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ENSO PHENOMENON PERSPECTIVES AND MONITORING FOR THE NORTH AND CENTRAL ALTIPLANO OF BOLIVIA: THE 2026-2027 EL NIÑO

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ABSTRACT

The El Niño-Southern Oscillation (ENSO) is an irregular ocean-atmosphere interaction that develops, on average, every 3 to 7 years in the Pacific Ocean and is one of the main drivers of interannual climate variability in the Andean region. This work synthesizes the ENSO monitoring and classification criteria used by the Japan Meteorological Agency (JMA) and the United States National Oceanic and Atmospheric Administration (NOAA), reviews the available evidence on its relationship with the climate of the North and Central Altiplano of Bolivia, and contrasts this historical evidence with the forecast outlooks available for the 2026-2027 El Niño event. To this end, monthly series of precipitation, maximum temperature, and minimum temperature (1976-2025) from seven stations of the National Meteorology and Hydrology Service (SENAMHI) were analyzed. Monthly synoptic classification of sea surface temperature (SST) anomalies of Kung and Chern (1995) for the developing event was compared with that of previous very strong El Niño events. As of May 2026, SST anomalies close to 2 °C were recorded in the Niño 1+2 region and close to 1 °C in the other regions; by July, these anomalies exceeded 3 °C in the Niño 1+2 region and reached 2 °C in Niño 3.4, with more than a 90% probability, according to NOAA, that the event will reach the very strong category between September and December 2026. The synoptic classification of the event (type C) coincides with that of 1982-1983 and 2015-2016, years in which the Altiplano recorded seasonal drought between December and March, cold anomalies of minimum temperature between December and January, and wet anomalies toward April. It is concluded that the ENSO-precipitation relationship in the Altiplano is weak and indirect, and is influenced by other factors such as the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO), among others; therefore, monitoring of the developing event must integrate synoptic analysis, multi-model ensembles, and ancestral knowledge within early warning systems, particularly given the absence of a simple relationship between the magnitude of the forcing and the magnitude of the local impact.

Keywords: ENSO, Bolivian Altiplano, PDO, NAO, climate risk management.

1. INTRODUCTION

The El Niño-Southern Oscillation (ENSO) is an ocean-atmosphere interaction that occurs, on average, every 3 to 7 years in the Pacific Ocean. This irregular cycle typically begins between March and July, lasts about 12 to 18 months, and reaches its peak intensity between October and January. Although ENSO was previously defined as a continuous, self-sustained cyclical oscillation (Gu & Philander, 1995), this view was superseded by several later studies, including Kessler (2002), which posits ENSO events as a succession of independent episodic events.

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Conceptually, ENSO is not a strictly regular cycle, owing to its asymmetric evolution between its El Niño and La Niña phases. This asymmetry is evident in the disparity of sea surface temperature (SST) anomaly intensities and spatial patterns, as well as in the temporal development of the events. This variability reflects nonlinear ocean-atmosphere coupling dynamics and stochastic forcings such as westerly wind bursts (An et al., 2020). Its warm phase (El Niño) is associated with a weakening of the trade winds, the displacement of warm water masses to the eastern Pacific, suppression of the thermocline (the boundary between cold deep water and warm surface water) in the eastern Pacific, and weakening of the Walker Circulation, which in turn exponentially fuels further weakening of the winds; its cold phase (La Niña) shows the opposite behavior (Bjerknes, 1969; Gu & Philander, 1995).

The study of this phenomenon has a long history. It originated with empirical observations by fishermen in northern Peru and southern Ecuador, who identified a warm ocean current that tended to appear around December — near Christmas — and called it El Niño, in reference to the Christ Child (Martinez, 2020). Walker (1920) described the Southern Oscillation and, together with Bliss (1932), documented its link to the Indian monsoon. Bjerknes (1969) established the physical relationship between the two phenomena, linking the oceanic and atmospheric components and giving rise to the concept of ENSO (Cane, 1983). The 1982-1983 event consolidated the phenomenon's scientific and media relevance owing to the unprecedented magnitude of its impacts — at the time — on infrastructure, agriculture, and fishing activity in Peru, Ecuador, Bolivia, and the rest of South America (Glantz, 2001; Quinn et al., 1987).

1.1. ENSO classification and monitoring

Because ENSO involves the ocean and atmosphere, its monitoring began with the Southern Oscillation Index (SOI), defined as the sea-level pressure difference between Tahiti and Darwin. Currently, SSTs are monitored in four regions of the equatorial Pacific, defined through various studies (NCAR, 2026): Niño 1+2 (used to track the coastal Niño that impacts Peru and Ecuador), Niño 3, Niño 3.4, and Niño 4. The JMA (Japan Meteorological Agency) uses the Niño 3 region to define ENSO, while NOAA (National Oceanic and Atmospheric Administration) uses the Niño 3.4 region; both institutions consider the ±0.5 °C threshold to classify an event as Neutral, El Niño, or La Niña. Classification indices have been redefined over time: NOAA recently incorporated the RONI (Relative Oceanic Niño Index) to replace the ONI (Oceanic Niño Index), to remove the influence of long-term global warming and improve the ability to track the phenomenon.

Table 1. Conceptual differences in the definition of an El Niño/La Niña event

Criterion	(JMA) Japan	(NOAA) United States
Index used	JMA Index	RONI Index (formerly ONI)
Monitoring zone	Niño 3 (Eastern Pacific)	Niño 3.4 (Central Pacific)
Time window	5 months (moving average). Seeks very stable changes.	3 months (moving average). More sensitive to abrupt changes.
Effect of Climate Change	Does not account for global warming.	Accounts for global-warming noise by subtracting the warming of the entire tropics, to ensure that the anomaly is solely due to El Niño.
Months required for classification	6 consecutive months	5 consecutive months

Source: Prepared by the authors

Using a different approach, Takahashi et al. (2011) defined the E and C indices through an empirical orthogonal function (EOF) analysis of monthly SST anomalies from the HadISST database, based on the two main modes of variability. The E-index is primarily associated with extreme warming events concentrated in the eastern Pacific, whereas the C-index relates to moderate cold or warm events in the central Pacific. Using these indices, Cai et al. (2020) identified the 1982-1983 and 1997-1998 events as very strong El Niño episodes, expressed mainly in the E-index, while the 2015-2016 event manifested simultaneously in both the E-index and the C-index.

