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The Influence of Large-Scale Phenomena on La Paz Bay Hydrographic Variability

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Abstract

We analyzed the hydrographic variability of La Paz Bay, the largest coastal water body in the Gulf of California, and its relationship with Pacific large-scale phenomena, including the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Pacific-North America pattern (PNA), and North Pacific pattern (NP). We used several indices related to these phenomena and the hydrographic variability data of La Paz Bay, consisting of the annual sea surface temperature patterns from satellite imagery from 2000 to 2010 and the mixed layer depths measured with *in situ* data from 1994 to 2009. The results indicate the sea surface temperature fluctuated during the study period, with 2007 as the coldest year and 2009 as the warmest. Two periods were identified in the annual thermal cycle of the bay, one period of warmth from June to November, and one of cold from December to May. The sea surface temperature is primarily influenced by the ENSO. The mixed layer depth analysis showed its absence during August-September, while the deepest ones were in November-March. The unusual 100 m mixed layer depth noted during February 2002 and its absence in March 1996 and 2009 were related to uncommon atmospheric conditions in the annual patterns of the ENSO, PNA, and NP. The variability of the mixed layer depth is primarily related to the variability of the NP. We concluded that the hydrographic conditions of La Paz Bay are most influenced by the NP during the cold phase of its annual cycle, and by the ENSO during the warm phase.

Keywords

Pacific Large-Scale Phenomena, La Paz Bay, Gulf of California, Hydrography, Annual Patterns

1. Introduction

Many large-scale phenomena occur in the Pacific Ocean that act on varied time-scales, from the El Niño-

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Southern Oscillation (ENSO) with month-year cycles to decadal-to-multidecadal frequency events such as the Pacific Decadal Oscillation (PDO). Their effects are detectable in global to local ecosystems, and their aggregate contributions establish climatic shifts that have shown fluctuations in the atmospheric and oceanic conditions such as sea temperature [1], wind fields associated with atmospheric pressure variations [2], ocean currents [3], coastal upwellings [4], and mixed layer depths [5]. Many of these climatic variations occur via atmospheric-oceanic teleconnections [6], which extend from the troposphere to the ocean surface, including fluctuations in sea level pressure that are closely linked to changes in the surface winds, sea surface temperature, heat content, mixed layer, and thermocline depth. Climate variability due to large-scale influences in the North Pacific receives considerable attention due to its impact on tropical and extra-tropical climate [7] and the weather over North America [8].

The ENSO, perhaps the most studied large-scale phenomenon, is comprised of two phases. The warm El Niño phase, which has been studied extensively in the Pacific Ocean [6] [9], is characterized by the weakening of trade winds, warming of the sea surface layer in the tropical-subtropical eastern Pacific, a switch from low to high atmospheric pressure near Darwin, Australia, and the opposite effect near the Tahiti Islands, which is termed the Southern Oscillation. The La Niña cold phase of the ENSO is much less studied in the Pacific. It is characterized by an intensification of the trade winds, the cooling of the sea surface layer in the tropical-subtropical Eastern Pacific, very low atmospheric pressure near Darwin, Australia, and very high pressure near the Tahiti Islands [10] [11].

The Pacific Decadal Oscillation (PDO), another large-scale phenomenon, is a pattern of ocean variability over the entire Pacific that is similar to the ENSO in some respects, but with a much longer cycle [12] [13]. It is also defined by two phases; the positive phase in the North Pacific occurs when the sea surface temperature anomalies are cold in the central North Pacific and warm along the Pacific coast and when the sea level pressure is below average in the North Pacific [14], while the converse occurs during the negative phase. Both phases are calculated by the standardized difference between sea surface temperatures in the north-central Pacific and Gulf of Alaska. The phases of the PDO may be important in enhancing or dampening the ENSO impacts [15].

