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Extreme Droughts and Their Relationship with the Interdecadal Pacific Oscillation in the Peruvian Altiplano Region over the Last 100 Years

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Abstract: The Peruvian Altiplano Region (RAP) is a high plateau area surrounded by the Western and Eastern Andes mountain ranges. This study examines the relationship between extreme droughts in the region and the interdecadal Pacific Oscillation (IPO) over the past century. Previous research has shown that precipitation patterns in the region follow a decreasing trend, with systematic increases in precipitation on the western slope and decreases in the eastern, southern, and central parts. The temporal and spatial variability of precipitation in the Altiplano region is influenced by the easterly moisture flux and the interaction between the El Niño Southern Oscillation (ENSO) and below-average values. The study utilizes water level data for Lake Titicaca and IPO data from 1914 to 2015. The analysis employs wavelet transform and empirical orthogonal function (EOF) techniques to identify the relationship between water levels and IPO. The results indicate multidecadal variability in water levels associated with El Niño/La Niña events and the IPO. The negative phase of the IPO aligns with extreme drought periods, suggesting a connection between the IPO climate index and drought events. The EOF analysis shows a moderate positive correlation between water levels and IPO. The findings highlight the importance of considering IPO and its interaction with ENSO in understanding drought patterns in the Altiplano region. However, other atmospheric conditions also influence precipitation in the region. The study contributes to a better understanding of the factors affecting water levels and droughts in the Peruvian Altiplano, with implications for water resource management in the region.

Keywords: extreme droughts; interdecadal Pacific Oscillation (IPO); Peruvian Altiplano Region (RAP); precipitation patterns; El Niño Southern Oscillation (ENSO); Lake Titicaca; water levels; wavelet transform; climate variability

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1. Introduction

The Peruvian Altiplano Region (RAP) [1] is a high plateau area situated at an altitude above 3810 m (Figure 1). It is surrounded by the Western and Eastern Andes mountain ranges and is drained primarily by a river system that includes Lake Titicaca (LT), as well as the Poopó, Coipasa, and Uyuni basins. Precipitation patterns in the RAP exhibit a tendency to decrease, although there are no clearly defined patterns [2,3]. However [4], observed trends indicate systematic increases in precipitation on the western slope of the RAP, while decreases are observed in the eastern, southern, and central parts of the slope. According to Garreaud (2000) and Garreaud and Aceituno (2001) [5,6], the temporal and spatial variability of precipitation in the Altiplano region is influenced by the easterly moisture flux and the interaction between the El Niño Southern Oscillation (ENSO) and below-average values. The influence of ENSO on reducing precipitation in the Altiplano region during the rainy season has been identified [7,8]. Previous studies [9–14] have demonstrated the interaction between ENSO events (La Niña/El Niño) and the precipitation regime (positive/negative) in the Altiplano region. For the southern region of Lake Titicaca [15,16], the temporal and spatial variability of precipitation in the southeast to southwest direction of the Altiplano basin has been shown, establishing its relationship with the equatorial sea surface temperature (SST). Additionally, studies [17–20] have indicated the strong influence of the South American Monsoon (SMAS) on precipitation at a large scale.