Kung & Chern (1995), for their part, developed a classification of SST anomalies based on cluster analysis, identifying seven synoptic patterns (A through G) that group the spatial behavior of such anomalies and allow for their visual identification, albeit with a certain degree of subjectivity. Types C, D, and F are related to El Niño events; C and F are the most similar to each other, although type F is associated with greater coverage of warm anomalies — generally between 1 and 3 °C — extending also into the North Pacific and the Atlantic Ocean. Type C is characterized by more intense warm anomalies concentrated along the equatorial Pacific, typically exceeding 3 °C (Lupo et al., 2008).

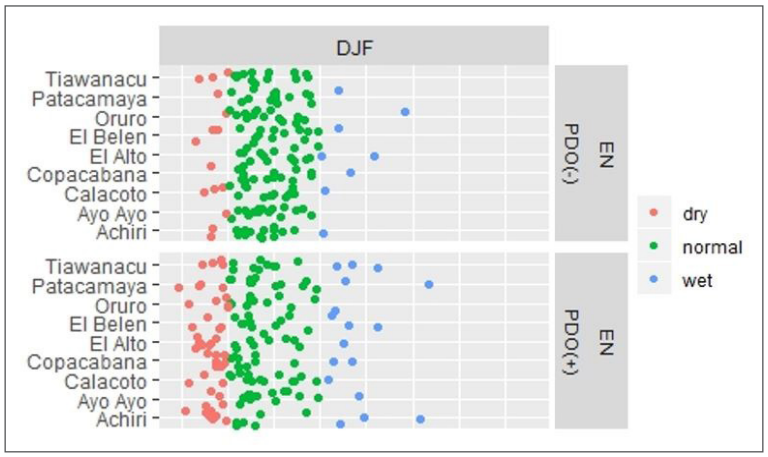
1.2. Precipitation climatology in the Altiplano and its relationship with ENSO

Around 80% of the Altiplano's annual precipitation falls between December and March (Andrade et al., 2018); this "wet season" depends strongly on the position and intensity of an upper-level anticyclone (200 hPa) known as the Bolivian High (BH). This high-pressure system is typically associated with divergent flows aloft, sustained by ascent linked to a surface low-pressure system (Krishnamurti et al., 2013). A more northerly position of the BH increases westerly wind anomalies and the occurrence of dry events, whereas a more southerly position favors precipitation in the region (Garreaud et al., 2003; Vuille & Keimig, 2004), owing to the BH's role in transporting moisture from the interior of the continent toward the Altiplano (Cai et al., 2020).

The relationship between ENSO and precipitation during the wet season in the Altiplano — located in the central Andes of South America — has been previously studied (Canedo-Rosso et al., 2019; Garreaud & Aceituno, 2001; Segura et al., 2019; Vuille & Keimig, 2004). These studies agree that the relationship between El Niño/La Niña phases and dry/wet anomalies is not direct and generally weak (Garreaud et al., 2003; Perry et al., 2017). Although dry anomalies in the Altiplano are associated with strengthened westerly winds at mid and upper levels of the atmosphere — which inhibit moisture transport from the east — and these winds tend to intensify during El Niño events, the relationship between ENSO and Altiplano precipitation remains weak (Garreaud & Aceituno, 2001). This is confirmed in the work of Canedo-Rosso et al. (2019), who evaluated the relationship between precipitation and the Niño 3 and Niño 3.4 indices, the NAO, and the Atlantic Meridional Mode (AMM), among others, through a Maximum Covariance Analysis (MCA); this study shows that the Niño 3, Niño 3.4, and NAO indices together explain the largest proportion of the covariance of Altiplano precipitation during Dec-Jan-Feb. Additionally, forcings such as the PDO (Pacific Decadal Oscillation) modulate ENSO impacts. Rojas-Murillo et al. (2022) show a greater number of dry standardized monthly precipitation anomalies during the positive phase of the PDO combined with El Niño during Dec-Jan-Feb. As of 2026, the PDO is in a negative phase, which, although also a scenario for dry anomalies, shows fewer of them; the same study shows that the BH is positioned, on average, farther north during El Niño events in the positive phase of the PDO, and shifts southward during the negative phase (Figure 1).

Another study also shows that a meridional temperature gradient at 400 hPa between 16° and 20° S could explain part of the precipitation variability during extreme drought events (Segura et al., 2019).

Figure 1. Classification of standardized precipitation anomalies (dry, normal, wet) at the North and Central Altiplano stations (SENAMHI) during the El Niño phase and the positive and negative phases of the PDO, for the December-January-February (DJF) quarter. The red dots show the number of years with dry anomalies, the green dots show years with little anomaly (normal), and the light-blue dots represent years with wet anomalies, by station.



Source:Adapted from Rojas-Murillo et al. (2022)

For the Bolivian Altiplano, understanding ENSO is critical because the region concentrates agricultural and livestock activities that are highly sensitive to precipitation variability and extreme events such as droughts, frosts, and floods. Knowing that the relationship between Pacific SST anomalies and Andean precipitation is neither simple nor direct, and that it is modulated by other climatic forcings (Canedo-Rosso et al., 2019; Rojas-Murillo et al., 2022), the objective of this article is to synthesize ENSO monitoring criteria, review its historical effects on the climate of the North and Central Altiplano, and contrast this evidence with the outlooks available for the 2026-2027 El Niño event.

2. METHODOLOGY

Monitoring of the development of the 2026-2027 El Niño event was conducted using official monitoring and forecasting sources (NOAA, JMA) as well as alternative statistical forecasting sources (International Research Institute for Climate and Society, Columbia Climate School-IRI). At the time of this review, these sources agreed that a very strong El Niño phase was expected toward the end of 2026.

Based on this, we analyzed previous events identified by NOAA as very strong El Niño events, also referred to by Cai et al. (2020): 1982-1983, 1997-1998, and 2015-2016. As a comparative baseline, monthly time series of precipitation, maximum temperature, and minimum temperature covering 49 years (1976-2025) were obtained from the database of Bolivia's National Meteorology and Hydrology Service (SENAMHI). The dataset includes seven stations located in the Northern and Central Altiplano, five of which provide records for all three variables, while the remaining two provide precipitation data only (Table 1). Monthly anomalies were calculated and standardized by dividing each anomaly by the corresponding climatological standard deviation for that month. This procedure removes the effect of differences in variability among months and expresses the magnitude of each anomaly relative to its typical seasonal variability (IRI, 2019). For each month, the 1991-2020 period was used as the climatological reference (WMO, 2017) to calculate the corresponding monthly mean and standard deviation. This approach allowed the identification of unusually warm, cold, or dry behavior compared with the 1991-2020 reference climatological conditions.

