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# Ocean Forcing on Titicaca Lake Water Volume

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## Abstract

The time series of water level of Titicaca Lake (TL) was compared to the time series of the Pacific Decadal Oscillation (PDO) and El Niño/Southern Oscillation (ENSO) indexes between 1914 and 2014 and 1969 and 2014, monthly and daily, respectively. Results indicate TL water level decreased (increased) during positive (negative) PDO phases. ENSO positive (negative) phase results were similar. Positive (negative) PDO and ENSO phases yielded negative (positive) precipitation anomalies and concomitant decrease (increase) of TL water level. These long-term relationships among TL water levels and both oceanic indexes can be useful and prognostic.

## Keywords

PDO, ENSO, Titicaca Lake

## 1. Introduction

The Peruvian Altiplano Region (PAR) is a high plateau at 3800 m altitude surrounded by the western and eastern ranges of the Andes Cordilleras. PAR is part of a larger drainage system with three main tributaries, namely, Poopó, Coipasa, and Uyuni basins that flow into Lake Titicaca [1] shown in **Figure 1**. TL water level has been reduced gradually from its normal level [2] [3]. The water level varied 5 m between extremes between 1944 (3806.7 m) and 1986 (3811.6 m). TL main water sources are over the lake rainfall (47%) and tributaries inflows (35%), especially from Ramis River [4], while the main water sinks are over the lake evaporation (91%) and outflow from Desaguadero River (9%). The surface lake temperature fluctuates between 7˚C and 10˚C [4].

Droughts have major societal and economic impacts on millions of people around the world, especially in arid and semi-arid regions [5] [6]. Changes in drought patterns are the focus of many recent studies though uncertainties remain. For instance, simulated TL temperature and precipitation with HadRM3


**Figure 1.** Map of the Lake Titicaca Watershed. It is indicated geographic and watershed contours, sub-basins, international boundaries, cities, parks, reserves, salt mines, and main pollution sources. Source: World Water Assessment Program (WWAP) by Association for Forest Development and Conservation (AFDC, 2002).

and ETA CSS models [7] suggest a temperature increase between 2˚C and 4˚C and a slight rainfall reduction by the late 21st century. The scenario suggests a 6 mm·day$^{-1}$ reduction in rainfall rates over southwestern TL in Summer [7]. However, observed precipitation trends are systematically positive in western and negative eastern, southern and central PAR slopes [8].

On the other hand, [9] has shown natural variability such as the one related to ENSO is the primary cause of many episodes of droughts around the world as well as extensive research on ENSO induced dry/wet anomalies over various regions [10] [11] [12] [13]. Nevertheless, the interannual variability between ENSO and the global climate is regulated by the Pacific Decadal Oscillation (PDO) [14] [15]. It modulates ENSO and its main teleconnections within the intertropics such as over South and North America [16], Mexico [17], Australia [18], and East Asia [19] [20]. Thus, the main objective of the study is to analyze the variability of TL water levels and relationships with the PDO and ENSO episodes.

## 2. Material and Methods

### Data and Material Used

This work was based on monthly TL water level (m) measurements between 1914 and 2014 and available datasets of thirty-four conventional meteorological stations between 1969 to 2014 (**Table 1**). Monthly and yearly PDO and ENSO indexes were used for the respective LT water levels and meteorological datasets. The spectral analysis technique was used to analyze the TL level time series. It provides a measure of the variance in the frequency domain by decomposing the total variance into frequency bands. The total variance results from overlapping mutually independent harmonics.

