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Multi-time scale analysis of the water level minima in Lake Titicaca over the past 103 years

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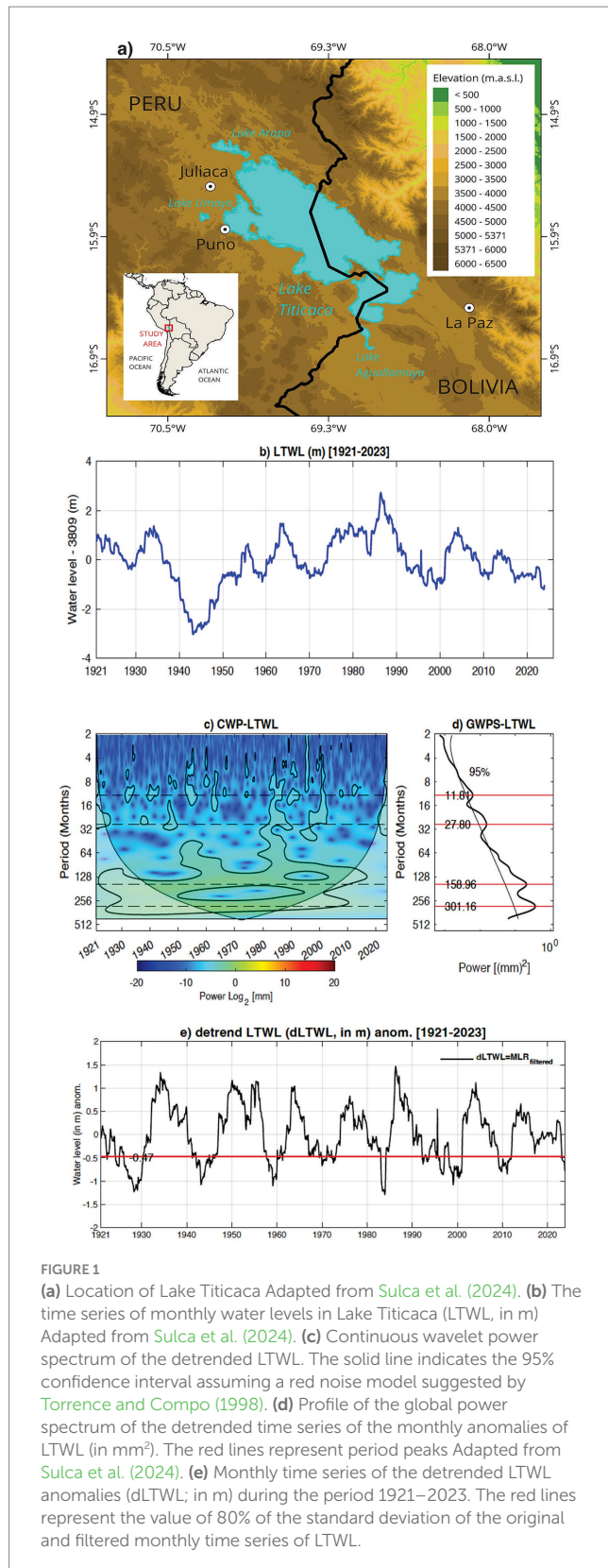
Lowest events in Lake Titicaca's water level (LTWL) significantly impact local ecosystems and the drinking water supply in Peru and Bolivia. However, the hydroclimatic mechanisms driving extreme lake-level lowstands remain poorly understood. To investigate these low lake-level events, we analyzed detrended monthly LTWL anomalies, sea surface temperature (SST) datasets covering the period 1921–2023. ERA5 reanalysis covers the period 1940–2023. A multiple linear regression model was developed to compute detrended LTWL anomalies, excluding multidecadal and residual components. Interdecadal Pacific Oscillation (IPO) and Pacific Decadal Oscillation (PDO) indices were also analyzed for the same period. Results indicate that 25% of all LTWL minima events have a short duration of <5 months, while the remaining 75% of all events have a long duration of more than 9 months, respectively. All long-lived LTWL minima events are associated with reduced moisture flow from the Amazon basin toward Lake Titicaca, but the large-scale forcing varies with the phase change of the decadal component in the 11–15 years band of the PDO (PDO_{11–15 years}). Under warm PDO_{11–15 years} phases, LTWL minima are driven by an enhanced South American low-level jet (SALLJ) caused by warm SST anomalies over the eastern Pacific Ocean. Warm SST anomalies over tropical North Atlantic and central Pacific cold events, which reinforce the cold PDO_{11–15 years} phases, driving long-lived LTWL minima through the reduction of SALLJ. Conversely, long-lived LTWL minima events under neutral PDO_{11–15 years} phases are caused by westerly flow anomalies confined to the Peruvian Altiplano. Therefore, PDO and IPO do not drive long-lived LTWL minima events because their relationship does not remain consistent over time. In conclusion, long-lived LTWL minima events exhibit a regional nature and are not driven by the PDO or IPO, as LTWL shows no consistent relationship with these decadal SST modes over time.