The Pacific/North American (PNA) pattern is one of the most prominent modes of low-frequency variability in the Northern hemisphere extra-tropics, and it describes the variation of atmospheric circulation patterns over the Pacific Ocean and North America that involve changes in the atmospheric pressure between the Aleutian Low and the high pressure over the Rocky Mountains [16] [17]. The PNA has the most impact on climate variables during the winter [18] [19]. As with the first two phenomena, the PNA also presents two phases, with the positive phase usually related to El Niño and the negative phase to La Niña. However, there is also a weak connection between the PNA and the ENSO [20]-[22]. During the positive phase of the PNA, the Aleutian Low in the intermountain region of North America shows anomalous low pressures, while the high pressure over the Rocky Mountains and Northeast Pacific Coast strengthens, increasing the pressure gradient between the two centers of circulation, in addition to increasing the wind speed, which steers more storms into the Northwest Pacific. The negative phase of the PNA is essentially the reverse pattern of the positive phase [16].

The North Pacific pattern is quite similar to the PNA, but the variables involved in this atmospheric process are considered differently. For the PNA, [16] considered four centers of action in the mid-tropospheric height field, one each of one sign near Hawaii and along the west coast of North America, and one each of the opposite sign over the north Pacific and southeastern United States. According to [23], these four centers of action and their resulting index have proven to be useful, but they also consider it inappropriate to weight the four centers of the PNA similarly, as the North Pacific has by far the most prominent height field. They proposed the North Pacific pattern and its index as a much more robust, but simpler measure of the atmospheric processes in North America.

The Pacific Ocean exerts a strong influence over the oceanographic conditions of the Gulf of California, the sea that shelters La Paz Bay, due its connection to the eastern tropical Pacific [24]. The dynamic forcing from the Pacific Ocean over the gulf is one of the most important oceanographic features, because it integrates relevant phenomena such as salt and heat global balances, thermohaline circulation, and barotropic ocean circulation [25] [26].

Studies have demonstrated the effects of these large-scale phenomena on the Gulf of California region, and satellite analysis has shown the influence of the ENSO over the sea surface temperature variability. Based on the satellite records of the sea surface temperature anomalies, [27] [28] showed that during El Niño, the temperature in the gulf registered up to 3˚C above normal, while during La Niña, it was up to 3˚C below normal.

Similarly, studies on the PDO have shown its influence on pressure, wind, temperature, and the precipitation patterns of the North Pacific [12] [29] [30]. Its temporal modulations are linked to several important biological and ecosystem variables in the ocean [31] [32]. Nevertheless, other parameters such as the decadal fluctuations in salinity, nutrients, and chlorophyll a in the eastern North Pacific are often poorly correlated with the PDO [33].

The relationship between the sea surface temperature over the Pacific Ocean and the PNA has also been studied by [34]-[36], who determined that the PNA pattern is positively correlated with the sea surface temperature anomalies over the tropical Pacific [34] [37] and negatively correlated with those anomalies over the North Pacific [38]. The link between the PNA and the tropical sea surface temperature anomalies is mostly attributed to the ENSO phenomenon. During an El Niño event, atmosphere-ocean interactions generate a seesaw pattern with opposing anomalies of the surface pressure in the eastern and western tropical Pacific [36].

On the other hand, a dependence of the western North Pacific (28˚ - 31.5˚N, 133˚ - 137˚E) mixed layer depth on decadal and inter-decadal time-scales (1950-1997) and large-scale, low-frequency North Pacific climatic variability has been reported [39]. These authors found an inverse relationship between the mixed layer depth and the NP index in 1962-1965 and 1973-1997 and suggested that its close linkage is caused by the alternating wind stress fields. Studies of the eastern North Pacific mixed layer depth variability (Baja California eastern boundary currents) are extremely important for evaluating the effects of local and basin-scale changes in the ocean surface. In particular, the low-frequency mixed layer depth changes in the eastern North Pacific are related to large-scale atmospheric forcing on the Pacific Ocean [40].

Some large-scale phenomena effects on La Paz Bay have already been reported, primarily related to El Niño events, such as the sinking of the thermocline and isotherms and a warming of the entire water column (>4˚C) during the summer-autumn of 1997. Nevertheless, some inconsistencies trying to relate other physical events with the ENSO cycles are present, such as the unusual 100 m mixed layer depth during the winter of 2002 in a non-ENSO period [41], and the absence of a mixed layer during the La Niña period in the winter of 1996 and 2009 [42] [43], a period when theoretically it should have been dominated by strong and persistent winds.