The relationship between TL water levels, PDO, and ENSO index was analyzed with a composite analysis of precipitation mean patterns associated with El Niño and La Niña episodes during the rainy season (DJF). The precipitation anomalies were obtained from the monthly rainfall accumulation mean of all-weather stations (**Table 1**). Seven + ENSO (El Niño) and eight − ENSO (La Niña) were

**Table 1.** General data analyzed of the meteorological network of the Peruvian Altiplano.

| No. | Station | Lat | Long | Alt | No | Station | Lat | Long | Alt |
|---|---|---|---|---|---|---|---|---|---|
| 01 | Ananea | −14.68 | −69.53 | 4660.0 | 18 | Juliaca | −15.47 | −70.17 | 3820.0 |
| 02 | Arapa | −15.14 | −70.12 | 3920.0 | 19 | Lagunillas | −15.77 | −70.66 | 4250.0 |
| 03 | Ayaviri | −14.88 | −70.59 | 3920.0 | 20 | Lampa | −15.44 | −70.21 | 3900.0 |
| 04 | Azangaro | −14.91 | −70.19 | 3863.0 | 21 | Laraqueri | −16.15 | −70.07 | 3970.0 |
| 05 | Cabanillas | −15.64 | −70.35 | 3890.0 | 22 | Llally | −14.95 | −70.90 | 4111.0 |
| 06 | Capachica | −15.62 | −69.84 | 3819.0 | 23 | Los Uros | −15.80 | −69.92 | 3808.0 |
| 07 | Chuquibambilla | −14.80 | −70.73 | 3910.0 | 24 | Mazo Cruz | −16.75 | −69.71 | 3970.0 |
| 08 | Cojata | −15.02 | −69.36 | 4344.0 | 25 | Muñani | −14.78 | −69.97 | 4119.0 |
| 09 | Crucero | −14.36 | −70.02 | 4130.0 | 26 | Pampahuta | −15.49 | −70.68 | 4320.0 |
| 10 | Desaguadero | −16.57 | −69.04 | 3860.0 | 27 | Pizacona | −16.92 | −69.37 | 3940.0 |
| 11 | Huancane | −15.20 | −69.76 | 3860.0 | 28 | Progreso | −14.69 | −70.36 | 3905.0 |
| 12 | Huaraya Moho | −15.39 | −69.49 | 3890.0 | 29 | Pucara | −15.03 | −70.37 | 3885.0 |
| 13 | Ilave | −16.08 | −69.64 | 3850.0 | 30 | Puno | −15.82 | −70.02 | 3840.0 |
| 14 | Isla Soto | −15.56 | −69.49 | 3853.0 | 31 | Putina | −14.91 | −69.87 | 3878.0 |
| 15 | Isla Suana | −16.34 | −68.86 | 3845.0 | 32 | Santa Rosa | −14.63 | −70.80 | 3940.0 |
| 16 | Isla Taquile | −15.78 | −69.69 | 3815.0 | 33 | Tahuaco | −16.31 | −69.07 | 3860.0 |
| 17 | Juli | −16.20 | −69.46 | 3825.0 | 34 | Taraco | −15.31 | −69.98 | 3820.0 |

identified between 1969 and 2014 based on [21]. The PDO index was calculated with SST anomalies of the North Pacific normalized with the average in the period between 1947 and 1995 [14].

## 3. Results and Discussion

### TL Water Levels

Figure 2 shows TL water level time evolution between 1914 and 2014 relative to an altitude of 3800 m. The water level varied 6.31 m from April 1943 to December 1986. It reached a record high during the 1985/1986 rainy season, causing severe flooding and losses in many cities around TL in Peru [22]. Record low levels in the 1940s were caused by successive + ENSO events between 1936 and 1943 [23]. The time evolution of TL water levels shows no trends but long-term fluctuations with highs and throughout decades. The longer negative water level oscillations occurred between 1933 and 1944 (−6.0 m) and between 1986 and 1997 (−4.2 m).