KEYWORDS

Lake Titicaca water level minima, Niño diversity, South American low-level jet, Western tropical North Atlantic, Pacific Decadal oscillation, Interdecadal Pacific oscillation, multiple linear regression model

1 Introduction

The Lake Titicaca Basin (LTB) is situated in the Central Andes between 68° 33' and 70° 01'W longitude and 15° 06' and 16° 50'S latitude along the border between Peru and Bolivia, with an average altitude of 3,810 m (Figure 1a). Lake Titicaca covers an area of 8,500 km² and is renowned as the world's highest-elevation navigable lake. The availability of water from Lake Titicaca is crucial for local ecosystems, domestic use, and a variety of economic activities,



including industry, fishing, agriculture, and tourism (Hastenrath and Kutzbach, 1985; Chura-Cruz et al., 2013; Villar et al., 2024).

The precipitation in the Central Andes presents a rainy season from December to February of the following year, while the dry season occurs between June and August (Garreaud et al., 2003; Imfeld

et al., 2019; Canedo-Rosso et al., 2019). Upper-level easterly flow induces a wet season in this region by entraining a lower-level moisture influx from the Amazon basin (Garreaud et al., 2003; Vuille and Keimig, 2004). However, the remote effect of anomalous deep convection over the northwestern Peruvian Amazon has led to a weakening of the negative linear relationship between Altiplano precipitation and 200-hPa zonal wind since 2000 (Segura et al., 2020). In the lower troposphere, the change in direction of the South American low-level jet (SALLJ, Jones, 2019; Montini et al., 2019; Gelbrecht et al., 2021), which transports humidity from the Amazon basin to the subtropics along the eastern flank of the Andes mountains, affects the depth of the water level in Lake Titicaca by modulating the intensity of the humidity flux from the east (Sulca et al., 2024). The intrusion of extratropical Rossby wave trains into South America and along the coast of Brazil can change the intensity and direction of the SALLJ (Montini et al., 2019; Jones et al., 2023).

The atmospheric circulation over the Altiplano is known to be linked to sea surface temperature (SST) patterns in the Pacific and Atlantic Oceans varying on both high- and low-frequency temporal scales (Mantua et al., 1997; Zhang and Levitus, 1997; Trenberth et al., 1998; Dong and Dai, 2016; Dong et al., 2018). High-frequency SST variability primarily consists of biennial and interannual components, while low-frequency SST variability includes decadal, interdecadal, and multidecadal components. The El Niño–Southern Oscillation (ENSO) primarily drives high-frequency, interannual temperature and precipitation variability in the tropics (Trenberth et al., 1998). Tropical Pacific SST oscillate between a warm and cold phase known as El Niño and La Niña, respectively. The oscillation period varies between 2 and 7 years, showing biennial (2–3 year) and low-frequency (3–7 year) components. From February 2023 to January 2024, El Niño conditions prevailed across the entire Pacific basin, including the emergence of a coastal El Niño in February 2023 (IGP, 2023a) and El Niño conditions in the Niño 3.4 region in May 2023 (IGP, 2023b; CPC, 2024). The main modes representing SST anomalies on decadal to multidecadal timescales are known as the Pacific Decadal Oscillation (PDO, Mantua et al., 1997), the Interdecadal Pacific Oscillation (IPO, Zhang and Levitus, 1997; Dai, 2013; Dong and Dai, 2016), and the Atlantic Multidecadal Oscillation (AMO, Knight et al., 2006). Deser et al. (2004) observed that the PDO and IPO exhibit similar interdecadal variability. The PDO typically oscillates over a period of 20–30 years, while the AMO's cycle spans 50–70 years.

Several studies have quantified the contribution of the precipitation and evaporation to the water level in Lake Titicaca using a water balance analysis over different timescales (Delclaux et al., 2007; Pillco-Zolá et al., 2019; Lima-Quispe et al., 2021; Guédron et al., 2023; Lima-Quispe et al., 2025). Climatologically, the LTWL follows a well-defined annual distribution, with the maximum water levels occurring between March and May and minimum levels between November and January (Sulca et al., 2024). The authors also noted that the LTWL lags the annual precipitation cycle in the Bolivian Altiplano (December–February) by 3 months. Lima-Quispe et al. (2021) reported that 80% of the fluctuations in the water level in Lake Titicaca are attributed to natural climate variability. Lima-Quispe et al. (2025) recently found that Lake Titicaca's water level is primarily driven by precipitation (744 mm year^{-1}) and evaporation ($1,616 \text{ mm year}^{-1}$), while snow and ice processes, and net irrigation withdrawals have a minimal impact on its variations. Regarding lake evaporation, Delclaux et al. (2007) identified a well-defined evaporation annual

cycle, with maximum evaporation in January and a minimum in August. The authors also found that annual evaporation causes 90% of lake output, ranging from 1,350 to 1900 mm year⁻¹ between 1965 and 1983. Using a simulated water balance, Lima-Quispe et al. (2025) recently estimated annual evaporation at 1616 mm yr⁻¹, with monthly values of 170 mm yr⁻¹ in January and 95 mm yr⁻¹ in August for the period 1982–2016.