It is important to mention that La Paz Bay is a coastal water body of economic interest due to its tourism industry and fishing activities that are maintained by the high biological productivity of the bay, as well as by its contiguity to La Paz City, the capital of Baja California Sur. Thus, a better understanding of the processes that affect that productivity such as the North Pacific large-scale phenomena is required, as most studies have only focused on the ENSO influence, particularly the temperature variations. Consequently, we analyzed the variability of two hydrographic characteristics, sea surface temperature from 2000 to 2010 and mixed layer depth from 1994 to 2009, to determine their relationships with the climatic phenomena of the North Pacific.

2. Materials and Methods

2.1. Study Area

La Paz Bay is located between 24.1˚ - 24.8˚N and 110.2˚ - 110.8˚W (**Figure 1**). It is the largest bay in the Gulf of California (80 km long and 35 km wide) and consists of two basins: one in the north with a depth of up to 450 m

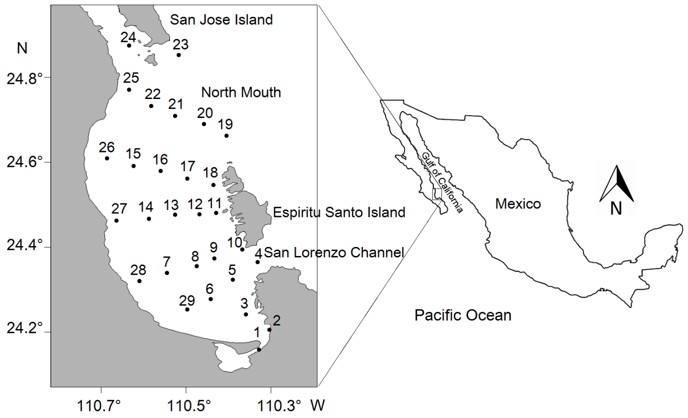

Figure 1. La Paz Bay location and sampling stations.

and another in the south with an average depth of 40 m. It is connected to the Gulf of California by two passages: the North Mouth (350 m depth) and the San Lorenzo Channel (10 m depth) [44]. The water column structure of the bay is characterized by a well-defined mixed layer during the winter and spring and a surface-stratified layer during the summer and fall [45] [46]. The winds over the bay are northwesterly from November to March (up to 10 m/s), with a moderate intensity during most of the year and southeasterly with less intensity (~2 m/s) during the summer with frequent calms [42] [47]. The bay presents an arid climate (BWh type) with scarce and irregular precipitation. The evaporation (215 mm/yr) exceeds the precipitation (180 mm/yr), and the tides are predominantly mixed semidiurnal [48].

2.2. Hydrographic Analysis

2.2.1. Sea Surface Temperature

To detect the sea surface annual variability of La Paz Bay, the temperature data was obtained from 130 NOAA-AVHRR images (2000-2010) of monthly averaged sea surface temperatures with a spatial resolution of 1.1 km at nadir, provided by the Scripps Institution of Oceanography in Hierarchical Data Format (HDF). These were visualized and processed with Windows Image Manager [49] to obtain the annual averages for comparison purposes to detect the variations over the study period with respect to the monthly mean data, thereby identifying the warmest and coldest years, the mean annual cycle, and the annual cycles of the thermally extreme years (*i.e.*, 2007, 2009). Temperature anomalies were also obtained from the satellite data and compared with the variability of the North Pacific climate indices.

2.2.2. Mixed Layer Depth

The mixed layer depth was measured and averaged from *in situ* temperature data collected from 29 stations with a Sea-Bird SBE 19 plus during sixteen oceanographic surveys performed in May, July, and October of 2001, February 2002, October 2004, February 2005, August 2006, March 2007, February, May and November of 2008, and March, June, September, and December of 2009 (**Figure 1**). Mixed layer depths from 1994 to 1999 were obtained from data reported by [41] [42].