Table 2. Weather stations used in the analysis, available variables, and coordinates

Station	Tmax/Tmin	Precipitation	Lat. (°)	Lon. (°)	Altitude (m)
Achiri	—	X	-17.212	-69.002	3880
El Alto (Aeropuerto)	X	X	-16.510	-68.198	4037
Ayo Ayo	X	X	-17.093	-68.007	3888
El Belén	X	X	-16.019	-68.712	3833
Calacoto	X	X	-17.283	-68.634	3826
Copacabana	—	X	-16.169	-69.088	3815
Oruro (Aeropuerto)	X	X	-17.966	-67.079	3719

After reviewing the impacts associated with the selected very strong El Niño events, their monthly correspondence with the synoptic classification of Kung & Chern (1995) was examined, based on the archives of Lupo et al. (2008), classifying the anomalies recorded through 2016 and the months of 2026. This classification was used because of its application in lines of research on regional climate variability and seasonal forecasting: Lupo et al. (2007, 2008) extended the monthly classification archive through 2007 and linked it to the PDO; Birk et al. (2010) analyzed its relationship with temperature and precipitation in the Midwestern United States; and Henson et al. (2017) applied it to agricultural yield series.

Finally, a literature review of the impacts of El Niño events in the study region was carried out, identifying the work of Poma (2018), who — to analyze the factors influencing change in production systems — built timelines together with producers from communities in the North and Central Altiplano, to determine milestone events, including those of climatic origin, in the history of these communities.

3. RESULTS

3.1. Status and forecast of the 2026-2027 El Niño event

Regarding the ongoing monitoring of the 2026 ENSO event, forecasts from the major operational climate centers consistently indicate the development of a Strong to Very Strong El Niño event. In May 2026, NOAA's Climate Prediction Center (CPC) reported sea surface temperature (SST) anomalies of approximately 2 °C in the Niño 1+2 region and around 1 °C across the remaining Niño regions (CPC, 2026). By July, SST anomalies in the Niño 1+2 region had exceeded 3 °C, while anomalies in the Niño 3.4 region had reached approximately 2 °C. Based on these observed conditions and model projections, NOAA's August 2026 assessment indicated a probability exceeding 90% that the event would meet the Very Strong El Niño criterion (≥2 °C) during the September–October–November (SON) and October–November–December (OND) seasons. Similarly, the IRI plume forecasts (2026), which integrate projections from a range of statistical and dynamical models, indicated mean SST anomalies of approximately 2.5–3.0 °C for the OND season. Forecasts issued by the Japan Meteorological Agency (JMA, 2026) were broadly consistent with these projections, supporting the expectation of an exceptionally strong El Niño event during the latter part of 2026.

As an independent source of ENSO predictability, the statistical forecasting framework developed by Ham et al. (2019) was additionally considered. This framework employs convolutional neural networks (CNNs) to predict ENSO-related SST variability and provides forecasts through the Seoul National University AI Climate platform (aiclimate.snu.ac.kr/enso). The model projects an evolution broadly consistent with the operational forecasts issued by NOAA, with Niño 3.4 SST anomalies reaching approximately 3 °C during November–December 2026. Figure

2 shows the Niño 3.4 SST anomaly time series spanning 2024–2027. Observations are indicated by the black line, while the red line represents the forecast initialized in September 2025. The shaded envelope denotes the model's correlation skill as evaluated during the 1984–2017 validation period, thereby illustrating the model's predictive performance as a function of forecast lead time.

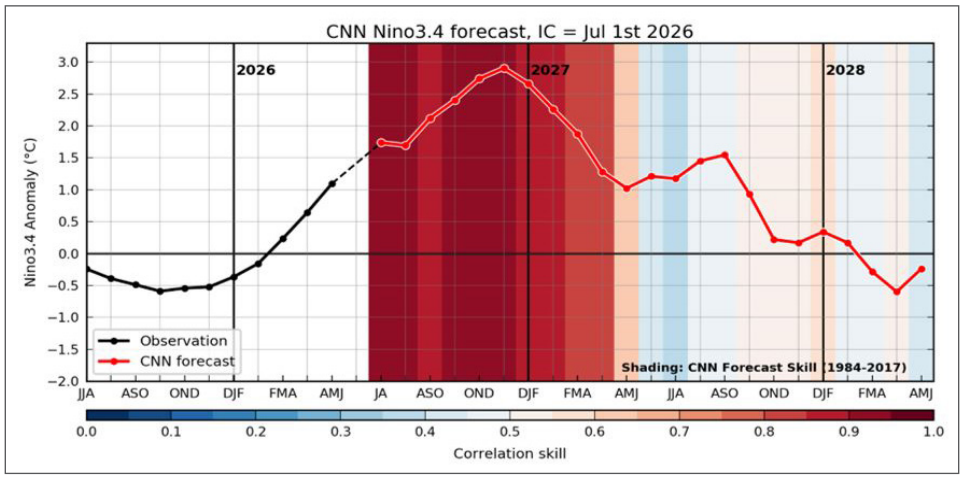


Figure 2. Forecast of the SST anomaly in the Niño 3.4 region using a convolutional neural network (CNN)

Source: ACE LAB (2026)

3.2. Synoptic classification of the developing event

Monthly mean SST anomaly maps for January-July 2026 were examined using the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalysis dataset[1]. In addition, SST anomaly maps from the Optimum Interpolation Sea Surface Temperature (OISST) dataset[2] were examined using the interactive animations provided by IRI[3]. The spatial evolution of the SST anomalies indicates that, during June and July 2026, the developing ENSO event exhibited a pattern broadly resembling synoptic type C described by Kung and Chern (1995), characterized by intense warm anomalies concentrated in the equatorial Pacific, exceeding 3 °C. To place the 2026 event in a historical context, monthly warming patterns from previous ENSO years were subsequently examined. A partially comparable spatial pattern was identified during the 1982-1983 and 2015-2016 events (Figure 3).