The Lake Titicaca water level (LTWL) exhibits variability on multiple timescales, including semiannual, annual, biennial, decadal, interdecadal, and multidecadal modes (Alburquerque et al., 2018; Angulo and Pereira-Filho, 2022; Sulca et al., 2024). Sulca et al. (2024) documented that the LTWL exhibits variability on various timescales: biennial (22–27 months), interannual (80–108 months), decadal (13–14 years), interdecadal (25–27 years), and multidecadal (30–65 years). Furthermore, Angulo and Pereira-Filho (2023) reported a negative correlation between LTWL and the IPO, while Sulca et al. (2024) observed a negative correlation with the PDO. However, Angulo and Pereira-Filho (2022) observed that the simultaneous warm phases of ENSO and PDO induced drought conditions in the Lake Titicaca basin. This is consistent with a reduction in precipitation over the Bolivian Altiplano due to the combined effect of the warm phases of PDO and El Niño, which drive the northward displacement of the Bolivian high during the DJF season (Rojas-Murillo et al., 2022). These findings align with the decrease in summer precipitation over the Altiplano region during the concurrent presence of the IPO warm phase and El Niño (Dong et al., 2018; Canedo-Rosso et al., 2021; Sulca et al., 2022b). Sulca et al. (2024) identified a significant negative linear relationship between LTWL and the AMO from 1921 to 2018. However, none of these studies have directly established a dynamic link between LTWL minima and ENSO, PDO, IPO, and AMO.

Limited research has been conducted on mechanisms that lead to LTWL extremes. Ronchail et al. (2014) observed an approximately 5-meter range of extreme LTWL variations between 1915 and 2009, from an absolute minimum of 3806.7 meters in 1944 to a high-stand of 3811.6 meters in 1986 (see Figure 1b). Sztorch et al. (1989) reported that heavy precipitation in 1985/86 resulted in the highest LTWL, significantly impacting the local population. Sulca et al. (2024) reported that the LTWL exhibited a multidecadal regime from 1921 to 1990 and transitioned to a decadal-interdecadal regime thereafter. Additionally, SENAMHI (2023) reported a progressive reduction in water levels since September 2022 due to drought conditions across the entire Altiplano region. This reduction persisted until November 2023, marking a new extreme LTWL minimum (SENAMHI, 2024). Gutierrez-Villareal et al. (2024) pointed out that 2022–23 drought conditions in the Altiplano region were caused by the intrusion of a cold and dry air mass originating over the subtropical South Atlantic. The authors suggested that the 2022–23 drought in the Altiplano region was caused by concurrent La Niña conditions through subtropical teleconnections. However, the authors used a short time series of 30 years, which is not capable of evaluating the role of longer-term climate modes, such as the PDO. Here we assess the relationship between LTWL minima events and long-term climate modes above 10 years using a much longer record of 103 years.

Numerous dynamical and statistical downscaling studies have projected that drought conditions in the Lake Titicaca basin are likely to increase in frequency, duration, and intensity by the mid-21st century (Urrutia and Vuille, 2009; Minvielle and Garreaud, 2011; Vera et al., 2019; Zubieta et al., 2021; Sulca and Da Rocha, 2021; Alonso

et al., 2022; Morales et al., 2023). Morales et al. (2023) identified an increase in the drought conditions over the northern South American Altiplano since the mid-1970s, based on 389 years of reconstructed precipitation data. The authors also highlighted that the last 17 years of the period 1970–2013 stands out as the driest in their 389 years of reconstructed precipitation data. Other studies, however, have come to different conclusions, finding no evidence for a recent precipitation decline (e.g., Segura et al., 2020). Nonetheless, it is crucial to better characterize the most severe reductions seen in the Lake Titicaca water level to mitigate the impacts of future drought conditions in this region by enabling their long-range prediction and thereby improving water resources management.

In consideration of these aspects, this study aims to (a) describe the climatological characteristics of LTWL fluctuations, (b) to document the connection between low-frequency climate modes (PDO and IPO) and LTWL minima, and (c) assess the global SST and upper-level atmospheric circulation anomalies associated with Lake Titicaca's water level minima. These new findings will be used to monitoring and to develop prediction models that forecast Lake Titicaca's water level minima and help mitigate future adverse effects on water resources, such as droughts and related climate change impacts.

2 Data and methods

2.1 Data

Monthly data of the water level of Lake Titicaca (LTWL, in m) from the Peruvian National Service of Meteorology and Hydrology (SENAMHI, 2021) for the 1921–2023 period were used in this study. The record 1921–2023 was selected to achieve the same temporal window as for the SST observations, which are of good quality in the tropical Pacific after 1921 (Dong and Dai, 2016).

The European Reanalysis version 5 (ERA5, Hersbach et al., 2020) monthly mean data of divergence (DIV, kg m⁻² s⁻¹) and vertically integrated humidity transport (VIHT, kg m⁻¹ s⁻¹) were obtained from the European Center for Medium-Range Weather Forecasts (ECMWF). We compute VIHT using Equation 1:

$$VIHT = \frac{100}{g} \int_{1000 \text{ hPa}}^{200 \text{ hPa}} q V_h dp \quad (1)$$

Where g is the acceleration due to gravity (10 m s⁻²), q is specific humidity (kg kg⁻¹), p is pressure and V_h is the horizontal wind. The ERA5 reanalysis presents a horizontal grid of 0.25° × 0.25° and covers the 1940–2023 period. We chose ERA5 reanalysis because it performs better over the Andes than the Japanese 55-year MERRA2 and the NCEP/NCAR reanalysis (Birkel et al., 2022).

Monthly SST data from HadISST v1.1 from the Met Office Hadley Centre (Rayner et al., 2003) were used. The resolution of the HadISST data is 1° × 1° and covers the 1921–2023 period.

