Precipitation variability and its relation to climate anomalies in the Bolivian Altiplano

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Precipitation variability over the Bolivian Altiplano is strongly affected by local climate and temporal variation of large-scale atmospheric flow. Precipitation is the main water source for drinking water and agricultural production. For this reason, a better understanding of precipitation variability and its relation with climate phenomena can provide important information for forecasting of droughts and floods, disaster risk reduction, and improvement of water management. We present results of an analysis of the austral summer precipitation variability at six locations in the Bolivian Altiplano and connections to climate variability. For this purpose, the variability of the summer precipitation was related to El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), Antarctic Meridional Mode (AMM), and Atlantic Multidecadal Oscillation (AMO). A statistically significant correlation between climate indices and precipitation was found in various spectral frequencies and power. The variability of the summer precipitation was associated with the climate indices using a band-pass filter, representing the signal at a particular period of time. For the ENSO, band-pass filtering was applied for Niño3.4 and Niño3 at band ~2–7 years, for NAO band ~5–8 years, and for AMM band ~10–13 years. The variability of summer precipitation was related to all studied climate modes by negative relationships. The physical explanation for this is first the dry air transported from the Pacific Ocean to the Altiplano during El Niño events. Second, NAO and ENSO are dynamically linked through teleconnections. Third, the intertropical convergence zone (ITCZ) shifts are northwards during the warm phases of AMM. These physical mechanisms lead to a reduced austral summer precipitation associated with positive phases of the ENSO, NAO, and AMM. The results can be used to better forecast precipitation in the Bolivian Altiplano and provide support for the development of policies to improve climate resilience and risk management of water supply.

KEYWORDS
AMM, AMO, austral summer precipitation, climate phenomena, ENSO, multivariate analysis, NAO, PDO, wavelet analysis

1 INTRODUCTION

More than 60% of annual precipitation fall during the summer months (DJFM) over the Bolivian Altiplano in association with the South American Monsoon (SAM; e.g., Lenters and Cook, 1999; Garreaud et al., 2003). The region presents a northeast–southwest decreasing precipitation gradient with the largest water body, Lake Titicaca, situated in the northern Altiplano, and the Uyuni salt flat in the south (Garreaud, 2009). Moreover, the inter-annual variability of
the summer precipitation is high. The relationship between inter-annual variability and atmospheric circulation has previously been investigated by, among others, Thibeault et al. (2012), Lenters and Cook (1999), Vuille (1999), and Garreaud and Aceituno (2001). These studies showed that easterly winds transport humid air from the lowlands east of the Altiplano to the region, while the prevalence of westerly winds inhibit moisture transport.

The Altiplano is located in the central part of the Andes mountain chain, and it is one of the largest high plateaus in the world (Figure 1). The Altiplano covers an area of approximately 200,000 km², with about two thirds of it in Bolivia. Agriculture is one of the major economic activities in Bolivia and more than 65% of the active population in the rural area work in this sector (INE, 2015b); however, only 9% of the Bolivian cropped surface area are irrigated (INE, 2015a). In the Altiplano, low precipitation is generally related with yield reductions, leading to shortages of food for humans and animals (Jensen et al., 2000; Garcia et al., 2007).

Precipitation variability in the Altiplano is related to a number of different climate phenomena and patterns, of which five major types are discussed in this paper. The most well-known climate phenomenon affecting the inter-annual variability of precipitation in the region is the El Niño–Southern Oscillation (ENSO; e.g., Thompson et al., 1984; Aceituno, 1988; Vuille, 1999). The ENSO is a periodical variation in sea surface temperature (SST) over the tropical Pacific Ocean, and it represents three phases: neutral, warm (El Niño), and cold (La Niña). The warm phase of ENSO is generally associated with dryer conditions of the tropical troposphere and changes in the upper-level zonal flow over the Altiplano, and the cold phase is associated with cooling and wetter conditions (Garreaud and Aceituno, 2001; Garreaud et al., 2003; Thibeault et al., 2012).