Figure 3 shows three periods of very high evaporation. The decadal-scale depletion of water resulted from droughts when evaporation was increased. The estimated annual average evaporation rate between MAR 1934 and DEC 1943,

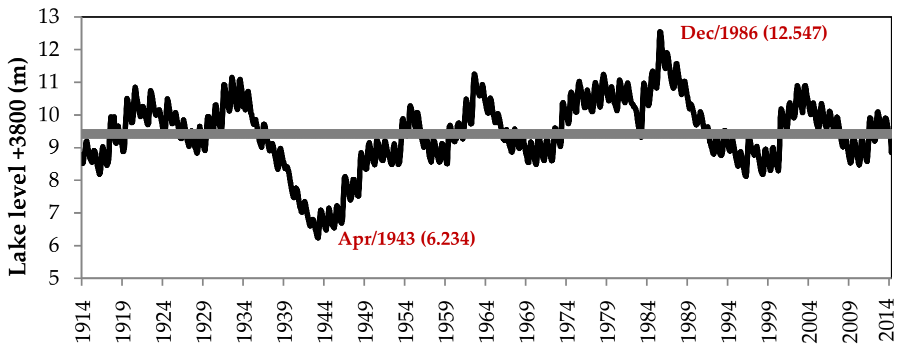


Figure 2. The behavior of Lake Titicaca level. Period 1914 to 2014. The Red line represents the average value.

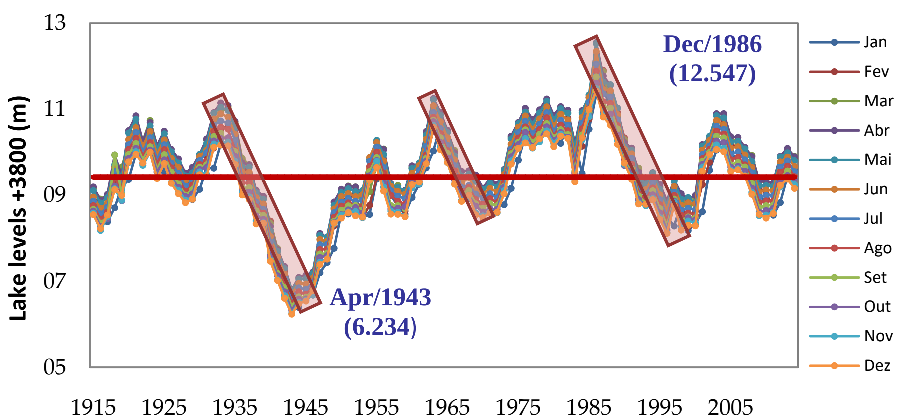


Figure 3. Monthly TL water level concerning 3800 m altitude between 1915-2014. Shaded rectangles indicate high evaporation periods.

between APR 1963 and DEC 1970, and between APR 1986 and DEC 1996 was 4.82 m, 2.77 m, and 4.43 m or estimated volumes of $4.55 \times 10^7$ $m^3$, $2.64 \times 10^7$ $m^3$, and $4.24 \times 10^7$ $m^3$, respectively. [24] showed regional climate scale variation causes water level oscillations related to the changes in net water inflow/outflow, precipitation, and evapotranspiration. A rainy season index was established by [3] from lake level differences between April and December.

**Figure 4** shows monthly averages of precipitation and water level for the periods of 1914-2014 and 1969-2014, respectively, similar to [3]. The water level is minimum in December and maximum in April. The average monthly water level lags three months behind the average precipitation during the rainy season and the minimum level occurs five months after the minimum rainfall in June and July.

**Figure 5** shows the monthly time evolution of the TL watershed area average precipitation and TL water level between 1969 and 2014. TL water level variations lag behind the average precipitation over the TL watershed.

