Reinterpreting Precipitation Stable Water Isotope Variability in the Andean Western Cordillera Due to Sub-seasonal Moisture Source Changes and Sub-cloud Evaporation

Lisa R. Welp\textsuperscript{1,2,3}, Elizabeth J. Olson\textsuperscript{1}, Adriana Larrea Valdivia\textsuperscript{4}, Juan Reyes Larico\textsuperscript{4}, Efraín Palma Arhuire\textsuperscript{4}, Lino Morales Paredes\textsuperscript{4}, Jonathan T. DeGraw\textsuperscript{1}, Greg M. Michalski\textsuperscript{1,2,3,5}

\textsuperscript{1}Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA; \textsuperscript{2}Purdue Center for the Environment; \textsuperscript{3}Purdue Climate Change Research Center; \textsuperscript{4}Centro de investigacion de contaminantes ambientales, Laboratorio LABINVSERV del Departamento de Química, Universidad Nacional de San Augustín de Arequipa, Arequipa, Peru; \textsuperscript{5}Department of Chemistry, Purdue University, West Lafayette, IN, USA.

Corresponding author: Lisa Welp (lwelp@purdue.edu)

Key Points

\begin{itemize}
  \item Daily rainfall in Arequipa, Peru was analyzed for stable water isotopes to study sub-seasonal precipitation sources and processes.
  \item Easterly moisture events produced isotopically enriched rainwater likely due to sub-cloud evaporation.
  \item During northerly moisture influence, intense rainfall occurred, and water isotopes shifted to more depleted values.
\end{itemize}
Abstract (150-word limit, 150 currently)
Precipitation in the arid Central Andean Western Cordillera is strongly sensitive to large-scale atmospheric circulation patterns which transport moisture from different source regions. As a result, the stable water isotopes of precipitation in this region have been difficult to interpret. We analyzed daily rainfall in the southern Peruvian city of Arequipa for water stable isotopes during the 2019 monsoon season to study sub-seasonal precipitation dynamics. At 2,300 masl elevation, most rain was sourced from easterly moisture transported over the Altiplano, and was isotopically enriched ($\delta^{18}$O = -5.2‰), likely due to sub-cloud evaporation. This was contrary to literature expectations that enriched isotopic values indicate Pacific moisture. During a two-week period of northerly moisture transport and intense rainfall, we observed rain stable water isotopes shifted to depleted values ($\delta^{18}$O = -10.3‰). This study provides new context for interpreting time- and elevation-varying moisture source influence in the Western Cordillera.

Plain Language Summary (149)
The extremely arid western Andean rain shadow receives approximately 100 mm of precipitation typically transported by strong Easterly winds at high altitudes from the Amazon basin over the Andes. Here, we examined daily rain amounts and oxygen and hydrogen isotopic ratios from a network of collectors in the southern Peruvian city of Arequipa at 2,300 meters elevation on the western flank of the Andes during the 2019 summer monsoon season (January – March). The isotopic signature of dominant easterly moisture transport was surprising enriched in heavy isotopes due to strong sub-cloud evaporation. Previously, enriched isotopic signatures have been interpreted as Pacific moisture influence. Shifting meteorologic conditions transported isotopically depleted northerly moisture into the area for two weeks including two days of intense rainfall, flooding, and landslides in several communities. Large-scale moisture transport in past climates may be studied through preserved isotopic proxies with this refined knowledge of isotopic signature controls.

Keywords
Precipitation, stable isotopes, oxygen isotopes, hydrogen isotopes, moisture source, Andes, flooding, orographic, South American Summer Monsoon, western cordillera
1. Introduction

The western rain-shadow of the Andes is an extremely arid region stretching from south central Peru through central Chile. Scarce water resources provide for millions of people, but infrequent extreme rainfall events cause flooding and landslides resulting in damage to infrastructure and loss of life (Bayer et al., 2014; Fraser, 2017; Rodríguez-Morata et al., 2018). Improved understanding of rain events can aid communities in future planning to manage critical water supplies and mitigate damage.