Another important phenomenon affecting inter-annual precipitation variability is the Pacific Decadal Oscillation (PDO). It is often described as a long-lived El Niño-like pattern (Zhang et al., 1997) that oscillates at multi-decadal scales (Mills and Walsh, 2013). In the past century, cold PDO phase was prevalent from 1890 to 1924 and from 1947 to 1976, in contrast warm PDO phase prevailed from 1925 to 1946 and from 1977 to mid-1990 (Mantua et al., 1997; Mantua and Hare, 2002). Rainfall anomalies in South America tend to be stronger (weaker) when ENSO and PDO phase coincide (differ) (Kayano and Andreoli, 2007). In South America, a decadal and inter-decadal variability of precipitation is related with PDO, which is similar to ENSO in spatial structure, but the amplitude of PDO is about the half (Garreaud et al., 2003; Thibeault et al., 2012). Other climate phenomena included in this study are North Atlantic Oscillation (NAO), Atlantic Meridional Mode (AMM), and Atlantic Multi-decadal Oscillation (AMO). The phases and signal variability of the climate indices ENSO, PDO, NAO, AMM, and AMO are described in Table 1.

The NAO is a fluctuation of atmospheric pressure at sea level between the Icelandic low and the Azores high (Walker and Bliss, 1932). The NAO presents a seasonal and inter-annual variability characterized by two phases, positive and negative (Mächel et al., 1998). The positive phase shows below-normal heights and pressure across high latitudes of the North Atlantic, and above-normal heights and pressure over the central North Atlantic. The negative phase is characterized by opposed anomalies of height and pressure to those that are shown during the positive phase. Both phases are associated with the variability of precipitation, temperature, and storms at the Atlantic Ocean and surrounding continents (Marshall et al., 2001).

The AMM is the predominant source of coupled ocean–atmosphere variability in the tropical Atlantic (Chiang and Vimont, 2004; Xie and Carton, 2004). The AMO is a North Atlantic surface temperature oscillation with a period of about 70 years described by Schlesinger and Ramankutty (1994) and named by Kerr (2000). While the AMM contains significant inter-annual variability, the AMO varies on multi-decadal timescales (Knight et al., 2005). The AMO variability is pronounced, and it displays warm (1930s–1950s, 1990s–present) and cool (1900s–1920s, 1960s–1980s) phases. The AMM and AMO are characterized by a variation of the SST
and consequently a shift of the climatological position of the intertropical convergence zone (ITCZ; Grossmann and Klotzbach, 2009; Marshall et al., 2001; Vimont and Kossin, 2007). The shift of the ITCZ is caused by warmer (cooler) SST and weak (strong) easterly wind flow in the northern (southern) tropical Atlantic (Chiang and Vimont, 2004; Smirnov and Vimont, 2011). From December to March, the ITCZ position and the formation of the Bolivian high result in a weak easterly flow at middle and upper troposphere over the Altiplano. This condition enhances the moisture transport into the Altiplano, and hence development of a rainy season during the austral summer (Garreaud et al., 2003).

As mentioned above, the summer precipitation plays an important role for water supply in the Altiplano region, and it is therefore important to assess precipitation variability. Moreover, knowledge of the mechanisms that affect precipitation variability in semi-arid regions improve seasonal forecasting. Thus, the aim of this study is to analyse the influence of the climate modes of variability such as the ENSO, PDO, NAO, AMM, and AMO on the austral summer precipitation over the Bolivian Altiplano. The focus of this study is the region within 15°–21°S where Copacabana, El Belen, El Alto, Patacamaya, Oruro, and Potosi Los Pinos are included. The study explores the physical mechanisms associated with precipitation variability connected to climate by examining the time frequency and spectral power of precipitation and major climate anomalies.