2.3. Climate Indices

To obtain a more precise scheme of the environmental fluctuations and their possible consequences for the Gulf of California and La Paz Bay region, the monthly values of the following climate indices were used: 1) Oceanic Niño Index (ONI), defined as the three-month running mean of sea surface temperature anomalies in the Niño 3.4 region (5˚N - 5˚S, 120˚ - 170˚W); 2) Multivariate ENSO Index (MEI), based on six variables over the tropical Pacific: sea level pressure, the zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and the total cloudiness fraction of the sky; 3) Bivariate ENSO Time series (BEST), calculated by combining a standardized SOI and a standardized Niño 3.4 sea surface temperature time-series; 4) Southern Oscillation Index (SOI), based on the observed sea level pressure differences between Tahiti and Darwin, Australia; 5) Northern Oscillation Index (NOI), based on the difference in sea level pressure anomalies at the North Pacific High (35˚N, 135˚W) and near Darwin Australia; 6) Pacific Decadal Oscillation (PDO), the first principal component of the North Pacific sea surface temperature anomalies field (20˚N - 70˚N) with subtracted global mean; 7) the Pacific North American index (PNA), consisting of anomalies in the geopotential height fields (typically at 700 or 500 mb) observed over western and eastern North America; and 8) the North Pacific pattern index (NP), the area-weighted sea level pressure over the region 30˚N - 65˚N, 160˚E - 140˚W. All indices were obtained from the National Oceanic & Atmospheric Administration data base [50].

2.4. Statistical Analysis

The climate index data were averaged annually to find trends and compare them with the interannual sea surface temperature anomalies. The monthly sea surface temperature anomalies and the eight Pacific climate indices were compared, while the mixed layer depths were only compared with the index values for each of the corresponding survey dates and with the indices representing atmospheric pressure fluctuations that could cause wind pattern changes (*i.e.*, NP, PNA, NOI, and SOI) and thus influence the mixed layer depth. Spearman correlation analyses were conducted for all comparisons.

To identify the causes of the unusual mixed layer depths (*i.e.*, February 2002 and March 2009), we plotted the annual patterns for the monthly data of the NP, PNA, NOI, and SOI indices to describe the differences that could cause these anomalous depths.

3. Results

The sea surface temperature annual averages (2000-2010) showed that 2003, 2004, 2006, 2009, and 2010 were the warm years (**Figure 2**), and 2000, 2001, 2002, 2005, 2007, and 2008 were the cold years, with abrupt changes from 2006 to 2007 and from 2008 to 2009.

Two periods were clearly distinguished in the annual cycle of the sea surface temperature in La Paz Bay (**Figure 3**), a cold period with an average temperature range of 20.5˚C - 26.0˚C during December-May and a warm period of 26.0˚C - 31.0˚C during June-November. **Figure 3** also shows the variations in 2007 and 2009, the coldest and warmest years of the study period. From January to April, the temperatures of both years were slightly above the mean, but from May to December the temperatures were above the mean in 2009 and below it in 2007, with the exception of October-November, when all of the temperatures were quite similar.

Table 1 shows the annual variability of the two sea surface temperature anomalies (SSTa) and the climate indices involved in this study, revealing that the SSTa variability is similar to that of the ONI and MEI climate indices in relation to the ENSO events. The Spearman correlation analysis corroborates this similarity, showing high correlations among the SSTa and the ONI and MEI indices.

Given the ONI had the highest correlation with the SSTa, we plotted both annual variabilities (**Figure 4**) and found a high similarity between them, reaffirming that the sea surface temperature changes occurring in the El Niño 3.4 zone have an influence on the changes in this parameter in La Paz Bay. However, a high discrepancy was observed in 2000 and 2002 when the sea surface temperature anomaly in the bay was negative and the ONI was positive and above 0.5.

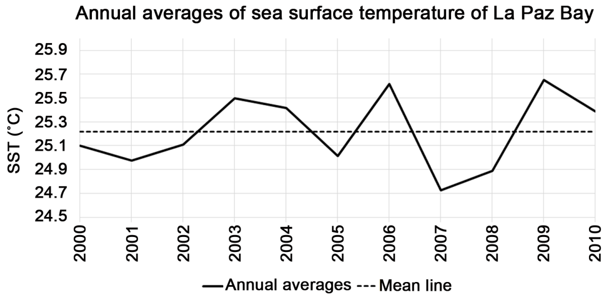

Figure 2. Annual average sea surface temperature of La Paz Bay from2000 to 2010.