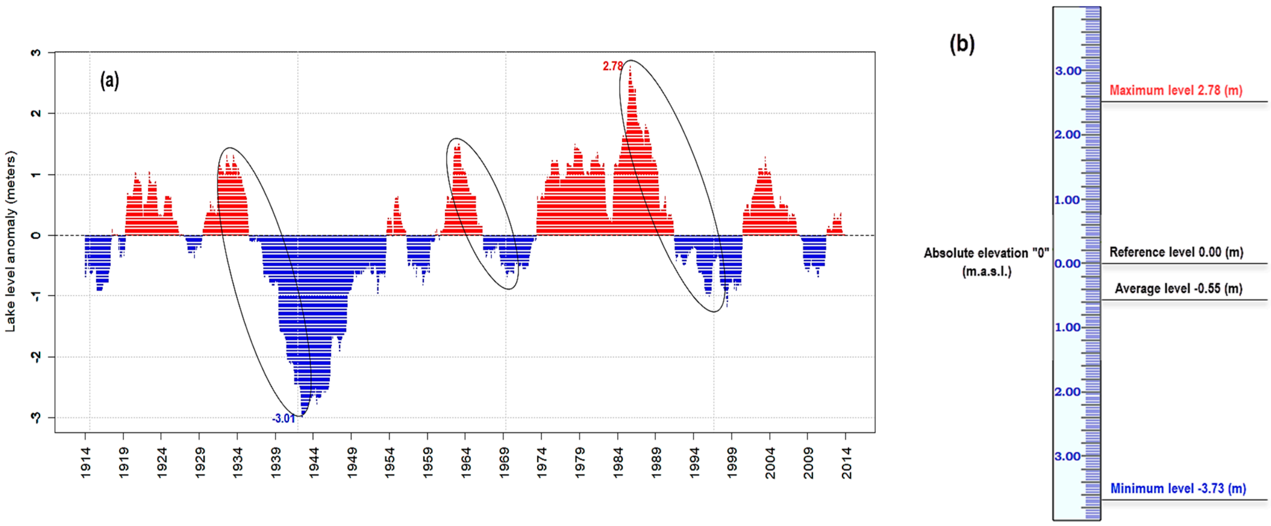

Figure 1. (**a**) Water level anomalies in Lake Titicaca. The regions in blue represent negative anomalies, while the regions in red represent positive anomalies. The regions in black lines represent periods of extreme drought. (**b**) Reference levels represented on the limnimetric scale.

Interdecadal Pacific Oscillation (IPO)

Research has revealed the relationship between the interdecadal Pacific Oscillation (IPO) and the interdecadal variability in sea surface temperature (SST) [21–28]. Historical SST records indicate periods of cold regimes during 1909–1925, 1944–1976, and from 1998 onwards, as well as warm regimes during 1925–1944 and 1976–1998 [29].

The connection between ENSO and the low-frequency modulation of the IPO has been explored in studies [29–34], demonstrating that the warm (positive)/cool (negative) phase of the IPO can strengthen El Niño events and weaken La Niña events. Similarly, [35] associated the cold (negative) phase of the IPO with reduced rainfall on the northern coast of Chile (18–30°S).

On the other hand, [36] observed a warm (positive) phase in the IPO series from 1970 to 2000, coinciding with extreme El Niño events in 1982–1983 and 1997–1998 [37–40], resulting in severe droughts in the PAR and a reduction in the water levels of Lake Titicaca. Despite extensive studies on the influence of ENSO and IPO on the spatial–temporal distribution of rainfall in the Altiplano region, the gradual decrease in the water levels of Lake Titicaca in recent years is a significant concern. According to SENAMHI-PERU statistics and [8,41], the water level of Lake Titicaca displayed substantial variations throughout the 20th century (Figure 1a), with a difference of up to 5 m between the extremes of 1944 (−3.01 m) and 1986 (2.78 m) (Figure 1b). Similarly, several authors [38–40,42–46] have identified the following periods (1934–1944, 1964–1970, and 1986–1999) as years of extreme drought based on the definitions of meteorological, agricultural, and hydrological droughts; these periods are shown in Figure 1a.

2. Data Sets and Methods

In this study, we utilized monthly water level data for Lake Titicaca spanning the period from 1914 to 2015. The data were sourced from the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI). Furthermore, we obtained Pacific Interdecadal

Oscillation (IPO) data for the same time frame from the Hadley Center, Meteorological Office, UK (http://cola.gmu.edu/c20c/, accessed on 27 July 2023).

2.1. Wavelet Transform

The fluctuation of water levels in Lake Titicaca, whether positive or negative, is directly linked to the presence or absence of precipitation in the region. To investigate the temporal variations, whether gradual or sudden, and the symmetric or asymmetric distribution of precipitation, we can employ the Morlet wavelet [47–49]. The Wavelet Transform (WT) allows for the decomposition of the time series into various levels of time–frequency resolution, facilitating the identification of dominant variability components within the data [50].

