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Analysis of the variability of water levels of Titicaca Lake

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Abstract: The purpose of this study is to compare the variability of the Titicaca Lake (TL) water level to the Pacific Decadal Oscillation (PDO) between 1914 and 2014 and relate it was compared to El Niño - Southern Oscillation (ENSO) between 1969 and 2014 to evalute the hydrological cycle and perform rainfall forecast. Results show that the Lake Titicaca water level decreases (increases) in the positive (negative) phase of the PDO. Likewise, the negative phase (positive) of ENSO generates patterns of positive anomalies (negative) of precipitation. Therefore, the positive (negative) phase of PDO, with greater probability of positive phase ENSO events (negative), precipitation anomalies shows negative (positive) which can be associated with the decrease (increase) in Titicaca Lake water level.

Keywords: ENSO; PDO; Titicaca Lake

1. Introduction

The Peruvian Altiplano Region (PAR), is a geographical area of high plateau morphology, located on the 3810 meters of altitude. It is surrounded by the western and eastern ranges of the Andes, and the drainage is part of a great fluvial system, integrated with the basins Poopó, Coipasa, and Uyuni, all of which have acommon collector in Lake Titicaca [1](Figure 1).

Used the HadRM3 and ETA CSS models to simulate temperature in two scenarios: A2 (High concentration and CO2) and B2 (Low CO2 concentration), temperatures increase between 2 ° C to 4 ° C, and to a maximum value of 6 ° C, in the northern region of Lake Titica by the year 2100. Unlike temperature trends, whih are clear [2]. Rainfall may decrease slightly over the PAR, but the patterns are not clearly defined. For example, in austral summer, in the southwestern part of the TL, a decrease of the precipitation up to 6 mm / day is observed [2]. However, observed trends show systematic precipitation increases in the western RAP slope as well as reductions in the eastern, southern and central slopes [3,4].

There has been a gradual decrease in TL level in recent years with reference to its normal level, according to the measurements taken by [5], TL level has changed significantly during the twentieth century with a difference of 5 meters between 1944 extremes (3806.7m) and 1986 (3811.6m).

Figure 1. Map of the Lake Titicaca Watershed. Developed by the World Water Assessment Program (WWAP) by Association for Forest Development and Conservation (AFDC), 2002.

The lake is supplied by rainfall (47%) and river water (35%), mainly by the river Ramis [6]. The lake loses water by evaporation (91%) and at the control point in the Desaguadero River (9%), the average annual temperature in the lake basin fluctuates between 7 and 10 ° C [6].

Drought is an extreme global climate event with major societal and economic consequences for millions of people in the world, especially in arid and semi-arid regions[7,8]. How patterns of drought are changing as the climate changes has been the focus of several recent studies, but the answer remains unclear.

Trenberth et al. [9] demonstrated that natural variability, especially El Niño-Southern Oscillation (ENSO), is the primary cause of many episodic droughts around the world. Extensive research has documented ENSO-induced dry–wet anomalies over various regions [10,11,12,13]. However, the typical interannual relationship between ENSO and the global climate is not stationary and can be regulated by the Pacific Decadal Oscillation (PDO) [14,15]. Many studies have revealed that the PDO exerts a modulating effect on ENSO teleconnections over many parts of the world, such as the South America[16], Mexico[17], Australia[18], and East Asia[19,20].

The main objective of the study is to analyze the variability of Lake Titicaca water levels, try to show possible trends and breaks, and relate this variability to the Pacific Decadal Oscillation (PDO) and ENSO events.

2. Experiments

To investigate the variability monthly and annual of Lake Titicaca water levels, were analyzed lake water levels monthly and yearly over the period 1914 – 2014 and precipitation data were analyzed from 34 conventional meteorological stations over the period 1969 to 2014. Montlhy and Yearly values of the Pacific Decadal Oscillation (PDO) and the ENSO were also analyzed for the same period of Lake Titicaca water levels and meteorological station data, respectively.

To describe the variability of the lake level, spectral analysis was performed. This statistical technique uses the fundamental concepts of Fourier analysis, where it is possible to transfer the information contained in the series to the frequency domain, in which the statistical characterization of the randomized phenomenon is more effective. In this technique, the variance of a process is a measure of the dispersion of the observations in relation to their mean value. In that sense, the variance provides a measure of the intensity of the fluctuations of the process over its average level, hence of its energy content. Spectral analysis helps to decompose the total variance into frequency bands in which the contribution of the total variance of the process is the result of overlapping many mutually independent contributions, each with an arbitrary frequency. In this way, a spectral decomposition of the Lake Titicaca level will be performed, in terms of amplitudes and phases, as a function of frequency.