Central Andean precipitation is highly seasonal and largely confined to austral summer when the Inter-Tropical Convergence Zone (ITCZ) moves southward and trade winds transport Atlantic moisture across the Amazon. The Eastern Cordillera receives strong precipitation driven by orographic uplift of moist air from the Amazon basin (Garreaud, 2009). Much of the moisture is removed before reaching the Western Cordillera except when upper atmosphere easterly winds are strong (Garreaud et al., 2003; Garreaud, 2009). The Bolivian High, a persistent high-pressure system generally centered over the Andean Altiplano, affects the position and strength of easterly winds, varying precipitation distribution in the central Andes depending on its location (Lenters & Cook, 1997). Strong easterly winds at 200 – 350 hPa have been shown to be a good predictor of summer rainfall on the Altiplano and Western Cordillera (e.g. Garreaud et al., 2003; Garreaud, 2009; Segura et al., 2020; Vuille & Keimig, 2004). Westerly upslope transport of Pacific moisture is generally inhibited by cold upwelling coastal waters creating a low-level, persistent atmospheric inversion near 1000 masl (Garreaud, 2009; Rutllant, 2003), but may occur during warm ocean conditions (e.g. during El Niño, (Jordan et al., 2018)). Recently, Segura et al. (2020) identified meridional atmospheric circulation controls northerly moisture input to the central Andes. Influence of these moisture sources (easterlies, westerlies, and northerlies) on Western Cordillera rainfall vary on sub-seasonal and decadal timeseries.

Stable isotope ratios of precipitation (H$_2^{18}$O/H$_2^{16}$O and HDO/H$_2$O) are useful in examining moisture source changes driven by large-scale atmospheric circulation. For example, Eastern Cordillera studies have shown that during a strong South American Low Level Jet (SALLJ), a southward flow of low-level winds along the eastern Andes, that easterly winds also strengthen and high altitude precipitation is more depleted in the heavy isotopes (Guy et al., 2019; Vimeux
Precipitation isotopic variation in the Western Cordillera of the Peruvian Andes is less studied with few published datasets from southern Peru and northern Chile (Aravena et al., 1999; Aron et al., 2021; Bershaw et al., 2016; Fritz et al., 1981; Herrera et al., 2018; Jordan et al., 2018; Valdivielso et al., 2020). Processes controlling isotopic fractionation of vapor transport and precipitation in the Western Cordillera are poorly understood and the interplay between easterly, westerly, and northerly sources makes interpreting elevation gradients and inter- and intra-annual variability more complicated.

Here we use daily precipitation stable water isotopes to investigate the intra-seasonal precipitation formation processes in southern Peru. Understanding the roles of large-scale atmosphere and ocean circulation, the El Niño Southern Oscillation (ENSO), terrestrial moisture recycling, and sub-cloud evaporation in generating precipitation in this vulnerable region is important for future management of water resources and landslide hazards.

2. Methods

2.1. Description of Arequipa

Arequipa is the second most populated Peruvian city with over 1 million people and an area of ~3,000 km² (INEI, 2018). It sits at 2,335 meters above sea level at 16°23’S and 71°32’W on the central Andean Western Cordillera, ~120 km from the Pacific Ocean, and just east of the Coastal Cordillera (see Figure S1 for elevation transect). The arid climate has a brief wet season December through March. Mean annual precipitation and temperature are 96 mm and 15°C respectively (Weatheronline.co.uk., accessed 2019).

2.2. Rain collection

A network of twelve stations around the city (https://paccsha.org/map) collected daily rain samples in funnel-style rain gauges (Stratus, USA) from January through March 2019. Rain amounts were recorded, and samplers were emptied every morning near 8:00 am and filtered using 0.45-µm syringe filters (Fischer Scientific) into 10-ml polyseal glass vials. No mineral oil was used in these collectors to prevent evaporation because other water chemistry analyses were conducted. Samples were stored indoors, on-site, out of the sun, until late March when they were shipped to the lab and refrigerated awaiting isotopic analysis.
2.3. Isotope Analysis
Stable water isotopologues measured included H$_2^{16}$O, HD$^{16}$O, and H$_2^{18}$O. Proportions of each in precipitation are sensitive to the original moisture source location and conditions including temperature and relative humidity, transport history including the degree of rainout, cloud microphysics, in-cloud and sub-cloud properties, and evapotranspiration recycling (Dansgaard, 1964; Gat, 1996). In general, as an airmass loses water via precipitation, the precipitation isotopic ratios become more depleted in the heavy isotopologues. We report isotopic differences using delta notation, $\delta = (R_{\text{sample}}/R_{\text{VSMOW}} - 1)$, where R is the ratio of heavy to light isotopologue, H$_2^{18}$O/H$_2^{16}$O for $\delta^{18}$O or HD$^{16}$O/H$_2^{16}$O for $\delta^D$ and multiplied by 1000 to report in permil (‰). Negative values indicate a lower ratio of heavy/light isotopologues than the seawater standard VSMOW (Coplen, 1994).