2 | DATA

Monthly indices of Niño3.4 and Niño3 (Rayner et al., 2003), PDO (Mantua et al., 1997; Zhang et al., 1997), NAO (Hurrell, 1995), AMM SST, and AMO (Enfield et al., 2001) were obtained from the US National Oceanic and Atmospheric site (NOAA, https://www.esrl.noaa.gov/psd). Monthly means were averaged seasonally for DJFM.

Monthly total precipitation from January 1948 to December 2016 at six locations in the Bolivian Altiplano: Copacabana, El Belen, El Alto, Patacamaya, Oruro, and Potosi Los Pinos were provided by the Bolivian National Service of Meteorology and Hydrology (SENAMHI, http://senamhi.gob.bo/index.php/sismet). The six precipitation stations are located in a semi-arid climate above between 3,700

TABLE 2  Precipitation time series description

| Station name     | Latitude  | Longitude  | Altitude | Annual mean (mm/year) | Standard deviation (mm/year) | Summer mean (mm/DJFM) |
|------------------|-----------|------------|----------|------------------------|-----------------------------|-----------------------|
| Copacabana       | 16°10’09” | 69°05’19” | 3,815    | 764                    | 266                         | 527                   |
| El Belen         | 16°00’59” | 68°41’52” | 3,833    | 599                    | 101                         | 408                   |
| El Alto aeropuerto| 16°30’37” | 68°11’55” | 4,071    | 400                    | 150                         | 265                   |
| Patacamaya       | 17°14’19” | 67°55’23” | 3,793    | 386                    | 101                         | 275                   |
| Oruro aeropuerto | 17°57’10” | 67°04’47” | 3,702    | 386                    | 124                         | 283                   |
| Potosi Los Pinos | 19°35’00” | 65°45’00” | 3,950    | 396                    | 181                         | 305                   |
and 4,070 m a.s.l. (Table 2). The highest is El Alto, located at 4,070 m. Copacabana, El Belen, and El Alto are located in northern Bolivian Altiplano, Patacamaya, and Oruro in the central part, and Los Pinos in the southern Altiplano. The choice of these stations was made due to data availability. Their locations are shown in Figure 1 and their coordinates in Table 2. Monthly precipitation was accumulated to hydrological annual data, from July to June, and seasonal data from December to March (DJFM) corresponding to the rainy season of the region.

El Alto and Oruro time series had no missing data. Copacabana, Potosi Los Pinos, and Patacamaya time series had less than 10% missing data, and Belen had less than 15% missing data. The missing data were replaced by a robust fitting regression method (Huber and Ronchetti, 2009) using spatially close time series. The robust fitting regression algorithm (Equation (1)) uses iteratively reweighted least squares that minimize the effect of outliers (Hampel et al., 1986).

Predicted precipitation = $\beta_1 + \beta_2$ neighbor’s precipitation + $\varepsilon$,

where the neighbour’s precipitation represents the spatially closest observed record. The $\beta_1$ estimates the intercept, $\beta_2$ estimates the slope, and $\varepsilon$ is the residual. The robust regression method minimizes the weighted sum of squares, where the given weight depends on the distance of the value to the fitted line, giving more weight to the values that are close to the fitted line. The bi-square objective function eventually levels off (for $|k| > k$), and declines as soon as $\varepsilon$ departs from 0, and equals 0 for $|k| > k$ (Equation (2)). The $k$ is a tuning constant that equals the standard deviation of the error times 4.685, and the standard deviation of the error is equal to the mean absolute deviation of the residuals from the median above 0.6745. The constant 0.6745 removes the bias of the estimate for normal distribution. The tuning constant is generally selected to produce 95% efficiency when errors are normal, and thus, avoiding effects of outliers.

$w_i = \begin{cases} 
(1 - (ui) \varepsilon)^2 & \text{if } |\varepsilon/k| < 1 \\
0 & \text{if } |\varepsilon/k| \geq 1
\end{cases}$

Data series from Santiago de Huata (longitude 68°48′37″W, Latitude 16°03′04″S), Potosí Aeropuerto (longitude 65°43′15″W, latitude 19°32′12″S), and Ayoayo (longitude 68°00′30″W, latitude 17°05′39″S), were used to replace missing data in El Belen, Potosí Los Pinos, and Patacamaya time series, respectively. Data spatially close to Copacabana were not found. For this reason, missing data here were replaced with monthly mean.