The National Oceanic and Atmospheric Administration-Physical Sciences Laboratory (NOAA-PSL) provided the nonfiltered monthly time series of the AMO index (Enfield et al., 2001). The AMO index is computed as the time series of the area-weighted average of SSTs

over the North Atlantic (0–70°N). The AMO index covers the period 1921–2022 and can be downloaded from <https://psl.noaa.gov/data/correlation/amon.us.long.data>.

The Pacific Decadal Oscillation (PDO) index was obtained from the Tokyo Climate Center.¹ The PDO index represents the monthly time series of the principal component of the first empirical orthogonal function (EOF) of North Pacific SST anomalies north of 20°N. The monthly time series of the PDO covers the period 1921–2023.

The IPO index was obtained following the methodology described by Dong and Dai (2016). Dong and Dai (2016) calculated a 3-year moving average of global SST prior to performing an EOF analysis of the SST data for the period 1921–2023. Two consecutive 9-year moving average filters were applied on the second principal component time series, which represents the IPO.

2.2 The multiple linear regression (MLR) model

We developed a multiple linear regression (MLR) model using the iterative reweighted least squares method (Beaton and Tukey, 1974; DuMouchel and O'Brien, 1989) to reconstruct monthly anomalies of LTWL following the methodology proposed by Sulca et al. (2022a, 2024). The MLR predictors correspond to the principal modes of LTWL, which are mutually uncorrelated and identified using the robust empirical mode decomposition (REMD) technique (Liu et al., 2022; Liu, 2024). The REMD technique is an effective tool for identifying dominant oscillation modes in the water level (Heddad et al., 2024).

The MLR model represented by Equation 2:

$$Y(t) = a_n X(t) + b + \varepsilon \quad (2)$$

Where $Y(t)$ represents the target variable (LTWL, Figure 1b) that varies with time t ; $X(t)$ represents the time series of the predictors (LTWL modes); and a_n and b represent the least-squares regression parameters (slope and intercept of each predictor of the multiple linear regression model and the regression coefficients, respectively). The local regression parameters are estimated by minimizing the model error ε . The calibration and validation periods for the MLR models were 1921–2010 and 2011–2023, respectively. The MLR models were tested using the F-test at a 95% confidence level (Wilks, 2011).

2.3 Methods

We propose a method to calculate detrended monthly anomalies of LTWL, referred to hereafter as dLTWL. Since the goal of this method is to identify the primary drivers of the long-term LTWL minima events occurring on timescales shorter than 30 years, we removed the long-term components of the monthly LTWL time series, including the multidecadal and residual components. The AMO influences the

multidecadal component of LTWL as they have been shown to be negatively correlated (Sulca et al., 2024). The residual component of LTWL can be removed because it represents the trend of the original time series. To exclude the multidecadal and residual components of LTWL, we set the regression coefficients for the multidecadal and residual modes to zero in the MLR model (denoted as LTWL_{filtered}). Finally, we removed the linear trend from the monthly LTWL time series after filtering. The technical details are shown in Supplementary material.

We defined LTWL minima events as periods when dLTWL falls below 80% of its standard deviation of the monthly anomaly time series. As this study focuses on LTWL minima events with long duration, we defined long-lived LTWL minima events as those lasting nine or more consecutive months. This definition allows us to identify more LTWL minima events compared to using only the threshold of the standard deviation of observed monthly LTWL anomalies. Since this study focuses on LTWL minima events with long durations (> 9 months duration), we will not discuss these short-lived LTWL minima events in this study.

We applied a superposed epoch analysis to describe changes in the values of the detrended LTWL before and after the peak of long-term LTWL minima events.

The continuous wavelet transform (CWT) technique is a robust technique for identifying principal oscillation modes in SST anomalies (Dewitte et al., 2011; Illig et al., 2014), precipitation anomalies (Labat et al., 2005, 2012; Mortensen et al., 2018; Sulca et al., 2022a, 2024), and water level variations in Lake Titicaca (Angulo and Pereira-Filho, 2022). The confidence level of the power spectrum profile is based on the red noise model, as suggested in Torrence and Compo (1998). We applied a bandpass-filter of 11–15 years to extract the decadal component of the PDO index (hereafter PDO_{11–15-years}). This bandpass-filter is based on the Morlet wavelet (Torrence and Compo, 1998). We did not analyze the interdecadal component of the PDO index because it is similar to the IPO index (Deser et al., 2004; Dong and Dai, 2016). Similarly, we extracted the decadal component of the global SST anomalies and divergence and vertically integrated humidity transport filtering the 11–15-years band of the monthly SST anomalies (hereafter dSST, dDIV, and dVIHT).

A composite analysis for the patterns of the global dSST and dDIV and dVIHT anomalies over South America during long-lived LTWL minima events under warm and cold phases of the PDO_{11–15 years} was performed. In contrast, unfiltered global SST, DIV and VIHT anomalies are utilized for long-lived LTWL minima events under neutral phases of the PDO_{11–15 years}. The statistical significance is based on a two-tailed Student's t -test at a 90% confidence level (Wilks, 2011).

3 Results

3.1 Climatological characteristics of the LTWL minima events

Using the detrended monthly anomalies of LTWL from 1921 to 2023 (Figure 1e), we identified 16 LTWL minima (Table 1). Figure 2a shows that 18.75, 6.25, and 75% of all LTWL minima have a duration that varies in range from 1 to 2 months, 3 to 4 months, and more than 9 months, respectively. Long-lived LTWL

¹ https://ds.data.jma.go.jp/tcc/tcc/products/elnino/decadal/pdo_month.html

TABLE 1 List of case studies, their onset date, and the total number of months.