**Figure 6** shows the spectral analysis for TL water level a maximum density at 12-year cycle and another smaller one at 6-year cycle probably related to a

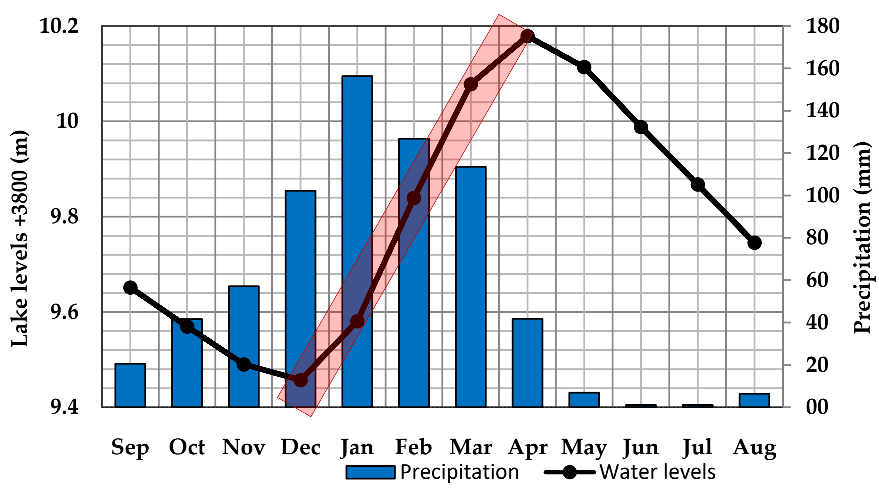


**Figure 4.** Monthly time evolution of average precipitation (mm) and average TL water level (m) between 1969-2004 and 1915-2014, respectively. Adapted from [3].

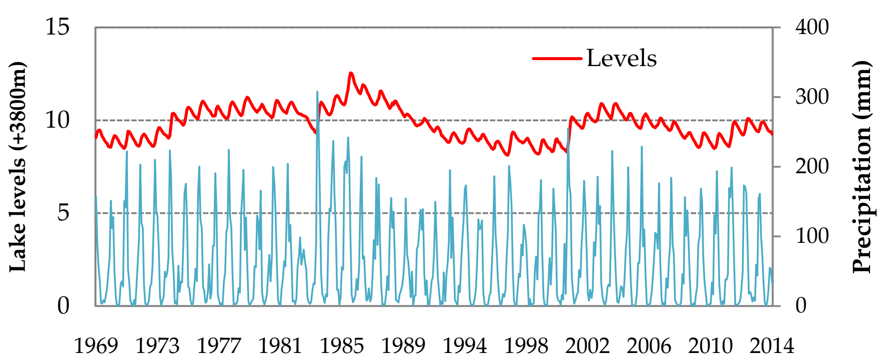


**Figure 5.** Time evolution of monthly TL watershed area average precipitation (mm) and TL water levels (relative to 3800 m altitude) between 1969-2014.

frequency leakage from the first cycle. This peak in spectral density is most probably related to the PDO. This ocean wide forcing is closely related to the 11-year solar cycle.

Figure 7 shows the time evolution of PDO and TL water level anomalies between 1914 and 2014. Negative (positive) PDO anomalies tend to be associated with positive (negative) TL water level anomalies. For both positive and negative PDO anomalies the TL water level lags behind (Figure 4).

Figure 8 shows a similar analysis by [3] for LT water level and the level difference between April and December from 1915 to 2009. In this work, no increase in NLT was detected between 1941 and 1983 for +ENSO events.

Figure 9 shows precipitation anomalies fields for −ENSO events (La Niña) between 1969 and 2014. For strong (moderate) La Niña events in Figure 9(b) there are positive (negative) precipitation anomalies. Strong −ENSO events induce higher positive precipitation anomalies towards the South over the whole area of TL. For very strong + ENSO events (Figure 10(b)), negative precipitation anomalies prevail over most TL basins, and for the moderate events (Figure 10(a)), anomalies are slightly positive.