The Spearman’s rank correlation was statistically significant at the 0.001 level with 0.84, 0.92, and 0.89, between predicted and neighbour’s time series. The coefficient of determination for the robust regression was 0.68, 0.76, and 0.79 for El Belen, Potosi Los Pinos, and Patacamaya, respectively. The gaps where the neighbours’ time series are also missing were filled with the monthly mean of each time series. Prior to analyses, all seasonal data were standardized to zero mean and unit standard deviation.

### 3 METHODS

Different statistical procedures were used to investigate the inter-annual variability of the total DJFM precipitation and its relationship with ENSO, PDO, NAO, and AMM. First, precipitation data quality and homogeneity analyses were performed to remove effects of measurement inconsistencies. Second, principal component analysis (PCA) was used to filter data after standardization. Filtered data and climate indices relationships were quantified using maximum covariance analysis (MCA). Finally, wavelet analysis was used to investigate the time frequency space and power of influence of climate indices on precipitation variability.

#### 3.1 Multivariate analysis of precipitation

DJFM precipitation totals at Copacabana, El Belen, El Alto, Patacamaya, Oruro, and Potosí Los Pinos were filtered by PCA and their time series reconstructed keeping about 90% of their original variability to reduce noise. PCA was developed by Pearson (Pearson, 1901) and Hotelling (Hotelling, 1933). PCA reduces data dimensionality and concentrates variance into a small number of variables. All numerical computations were performed using the Matlab software.

The MCA isolates linear combinations of variables by maximizing the covariance. Here, the MCA was applied to the cross-covariance matrix among total summer precipitation and averaged climate indices for the same season. Details of MCA are given by Bretherton et al. (1992) and Wallace et al. (1992). Each MCA mode consists of a pair of singular vectors together with associated time series. The heterogeneous correlation for each MCA mode represents the correlation coefficients between the summer precipitation and the expansion coefficients for the climate modes. Eigen-vectors of each mode are orthogonal to other modes in the space domain. Thus, the coupling strength of two fields is represented by the correlation coefficients. Each mode represents a fraction of the totally explained variance. The singular vectors describe the patterns of the fields having a covariance equal to the singular value. Singular values are used to define the squared covariance fraction (SCF) used to compare the relative importance of the expansion of each mode (Bretherton et al., 1992; Uvo et al., 1997; Rana et al., 2012).

#### 3.2 Local precipitation variability

Continuous wavelet transform (CWT) was used to analyse non-stationarity of summer precipitation and climate indices.
Wavelet transform was introduced by Morlet (1983), Grossmann and Morlet (1984), and Goupillaud et al. (1984), based on invariance under the affine group, which allows decomposition of a signal into contributions from both time and space. The theory of wavelet transform is discussed by Torrence and Compo (1998). The CWT decomposes time series into time–frequency space, enabling the identification of dominant modes of variability and variation in time. Morlet wavelet was chosen for this study defined as

$$\psi_n(\eta) = \pi^{-0.25} \delta^{0.25} e^{-0.5n^2},$$

where $\omega_0$ is dimensionless frequency ($\omega_0 = 6$). And, $\eta$ is dimensionless time and it is defined as: $\eta = st$ where $s$ is the wavelet scale. The wavelet is stretched in time by varying its scale ($s$) and after normalization the energy equals one.