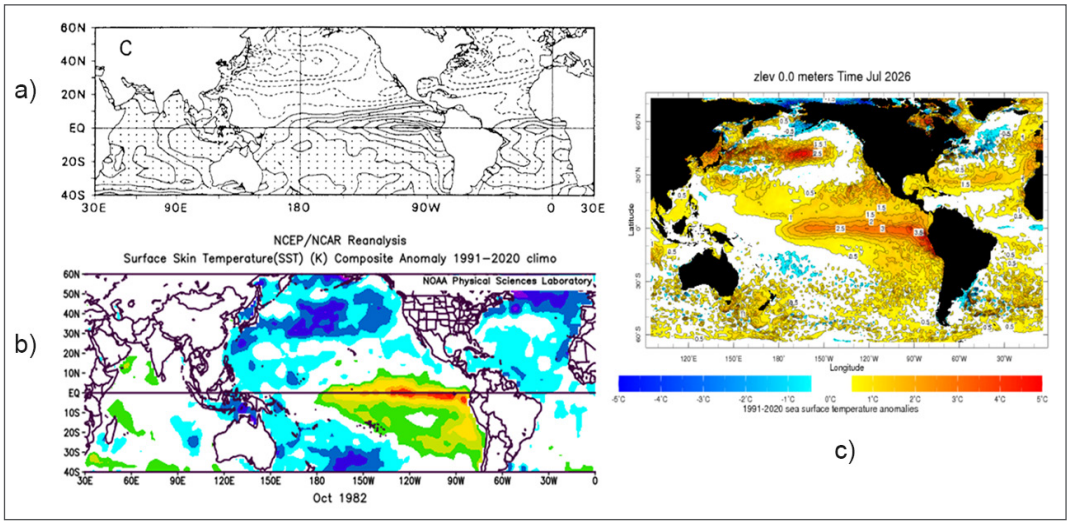


Figure 3. Comparison of SST anomalies:
(a) October 1982 (NCEP/NCAR Reanalysis, relative to the 1991-2020 climatology);
(b) reference type C synoptic pattern (Kung & Chern, 1995);
(c) July 2026 (1991-2020 climatology).

Source:
a) Kung Chern (1995),
b) NCEP/NCAR Reanalysis, c) IRI

[1] Available at https://psl.noaa.gov/cgi-bin/data/composites/printpage.pl [2]NOAAs 1/4-degree Daily Optimum Interpolation Sea Surface Temperature Version 2.1
[3] Available at https://iridl.ldeo.columbia.edu/maproom/Global/Ocean_Temp/Anomaly_Loop.html

Table 3 summarizes the monthly synoptic classification for the 1970–2016 period, compiled based on Lupo et al. (2008) and Kung and Chern (1995). In this classification scheme, types C, D, and F are associated with El Niño–type conditions. Type C occurs during several major El Niño events, including 1976–1977, 1982–1983, and 2015–2016. In contrast, the 1997–1998 event is predominantly classified as types E and F, with no occurrence of type C. For 2026 (Table 4), the classification indicates a rapid transition from types G and D, associated with negative SST anomalies, during the first quarter of the year to type C beginning in May and persisting through June. This transition coincides with the development of pronounced positive SST anomalies concentrated in the eastern equatorial Pacific, consistent with the spatial characteristics of type C.

Table 3. Monthly synoptic classification of SST anomalies (types A to G of Kung and Chern, 1995) for the 1970-2026 period, where types C, D, and F correspond to the El Niño classification. Type-C months and the reference years analyzed in this study are highlighted in color (prepared from Lupo et al., 2008).

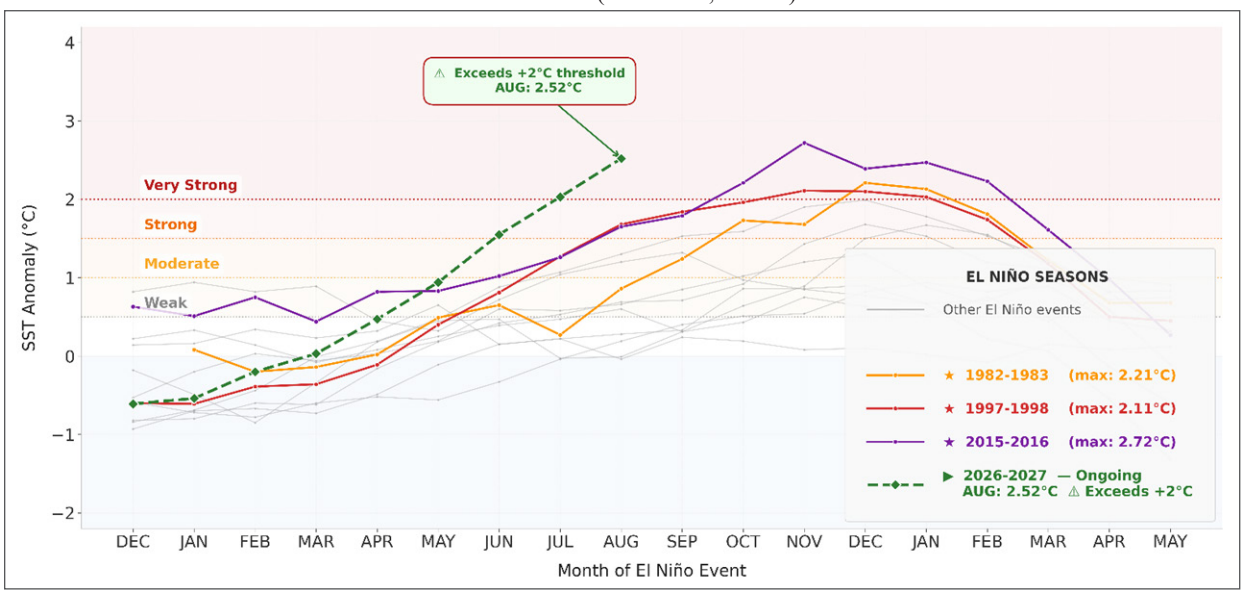
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970	C	C	C	C	C	C	C	B	B	B	B	B
1971	B	B	B	C	B	B	B	B	B	B	B	B
1972	B	B	B	C	C	C	C	F	C	C	C	C
1973	C	C	C	B	B	B	B	B	B	B	B	B
1974	B	B	B	B	B	B	B	B	B	B	B	B
1975	B	B	B	B	B	B	B	B	B	B	B	B
1976	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**C**	**C**	**C**	**F**	**F**
1977	**C**	**C**	**C**	**B**	**B**	**E**	**E**	**E**	**E**	**E**	**C**	**F**
1978	F	F	F	E	E	B	C	E	E	C	F	F
1979	C	C	C	C	C	C	F	F	F	F	F	F
1980	F	F	F	F	F	E	E	E	E	E	E	E
1981	F	F	F	C	C	E	E	E	E	E	E	E
1982	**E**	**E**	**E**	**E**	**C**	**F**	**F**	**C**	**C**	**C**	**C**	**F**
1983	**C**	**F**	**F**	**F**	**F**	**F**	**F**	**E**	**E**	**C**	**E**	**E**
1984	E	E	F	B	E	B	E	E	E	E	B	B
1985	B	B	B	B	B	E	E	E	E	E	E	E
1986	E	E	F	E	E	F	F	F	F	F	F	F
1987	F	F	E	E	F	C	F	E	F	E	F	F
1988	E	E	E	E	E	E	E	E	E	A	A	G
1989	G	G	G	G	F	F	E	E	E	E	F	F
1990	A	E	E	F	F	F	F	F	D	D	D	D
1991	D	F	F	C	C	E	E	E	E	F	F	F
1992	F	F	F	F	F	F	F	F	F	F	F	F
1993	F	F	F	F	F	F	F	F	D	F	F	F
1994	D	D	F	E	F	F	D	E	D	D	D	D
1995	E	E	E	E	E	E	E	E	E	E	E	E
1996	E	E	E	E	E	E	E	E	E	E	E	E
1997	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**F**	**F**
1998	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**G**	**G**	**G**	**G**	**G**
1999	G	G	G	G	G	G	G	G	G	G	G	G
2000	G	G	B	B	B	G	G	A	A	A	A	G
2001	G	B	B	B	G	G	G	G	G	A	A	A
2002	B	A	A	A	A	D	D	D	D	D	D	D
2003	D	D	D	B	B	A	A	A	E	E	A	A
2004	A	A	A	B	B	D	D	D	D	D	D	D
2005	D	D	D	B	B	B	B	A	A	A	A	A
2006	A	B	B	B	B	B	B	D	D	D	D	D
2007	D	A	G	G	G	G	G	G	G	A	A	G
2008	G	G	G	G	G	B	B	B	B	B	B	B
2009	B	G	G	B	B	F	F	F	F	D	D	D
2010	D	D	D	D	B	B	G	G	G	G	G	G
2011	G	G	B	B	B	G	G	G	G	G	G	G
2012	G	G	G	B	F	F	F	F	F	G	G	A
2013	A	B	B	B	B	B	G	G	G	G	A	A
2014	A	A	G	G	F	F	F	F	E	E	F	F
2015	**E**	**G**	**G**	**D**	**F**	**C**	**C**	**C**	**C**	**C**	**C**	**C**
2016	**F**	**F**	**F**	**F**	**F**	**G**	**G**	**G**	**G**	**G**	**G**	**G**