In order to establish a relationship between Lake Titicaca water levels, the Interdecadal Pacific Oscillation index (PDO), and the El Niño-Southern Oscillation (ENSO), composite analysis was used considering events. Composite analysis consists of the calculation of the average of the events to be studied; thus, composites describe the average characteristics of the event. In this study, composite analysis will describe the behavior of precipitation in El Niño and La Niña events. Where the rainy season (DJF) of the El Niño / La Niña events was considered, to then calculate the mean of the accumulated rainfall and make the difference with the accumulated climatic mean for the analyzed period of the 34 climatic stations used in this work .

Based on the work of Prado [21], seven ENSO (+) and eight ENSO (-) were counted for the PDO phases and for our study period (1969 - 2014). The PDO index, according to Mantua et al. [14] was calculated by means of the analysis of compositions for the SST anomalies of the North Pacific, being that these anomalies are normalized by the average of the period from 1947 to 1995. The ENSO event is a ENSO (+) as the SST of the equatorial Pacific ocean is anomalously hot (El Niño) and ENSO (-) correspond to negative SST anomalies (La Niña).

3. Results

3.1. Level of Lake Titicaca

The changes in TL level during the period 1914 - 2014 were analyzed considering a reference altitude of 3800 meters in Figure 2, a variation of 6,309 meters can be seen in the period from April 1943 to December 1986. The rainy period from 1985 to 1986 reached a very high water level of the lake compared to the historical average for the period 1914 - 2014. According to Sztorch et al. 1989 [22], the levels reached in that period caused floods and disturbances in several cities that are located around the TL generated the government of Peru, a call for international support. On the other hand, the very low levels recorded during the 1940s were attributed to repeated occurrences of El Niño events between 1936 and 1943 [23].

The series of TL levels do not show a trend, but when performing a visual analysis shows a variability characterized by low frequency fluctuations, presenting many peaks throughout the century. The strongest fluctuation was observed during the period 1933 - 1944 in which the level of the lake decreased by 6 meters. Another important event was registered in the period 1986 - 1997, where the value of decrease was of 4.2 meters.

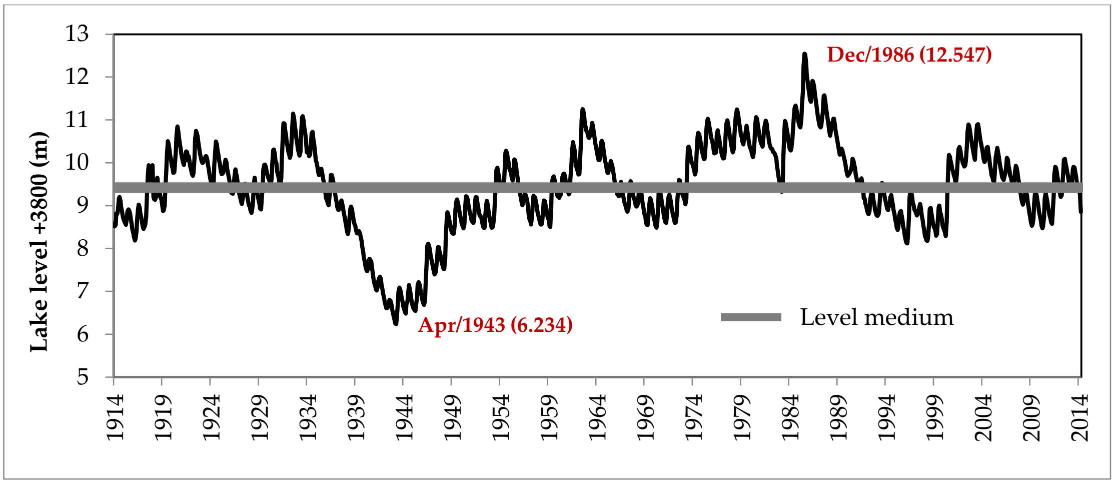

Figure 2. Behavior of Lake Titicaca level. Period 1914 to 2014. The red line represents the average value.

