et al., 2006).

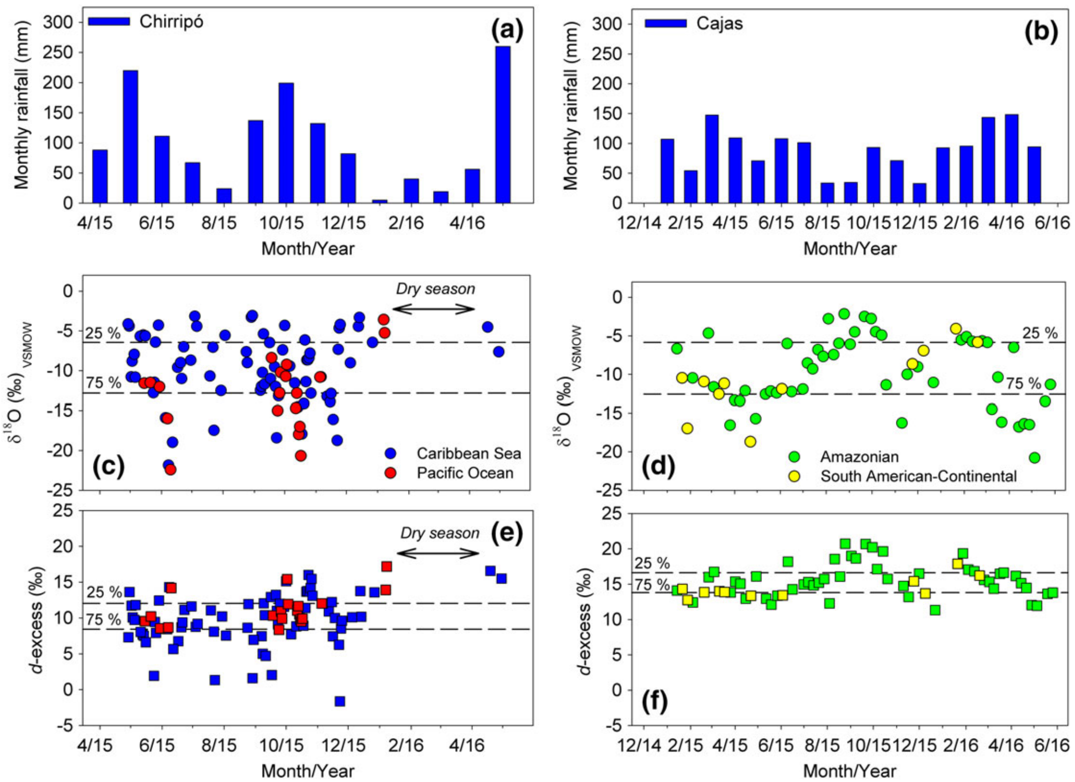

FIGURE 4 Time series showing (a) monthly precipitation at Chirripó between April 2015 and May 2016, (b) monthly precipitation at Cajas between January 2015 and May 2016. (c, d) Temporal variation of the δ^{18}O isotopic compositions at Chirripó and Cajas, respectively. (e, f) Temporal variation of *d*-excess at Chirripó and Cajas, respectively. The 25th and 75th percentiles of the δ^{18}O and *d*-excess values are shown in c–f for reference. δ^{18}O and *d*-excess values in c–f are classified into four main groups according to their preferential trajectory pathways: (1) maritime origin from the central and southern Caribbean Sea (blue), (2) maritime origin from the Pacific Ocean (red), (3) continental origin from northern South America (yellow), and (4) continental origin from the Amazonia (green). The 2015 and 2016 dry season for Chirripó is indicated in (c) and (e). VSMOW: Vienna Standard Mean Ocean Water