The CWT (Equation (4)) of a discrete time series $x_n$, with a constant time step $\delta t$ and $n = 0, \ldots, N - 1$ is defined as the convolution of $x_n$,

$$W_n^X(s) = \sqrt{\frac{\delta t}{N}} \sum_{n'=1}^{N} x_n^* \left[ \left( \frac{n' - n}{s} \right) \right],$$

where * denotes complex conjugate. The wavelet power is equal to $|W_n^X(s)|^2$, where $W_n^X(s)$ is the local phase. The power spectrum describes the temporal oscillations of the time series at the scale $s$. The estimation of power spectrum is defined as the time-averaged wavelet power spectrum or global wavelet power spectrum. As the wavelet is not completely localized in time, CWT presents edge artefacts called cone of influence (COI). In the COI is the area in which the wavelet power for a discontinuity at the edge decreases by a factor $e^{-2}$. So, the COI is the region of the spectrum where edge effects are important. In this study, the circular mean of the phase was quantified for the regions statistically significant at 5% level and outside the COI.

Time frequency spaces with common power and consistent phase relationships indicate a causality between the time series (Torrence and Compo, 1998). The information obtained from CWT for summer precipitation and climate indices was used to define the cross wavelet transform (XWT). Grinsted et al. (2004) described the theory and application of XWT. The XWT of time series $x^n$ and $y^n$ shows regions with high common power between two CWT, defined as $W_n^{XY} = W_n^X W_n^{Y*}$. As XWT gives complex values, it can be decomposed into amplitude and phase angles. The phase angles describe the delay between the two signals at time $t$ at scale $s$. The phase angles define the phase relationship. The phase arrows point to the right and anti-phase point to the left, $x$ leading $y$ by 90° point downwards, and $y$ leading $x$ by 90° point upwards. Identification of the frequency bands and time intervals where two time series co-vary is determined by the wavelet coherence (WTC; Torrence and Webster, 1999). The WTC does not necessarily have high power, but represents the coherence of XWT. Its definition is similar to the correlation coefficient but with a time and frequency space. The significance level of the WTC is defined using Monte Carlo methods, through estimation of significance by an order of 1,000 surrogate data set pairs. The phase angles of the WTC follow the same interpretation as for XWT.

Finally, a band-pass filter using the inverse CWT was applied to reconstruct the time series of the climate modes and precipitation for specific band periods of high power spectrum. Here, the analytic Morlet wavelet was used to define the inverse CWT. The reconstructed time series of summer precipitation and climate indices were correlated using spearman correlation to seek statistically significant relationships at 95% confidence level, and the variation of the precipitation explained by the climate indices was defined by the coefficient of determination (square of correlation) between reconstructed series.

### 4 RESULTS AND DISCUSSION

Higher annual precipitation is usually recorded for the northern Altiplano (Copacabana, El Belen, and El Alto). Monthly mean precipitation and variability shown in Figure 2 illustrate the peak of precipitation during austral summer months (Garreaud et al., 2003; Vuille and Keimig, 2004). This peak is more noticeable in the southern locations (Figure 2f). The summer months (DJFM) concentrate about 68% of the total precipitation in the north and 77% in southern Altiplano (Table 2).

#### 4.1 Multilinear relationship of precipitation and climate modes

Results from the MCA are presented in the heterogeneous correlation in Table 3. Together, the first two modes explain 77% of total variance (the first mode 51% and the second 26%). The third mode explains 14% of the total variance. However, this mode is not significant at 95% of confidence level and for this reason it was not considered for further analyses. The squared covariance factor (SCF) for the first mode represented 74%. This mode is characterized by Niño3.4, Niño3, and NAO, negatively correlated with summer precipitation at all stations. The negative correlation between ENSO and precipitation in the Altiplano has been explained by, for example, Garreau (2009) and Thibeault et al. (2012). The influence of NAO on precipitation is an interesting finding that can be explained by the dynamic teleconnections between ENSO and NAO (Huang et al., 1998; Li and Lau, 2012). The equatorial Pacific may influence the tropical Atlantic via exchange along the equator, which modulates the intensity of the rising branch of the Hadley cell over Central and South America (Marshall et al., 2001). The negative NAO phase occurs frequently during El Niño events, and the positive NAO during La Niña events (Li and Lau, 2012). The teleconnection between the ENSO and
NAO patterns suggests a similar response associated with precipitation variability.