We measured $\delta^{18}$O and $\delta^D$ using a Los Gatos Research (LGR) Enhanced Performance Triple Liquid Water Isotope Analyzer (T-LWIA-45-EP). Samples were injected ten times, discarding the first four to remove memory effects and averaging the last six injections. In-house water standards were used to correct the data to the VSMOW-SLAP scale. Reproducible injection sizes minimized the water concentration dependence of the analyzer, but a small correction was made using the USGS LIMS post-processing software. Analytical precision for repeated quality control samples was better than 0.2‰ for $\delta^{18}$O and 1.0‰ for $\delta^D$.

2.4. Supporting data:
2.4.1. Local weather data
Meteorologic data from a weather station at the Rodríguez Ballón International Airport at the city’s edge included 2-m daily maximum and minimum air temperature, relative humidity, and precipitation amount (Weather Online Data Center, https://www.woeurope.eu/). We estimated daily specific humidity using the daily relative humidity and the average of daily maximum and minimum temperatures. Coastal rainfall amounts were obtained from the Servicio Nacional de Meteorología e Hidrología del Perú (Senamhi) in Peru and the Dirección Meteorológica de Chile (Meteochile) in Chile.
2.4.2. Satellite data

Satellite estimates of regional half-hourly rainfall amounts were obtained from the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals (IMERG) final precipitation (level 3 V06) product on a 0.1 x 0.1-degree grid (Huffman et al., 2019). We averaged the daily rainfall for a small 0.2 x 0.2-degree area around the city from -16.45 to -16.55°S and -71.45 to -71.55°W and also a larger regional area from -16.05 to -17.05°S and -70.95 to -71.95°W. We examined patterns in the timing of daily rainfall by calculating totals for the mornings (7:30-14:00 local time), afternoons (14:30-18:30), and nighttime (19:00-7:00).

Daily mean sea surface temperature (SST) was obtained from NOAA’s High-resolution Blended Analysis, version 2, using AVHRR satellite data (https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html) (Reynolds, 2007). Mean values and anomalies relative to 1971-2000 were averaged over the region defined by -11 to -20°S and -70 to -78°W including the coastal regions of southern Peru and northern Chile.

2.4.3. Atmospheric reanalysis and transport models

We examined atmospheric winds and geopotential height from ERA-5 reanalysis (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5). Zonal and meridional winds over Arequipa were extracted at 300 mb at -16.25°S and -71.25°W. We compared ERA-5 coastal ocean SSTs screened using a land mask and averaged from 11.75°S to -20°S and -78.0 to -70.5°W with satellite observations. NOAA’s Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to run 48-hour back-trajectories using the Global Data Assimilation System (GDAS) meteorology.

3. Results and discussion

3.1. Mean rainfall amounts and isotope values

The rain collection network demonstrated how precipitation varied throughout the city reflecting small-cell convective precipitation patterns. Not all network stations recorded rain on the same days (Table S1). The maximum and minimum total three month rainfall reported by the network stations was 162 and 86 mm respectively, with a mean of 114 ± 24 mm (Table S2) similar to the
airport observation of 98 mm. Daily mean rainfall amounts for the airport and network stations are shown in Figure 1a and Table S1.