Therefore, negative precipitation anomalies over the TL basin occur during El Niño events. They tend to reduce TL water levels during +PDO phases, similar

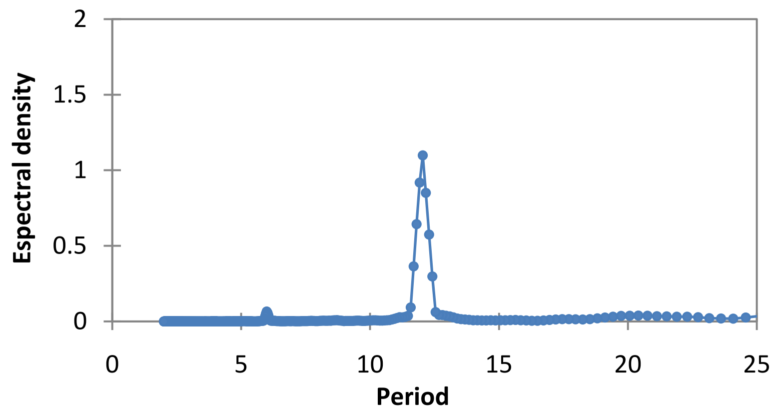


Figure 6. Spectral density of TL water level as a function of the period (year) for the spectral analysis for the 1914-2014 period.

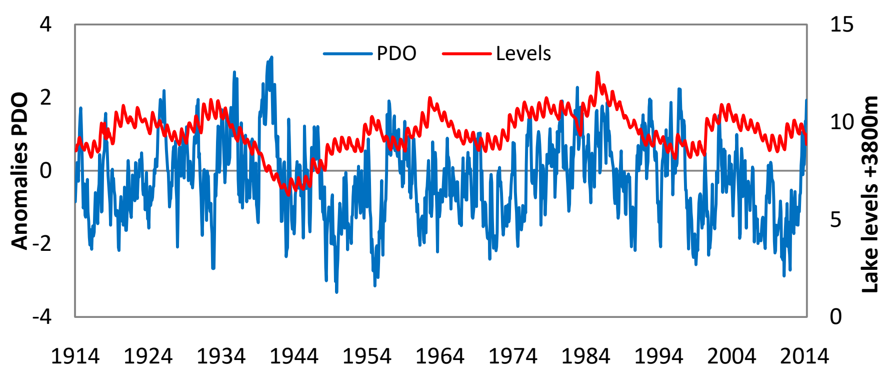


Figure 7. Anomalies (PDO) and water levels of Lake Titicaca. Period 1914-2014.

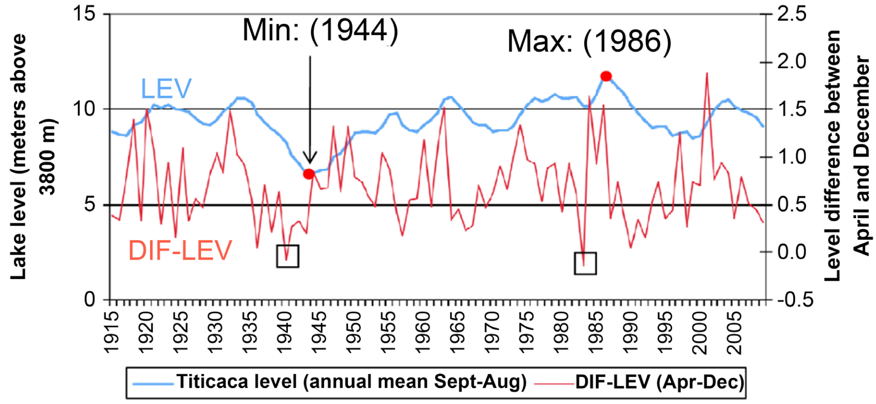


Figure 8. Time evolution of annual mean TL water level and water level difference between April and December. Adapted [3].