The second SCF mode (19% of total variance) is characterized by a PDO negatively correlated and an AMO positively correlated with precipitation at Potosi Los Pinos. The ENSO and PDO have similar influence on precipitation variance (Andreoli and Kayano, 2005). This explains the negative correlation for the Potosi Los Pinos. The other stations display non-significant correlation. The second mode shows positive relationship between seasonal precipitation in Potosi Los Pinos and AMO. This means that wetter conditions in this region appear during AMO positive phases. This, however, contradicts previous research. The AMO warm phase is characterized by warmer SST anomalies in North Atlantic and a northwards displacement of the ITCZ (Kossin and Vimont, 2007) and thus should reduce tropical summer precipitation (Flantua et al., 2016). For this reason, a separate analysis of the relationship between seasonal precipitation and the climate indices was performed using wavelet analysis and time series reconstruction.

### Table 3

| Left heterogeneous correlation maps | Right heterogeneous correlation maps |
|-------------------------------------|-------------------------------------|
| Niño3.4 | Niño3 | PDO | NAO | AMM | AMO |
| Copacabana | El Belen | El Alto | Patacamaya | Oruro | Potosi Los Pinos | Niño3.4 | Niño3 | PDO | NAO | AMM | AMO |
| 1 | −0.32 | −0.20 | −0.28 | −0.24 | −0.24 | −0.32 | 0.30 | 0.33 | 0.06 | 0.26 | −0.14 | 0.01 |
| 2 | −0.05 | 0.01 | 0.24 | 0.01 | 0.22 | −0.29 | −0.10 | −0.08 | 0.33 | 0.09 | −0.10 | −0.34 |

### Figure 2

Total monthly, summer (DJFM) and annual precipitation for the six observed stations in the Bolivian Altiplano: (a) Copacabana, (b) El Belen, (c) El Alto, (d) Patacamaya, (e) Oruro, and (f) Potosi Los Pinos.
4.2 Wavelet analyses

Wavelet analyses were performed for climate indices and seasonal summer precipitation at the six studied locations. The CWT of summer precipitation shows a statistically significant power during about 1980 for all regions (Figure 3). In addition, high power is present during mid-1990s until about 2000 with statistical significance for Copacabana and El Belen. During the 1960s, statistically significant power is noticeable especially for Potosi Los Pinos. The difference as compared to the power spectrum at Potosi Los Pinos could be related to its location in the southern area of the Altiplano (see Figure 1), where annual precipitation is low compared to the northern region. Statistically significant wavelet power is present for the band ~2–8 years. El Alto and Oruro show high power for the band ~10–15 years. However, only CWT for El Alto presents statistically significant power. Only Patacamaya shows statistically significant power periods of 16–20 years. However, most of the power is inside the COI except about 1980.

The CWT results show that Niño3.4 and Niño3 represent statistically significant power for a band of ~2–7 years. The time periods when Niño3.4 shows a significant average variance at this scale is 1965–1974, 1981–1988, 1993–1999, and 2006–2011. This coincides with El Niño and La Niña years where anomalies represent large variability. For instance, strong El Niño years occurred 1982–1983 and 1997–1998. The PDO displays high power for band ~16–20 years, but most of this is inside the COI. NAO presents high power for the band ~6–8 years during the period 1960 to mid-1980s. This is in agreement with previous findings stressing an NAO highest power for a periodicity of 7.7 years (Rogers, 1984; Gámiz-Fortis et al., 2002; Feliks et al., 2010; Paluš and Novotná, 2011; Sen and Ogrin, 2016). NAO also shows statistically significant power in the band ~4 years during about 2010. The CWT for the AMM shows statistically significant power for bands of 2 and 10–13 years, during the period 1970s to mid-1980s. Finally, AMO shows relatively high power for a periodicity of ~20 years, but most of this is inside the COI. Schlesinger and Ramankutty (1994) claimed that the AMO has an oscillation of 65–70 years, but that band period is also inside the COI where edge effects cannot be ignored, and therefore the results in this area are unreliable.