At Cajas, the most important variations in $\delta^{18}O$ occurred between August–October, coinciding with the period of the lowest precipitation amounts (Figure 4b). During this period, a systematic increase in the isotopic values was recorded ($\delta^{18}O$ range: −2.16‰ to −11.37‰, mean value: −5.00‰; Figure 4d). On the other hand, during the most humid periods (April–May; Figure 4b), a depletion in $\delta^{18}O$ was observed ($\delta^{18}O$ range: −12.11‰ to −18.69‰, mean value: −13.81‰; Figure 4d). Mosquera, Segura, et al. (2016) reported similar variations in the $\delta^{18}O$ isotopic composition of rainfall at the Zhurucay River Observatory on the western slope of the Andes. These authors also observed higher isotopic values during the relatively dry periods and depleted ones during wetter periods. The lower $\delta^{18}O$ values during wetter periods are likely the result of the passage of the ITCZ over the Andes of Ecuador and the Amazon region, particularly associated to air masses arriving from the Amazonia and northern South America between January and May. This depletion effect is also linked to enhanced convective activity in the region (Gastmans et al., 2017; Różanski & Araguás-Araguás, 1995). The higher $\delta^{18}O$ values, in turn, are linked with orographic rainfall formed during the less intense rainy period at Cajas. During such periods, the isotopic enrichment is likely linked to the recycling of moisture arriving from the Ecuadorian and Peruvian Amazonia, which is less influenced by subcloud local reevaporation by the short distance between the could base and the mountain range and by the low moisture saturation deficit due to the high year-round air humidity at Cajas (annual average > 92%; Muñoz, Célleri, & Feyen, 2016).

These results illustrate that convective and trade-wind orographic precipitation seasonally influence the $\delta^{18}O$ of rainfall reaching both Páramo sites. The precipitation types are formed at different altitudes, where different atmospheric temperatures and water vapour compositions contribute to seasonally distinct rainfall isotopic compositions (Scholl & Murphy, 2014). The lowest $\delta^{18}O$ in convective rainfall values is probably due to higher clouds (reported with maximum radar echo at top heights of ~9,000 m; Scholl & Murphy, 2014) in the atmosphere with lower cloud temperatures, isotopically depleted source vapour, and Rayleigh fractionation during rainout before reaching the high-elevation mountainous areas (Otte et al., 2017; Scholl & Murphy, 2014). Orographic precipitation, in turn, is generated by the uplift of air masses by trade winds or local thermal effects and is associated with the highest $\delta^{18}O$ values during the drier seasons at both sites. These seasonal variations observed at our Páramo monitoring sites are in agreement with precipitation isotope variations observed over Costa Rica and the Amazon region, mainly related to the influence of ITCZ movement (Salati et al., 1979; Różanski & Araguás-Araguás, 1995; Sánchez-Murillo et al., 2013).

The rainfall *d*-excess had a site-specific signature, showing greater overall variation at Chirripó compared with Cajas during the study period (Figure 4e,f). At Chirripó, *d*-excess values ranged between −1.63‰ and +17.2‰ (mean value: +10.1‰; Table 2), with 58.0% of all observations between +8‰ and +12‰ (Figure 4e). The variation of *d*-excess between these values and its mean value of approximately +10‰ confirm that local precipitation at this site underwent equilibrium fractionation preferentially (Clark & Fritz, 1997). This effect is likely due to its proximity to its main water vapour source of oceanic origin (i.e., the Caribbean Sea). It is also reflected in samples with low *d*-excess values (up to −1.63‰) recorded during the most intense rainy periods and probably linked to precipitation forming high humidity conditions (Benetti et al., 2014; Figure 2). Towards the end of the wet season (August–October), rainfall stemming from the Caribbean Sea with *d*-excess values greater than +12‰ also was observed (Figure 4e). These observations show that water vapour transported from this moisture source was likely subjected to moisture recycling when the air masses travelled across the Caribbean slope of Costa Rica during this period. This effect was also reported by Rhodes et al. (2006) and Sánchez-Murillo et al. (2013, 2016) in Monteverde (Pacific domain) and the Central Valley of Costa Rica, respectively. Rainfall originating from the less frequent precipitation source, the Pacific Ocean, was also linked with *d*-excess values around +10‰. These precipitation events likely resulted from the presence of the ITCZ across Central America and the intensification in the genesis and development of localized deep convective rainfall systems on the Pacific coast of Costa Rica during this period (Durán-Quesada et al., 2010). Few samples collected during the wet season (August–October) presented *d*-excess values greater than +12‰ (up to +15.4‰; Figure 4e). These values likely reflect strong convective local events fed by evapotranspiration fluxes (Sánchez-Murillo, Birkel, et al., 2016). Overall, these *d*-excess seasonal variation patterns are in agreement with those reported by Pfahl and Sodemann (2014) based on their analyses of statistical mode predictions, which related the *d*-excess of water evaporating from the ocean and the ocean's near-surface relative humidity.