LTWL minima		
Case study no.	Starting month	Duration (months)
1	May 1922	1
2	April 1924	10
3	February 1926	51
4	April 1941	1
5	February 1942	51
6	October 1957	36
7	April 1961	1
8	March 1967	4
9	June 1969	20
10	October 1971	15
11	February 1983	14
12	April 1992	18
13	May 1995	22
14	March 1998	35
15	February 2009	35
16	February 2023	> 9

These characteristics are based on the detrended monthly time series of the water level in Lake Titicaca (dLTWL) during the period 1921–2023.

minima have an average duration of 26.3 months. Hence a long-term, persistent change in the large-scale circulation over South America is required to cause these long-lived LTWL minima. On average, these events are characterized by a decrease in water level from -0.2 m in month -19 , to an average minimum of -0.65 m in month $+3$, followed by a recovery from month $+4$ to month $+24$ (Figure 2b).

Since many LTWL minima persist for more than 9 consecutive months, we assess the connection between long-lived LTWL minima and the $\text{PDO}_{11-15 \text{ years}}$ and IPO during the period 1921–2023. Figure 2c illustrates the phases of the $\text{PDO}_{11-15 \text{ years}}$ and the IPO for the onset month of each LTWL minima episode, covering the period from 1921 to 2023. The warm, cold, and neutral phases of the IPO represent 40, 40, and 20% of all LTWL minima events, respectively (Table 2), showing that IPO does not favor or prevent LTWL minima events. According to Table 2, warm $\text{PDO}_{11-15 \text{ years}}$ phases represent 50% of all LTWL minima events between 1921 and 2000, while cold PDO phases account for 30% of these events after 2001. This suggests that the positive phase of the $\text{PDO}_{11-15 \text{ years}}$ may favor long-lived LTWL minima events, consistent with prior research (Garreaud et al., 2009; Flantua et al., 2016). In addition, Figure 2c shows an increase in the amplitude of the $\text{PDO}_{11-15 \text{ years}}$ in the mid-2010's and late in 2022. The increase in the amplitude of the negative phase of the $\text{PDO}_{11-15 \text{ years}}$ around mid-2010 is caused by strong cold anomalies in the Niño region (e.g., strong La Niña conditions), which persisted from mid-2010 to April 2012 (CPC, 2024). The increase in the amplitude of the negative phase of the $\text{PDO}_{11-15 \text{ years}}$ in 2022–23 is due to the triple-dip Las Niñas 2020–2023 (Jiang et al., 2023; Li et al., 2023; Iwakiri et al., 2023).

3.2 Circulation patterns associated with the different types of long-lived LTWL minima events

LTWL minima occur during the neutral, positive and negative phases of the $\text{PDO}_{11-15 \text{ years}}$. We analyzed filtered anomalies of the VIHT and divergence over South America to describe the atmospheric circulation patterns associated with the warm and cold phases of the $\text{PDO}_{11-15 \text{ years}}$. In contrast, unfiltered anomalies of VIHT and divergence over South America were analyzed to describe circulation patterns associated with long-term LTWL minima during neutral phases of $\text{PDO}_{11-15 \text{ years}}$.

During positive phases of the $\text{PDO}_{11-15 \text{ years}}$, long-term LTWL minima are associated with positive divergence anomalies over the Altiplano region (Figure 3a), implying dry conditions, consistent with the long-term LTWL minima. Figure 3a also highlights significant convergence anomalies over the Peruvian Amazon and northeasterly VIHT anomalies originating in the tropical North Atlantic. This suggests strengthened moisture transport from the Amazon basin to the midlatitudes but no upward moisture flow from the east to the Altiplano region. These findings suggest that warm phases of the $\text{PDO}_{11-15 \text{ years}}$ induce long-term LTWL minima by inhibiting moisture transport from the lowlands. In addition, these long-term LTWL minima are correlated with significant warm SST anomalies over the eastern Pacific and western North Atlantic oceans on decadal timescales within the 11–15 years band (Figure 3b). These findings are consistent with previous studies showing that warm SST anomalies over the eastern Pacific Ocean and western North Atlantic oceans reduce water levels in Lake Titicaca on decadal timescales (13–14 years) (Sulca et al., 2024).

During negative phases of the $\text{PDO}_{11-15 \text{ years}}$, long-term LTWL minima are linked to positive divergence anomalies and southeasterly VIHT anomalies over the Altiplano region (Figure 3c), resulting in dry conditions. These conditions result from the weakening of the SALLJ. Figure 3c also depicts significant westerly VIHT anomalies and convergence anomalies over the eastern tropical Amazon and tropical South Atlantic, showing the weakening of trade winds limiting moisture availability in the eastern part of the continent. These results indicate that extreme cold phases of the $\text{PDO}_{11-15 \text{ years}}$ can lead to long-term LTWL minima by reducing moisture over the Altiplano region. Notably, these extreme cold phases of the $\text{PDO}_{11-15 \text{ years}}$ are associated with extreme central-Pacific cooling events (Figure 3d). In addition, Figure 3d also shows that these long-term LTWL minima events are linked to a significant SST anomaly dipole in the southwestern South Pacific Ocean, suggesting a northeastward displacement of the SPCZ. Warm SST anomalies dominate the western tropical North Atlantic, leading to westerly VIHT anomalies that reduce humidity flow from the Atlantic Ocean to South America on decadal timescales within the 11–14 years band (Sulca et al., 2024). These westerly VIHT anomalies over the eastern and central equatorial Amazon basin weaken the SALLJ.