Table 4. Monthly synoptic classification of SST anomalies (according to Kung and Chern, 1995) for 2026

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2026	G	D	D	D	C	C						

A comparison of the SST anomalies observed during 2026 with those recorded during previous Very Strong El Niño events indicates a marked intensification of the current event. By August 2026, the SST anomaly had reached 2.52 °C according to NOAA OISSTv2.1 (Figure 4), exceeding the anomaly values recorded in July during the 1982–1983 and 2015–2016 Very Strong El Niño events. The increase in SST anomalies has been particularly pronounced since May 2026, indicating a sustained intensification of the warming signal throughout the end of the year.

Figure 4. Evolution of the SST anomaly (Niño 3.4 region) during 2026 compared with historical very strong El Niño events (OISSTv2.1, NOAA)



Source: Prepared by the authors

3.3. Precipitation, minimum temperature, and maximum temperature anomalies in analogous events

Given the similarity between the 2026 SST anomaly patterns and the type-C configuration, together with the classification of the ongoing event as Strong to Very Strong El Niño as of August 2026 (Table 2), the standardized anomalies of precipitation, minimum temperature, and maximum temperature were analyzed for the 1982–1983 and 2015–2016 events. The analysis was based on 24-month time series from meteorological stations located in the Northern and Central Altiplano (Table 1; Figures 5–7).

For both events, precipitation exhibited a recurring seasonal pattern characterized by negative anomalies from December through March (Figure 5), coinciding with the local wet season, followed by a transition toward positive anomalies in April. However, the magnitude and spatial distribution of the precipitation deficits varied substantially among stations and between events. In April, six of the seven stations with available precipitation records exhibited positive anomalies, indicating above-normal monthly precipitation. These positive anomalies may have resulted from intense precipitation events capable of producing surface erosion or degradation in areas previously affected by drought; however, this interpretation is beyond the scope of the present analysis.

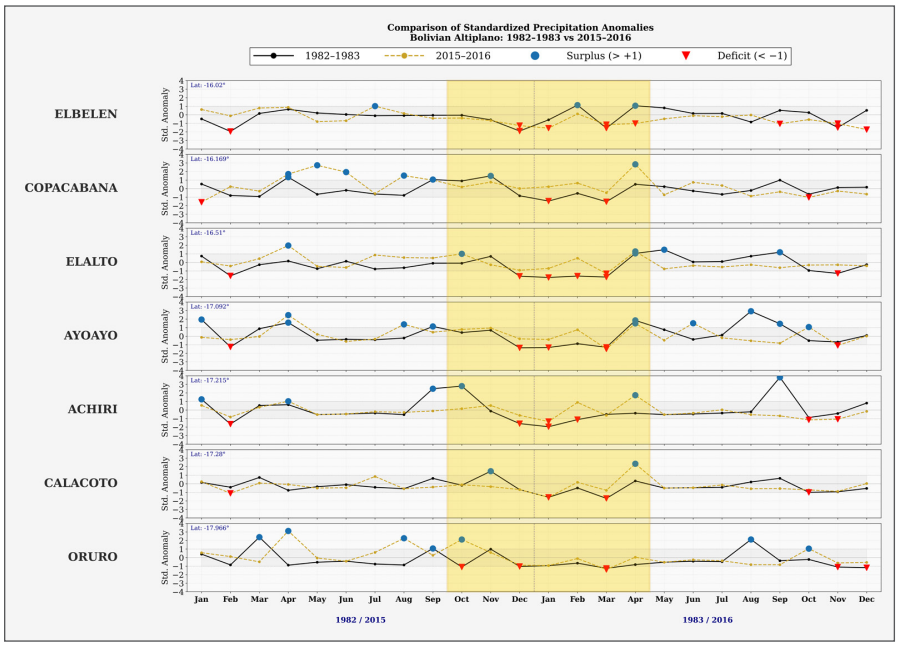
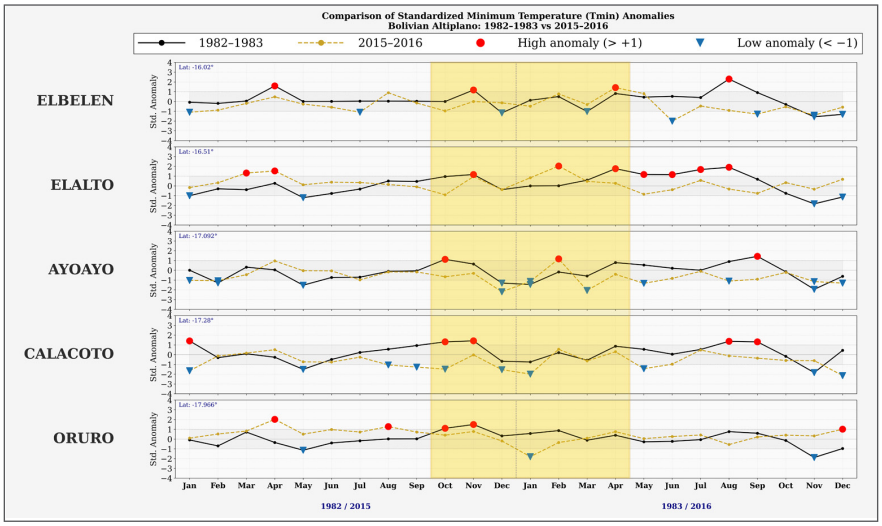