At Cajas, *d*-excess values ranged between +11.3‰ and +20.7‰ (mean value: +15.4‰), with 55.0% of the total observations between +14‰ and +17‰ (Figure 4f). The smaller *d*-excess variation observed at Cajas compared with Chirripó likely results from the year-round preferential moisture contribution from a moisture source of continental origin (i.e., Amazonia; Figure 2). This source contributes moisture with *d*-excess values greater than 12‰ (up to 18–20‰ during the less humid period in August–October; Figure 4e) as a result of the recycling of water vapour as air masses are transported across the Amazon forest towards Cajas (Pfahl & Sodemann, 2014; Figure 2). These observations are likely associated with the strong influence of the SALLJ, which is active year-round east of the Andes. This low-level jet is part of the so-called "atmospheric rivers," which are responsible for the formation of precipitation along the eastern side of the Andes (Poveda et al., 2014). Water vapour that enters the eastern tropical South America and the Amazon River basin mixes with local recycled water to augment the amount of moisture available for precipitation (Poveda et al., 2014; Salati et al., 1979; van der Ent & Savenije, 2011). Our findings thus suggest that the intensification of the SALLJ could increase the transport of water vapour originated in the Amazon region to the highlands of the Andes. This contribution is a remarkable finding for the Páramo of southern Ecuador because it is generally accepted that the Andes generally block the moisture flux arriving from the Amazonia that could be transported to the Pacific side of the Cordillera (Chaves & Takahashi, 2017; Silva et al., 2009).

3.4 | $\delta^{18}O$ and *d*-excess lapse rates

Using the average $\delta^{18}O$ and *d*-excess of our Páramo sites and the potential sources of moisture determined by our HYSPLYT analyses (i.e., Bataan and Turrialba for Chirripó and Porto Velho, Iquitos, and Amaluza for Cajas; Figure S1), we analysed how the isotopic composition of rainfall varied with elevation from the moisture source to each study site. As shown in Figure 5, there is a decrease in the $\delta^{18}O$ values of rainfall as altitude increases at both sites (from east to west, i.e., from sea level to the mountain tops). At Chirripó, the observed trend is likely associated with the rainout effect of the rising air masses from the Caribbean Sea to the Talamanca range. This effect took place at a $\delta^{18}O$ lapse rate of −0.24‰ per 100 m. This value is in agreement with the mean value reported by Sánchez-Murillo et al. (2013) in the Central Valley of Costa Rica (−0.2‰ per 100 m). We also found an insignificant increase in the *d*-excess values as air masses travelled from Bataan (+8.98‰) to Chirripó (+10.08‰), which resulted in a *d*-excess lapse rate of only +0.03‰ per 100 m. This lack of variation in *d*-excess as elevation increases is likely due to the following: (a) the relatively short distance travelled by air masses from the Caribbean coast of Costa Rica to the highlands of Chirripó (~84 km), limiting a potential increase in *d*-excess due to moisture recycling along its pathway and/or (b) air parcels travelling at higher altitudes, which limits the exchange of moisture with the ground, and thus, decreases the *d*-excess in rainfall.

At Cajas, the observed trend of decreasing $\delta^{18}O$ values as altitude increases is likely related to the rainout effect of the rising air masses from the Amazonia to the southern Ecuadorian Andes. This effect results in a $\delta^{18}O$ lapse rate of −0.15‰ per 100 m. This value is in agreement with the mean value reported by Gonfiantini et al. (2001) in Bolivia (−0.19‰ per 100 m) and Windhorst et al. (2013) in southern Ecuador (−0.22‰ per 100 m). At Cajas, the observed altitudinal variation of *d*-excess in meteoric waters along the transect between Porto Velho (+7.09‰) and Cajas (15.39‰) resulted in a lapse rate of +0.22‰ per 100 m. The estimated *d*-excess altitudinal changes at Cajas is within the range of previously reported values at Yungas–Altiplano (approximately +0.13‰ per 100 m) and the Tibetan Plateau (approximately +0.40‰ per 100 m; Bershaw et al., 2012; Gonfiantini et al., 2001). The observed altitudinal variation in *d*-excess with altitude at Cajas is likely related to the long distance travelled by the air masses at low altitudes across the humid Amazon forest. This effect likely increases the exchange of water vapour in the canopy–atmosphere interface and, thus, leads to an increase in *d*-excess at Cajas as recycled water vapour from the lowlands of the Amazonia transport towards the Páramo highlands of the south Ecuadorian Andes. These two processes affecting the decrease of $\delta^{18}O$ and increase of *d*-excess as altitude increases are interlinked as recycled moisture arriving at Cajas has undergone the rainout of the heavy isotopes as water vapour masses transport from the Amazonia to the Páramo highlands.