During neutral $\text{PDO}_{11-15 \text{ years}}$ phases, long-term LTWL minima are associated with positive divergence anomalies and westerly VIHT anomalies confined locally over the Peruvian Altiplano (Figure 3e), suggesting that the regionally dry conditions are causing the reduction of the water level in Lake Titicaca. However, there are no significant VIHT or divergence anomalies along the eastern flank of the Andes

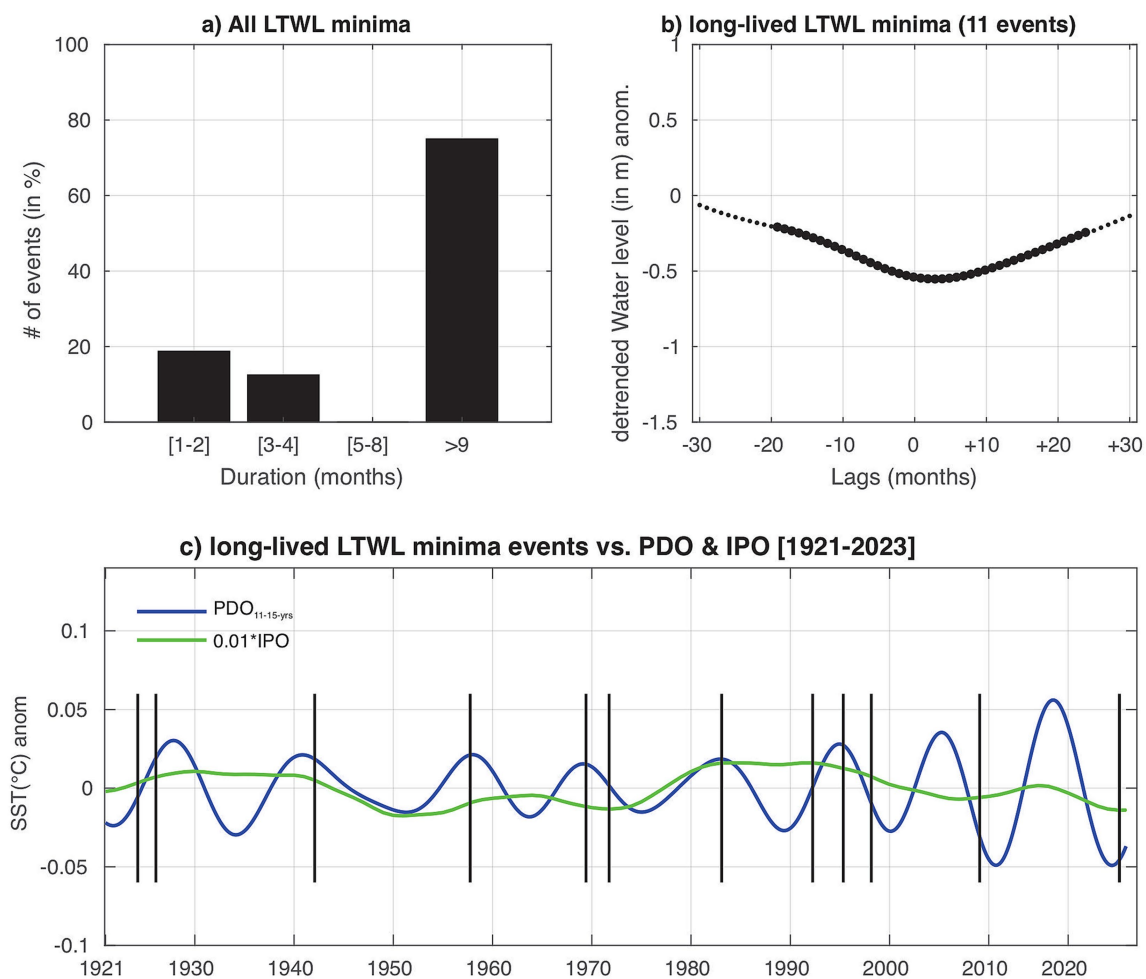


FIGURE 2

(a) Histogram of the number of events (in %) with respect to the duration (in months) of the LTWL minima. (b) Superposed epoch analysis applied to detrended monthly water level anomalies in Lake Titicaca (dLTWL, in m) for the long-lived LTWL minima events statistically significant from zero at the 95%-confidence level based on the Student's *t*-test. (c) Monthly time series of the decadal component (11–15-years) of the Pacific Decadal Oscillation (PDO, blue line) and the Interdecadal Pacific Oscillation (IPO, green line). The black vertical lines represent the initiation (e.g., month zero) of the water level minima in Lake Titicaca (LTWL minima) with a duration above nine consecutive months (April 1924, February 1926, February 1942, October 1957, June 1969, October 1971, February 1983, April 1992, May 1995, March 1998, February 2009 and February 2023). The IPO index was rescaled by a factor of 0.01. The analysis is based on the period 1921–2023.