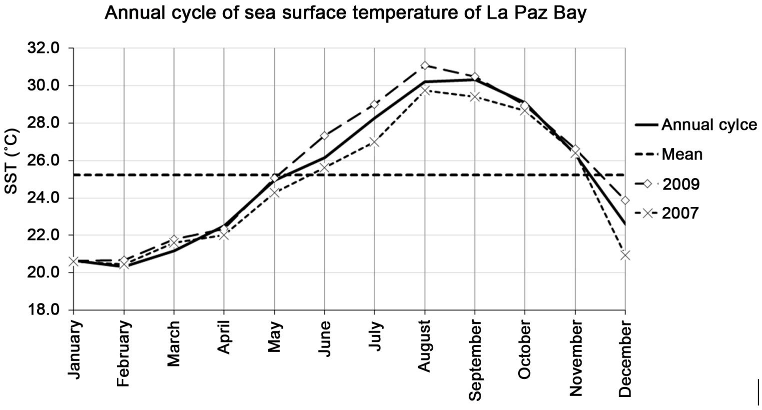

Figure 3. The annual cycle of sea surface temperature variability in La Paz Bay (solid line) and the monthly variability in 2007, the coldest (short-dashed line) year, and 2009, the warmest (large-dashed line).

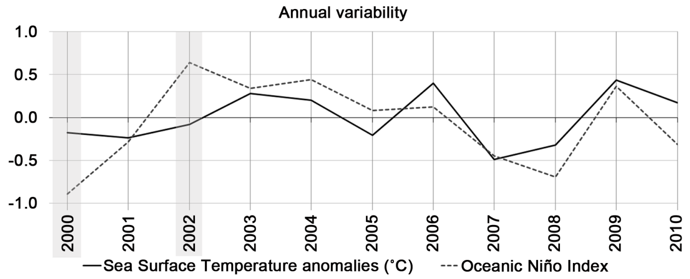

Figure 4. The 11-year time series of sea surface temperature anomalies of La Paz Bay from satellite images (solid line) and the Oceanic Niño Index (dashed line) (shadow areas denote high discrepancies).

Table 1. The annual series of sea surface temperature anomalies (SSTa) in La Paz Bay and the eight North Pacific climate indices involved in this study from 2000 to 2010 with their Spearman correlations. $P < 0.005$; bolded numbers have a significant correlation.

Year	SSTa (˚C)	ONI	MEI	BEST	SOI	NOI	PDO	PNA	NP
2000	−0.17	−0.82	−0.48	−0.82	1.42	0.41	−0.46	−0.18	1011.60
2001	−0.24	−0.28	−0.16	−0.10	0.40	0.32	−0.56	0.03	1012.17
2002	−0.08	0.72	0.63	0.91	−0.64	−0.69	0.22	−0.07	1012.42
2003	0.28	0.34	0.45	0.45	−0.15	−0.99	0.97	0.00	1011.90
2004	0.20	0.44	0.41	0.49	−0.43	0.63	0.35	−0.04	1011.82
2005	−0.20	0.08	0.32	0.40	−0.31	−0.23	0.38	0.53	1011.28
2006	0.40	0.13	0.30	0.32	0.02	0.52	0.19	−0.28	1014.06
2007	−0.49	−0.45	−0.34	−0.28	0.43	2.83	−0.20	0.57	1012.27
2008	−0.32	−0.69	−0.69	−0.93	1.88	2.29	−1.29	−0.11	1013.66
2009	0.44	0.37	0.39	0.36	0.28	0.88	−0.61	0.04	1013.31
2010	0.17	−0.32	−0.43	−0.92	1.53	−0.45	−0.31	0.49	1012.66
SSTa Spearman r_s =		**0.64**	**0.61**	0.54	−0.48	−0.25	0.26	−0.31	0.22

In the case of the mixed layer depth variability, the larger depths were measured during December, February, and March, corresponding to the cold period of the bay, and during October and November, the months when temperature decreases begin in the bay. Standing out, the largest mixed layer depth of 100 m was during February 2002, while the common depth during this period was ~50 m (**Table 2**). This contrasts with the absence of the mixed layer during March of 1996 and 2009. **Table 2** also shows the Spearman correlation analysis, which only found a statistically significant negative correlation between the mixed layer depth and the NP index.