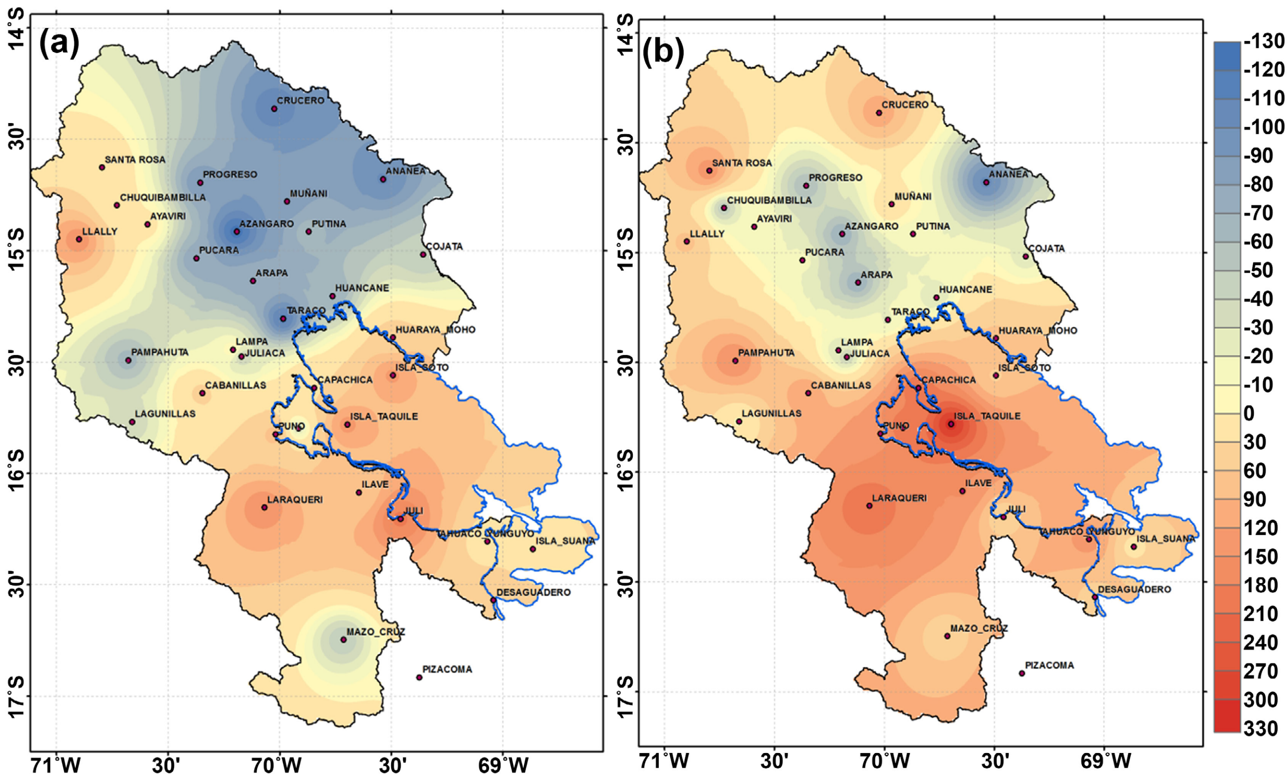


Figure 9. Precipitation anomalies (mm) for (a) moderate and (b) very strong La Niña events. Latitudes, longitudes, basin contours, rain gauge location are indicated. The color bar indicates precipitation anomalies (mm).

to [3] for +ENSO events. On the other hand, −ENSO during −PDO phases yields positive precipitation anomalies, especially in the south part of the TL basin.

## 4. Discussion

This work demonstrates a strong relationship between PDO and ENSO (La Niña & El Niño) anomalies with the TL water level. La Niña events precipitation anomalies are positive northeast of TL basin and for moderate and very strong El Niño events, positive precipitation anomalies are found in the central TL