Overall, the $\delta^{18}O$ and *d*-excess altitudinal variations are likely consistent with the distillation of the parental water vapour from the Caribbean Sea and the Amazon region, which were orographically lifted and adiabatically cooled across the Caribbean slope of the Talamanca range (Durán-Quesada et al., 2010) and the eastern Andes (Chaves & Takahashi, 2017), respectively. At Chirripó, however, it is apparent that the stronger effect of the annual migration of the ITCZ, which modifies the local moisture recycling and decreases the *d*-excess altitudinal variations, was probably related to a greater contribution of convective precipitation formed at higher altitudes than at Cajas during the study period (Sánchez-Murillo, Durán-Quesada, et al., 2016; Scholl & Murphy, 2014). At Cajas, the influence of the SALLJ is probably associated with a greater contribution of orographic precipitation and moisture recycling along the Amazonia–Cajas transect. This effect is consistent with a reduction in the convection during El Niño events in northern Brazil, but extending westward to the Andean foothills of Ecuador and northern Peru (Vuille et al., 2000). In general, these altitudinal relationships could be useful to help discern groundwater recharge areas and to identify surface water sources for ecosystems and people living in lowland regions.

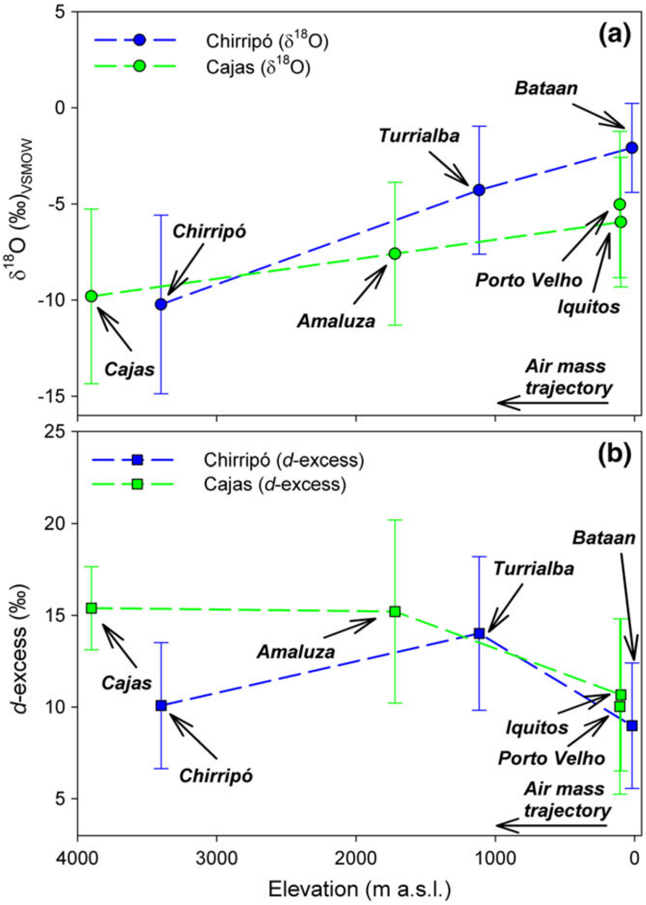

FIGURE 5 (a) $\delta^{18}O$ and (b) *d*-excess altitudinal relationships for Chirripó (blue circles and squares, respectively) and for Cajas (green circles and squares, respectively). These altitudinal relationships were estimated using the average $\delta^{18}O$ and *d*-excess of the Páramo sites. The elevation of the monitoring stations is shown on the *x*-axis. Lower elevations correspond to the east direction (e.g., Atlantic Ocean or Caribbean Sea) and higher elevations to the west direction (e.g., Talamanca range or the Andes). The distance travelled by the air masses from Bataan (located ~12 km from the Caribbean coast) to Chirripó is ~72 km and from Porto Velho to Cajas is ~1,800 km. $\delta^{18}O$ and *d*-excess error bars represent ±1σ

3.5 | Implications for future hydrometeorological research in the Páramo

In light of global change drivers (e.g., changes in climate and land use) rapidly affecting climate patterns—in particular at high-elevation tropical latitudes (Wright et al., 2017), our findings provide much-needed baseline information that can help delineate future hydrometeorological research in tropical montane ecosystems. This research can inform adaptation policies to mitigate the impacts of changes in the current water balance of the Páramo and the lowlands that depend on its water supply.