Because the highest correlation was between the mixed layer and the NP index time series, both variables were plotted, revealing an inverse relationship between them (**Figure 5**). This negative and proportional relationship prevailed during most of the analysis period, with the exceptions of February 2002, when the 100 m mixed layer depth was registered and the relationship became very disproportional, and for March of 1996 and 2009, when the proportion of the negative relationship is unclear. Discarding these months the negative relationship becomes extremely high.

To analyze the anomalous conditions in the mixed layer depths described previously for 1996, 2002, and 2009, plots were made of the annual patterns for the NP, PNA, NOI, and SOI indices of these years (**Figure 6**). These plots show the contribution of the variability of each large-scale atmospheric related index that had an influence during the years of the anomalous mixed layer depths. In the case of the 100 m mixed layer depth in February 2002, the NP and SOI (**Figure 6(a)** and **Figure 6(d)**) values were lower than those in 2009, while the PNA and NOI (**Figure 6(b)** and **Figure 6(c)**) were higher than those in 2009. In the case of March 2009, the NP, NOI, and

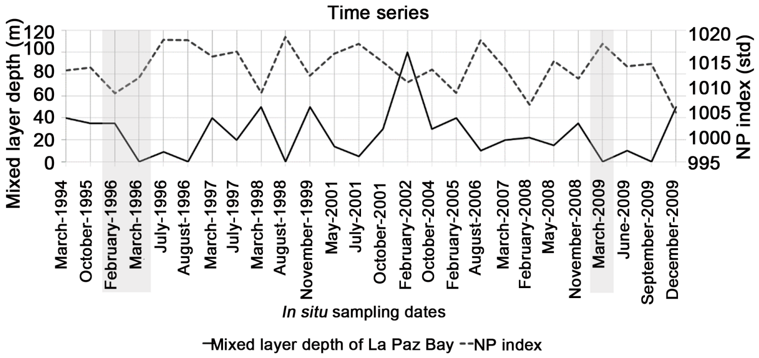

Figure 5. Time series of the mixed layer depth of La Paz Bay (solid line) and the corresponding NP index data (dashed line) from 1994 to 2009 (shadowareas denote unclear relationships).

Table 2. The mixed layer depth of La Paz Bay and the four North Pacific climate indices related to pressure variations from 1994 to 2009 with their Spearman correlations. $P < 0.005$, bolded numbers have a significant correlation.

Samples	MLD	NP	PNA	NOI	SOI
March 1994	40	1012.37	0.23	−1.00	−1.10
October 1995	35	1012.92	0.11	1.31	0.00
February 1996	35	1007.99	−0.70	−3.87	0.40
March 1996	0	1010.94	−0.75	−1.12	1.90
July 1996	9	1018.22	0.18	0.02	1.10
August 1996	0	1018.09	−0.93	0.94	1.20
March 1997	40	1014.99	−1.56	2.00	−0.70
July 1997	20	1015.95	0.10	−0.97	−1.20
March 1998	50	1008.11	0.69	−3.58	−4.00
August 1998	0	1018.76	−0.60	1.58	1.90
November 1999	50	1011.32	0.45	−2.03	1.70
May 2001	14	1015.52	−0.01	−0.61	−0.80
July 2001	5	1017.41	−0.36	0.53	−0.30
October 2001	30	1013.92	−0.08	0.73	−0.10
February 2002	100	1010.13	−0.11	2.94	1.80
October 2004	30	1012.55	−1.37	−2.11	−0.10
February 2005	40	1008.07	−0.11	−5.40	−5.20
August 2006	10	1018.12	−1.45	−0.47	−1.70
March 2007	20	1012.74	−0.12	5.11	0.30
February 2008	22	1005.85	0.37	5.69	4.40
May 2008	15	1014.14	1.25	0.57	−0.10
November 2008	35	1010.81	1.05	2.52	2.20
March 2009	0	1017.40	−1.29	4.57	0.70
June 2009	10	1013.16	0.48	−2.38	0.20
September 2009	0	1013.60	1.03	1.42	0.50
December 2009	50	1004.34	0.04	−3.44	−1.20
MLD Spearman r_s=		**−0.69**	0.22	−0.27	−0.30