The 2019 amount-weighted means for δ\(^{18}\)O and δD were -7.1 and -45.9‰ respectively and 10.6‰ for deuterium excess in our study. Aron et al. (2021) also collected bimonthly rain samples in Arequipa and report similar 2019 weighted mean values of -6.7 and -40.1‰ for δ\(^{18}\)O and δD respectively. Similar values have been reported from the northern coast of Chile (2200 to 2880 m), ranging from -4.5 to -11.4‰ (Aravena et al., 1999; Fritz et al., 1981). Maximum and minimum daily average values in this study ranged from +2.2 and -13.2‰ for δ\(^{18}\)O, +13.3 and -97.6‰ for δD, and +17.3 to -9.6‰ for deuterium excess (Table S1). Aron et al. (2021) values ranged from -1.8 to -9.4‰ in δ\(^{18}\)O with the most negative collection on February 15, consistent with the pattern of variability we report here. Aravena et al. (1999) also measured event-level variability of summer precipitation δ\(^{18}\)O in northern Chile in 1984 (below 3,000 m) ranging from +4.1 to -9.2‰. Our samples fall along a δD versus δ\(^{18}\)O meteoric water line with slope 8.12 and intercept 10.57‰ (r\(^2\) = 0.98, Figure S2).

3.2. Synoptic-scale variability in rainfall and isotope values

Intra-seasonal variability of rainfall stable water isotopes within the city showed a coherent pattern of decrease in δ\(^{18}\)O and δD values in the middle of the record (referred to as middle period, Figure 1b and c). Daily mean (not amount-weighted) δ\(^{18}\)O and δD values from January 31–February 14 were -9.6 ± 2.2‰ and -70.1 ± 18.0‰ respectively and outside the middle period (referred to as early and late periods), they were -3.3 ± 2.2‰ and -18.3 ± 14.2‰ for δ\(^{18}\)O and δD respectively (Table 1). By contrast, there was no clear change in the deuterium excess (d-ex) values during the middle period (Figure 1d). Mean d-ex values from January 31–February 14 were 7.3 ± 3.3‰ and in the early and late periods, they were 8.3 ± 6.4‰ (Table 1). Daily air temperature and relative humidity measured at the airport are shown in Figure S3.
**Figure 1**: Timeseries of daily rain stable isotopes and amounts. (a) Daily rainfall amounts from the network mean and the airport. Network mean (b) δ^{18}O, (c) δD, and (d) deuterium excess (‰). Daily mean values are not amount-weighted. Error bars are standard deviations of all station values with rain on each day. Shaded bar denotes the middle period of the record with most negative δ^{18}O and δD water isotope values.
Table 1

Mean (mn) and standard deviations (sd) of 2019 daily rain stable water isotope values.

<table>
<thead>
<tr>
<th></th>
<th>δ^{18}O mn (%o)</th>
<th>δ^{18}O sd (%o)</th>
<th>δD mn (%o)</th>
<th>δD sd (%o)</th>
<th>d-ex mn (%o)</th>
<th>d-ex sd (%o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire record</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Jan 1 – 30 (early easterly)</td>
<td>-5.4</td>
<td>3.7</td>
<td>-35.2</td>
<td>28.9</td>
<td>7.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Jan 31 – Feb 14 (mid northerly)</td>
<td>-9.6</td>
<td>2.2</td>
<td>-70.1</td>
<td>18.0</td>
<td>7.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Feb 15 – Mar 9 (late easterly)</td>
<td>-3.6</td>
<td>2.3</td>
<td>-19.0</td>
<td>13.0</td>
<td>9.9</td>
<td>6.5</td>
</tr>
<tr>
<td>Early and late</td>
<td>-3.3</td>
<td>2.2</td>
<td>-18.3</td>
<td>14.2</td>
<td>8.3</td>
<td>6.4</td>
</tr>
</tbody>
</table>

GPM rain daily totals around Arequipa showed higher rainfall during January 31 – February 14 (Figure S4a). When separated by the time-of-day, there was an increase in nighttime rainfall (Figure S4b) suggesting increased stratiform activity during the middle period.