TABLE 2 Percentage of the detrended Lake Titicaca water level events (dLTWL, in m) that start during the warm, cold and neutral phases of the interdecadal Pacific Oscillation (IPO, in °C) and the decadal component (11–15-years band) of the Pacific Decadal Oscillation (PDO_{11–15-years}, in °C) index during the period 1921–2013.

Long-lived LTWL minima			
Climate mode	Warm phase	Cold phase	Neutral
IPO	40%	40%	20%
PDO _{11–15-years}	50%	30%	20%

Mountains, suggesting that these long-term LTWL minima are primarily caused by westerly flow anomalies over the Peruvian Altiplano. In addition, Figure 3f exhibits that these long-term LTWL minima are associated with weak warm SST anomalies over eastern Pacific Ocean and the Peruvian coast, with strongest values in the far-eastern Pacific Ocean and near the Peruvian coast. This suggests that eastern El Niño-like conditions may contribute to long-term LTWL minima by weakening the upper-level easterly flow over the Peruvian Altiplano (Sulca et al., 2018).

4 Discussion and conclusions

In this paper, we documented the low-frequency atmospheric dynamics associated with water level minima in Lake Titicaca during the period 1921–2023, performing composite and superposed epoch analyses using monthly time series of Lake Titicaca water level (LTWL) and the global SST, divergence (DIV) and vertically integrated humidity transport (VIHT) anomalies over South American continent from the ERA5 reanalysis.