The XWT was applied to find periods where climate indices and precipitation present common power, and it was compared with the WTC to quantify the local correlation of the time series. The XWT between ENSO (Niño3.4 and Niño3) and summer precipitation shows that the common features found in the CWT are significant at the 5% level (Figures S1 and S3, Supporting Information). All stations show statistical significance for power during ~2–5 years. The XWT of El Belen, El Alto, and Patacamaya also present significant common power in the band period ~5–7 years. The XWT phase angle within the 5% significant regions and outside the COI for Copacabana, El Belen, El Alto, Patacamaya, Oruro, and Potosi Los Pinos has a mean phase of 187 (±29), 161 (±24), 185 (±14), 145 (±46), 177 (±23), and 123 (±39) degrees (where ± is the circular standard deviation in degrees), respectively. This suggests that ENSO and precipitation are in anti-phase. However, the large standard deviation mainly for Patacamaya and Potosi Los Pinos indicates influence from climate indices as well. The WTC for the ENSO (Niño3.4 and Niño3) and precipitation shows statistically significant correlation for all locations, with arrows pointing to the left suggesting an anti-phase
relationship (Figures S2 and S4). The XWT between PDO and precipitation presents common power in the band ~18–22 years during 1975–1985, significant at 5% only for Patacamaya (Figure S5). For the same band, the CWT between PDO and precipitation shows common power for El Belen, El Alto, Patacamaya, and Oruro (Figure S6). However, most of the power is inside the COI, and therefore no further analysis was performed for this climate index.

The results of XWT between NAO and precipitation show high common power for the band ~5–8 years (Figure S7). During the 1960s the XWT presents common power for all locations, but with a statistically significant relationship only for Patacamaya. And, the CWT for the same time period is statistically significant for El Alto, Patacamaya, and Oruro (Figure S8). High power on the XWT is shown during the mid-1970s to the mid-1980s for the NAO and precipitation for El Belen, El Alto, Oruro, and Potosi Los Pinos, but with statistical significance only for El Belen. For that periodicity, the WTC shows statistically significant correlation for Los Pinos. The XWT mean phase angle within the 5% significant regions and outside the COI for the band ~6–8 years is 168 (±18) degrees for El Belen. The XWT mean phase angle for the band ~5–6 years is 182 (±8), and 204 (±11) degrees for El Belen and Oruro, respectively. The arrows pointing to the left for the XWT and WTC suggest an antiphase relationship between the NAO and summer precipitation.

For the XWT between the AMM and summer precipitation statistical significant power is evident in the band ~8–13 years for at all stations, except Copacabana (Figure S9). At this band period, the power of the WTC is statistically significant, except for Patacamaya (Figure S10). The XWT for the AMM and precipitation mean phase angle within the 5% significant level and outside the COI for the ~8–13 year band is 108 (±27), 158 (±12), 165 (±8), and 94 (±5) degrees for El Belen, El Alto, Oruro, and Potosi Los Pinos, respectively. Also here, we have evidence of an antiphase relationship indicated by arrows pointing left.

The XWT for the AMO and precipitation (Figure S11) shows high power for a band period of ~8–13 years, only significant for El Alto, where the mean phase angle within the 5% significant level and outside the COI is 220°. And the WTC for that band is significant for Copacabana, El Belen, El Alto, and Oruro (Figure S12). Also here, the arrows pointing left indicate an antiphase relationship. High power for the XWT and WTC is shown for the band ~16–22 years, but most of this power is inside the COI.