Figure 5. Standardized monthly precipitation anomalies at the North and Central Altiplano stations during the very strong El Niño events of 1982-1983 and 2015-2016. Red (blue) dots denote negative (positive) standardized anomalies below (above) one standard deviation, indicating a precipitation deficit (surplus) relative to the mean.

Source: Prepared by the authors

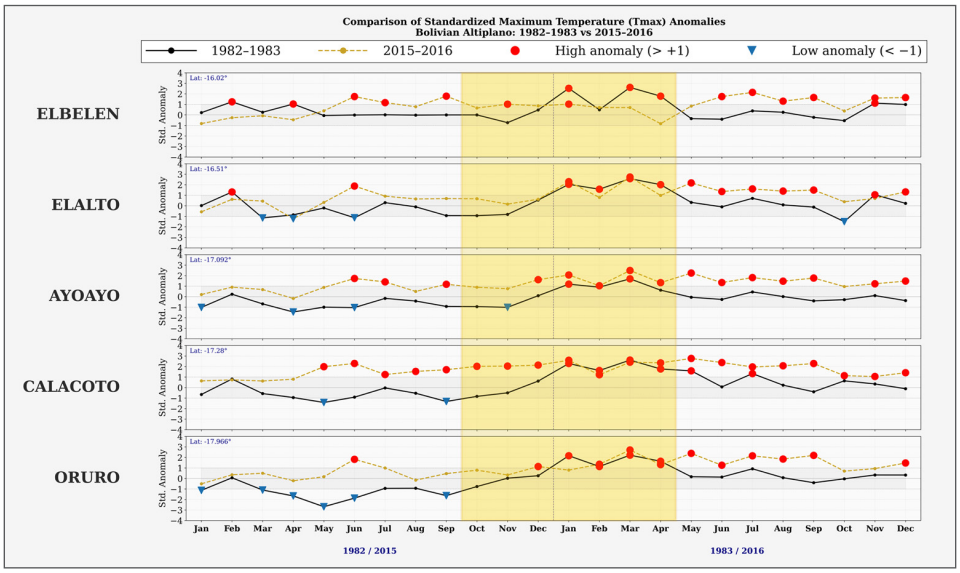
Regarding monthly minimum temperature, Figure 6 indicates negative anomalies between December and January, corresponding to periods of below-normal minimum temperatures that may be associated with an increased likelihood of frost occurrence. These conditions represent a potential environmental and agricultural risk, particularly during the local growing season, although the magnitude of their effects would depend on the intensity, duration, and timing of individual frost events and on the specific crops and phenological stages involved. In contrast, Figure 7 shows a persistent predominance of positive maximum temperature anomalies from October onward, consistently across the stations analyzed and throughout the subsequent year. This pattern indicates a sustained signal of above-normal monthly temperatures following the development of the El Niño events, mainly in 2015-2016.

Figure 6. Standardized monthly minimum temperature anomalies at the North and Central Altiplano stations during the very strong El Niño events of 1982-1983 and 2015-2016.



Source: Prepared by the authors

Figure 7. Standardized monthly maximum temperature anomalies at the North and Central Altiplano sta-tions during the very strong El Niño events of 1982-1983 and 2015-2016.



Source: Prepared by the authors

Taken together, the two Very Strong El Niño events examined show at least two to three months with dry anomalies during the typical rainy season, cold minimum-temperature anomalies between December and January indicative of conditions favorable for frost oc-currence, and wet anomalies in April. This latter may increase the potential for localized flooding and erosion following prolonged dry conditions. Since the type-C synoptic pattern has persisted through August 2026, similar precipitation and temperature responses may occur during the current event. However, this should not be interpreted as a deterministic forecast, given the unusually strong SST anomalies observed in 2026 and the inherent vari-ability of the atmospheric response.