On February 7 and 8, daily rainfall from Senamhi and Meteochile show anomalous intense rainfall from Apalo, Peru through Calama, Chile (Figure S5). For example, the rainfall reported in Arica, Chile totaled 5.4 mm over these days while this desert city receives on average ~1.0 mm annually (https://climatologia.meteochile.gob.cl/application/historicos/datosNormales/180005#). Flooding and landslides were reported from many locations resulting in at least 13 fatalities, thousands of people displaced, and many more without electricity (Al Jazeera, 2019; Floodlist, 2019; PAHO, 2019). Given the synchronized timing, it is likely that rainfall throughout the region was caused by large-scale atmospheric conditions. ERA-5 total column water showed high moisture extending along the coast of southern Peru and northern Chile on February 6-8 (Figure S6) in the same area as anomalously warm sea surface temperatures (SSTs) (Figure S7).

3.3. Large-scale wind patterns and ocean conditions
ERA-5 zonal winds at 300 hPa above Arequipa showed strongest easterly winds during mid-to-late January and late February with weakening in early February (Figure S4c). During the middle period of the record, meridional winds were from the north (Figure S4c). ERA-5 vertically integrated moisture transport indicates a stronger SALLJ during the early and late periods of the 2019 wet season with small amounts of moisture leaking across the Andes in easterly flows (Figure 2ab). The convergence intensified at lower elevations nearer the coast during the middle period with northerly moisture influence which extended even further south during the February 7 – 8 intense rainfall period (Figure 2cd).

**Figure 2:** ERA-5 vertically integrated moisture transport (vectors) and divergence (shading) for the time periods: (a) early, January 1 – 30, (b) middle, February 15 – March 15, (c) late, January 31 – February 14, and (d) the intense rainfall period, February 7 – 8. Regions of convergence are indicated by negative divergence values in blue. Arequipa is marked with the yellow circle.

Large-scale circulation was influenced by the position of the Bolivian High (BH), which controls upper-level wind directions. The BH was south of Arequipa during the early period with northern-edge counterclockwise anticyclonic winds enhancing easterly flow above the study site. The BH moved northward from 22°S to 17°S during the middle period, positioning the western edge over Arequipa, enhancing northerly flow. The BH shifted westward to center on Arequipa during the late period (Figure S8). ERA-5 and HYSPLIT back-trajectories indicated a complex vertical wind structure. At 1000 hPa, coastal winds arrived near Arequipa from the south, at 850 hPa, from the northwest, and at 650 hPa, from the southwest (Figure S9). Back trajectories were
therefore sensitive to their initialization altitude. Figure S10 shows back-trajectories arriving at 2,000 and 5,700 m above the surface during rainy days with the higher initialization showing more easterly trajectories. Without accurate estimates of cloud height, it is difficult to determine which altitude is most appropriate to initiate back-trajectories.

Anonymously warm coastal waters in the middle period, 2-sigma greater than 1982 – 2019 variability, were confined close to the coast (Figures S7). Warm coastal waters are often associated with the positive phase of ENSO because of wind-driven suppression of cold-water upwelling. Weak El Niño conditions were present based on the Niño 3.4 and 1+2 indices (Figure S11).

3.4. Easterly influence during the early and late periods

Outside of the middle period, precipitation in Arequipa was isotopically enriched (weighted mean δ¹⁸O = -4.7‰) and strongly influenced by easterly Amazonian moisture transport according to ERA-5. Water vapor crossing the Andes from the east is expected to become progressively depleted as it moves farther from the source region. This makes it difficult for easterly influence to explain the more enriched isotopic values at lower elevations in the Western Cordillera, observed in our study and others, and increased westerly Pacific influence has been invoked (Bershaw et al., 2016; Valdivielso et al., 2020). Aron et al. (2021) used back-trajectory analysis to interpret annual mean rain water isotopes from Arequipa as a mix of enriched moisture from the Pacific and depleted moisture from the east. Earlier observations also assumed that enriched isotopic values indicated Pacific moisture influence (Aravena et al., 1999), and some event-specific observations confirmed Pacific moisture-sourced enriched precipitation along the coast (Jordan et al., 2018). Our 2019 synoptic observations challenge this previous interpretation that moisture transported from the Amazon basin to mid-elevation on the Western Cordillera is depleted and enriched moisture comes only from the Pacific.