3.2. Lake level fluctuations

These fluctuations are associated with evaporation, according to the analysis of the data of water levels. Three periods with very high values of evaporation were observed (Figure 3).

The first event was from Mar / 1934 to Dec / 1943, where the value of the difference was 4,816m with an average of 0.482 m / year, representing a volume of 455 million cubic meters of water. For the period from April 1963 to December 1970, the value was 2,767m and an average of 0.260 m / year, equivalent to 264 million cubic meters. The last period analyzed was from Apr / 1986 to Dec / 1996, registering a fall of 4,430 m which represents an average of 0.44 m / year and a volume of 424 million cubic meters.

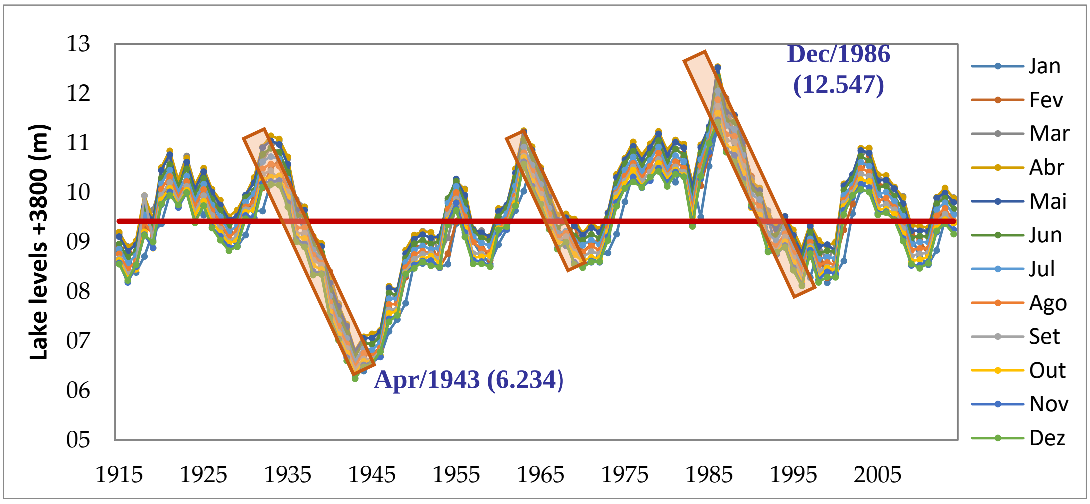

Figure 3. Comparison of Lake Titicaca level. Period 1915 to 2014. Shaded areas represent periods with high evaporation values.

3.3. Annual increase in the level of Lake Titicaca.

Carmouze et al. [24] showed that the annual fluctuations of the TL correspond to the differences, at the annual level, between the flows that enter and leave the lake. Lake level variations are represented by the differences between rainwater inflows, outflows and evapotranspiration, as well as regional climatic fluctuations. Ronchail et al. [5] calculated the differences in lake level between April and December which represent an index of rainy season activity.

Figure 4 was adapted [5], and constructed with the data used in the present study (levels, period 1914 - 2014 and precipitation, period 1969 - 2014). When the analysis was made, it was observed that it presents two months corresponding to the extremes of the annual cycle of lake level and that shows a lag of three months in comparison to the annual cycle of the rains, the maximum levels of the lake are observed in April and the maximum rainfall values in January, minimum levels occur in December, five months after the minimum rainfall in June and July.