3.4. Local perception of historical impacts

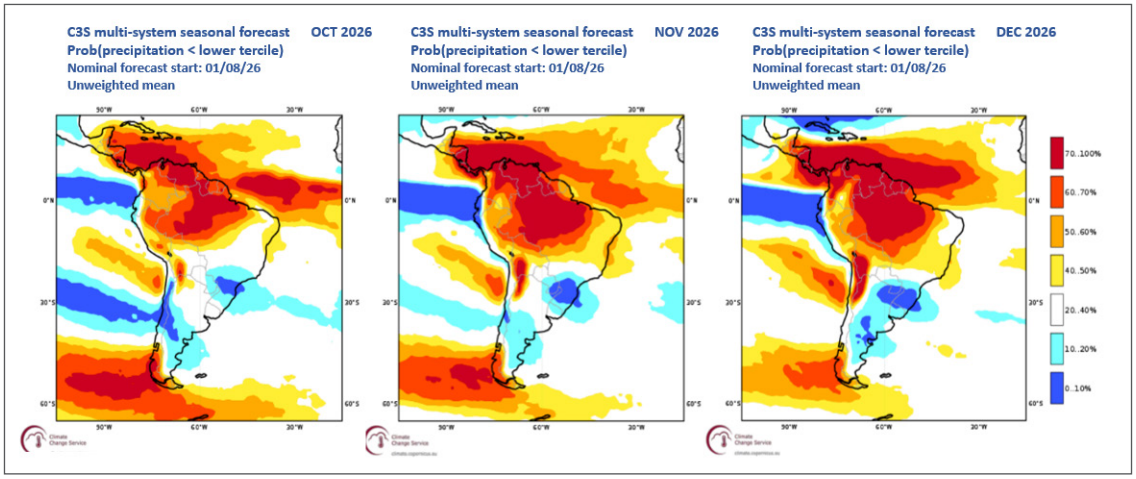
Poma (2018), using a timeline-based approach to assess drivers of change in production systems, reported that producers in the Central Altiplano identified drought conditions in 1983 and 2016, associated with forage losses, reduced potato production, and substantial out-migration. In the Northern Altiplano, respondents reported severe frosts in 1983 and intense drought conditions during 2014–2016. The co-occurrence of drought, frost, and subsequent wet conditions may help explain the magnitude of the impacts reported by pro-ducers in both regions, particularly in the context of Very Strong El Niño events and the occurrence of months characterized by the type-C synoptic pattern.

3.5. Multi-model seasonal outlooks for 2026-2027

Multi-model ensemble forecasts from C3S, CCSR/IRI, CIIFEN, and SISSA-NMME[1] show broadly consistent probabilities of below-normal precipitation for the October–November–December (OND) 2026 season. For the Central and Southern Altiplano, the projected probabilities range from 50% to 80%, with a tendency toward higher probabilities in December. In the Northern Altiplano, however, greater uncertainty is evident: C3S projects

a 40–70% probability of below-normal precipitation toward the end of the season, whereas CCSR/IRI indicates probabilities below 50%. For temperature, the models show greater consistency, with high probabilities of above-normal values across the study region (Figures 8 and 9).

Figure 8. Probability (%) of precipitation below the lower tercile according to the ECMWF's C3S multi-model system, for October, November, and December 2026 (forecast issued 08/01/2026).



Source: C3S multi-system precipitation 1-month
https://climate.copernicus.eu/charts/packages/c3s_seasonal/products/c3s_seasonal_spatial_mm_rain_1m?area=area13&base_time=202609010000&type=terc_lo&valid_time=202612010000

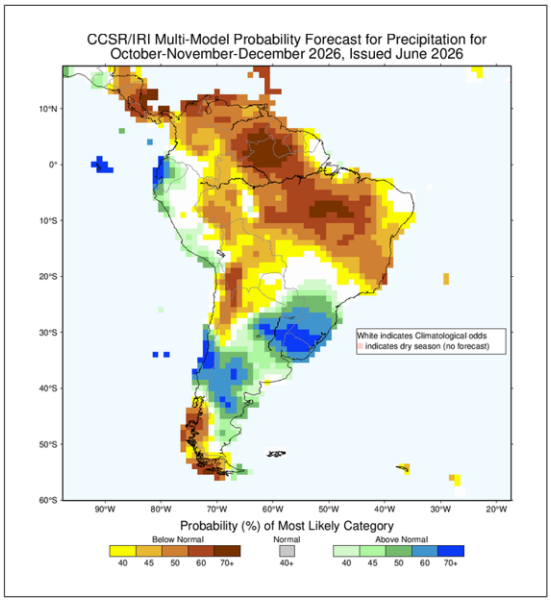


Figure 9. CCSR/IRI multi-model probabilistic precipitation forecast for the October-November-December 2026 quarter, issued in June 2026, for South America with a regional detail of the Bolivian Altiplano

Source: CCSR/IRI Multi-model probability forecast for precipitation
https://iri.columbia.edu/our-expertise/climate/forecasts/seasonal-climate-forecasts/

4. DISCUSSION

The results indicate that the relationship between SST anomalies and Altiplano precipitation is complex and non-linear (Garreaud et al., 2003; Perry et al., 2017). Both dry La Niña and wet El Niño conditions may occur, while individual events can also exhibit contrasting dry and wet periods. This variability reflects the strong spatial

heterogeneity of precipitation, changes in the latitudinal position of the Bolivian High, and variations in moisture transport from the east and north (Vuille & Keimig, 2004). Other climate modes, such as the PDO and NAO, may further modulate the regional response to ENSO (Mokhov et al., 2004; Canedo-Rosso et al., 2019).

The recurrence of the type-C pattern during the 1982–1983, 2015–2016, and 2026 events provides a basis for considering potentially analogous hydroclimatic responses, although the similarity in synoptic classification does not necessarily imply comparable impacts.

4.1. Corresponding between the Kung and Chern synoptic type and the E/C indices

Comparison of the Kung and Chern (1995) synoptic classification with the E- and C-indices proposed by Takahashi et al. (2011) suggests a conceptual correspondence, rather than a direct equivalence. Type C, characterized by intense positive SST anomalies concentrated in the central-eastern equatorial Pacific, broadly resembles the spatial structure of extraordinary eastern Pacific events identified by the E-index. In contrast, type F, which exhibits a broader extension toward the North Pacific and Atlantic, shows greater similarity to the spatial characteristics associated with moderate central Pacific events described by the C-index. Importantly, type E in the seven-cluster classification of Kung and Chern, which represents transitional conditions, is conceptually distinct from the E-index of Takahashi et al. (2011), despite the shared nomenclature. This distinction is necessary to avoid potential terminological confusion. Using the E-index, Cai et al. (2020) classified the 1982–1983 and 1997–1998 events as extraordinary eastern Pacific El Niño events of comparable magnitude, whereas the 2015–2016 event exhibited characteristics captured by both the E- and C-indices.

4.2. Why 1982-1983 and not 1997-1998: the weight of the spatial pattern over magnitude

This last point helps to partly explain, at least in part, why 1997-1998 did not reproduce the same impacts in the Bolivian Altiplano as 1982-1983, despite both being among the most intense El Niño events on instrumental record and sharing, in magnitude-based SST indices — such as the E-index (Cai et al., 2020) or the EP/CP scheme (Yu & Kim, 2013) — a classification as an extraordinary eastern Pacific event. In the monthly Kung and Chern archive reproduced in Table 2, the 1982-1983 synoptic pattern predominantly corresponds to types C and F — the same pattern observed in two months of the 2026-2027 event — while 1997-1998 is consistently classified as types E and F, with no expression of type C. This difference in the spatial pattern of the anomaly, rather than in its absolute magnitude, could partly explain why the Altiplano's drought and frosts in 1982-1983 were not replicated with the same severity in 1997-1998, and reinforces the argument that the Kung and Chern classification provides complementary — and in this case more discriminating — information than conventional ENSO magnitude indices for anticipating potential regional impacts in the Altiplano.