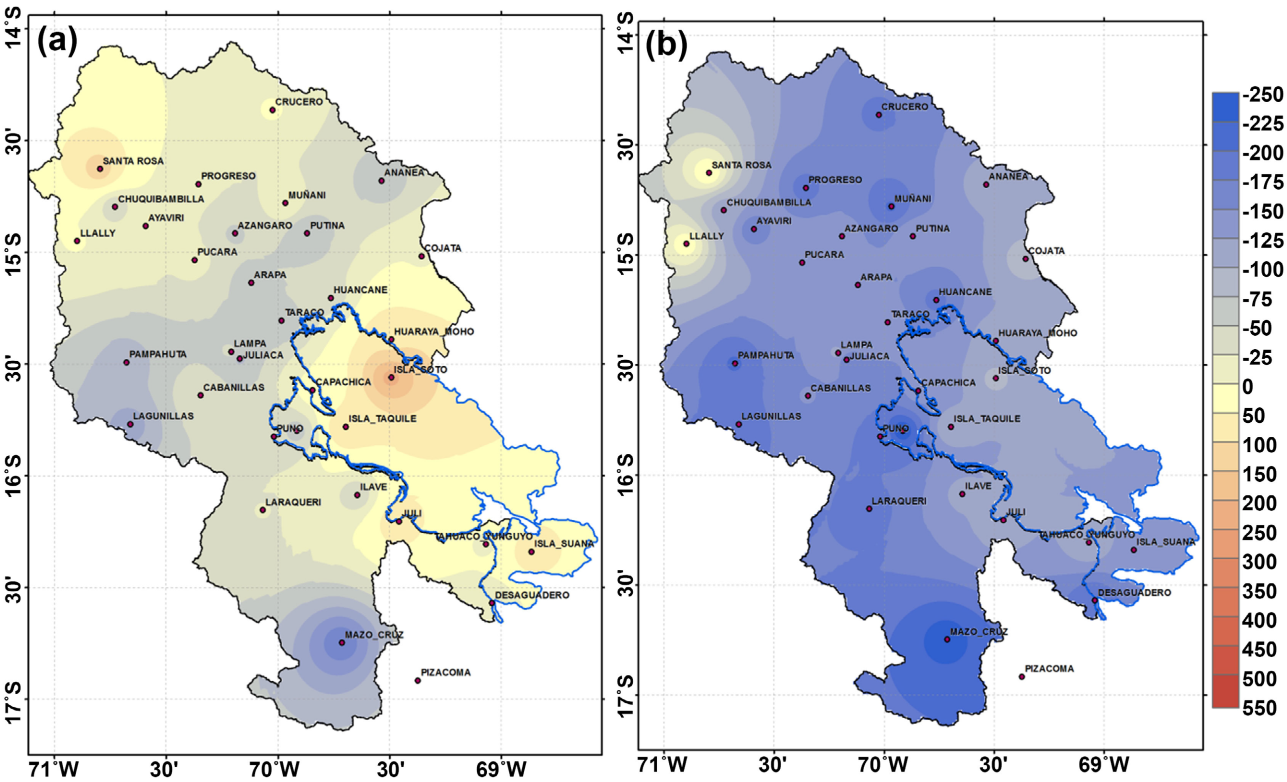


**Figure 10.** Similar to **Figure 9** except for (a) moderate and (b) strong El Niño events.

basin. On the other side [3] suggested TL water level oscillates in response to oceans thermal anomalies in tropical regions and negative SST northern tropical Atlantic Ocean would be related with TL water levels rises. This relationship between TSS and water levels allows us to better understand the PDO-ENSO relationship.

## 5. Conclusion

The analysis of the behavior of Lake Titicaca, for the period from 1914 to 2014 by spectral analysis of the TL, shows a period of variability of 12 years that was associated with the PDO climate index. The results indicate an inverse relationship between TL and PDO, with the increase in NLTs being related to the negative phase of PDO. Likewise, the behavior of precipitation in the ENSO events was evaluated through composition analysis since the precipitation is related to the variation of the TL. The analysis showed negative precipitation anomalies in most of the RAP in the El Niño years, on the other hand for La Niña years, precipitation anomalies were positive. Thus, in the positive phase (negative) of the PDO, with a higher probability of positive phase (negative) ENSO events, precipitation presents negative (positive) anomalies that may be associated with the decrease (increase) in TL.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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