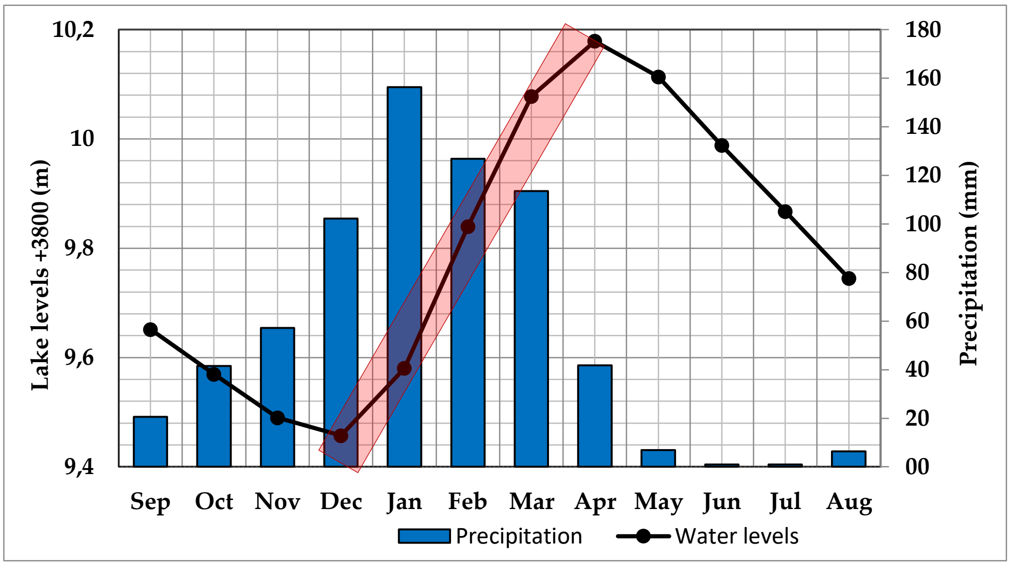

Figure 4. Annual increase of the level of Lake Titicaca period 1915 - 2014. Annual average precipitation period 1969 - 2014. Adapted from Ronchail et al, 2014.

3.4. Relationship between water levels and rainfall in the basin.

Figure 5 shows the response time of TL levels after rainfall for rainy season (DJF) and spectral analysis (Figure 6), have a maximum single value with the period of 12 years associated with an interdecadal variability. This variability is linked to the phases of the Interdecadal Pacific Oscillation (PDO).

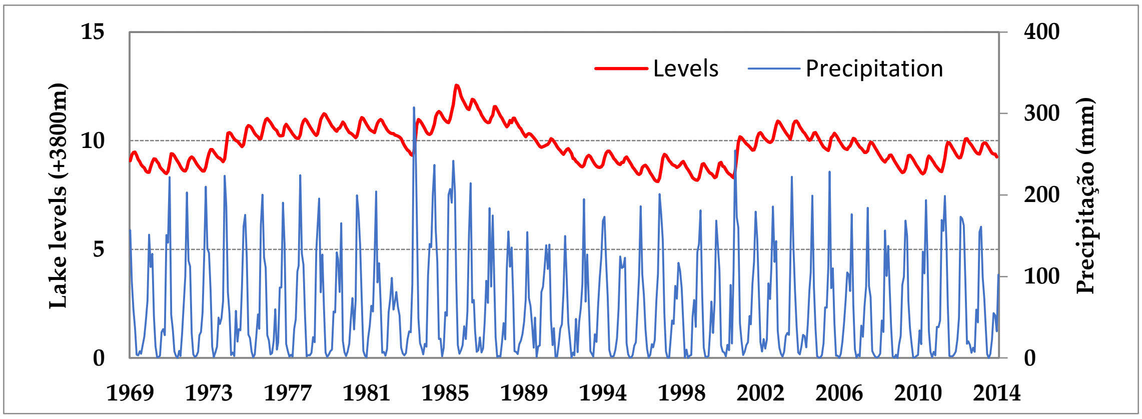

Figure 5. Water levels and monthly precipitation in the Lake Titicaca Watershed for the period 1969 - 2014.