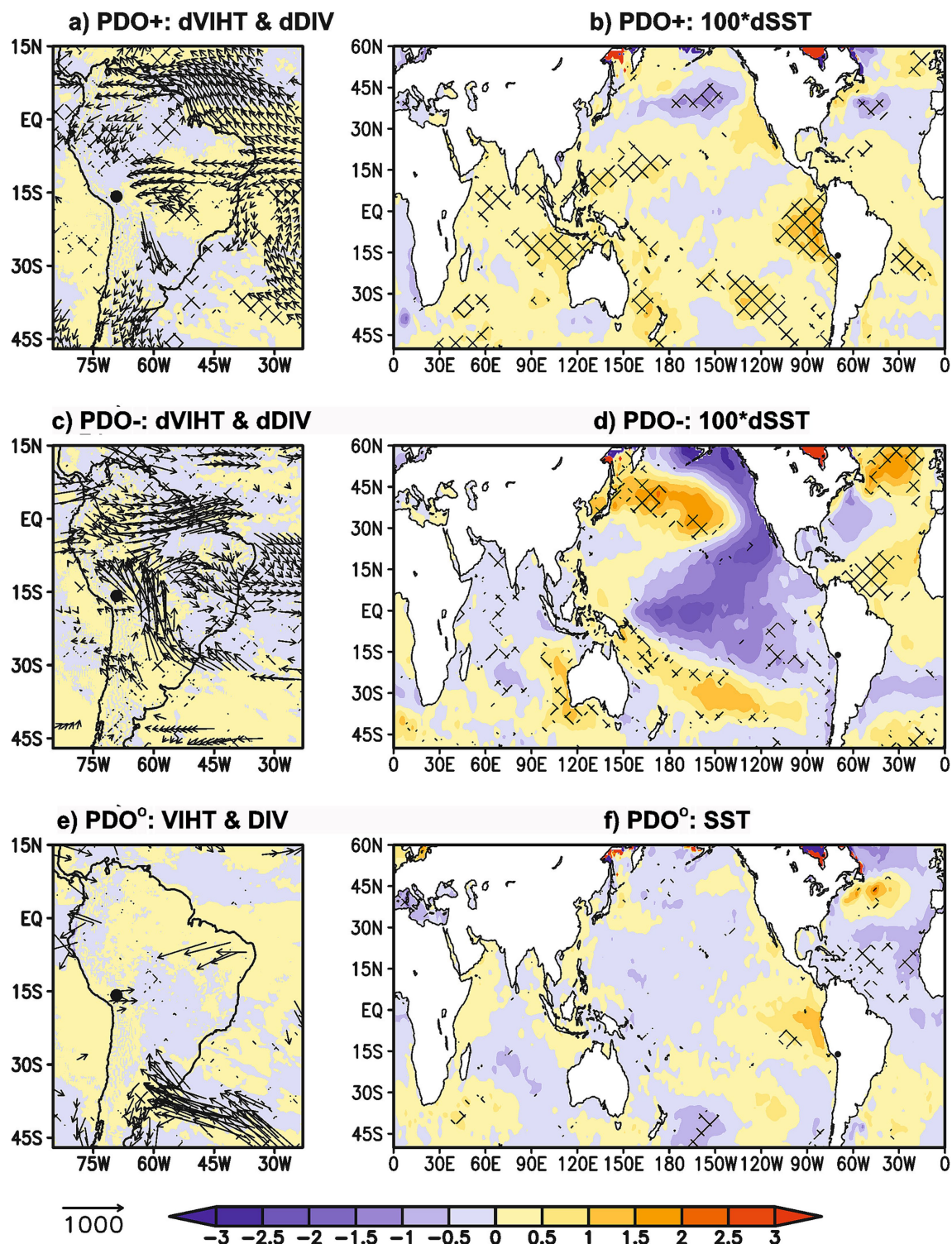


FIGURE 3

Composite of the decadal component in the 11–15-year band of the (a) vertically integrated humidity transport (dVIHT, $\text{kg m}^{-1} \text{s}^{-1}$) and divergence (dDIV, $\text{kg m}^{-1} \text{s}^{-2}$) anomalies during the long-lived events of water level minima in Lake Titicaca under the warm phase of the 11–15-year band of the PDO index (PDO+) during the period 1921–2023. (c) As in (a) but for cold phase of the 11–15-year band of the PDO index (PDO-). (e) Composite of the vertically integrated humidity transport (VIHT, $\text{kg m}^{-1} \text{s}^{-1}$) anomalies during the long-lived events of water level minima in Lake Titicaca under neutral phases of the 11–15-year band of the PDO (PDO°) during the period 1921–2023. The black circle represents the location of Lake Titicaca. The black vectors represent nonfiltered and filtered VIHT anomalies that are statistically significant at the 90% confidence level. The divergence anomalies were rescaled by a factor of 5×10^4 . Hatching areas represent nonfiltered and filtered divergence anomalies that are statistically significant at the 90% confidence level. The analysis is based on ERA5 reanalysis. (b) SST anomaly composite for the decadal component in the 11–15-year band (dSST, in $^{\circ}\text{C}$) during the long-lived events of water level minima in Lake Titicaca under the warm phase of the 11–15-year band of the PDO index (PDO+) during the period 1921–2023. (d) As in (b) but for cold phase of the 11–15-year band of the PDO index (PDO-). (f) Composite for the global SST (in $^{\circ}\text{C}$) anomalies during the long-lived events of water level minima in Lake Titicaca under the neutral phase of the 11–15-year band of the PDO index (PDO°). The dSST anomalies were rescaled by a factor of 100. Hatching areas represent nonfiltered and filtered SST anomalies that are statistically significant at the 90% confidence level.

The multiple linear regression model shows that monthly LTWL anomalies can be explained as a linear combination of their principal modes. The result enables us to propose a new method for calculating detrended LTWL anomalies by removing the multidecadal and residual components of LTWL (Figure 1b). This new criterion enabled the identification of May 1922, November 1924, June 1927, February 1959, April 1961, January 1970, July 1972, December 1983, June 1992 and November 2009 as months marking the peak of LTWL minima, in contrast to relying solely on the traditional threshold based on the standard deviation of observed LTWL (Figure 1a).

We identified 16 LTWL minima based on detrended LTWL anomalies during the period 1921–2023. 25% of all LTWL minima events have a duration of 4 months or less, indicating that short-term changes in the large-scale atmospheric circulation cause these extreme events. Conversely, 75% of all LTWL minima events are long-lived, with an average duration of 26.33 months. This suggests that these extreme events are driven by long-term changes in global SST anomalies and large-scale atmospheric circulation. All long-lived LTWL minima events result from a weakened moisture flux from the Amazon basin to Lake Titicaca, though large-scale drivers primarily vary with the season and the phase of the decadal component in the 11–15-year band of the PDO (PDO_{11–15 years}) index. Prior to the year 2000, long-lived LTWL events were associated with warm phases of the PDO_{11–15 years} coupled with warm SST anomalies over the tropical North Atlantic and the eastern Pacific Ocean, and an enhanced SALLJ, reducing moisture flux from the Amazon basin to the Lake Titicaca basin, ultimately leading to an extreme reduction in the lake's water level. After 2001, long-lived LTWL events appear to be linked to cold phases of the PDO_{11–15 years} coupled with cold SST anomalies over the western and central equatorial Pacific Ocean, which have recently been prolonged by a period of strong La Niña conditions (Jiang et al., 2023; Li et al., 2023; Iwakiri et al., 2023). In contrast, long-lived LTWL events during neutral PDO_{11–15 years} phases are primarily caused by a weakened moisture flux from the east induced by prevailing westerly VIHT anomalies localized over the Peruvian Altiplano.

This study has some limitations, including the absence of a water balance analysis for Lake Titicaca's water level due to the lack of long-term records of precipitation, evaporation, and upstream and downstream flows needed to assess how each component influences LTWL variability. The primary limitation is the lack of identification of the physical processes that explains the change of sign of the connection between long-lived LTWL minima and the PDO_{11–15 years} in the 21st century. Hence, the development of dynamical downscaling models is required to address this limitation as well as future changes, similar to those observed in the Great Lake (Kayastha et al., 2022).

Finally, this study provides a detailed description of the mechanisms and the teleconnections related to long-lived LTWL minima events. These new findings will help reduce the strain on water resources and natural areas caused by the significant reduction of the water level in Lake Titicaca, which is currently decreasing due to ongoing drought conditions over the Altiplano region, with a future decrease projected by climate models, which project a reduction of precipitation accompanied by significant westerly flow anomalies over the Altiplano region at upper-tropospheric levels by the end of the 21st century (Minvielle and Garreaud, 2011; Neukom et al., 2015; Vera et al., 2019; Sulca and Da Rocha, 2021). However, further dynamic analyses will be required to build and implement a predictive model for long-lived LTWL minima events.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author. The monthly time series of Lake Titicaca water levels is available upon request from Sixto Flores (sflores@senamhi.gob.pe).

Author contributions

JS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. MV: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. KT: Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. PR: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. BD: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. VM: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. JT: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. JA: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fclim.2025.1564040/full#supplementary-material>

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