Sub-cloud evaporation may modify the isotopic signature of easterly moisture observed in Arequipa. Daily environmental correlations within the early and later periods showed more positive δ¹⁸O values on days with smaller precipitation amounts and lower surface humidity which are consistent with increased evaporation influence (Table S3). Daily environmental
correlations of $d_{\text{ex}}$ also indicated evidence of sub-cloud evaporation (Table S4). Lower $d_{\text{ex}}$, a sign of increased evaporation influence, was significantly correlated with less negative $\delta^{18}O$, lower rainfall amounts, lower relative humidity, and higher surface air temperatures. Vertical profiles of atmospheric conditions from ERA-5 confirm easterly zonal winds above 500 hPa and very weak meridional winds (Figure 3ab), a confined cloud layer between 100 – 300 hPa (Figure 3c), and low relative humidity below the clouds (Figure 3d). Specific rain and snow water content was smaller in the early and late periods compared to the middle period (Figure 3e). Vertical soundings during wet conditions in Arequipa by Falvey and Garreaud (2005) validate model predictions of moisture transported in the upper atmosphere. The correlations of daily isotopic variability and the atmospheric vertical conditions support the hypothesis that sub-cloud evaporation modifies precipitation water isotope values of easterly moisture transported from the Altiplano to lower elevations of the Western Cordillera.

Despite these indicators of sub-cloud evaporation during easterly moisture influence, mean $d_{\text{ex}}$ values observed in Arequipa (mean $d_{\text{ex}} = 8.3\%_o$ during the early and late periods) were not exceptionally low as may be expected due to kinetic fractionation during evaporation. They were, however, lower than mean observations on the Altiplano which characterize up-wind precipitation: $d_{\text{ex}} = 15\%_o$ at Pamphuta in Aron et al. (2021) and $d_{\text{ex}} = 17\%_o$ at Oruro in Fiorella et al. (2015). Many processes influence $d_{\text{ex}}$ in this region in addition to sub-cloud evaporation including changing moisture sources, ice crystal formation in deep convection, condensation from upper troposphere water vapor, and airmass mixing which makes it challenging to identify a baseline $d_{\text{ex}}$ for unevaporated precipitation and to interpretate temporal variability (Aron et al., 2021 and references therein).
Figure 3: Vertical profiles of ERA-5 variables on pressure surfaces averaged for the Arequipa grid for rain-only model timesteps during the early, mid, late, and intense rain periods of 2019. (a) Zonal $u$-wind, (b) meridional $v$-wind, (c) cloud cover fraction, (d) relative humidity, (e) specific rain and snow water content sum. The model surface altitude is 605 hPa.

Relatively enriched precipitation water isotopes have also been observed on the leeward sides of other large mountain ranges including the Tibetan Plateau (Juan et al., 2020) and the Himalayas (Ren et al., 2017). The Qilian Mountains region near the Tibetan Plateau is also a transition region between monsoonal and arid climates. The spatial-temporal rain water isotope variability was found to be influenced by sub-cloud evaporation at low altitudes and local moisture recycling at high altitudes (Juan et al., 2020). Similar conclusions have been reached in the leeward side of the Himalayas where sub-cloud evaporation in this arid climate alters the stable isotopes in precipitation (Ren et al., 2017). The patterns are described as a pseudo-elevation effect where precipitation becomes more enriched at lower elevations on the leeside because of greater evaporation influence during the longer droplet descent distances from the clouds to the surface. These leeward mountain examples are evidence that sub-cloud processes can mimic spatial-temporal patterns observed in the Western Cordillera, without needing to invoke enriched ocean evaporation (Pacific moisture) influence at the study elevation.
3.5. Northerly influence during the middle period

Within the middle period of the record, a shift to moisture transport from the north resulted in relatively isotopically depleted rain (weighted mean $\delta^{18}O = -10.3\%$). Vertical profiles of atmospheric conditions from ERA-5 confirm that upper atmosphere northerly meridional winds appeared between 200 – 300 hPa while easterly zonal winds weakened. The cloud layer extended to lower altitudes, and the lower atmosphere was wetter (Fig 3cde). Daily $\delta^{18}O$ correlation within the middle period showed days with decreased specific humidity, perhaps indicating more upstream rainout, had more depleted $\delta^{18}O$ values (Table S3). The only significant correlation with d-ex was rainfall amount showing less evaporation isotopic influence at higher daily rainfall rates (Table S4). Insel et al. (2013) found that annual weighted mean isotope values were more negative with increasing proportions of back trajectories from the north. Insel et al.’s model prediction is consistent with our observations of the most isotopically depleted rainfall events originating from the northern moisture sources (Figure 2).