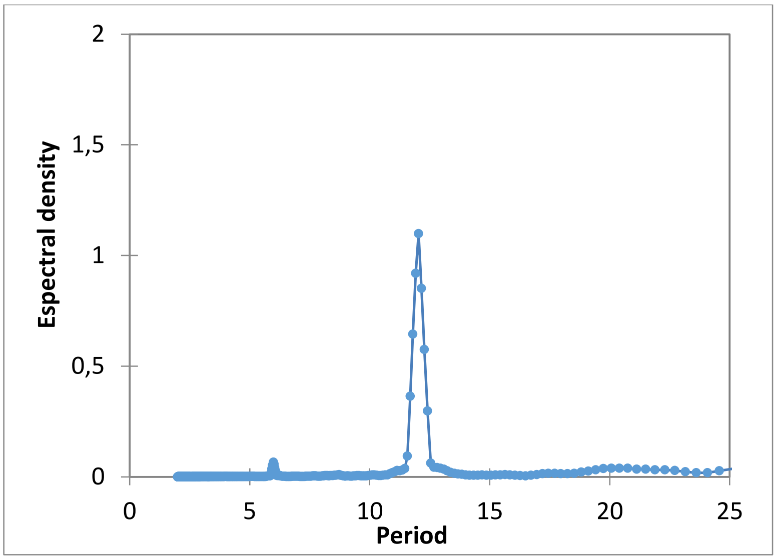

Figure 6. Spectral analysis of Lake Titicada level. Period 1914-2014

3.5. Relationship between PDO , ENSO and water levels in the basin.

Figure 7 shows the variations of PDO with lake level anomalies for the period 1914 - 2014, where it can be seen that for PDO (-) there are increases in lake level anomalies and for PDO (+), there is a decrease in the levels (Figure 7), in both cases there is a lag period as detailed in Figure 4. Recalling that when we have PDO (+) there is a greater probability of occurrence of El Niño and PDO (-) events, occurrence of La Niña events. The results of the analysis of compositions of ENSO events for the period 1969 to 2014 are presented in Figures 9a. (La Niña) and 9b. (El Niño).

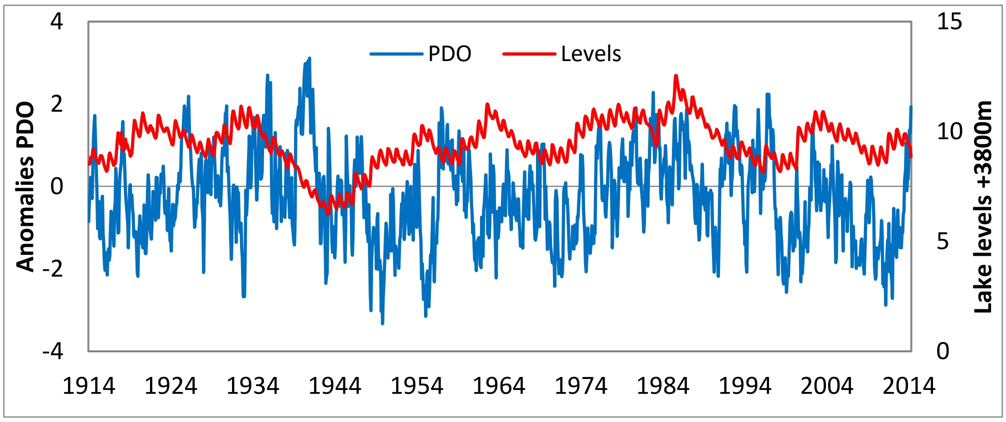

Figure 7. Anomalies (PDO) and water levels of Lake Titicaca. Period 1914 - 2014.

For La Niña events it can be seen that the anomalies of the precipitation compositions, both for the moderate (Figure 9a) and strong (Figure 9b) events, there is a positive pattern in the precipitation with greater predominance in the South, covering the whole area of TL, and negative values in the North.

For the El Niño-very strong events (Figure 10b) the anomalies of the compositions show that there is a decrease in precipitation anomalies in most of the basin, and for the moderate event (Figure 10a), the anomalies of the compositions are not very intense as in the previous case. Therefore, during an El Niño event precipitations in the basin present negative anomalies which would be correlated with the decrease of lake levels when a positive phase of the PDO is found, during which El Niño events exist, this result was also determined by Ronchail et al. [5], who produced a graph of the TL and the level difference of the month of April and December (Figure 8), for the period from 1915 to 2009, in which it determined no increase in the TL for the period of 1941 and 1983, where they had greater presence of El Niño events. In the opposite case for the event La Niña the anomalies is positive (with greater predominance in the south), corresponding to a negative phase of the PDO with increases in the TL.