Despite a positive relationship between AMO and Potosi Los Pinos for the MCA (Table 3), the XWT for this location presents arrows pointing to the left, suggesting an antiphase relationship for the band ~8–16 years (Figure S11f). However, the arrows for the band ~2–4 years are pointing to the right, suggesting a positive relationship. In any case, the similarity between the patterns for this period is low and might be a coincidence. We conclude that longer records are needed for a more certain analysis. Like the AMM, the AMO is related to an anomalous meridional SST gradient in the tropics, and a meridional shift in the ITCZ location (Vimont and Kossin, 2007). Summer precipitation in the Altiplano is strongly negatively correlated with the AMM on decadal time scales (Figure S9), but this relation was not significant for AMO (Figure S11). We note that further analysis is needed to identify the physical mechanisms of the AMO variations, and associate the AMO and AMM, and summer precipitation in the Altiplano.

4.3 | Band-pass filtered reconstruction from the CWT

To analyse relationship between precipitation and climate indices, a band-pass filtered reconstruction of the time series was defined using the inverse of the CWT. For instance, Niño3.4 and Niño3 present high power in the band period ~2–7 years. Therefore, the summer precipitation, Niño3.4, and Niño3 time series were reconstructed for this band period (Figure 4). The ENSO (Niño3.4 and Niño3) and summer precipitation are negatively correlated. The correlation coefficients for Niño3.4 and precipitation, significant at 5% level, are −0.32, −0.36, −0.46, −0.39, and −0.26 for Copacabana, El Alto, Patacamaya, Oruro, and Los Pinos, respectively. And correlation coefficients between Niño3 and precipitation are −0.48, −0.32, −0.47, −0.63, −0.40, and −0.30 for Copacabana, El Belen, El Alto, Patacamaya, Oruro, and Los Pinos, respectively. All correlations are negative, confirming the hypothesis that ENSO has a negative relationship with precipitation in the studied region.

The variance of precipitation explained by ENSO was quantified using the coefficient of determination ($R^2$). The $R^2$ of reconstructed time series between Niño3 and precipitation for band ~2–7 years are 18, 10, 23, 33, 20, and 10% for Copacabana, El Belen, El Alto, Patacamaya, Oruro, and Los Pinos, respectively. In conclusion, Niño3 explains from 10 to 33% of the precipitation variance in the Altiplano. The precipitation variance in response to ENSO is larger in the central Altiplano (Patacamaya and Oruro).

The time lapse reconstruction for NAO and summer precipitation was applied for the band ~5–8 years (Figure 5). NAO presents a negative relationship with precipitation. This negative relationship, significant at 5% level, is significant for El Belen, El Alto, Oruro, and Los Pinos, showing a correlation coefficient of −0.25, −0.43, −0.30, and −0.49, respectively. And the $R^2$ for these time series are 10, 24, 15, and 29%.

Figure 6 shows the reconstructed time series of AMM and summer precipitation for the band ~10–15 years. The Spearman’s rank correlations, significant at 5% level, between AMM and precipitation for Copacabana, El Alto, and Oruro are −0.29, −0.32, and −0.36, respectively, with $R^2$ equal to 7, 16, and 18%. The negative relationship can be explained by the fact that during positive
AMM the ITCZ is displaced northwards (Kossin et al., 2010). This condition can cause drier conditions (less precipitation) in the studied region. These Atlantic modes are relevant considering their influence on the humid air transport from the low lands of Brazil and Bolivia to the Altiplano, and thus influencing the precipitation occurrence.

5 | CONCLUSION

Austral summer precipitation variability was analysed and related to large-scale climate anomalies. A negative correlation was identified between precipitation and ENSO. This means that less precipitation generally occurs during the ENSO warm phase. The influence of ENSO on precipitation
has been extensively studied previously, and these studies suggest the influence of other climate phenomena on climate variability as well. Considering this, other climate indices such as PDO, NAO, AMM, and AMO were investigated in this study. The findings suggest less rainfall during NAO and AMM positive phases, as a consequence of that ENSO and NAO are dynamically linked through teleconnections. Hence, a similar response is shown in association with the summer precipitation variability. Second, AMM positive phases represent drier conditions in the studied area due to the northwards shift of the ITCZ. This knowledge can be used to improve forecasting of seasonal precipitation.

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Conflict of interests

The authors declare no potential conflict of interests.

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