In Costa Rica, due to the location of Chirripó in the Central American Isthmus, rainfall variations are mainly associated with SST anomalies in the Pacific and Atlantic Oceans (Durán-Quesada et al., 2017; Maldonado et al., 2013). Under neutral ENSO conditions, for example, higher precipitation input is expected from air masses arriving from the Pacific Ocean to the Central American Páramo. This rainfall contribution could be related with the presence and intensification of convective systems caused by the "Chorro del Occidente Colombiano," known as the CHOCO jet, during the wet season in Costa Rica (Durán-Quesada et al., 2010; Durán-Quesada et al., 2017). In addition, with regard to SSTs in the region, a clear spatial and temporal positive (negative) correlation between SST anomalies in the Pacific Ocean (Caribbean Sea) and $\delta^{18}O$ of rainfall in Central America has been reported (Lachniet, 2009). Lately, it was also demonstrated that the intensification of the easterly flow during the last ENSO warm phase 2014–2016 modified the seasonal moisture supply from the Caribbean Sea due to the acceleration of the Caribbean low-level jet. This effect caused a redistribution of local moisture uptake/transport, and as a result, a systematic decrease in the *d*-excess of precipitation in the central mountainous region of Costa Rica (Sánchez-Murillo, Durán-Quesada, et al., 2016).

In the northern Andes, the Páramo is a sustained and reliable source of high quality water that helps supply urban, industrial, and agricultural water demands. As such, this ecosystem helps support the socio-economic development of major cities in the region such as Bogotá, Quito, Mérida, and Cuenca. In this region, the detected strong influence of the Amazon forest water vapour recycling contributing moisture to the southern Ecuadorian Páramo can pose an important constrain in the ecosystem's water production capacity. For example, increasing deforestation rates in the Amazonia could impact negatively the current recycling of moisture of the Amazon forest canopy, and hence, cause a decrease in the contribution of moisture to the Andean Páramo (Spracklen, Arnold, & Taylor, 2012). These changes will also likely modify the isotopic composition of the water vapour reaching the Páramo of the northern Andes. Likely observations due to the described changes could include, for example, more depleted isotopic ratios in the wet season, consistent with increases in run-off fractions and/or reductions in recycling through nonfractionating processes (Henderson-Sellers & McGuffie, 2006). Thus, the application of water stable isotope analyses can be used to track spatio-temporal changes of atmospheric water vapour contributions along the Andes.

4 | CONCLUSIONS

Our combined analysis of HYSPLIT air mass back trajectories and the temporal rainfall isotopic variations for the Central American Páramo (Chirripó) revealed the effective contribution of maritime moisture from the Caribbean Sea and the Pacific Ocean, with an enhanced contribution from the former due the influence of the north-east trade winds travelling over the central and south-eastern Caribbean Sea towards Chirripó. The contribution of recycled water vapour was rather limited at Chirripó due to the relatively short distance travelled by air masses from the Caribbean coast of Costa Rica to the study site. For the northern Andean Páramo (Cajas), our findings showed the predominant year-round contribution of recycled continental moisture originated from the Amazon forest as a result of the strong influence of the SALLJ on the transport of water vapour from the Amazon Forest to the southern Ecuadorian Páramo.

It is also worth highlighting that even though our analysis was conducted during a period with large SST anomalies in the eastern Pacific Ocean related to ENSO, our determined preferential air mass trajectories are generally consistent with other Lagrangian models applied to track patterns of moisture transport during non-El Niño conditions in nearby regions. Nevertheless, future research should be aimed to investigate whether our identified water vapour pathways and seasonal changes in the precipitation isotopic composition differ under non-El Niño conditions in the Páramo of Central America and the Andes.

Finally, we anticipate that the implementation and maintenance of long-term monitoring of rainfall stable isotopic composition at fine spatio-temporal resolution can become a reliable source of information to evaluate how changes in land use and climate could affect the variety of ecosystem and economic services provided by the Páramo and other high-elevation Andean and Central American ecosystems.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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