4.3. Limitations of the historical-analogue approach

The historical-analogue approach adopted in this study has several limitations. First, the small number of Very Strong El Niño events in the instrumental record (1982–1983, 1997–1998, and 2015–2016) limits the statistical robustness and generalizability of comparisons based on individual events. Second, the relationship between Pacific SST anomalies and Altiplano climate is potentially non-stationary. Long-term warming alters the SST baseline against which ENSO thresholds are defined, motivating the use of the Relative Oceanic Niño Index (RONI) alongside conventional indices such as the ONI. Consequently, spatial classifications such as that of Kung

and Chern may partly reflect both interannual variabil-ity and longer-term changes in the background climate state. Third, the comparison of 2026–2027 with the 1982–1983 and 2015–2016 events is currently based on the similarity of synoptic patterns observed through July. A more robust assessment will require extend-ing the analysis as the event evolves and incorporating forecast-verification products issued by NOAA, JMA, and IRI following the OND season. Finally, the 1997–1998 event war-rants further quantitative assessment, particularly through station-level comparisons of standardized precipitation and temperature anomalies with those observed during 1982–1983 and 2015–2016.

4.4. Integrating ancestral knowledge and formal forecasts

Multi-model ensembles provide greater confidence in the projected tendency toward be-low-normal precipitation and above-normal temperatures during the OND–NDJ seasons over the Central and Southern Altiplano. However, the coarse resolution of global forecasts does not fully capture the region's strong spatial variability associated with topography and regional circulation.

Local observations also reveal contrasting conditions: heavy snowfall on August 17–18 in the Central Altiplano was perceived by producers as favorable for near-average production, whereas limited snowfall in the Northern Altiplano supported a different assessment. These differences highlight the potential value of integrating local and Indigenous knowledge with model-based forecasts, particularly where model signals are weak or spatially incon-sistent.

4.5. Implications for risk management and adaptation

The co-occurrence of seasonal drought, frost events, and late-season wet anomalies identi-fied in the analogue events, consistent with the impacts reported by Poma (2018), suggests that climate-risk management in the Northern and Central Altiplano should account for se-quences of interacting hazards rather than isolated events. Potential adaptation measures could therefore be phased according to the seasonal progression of risks, including water and livestock-feed management during the December–March dry period, frost protection during December–January, and drainage and water-management measures in response to late-season wet conditions and potential flooding. Integrating these measures into early-warning systems, together with continuous monitoring based on synoptic classifications, multi-model forecasts, and local knowledge, may improve preparedness for compound and sequential hazards. More broadly, agroecological practices such as maintaining soil cover, integrating native tree species, using protected production systems, and applying soil amendments may contribute to strengthening the resilience of agroecosystems to climatic variability and associated economic impacts.

5. CONCLUSIONS

Based on the results presented, the following conclusions are proposed, organized from general to specific:

- The relationship between Pacific Sea surface temperature (SST) anomalies and precipitation variability in the Bolivian Altiplano is complex and not univocal. The regional response to ENSO may be modulated by other modes of climate variability, including the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO), whose influence may vary according to their phase. Their consideration in future analyses may therefore contribute to a more comprehensive understanding of the factors governing precipitation variability over the Altiplano.

- As of July 2026, the ongoing 2026–2027 El Niño event showed a marked intensification, with SST anomalies exceeding those observed during the corresponding period of previous Very Strong El Niño events (1982–1983, 1997–1998, and 2015–2016). NOAA forecasts indicated a probability exceeding 90% that the event would reach the Very Strong category between September and December 2026.

- The synoptic evolution of the 2026 event exhibits characteristics consistent with type C in the classification of Kung and Chern (1995), a pattern also identified during the 1982–1983 and 2015–2016 events. During these historical analogues, the Northern and Central Altiplano experienced negative precipitation anomalies between December and March, negative minimum-temperature anomalies associated with conditions favorable for frost occurrence between December and January, and positive precipitation anomalies toward April, potentially increasing the likelihood of localized flooding and erosion following prolonged dry conditions.

- The comparison with the 1997–1998 event, which was of comparable magnitude but predominantly classified as types E and F, with no occurrence of type C, indicates that the spatial structure of SST anomalies provides complementary information to conventional ENSO magnitude indices when examining potential regional impacts over the Altiplano. However, this interpretation should be further evaluated through quantitative comparisons across a larger set of events and stations.

- Multi-model ensembles from C3S, CCSR/IRI, CIIFEN, and SISSA-NMME indicate probabilities of 50–80% for below-normal precipitation during the October–November–December (OND) 2026 season over the Central and Southern Altiplano, together with a consistent signal of above-normal temperatures across the region. Greater uncertainty is evident in the Northern Altiplano, where the models provide contrasting probabilities of dry conditions. Local observations also indicate regional differences: producers associated the snowfall observed in August with the possibility of delayed rainfall in the Northern Altiplano, whereas in the Central Altiplano it was interpreted as potentially consistent with near-average seasonal conditions. These observations highlight the value of considering local information alongside model-based forecasts, particularly where model signals are spatially inconsistent.

- Taken together, these findings highlight the potential value of strengthening early-warning systems in the Northern and Central Altiplano through an integrated framework combining synoptic classifications, statistical and dynamical forecasts, and local and Indigenous knowledge. Such a framework could support differentiated preparedness and adaptation measures addressing seasonal water deficits, frost occurrence, and late-season wet conditions. Rather than being implemented solely in response to individual El Niño events, these systems should operate continuously to account for the substantial interannual variability and the occurrence of multiple and sequential climate hazards.

- As an immediate research priority, the 1997–1998 event should be incorporated into the comparative analysis through station-by-station standardized precipitation and temperature anomaly series, following the approach applied to the 1982–1983 and 2015–2016 events. This analysis would provide a quantitative basis for testing the hypothesis that the spatial structure of SST anomalies contributes to differences in Altiplano hydroclimatic responses beyond the effect of ENSO magnitude alone.

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