According to Andreoli et al. (2004) [51], the Morlet wavelet can be described as a complex exponential function modulated by a Gaussian function (Equation (1)), where $\eta = t/s$. Here, t represents time, and s corresponds to the wavelet scale as a function of time ($= 2/dt$). Additionally, w_0 denotes a non-dimensional frequency ($lag1 = 0.7$). For this study, we have adopted the value proposed by Andreoli et al. (2004).

$$\psi(t) = e^{iw_0\eta}e^{-\eta^2/2} \tag{1}$$

2.2. Empirical Orthogonal Function (EOF)

Empirical Orthogonal Function (EOF) analysis, also known as Principal Component Analysis (PCA), is a widely utilized statistical technique in climate and atmospheric sciences to examine spatiotemporal patterns in data. The concept of EOF analysis was initially introduced [52] as a means to decompose complex atmospheric fields into orthogonal patterns representing different temporal variability. Subsequently, [53,54] provided a mathematical framework for EOF analysis, elucidating its mathematical properties and its relationship with the Eigen decomposition of covariance matrices. Hannachi et al. (2007) [55] highlighted the application of EOF analysis in climate studies, particularly for model evaluation and comparison. Furthermore, Wilks (2019) [56] explored the potential use of EOFs in weather and climate forecasting, demonstrating their efficacy as predictors for long-range predictions.

To analyze the relationship between water levels (WLs) and the interdecadal Pacific Oscillation (IPO) using EOFs, we considered a monthly time scale spanning from September 1914 to July 2018.

3. Results

3.1. Wavelet Transform Analysis of WLs

The water levels (WLs) were analyzed using the wavelet transform on a monthly scale from 1914 to 2017. The results obtained from this technique reveal variability on a multidecadal time scale of 20 to 30 years. In Figure 2, the red contours represent the negative phase (decrease) of the WLs, which exhibit the highest energy in the Wavelet Power Spectrum (EPO). This energy is concentrated in the multidecadal variability associated with El Niño/La Niña events, as indicated by the period axis.

During the period from 1934 to 1944 (Figure 1), the WLs experienced a negative phase, resulting in a decrease of 4.816 m in water, equivalent to 455 million m^3. Similarly, from 1986 to 1996, the WLs decreased by 4.430 m (424 million m^3). Both periods align with the IPO (highlighted as the red-colored region in Figure 2) on the multidecadal time scale, suggesting a relationship with the IPO climate index. According to [57], mega-drought events (prolonged droughts lasting several decades) are associated with persistent time-scale SST anomalies in the tropical Pacific, specifically negative anomalies of the IPO. The negative phase of the WLs during the driest period (1934 to 1943) coincides with the strongest phase of the IPO (Figure 2).