Depleted isotopic values from northerly moisture influence could be due to either rainout processes or a shift in storm type which is also known to influence precipitation isotopes (Aggarwal et al., 2016). An increase in stratiform relative to convective precipitation during the middle period may have also contributed to decreased precipitation water isotope values. Figure S4 shows that while afternoon precipitation was most common throughout the 2019 wet season, nighttime precipitation, consistent with stratiform precipitation events (Endries et al., 2018), increased in the middle period. The isotopic values of stratiform precipitation events tend to be more depleted than convective events because of differences in cloud dynamics, surface vapor entrainment, and hydrometeor growth (Aggarwal et al., 2016).

Segura et al. (2020) identifies an increasing influence of northerly moisture source input to the central Andes (-20 to -10°S, > 3,000 masl) since 2000. According to this mechanism, enhanced convection over the Western Amazon transports moisture originating over the North Atlantic through strengthened low-level northerlies. The ERA-5 patterns of moisture convergence (Figure 2), vertical profiles of moisture transport in 2019 (Figure 3), and the February 7 – 8 widespread coastal rainfall (Figure S5) are consistent with this hypothesis. The increased frequency of this atmospheric condition appears to have increased DJF rainfall in the central Andes (Segura et al.,...
If the February 2019 event is any indication, the frequency of high intensity rainfall under northerly moisture conditions should be examined further as a potential regional climate hazard.

3.6. Reinterpretation of Western Cordillera isotopic variability

There are conflicting interpretations of Western Cordillera moisture sources from atmospheric modeling and isotopic studies. The atmospheric models overwhelmingly indicate that the dominant moisture transport is from the east, via moist upper-atmosphere easterlies over high Andean elevations (e.g. Falvey & Garreaud, 2005). However, isotopic studies claim a significant contribution from westerly Pacific moisture influence due to enriched observations (e.g. Aron et al., 2021). Northerly moisture influence is not often discussed in previous studies, either because it has been overlooked or it has only recently become significant due to climate change induced increased convective atmospheric instability in the Western Amazon (Segura et al., 2020). The relative contributions of moisture sources from the east, west, and north certainly vary with time, elevation, and position in the western Andes.

The contributions of the pseudo-elevation effect via sub-cloud evaporation and northerly moisture sources complicate the interpretation of isotopic paleo-records. This study indicates that a trend towards isotopic depletion should not be interpreted as increased easterly influence because it could come from the north. Likewise, a trend towards isotopic enrichment does not necessarily correspond to increased Pacific moisture influence. The single year of observations analyzed here did not show clear Pacific influence, and therefore, we are unable to validate the isotopic influence of oceanic moisture at our study elevation.

Warm coastal SSTs occurred at the same time as northerly moisture transport, perhaps because weakened southerly surface coastal winds suppressed upwelling. Meteorologic studies of an intense 2015 rain event in the nearby Atacama identify warm SSTs as a driver of coastal rainfall (Barrett et al., 2016; Bozkurt et al., 2016). Ritter et al. (2019) also found that Atacama wet periods spanning the last 215 kyrs coincided with increased SST off the coast of Chile and Peru. Spatial-temporal variability in rain stable water isotopes during strong El Niño events should be
studied in more detail to better understand the connection between Andean precipitation and ocean SSTs.

4. Conclusions

Our results illustrate rainfall processes along the Western Cordillera mid-elevations. We showed that northerly moisture influence depleted precipitation water isotopic values in Arequipa. Furthermore, the isotopic composition of easterly Amazon moisture influence in Arequipa was more enriched than previously assumed, likely due to sub-cloud evaporation which increases at lower elevations in the Western Andes. The complex Andean topography presents challenges for interpreting water isotope signals in modern and proxy records, especially at mid-elevations with variable influence from north, east, and western moisture sources.

5. Acknowledgements

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