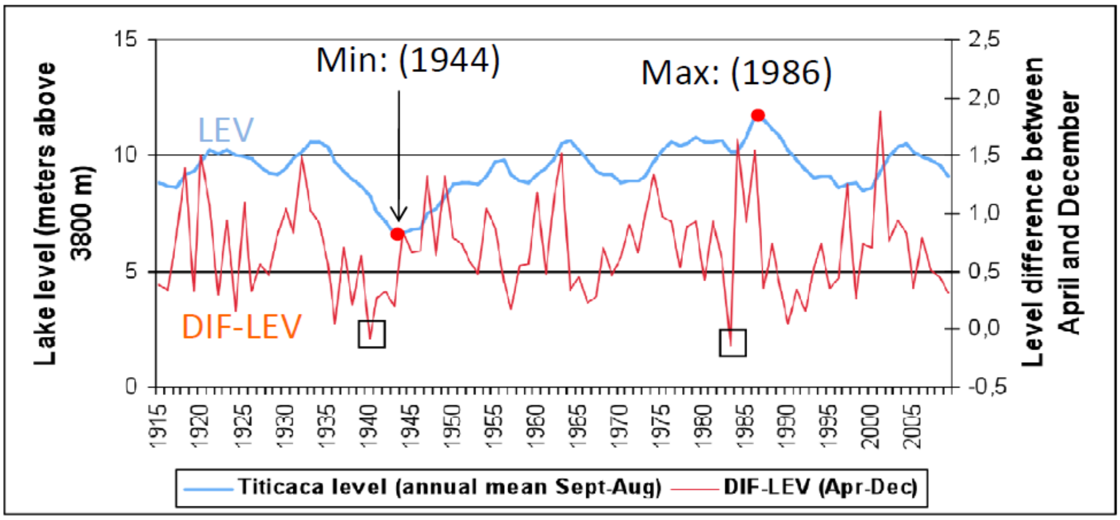

Figure 8. Anomalies (PDO) and water levels of Lake Titicaca. Period 1914 - 2014. Ronchail et al. [5]

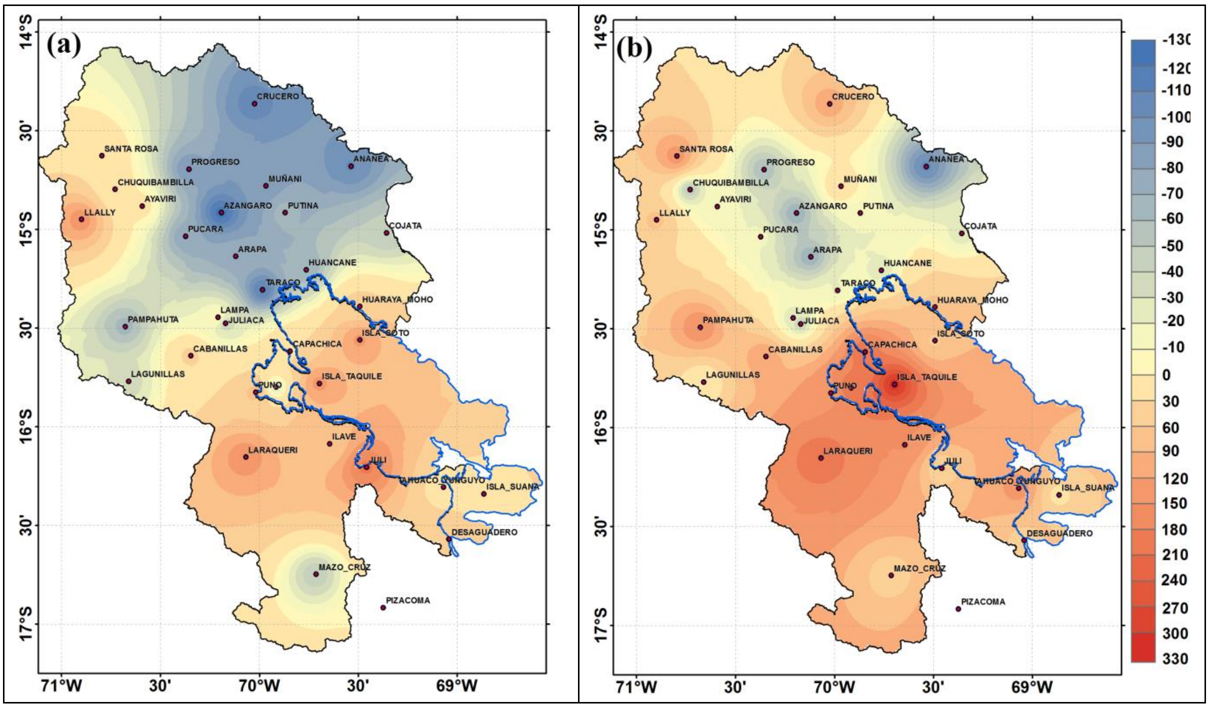

Figure 9. Anomalies of precipitation compositions for the moderate (a) and very strong (b) El Niño event. The color bar shows precipitation anomalies in millimeters. Vertical axis indicates the latitudes and the horizontal axis refers to the lengths, both in degrees (°).