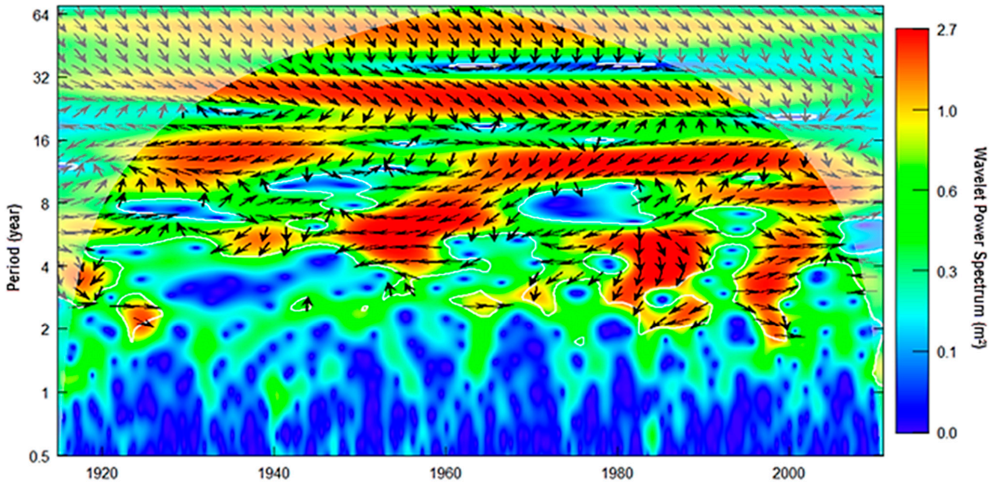

Figure 2. The Wavelet transform analysis was conducted on the WLs series after removing trends and seasonality from the data. The analysis covers the period from 1914 to 2017. The color scale in the results represents the global energy spectrum. The black arrows represent the orientation of high-frequency details and the presence of specific patterns in the water level anomalies signal.

3.2. EOFs between WLs and IPO Index

The correlation coefficients between EOF1 for the WL data and the IPO for the period from September 1914 to July 2018 were as follows: CP1 (0.55) and CP2 (0.45). The first component explains 55% of the total variance, and the coefficients of the eigenvector primer, 0.7071068 and 0.7071068 (CP1), are equal and both positive, indicating a strong positive correlation. This suggests that the first principal component, PC1, is a weighted average of both variables, capturing the common variability between the WLs and IPO. Figure 3 illustrates the time series of PC1 and the WLs from September 1914 to July 2018. Positive (negative) values of PC1 correspond to the warm (cold) phase of the IPO and the increase (decrease) in the WLs. The warm phase of the IPO from 1979 to 1999 was characterized by extreme El Niño events and some weak La Niña events, which could be associated with the presence or absence of precipitation in the region. Similar findings were reported by [31,36,58]. In Figure 3, a phase shift between the IPO values and the WLs is observed. According to [41], this would be determined by the balance between water inputs and losses.

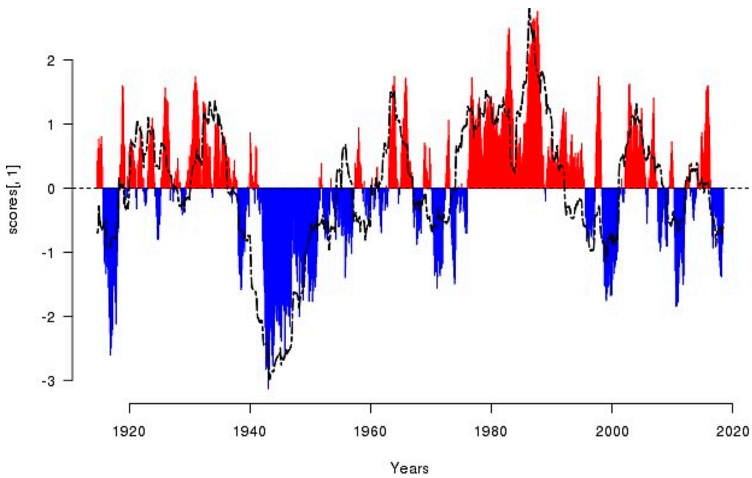

Figure 3. Water level anomalies (black dotted line) and the PC1 time series for the periods 1914/09 to 2018/07. The correlation coefficient between WLs and the IPO was 0.71; the positive (negative) values are associated with the warm (cold) phase of the IPO and directly related to the decrease (increase) in WLs.

4. Discussion

WLs in the region experienced a negative phase during the periods from 1934 to 1943 and from 1986 to 1996. These negative phases resulted in significant decreases in water levels, equivalent to 455 million m^3 and 424 million m^3, respectively.

The negative phase of WLs during the driest period (1934 to 1943) coincided with the strongest phase of the IPO, suggesting an association between the IPO climate index and extreme drought.

Mega-drought events, which are prolonged droughts lasting several decades, have been linked to persistent time-scale sea surface temperature (SST) anomalies in the tropical Pacific, specifically to negative anomalies of the IPO.

The correlation coefficients between the dominant mode of variability in WLs (represented by EOF1) and the IPO for the period 1914/09 to 2018/07 were 0.55 and 0.45 for two components (CP1 and CP2) of the EOF analysis. These coefficients indicate a moderate positive correlation between WLs and the IPO.

The time series of the first principal component (PC1) and WLs from 1914/09 to 2018/07 show that positive values of PC1 correspond to the warm phase of the IPO and an increase in WLs, while negative values represent the cold phase of the IPO and a decrease in WLs.

The warm phase of the IPO from 1979 to 1999 coincided with extreme El Niño events and some weak La Niña events, which could be related to the absence or presence of precipitation in the region.

The findings presented in the passage are consistent with previous studies [31,36,56,58] that also suggest a connection between the IPO, SST anomalies in the tropical Pacific, and drought events in the South American Altiplano region.

5. Conclusions

The results of the Empirical Orthogonal Function (EOF) analysis between the time series of water level anomalies (WLs) of Lake Titicaca and the IPO (interdecadal Pacific Oscillation) climate index show a correlation coefficient of 0.71 between the WLs and the first principal component (PC1).

With the aid of Wavelet analysis, multi-decadal variability (periods between 20 and 30 years) can be identified in the study.

Based on the results of multiple analysis techniques, we could establish an association between WLs and the IPO climate index. Thus, during the negative/positive phases (1916–1925, 1946–1975, and 1999–2013)/(1926–1941 and 1978–1998) of the IPO, there were El Niño/La Niña events that could be associated with the increase/decrease in Lake Titicaca water levels. Although there is a possible association between WLs and the IPO, other atmospheric conditions that influence precipitation [59–61] exist, such as the Bolivian High (AB) and its relation with the Intertropical Convergence Zone (ITCZ), the Northeast Trough, or Northeast Bight (NEB).

The IPO and ENSO are related, but they represent different timescales of climate variability. The IPO has a longer period of variability, typically around 20–30 years, while ENSO events occur on average every 2–7 years. However, the IPO can modulate the strength and frequency of El Niño and La Niña events, and vice versa.

During the positive phase of the IPO, there is a tendency for more frequent and stronger El Niño events and fewer La Niña events. This is because a positive IPO phase is associated with warmer sea surface temperatures in the central and eastern Pacific, which can create favorable conditions for the development of El Niño events. In contrast, during the negative phase of the IPO, there is a tendency for more frequent and stronger La Niña events and fewer El Niño events due to cooler sea surface temperatures in the central and eastern Pacific.

Negative phases of the interdecadal Pacific Oscillation (IPO) index, characterized by persistent time-scale sea surface temperature (SST) anomalies in the tropical Pacific, are associated with mega-drought events (prolonged droughts lasting several decades) in the region.

The negative phase of the water levels (WLs) in the study area during the driest periods (1934–1943 and 1986–1996) coincided with the strongest phase of the IPO. This suggests a relationship between the IPO and the decrease in water levels in the region.

The correlation coefficients between the dominant mode of variability in WL data (EOF1) and the IPO for the period 1914–2018 were 0.55 and 0.45 for two components (CP1 and CP2). CP1, which explained 55% of the total variance, showed a strong positive correlation between WLs and the IPO.

The time series analysis of the first principal component (PC1) and WLs showed that positive (negative) values of PC1 corresponded to the warm (cold) phase of the IPO and an increase (decrease) in WLs. The warm phase of the IPO from 1979 to 1999 coincided with extreme El Niño events and some weak La Niña events, which may be related to precipitation patterns in the region.

The referenced studies [36,56,58] support similar findings regarding the association between IPO, El Niño events, and precipitation variability in the study area.

However, it is important to note that the relationship between the IPO and ENSO is not always consistent, and there are other factors that can also influence the occurrence and intensity of El Niño and La Niña events. Therefore, the IPO and ENSO should be studied and analyzed together in order to fully understand their impacts on climate variability and weather patterns.

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Abbreviations

The following abbreviations are used in this manuscript:

WLs	Water Levels
WT	Wavelet Transform
IPO	Interdecadal Pacific Oscillation
EOF	Empirical Orthogonal Functions
ENSO	El Niño Southern Oscillation
SST	Sea Surface Temperature
RAP	Peruvian Altiplano Region
LT	Titicaca Lake

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