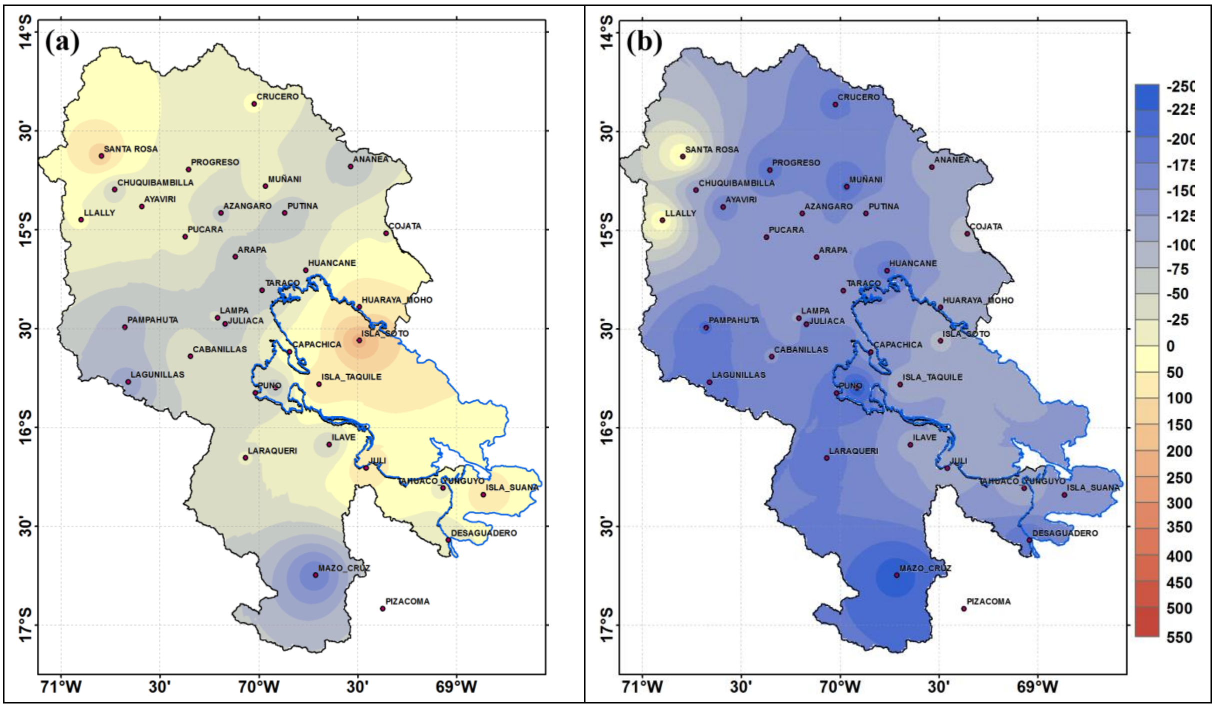

Figure 10. Anomalies of precipitation compositions for the La Niña event moderate (a) and strong (b). The color bar shows precipitation anomalies in millimeters. Vertical axis indicates the latitudes and the horizontal axis refers to the lengths, both in degrees (°).

4. Discussion

The studies carried out by Ronchail et al. They show that Lake Titicaca has a frequency variability which is associated with the thermal conditions of tropical oceans. To this we can add the results obtained in the present research work. Where can be demonstrated the relationship that exists between the PDO and the ENSO with the variability of the water levels of Lake Titicaca. Ronchail et al affirm that the growth of the lake level occurs when there are La Niña events and when the northern tropical atlantic ocean is cooler than normal. In our case, it has been shown that for La Niña fuerte events there are precipitation anomalies and in front of La Niña events there are positive anomalies northeast of Lake Titicaca.

For El Niño events (moderate and strong) the analysis of compositions shows positive precipitation anomalies in the central part of Lake Titicaca.

5. Conclusions

From the analysis of the behavior of Lake Titicaca, for the period from 1914 to 2014 by spectral analysis of the TL, show 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 by means of 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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Author Contributions: Eleazar Chuchón and Augusto Pereira analyzed the data; Augusto Pereira contributed materials and analysis tools; Eleazar Chuchón wrote the article.

Conflicts of Interest: “The authors declare no conflict of interest." and “The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results”.

Abbreviations
The following abbreviations are used in this manuscript:

TL: Titicaca Lake
PDO: Pacific Decadal Oscillation
ENSO: El Niño-Southern Oscillation
SST: Sea Surface Temperature

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