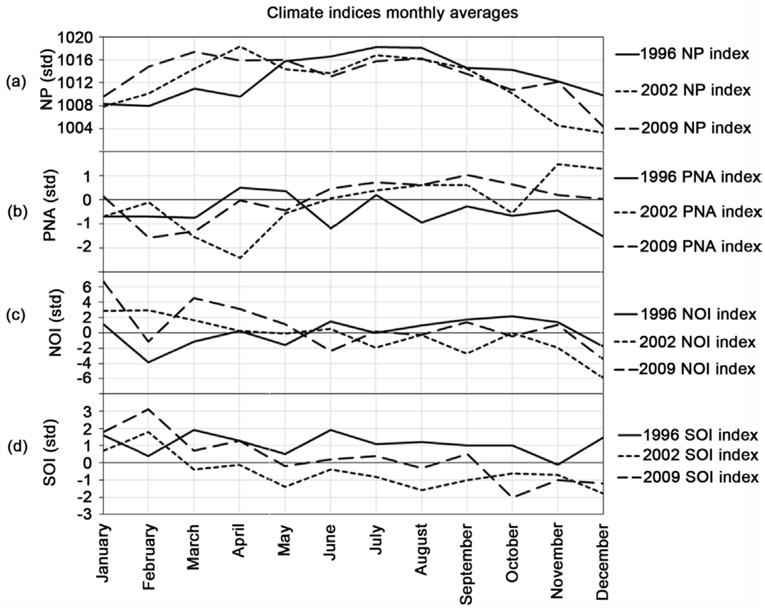

Figure 6. Annual patterns for the climate indices in 1996, 2002, and 2009. (a) NP, (b) PNA, (c) NOI, and (d) SOI.

SOI were higher than in 2002 (**Figure 6(a)**, **Figure 6(c)** and **Figure 6(d)**). The differences among the indices for these winter months and the correlations shown in **Table 2** demonstrated that, not only does the NP phenomenon influence the mixed layer depth, but other atmospheric phenomena such as the PNA, NOI, and SOI do as well. In the particular case of 1996, different patterns registered throughout the year from those in 2002 and 2009, but in March, the PNA and SOI (**Figure 6(b)** and **Figure 6(d)**) were higher than those of 2002 and 2009.

4. Discussion

The annual variability of the La Paz Bay sea surface temperature showed that, although the bay is a semi-enclosed body of water, it has interannual variability and abrupt changes, such as occurred during the 2007 and 2009 years. This indicates La Paz Bay is highly dynamic and influenced by the North Pacific, which agrees with reports by [24] [41] [42] [45] [48], who described the seasonal changes of this bay and emphasized the influence of the ocean-atmospheric processes that determine its hydrographic conditions.

The mean annual thermal cycle occurs in two phases (warm and cold) with their respective transition periods having similar temperatures. This differs somewhat from the findings of [41] [42] [48], who consider the bay's hydrographic variability based on four seasons. The differences in the annual thermal cycle between 2007 and 2009 showed that the changes in the temperature of La Paz Bay occurred not only during the El Niño events, when the warm waters from the tropical regions influence the marine environment, but also during La Niña, when the changes in La Paz Bay also occurred alongside decreases in the temperature during the warm phase of the annual cycle. This contrasts with reports by [41] [42] [48] [51]-[53], who only focused their research efforts on the temperature increases in La Paz Bay during the El Niño events.

The anomalous surface temperature variations of La Paz Bay showed a high correlation among the ENSO indices, corroborating that the thermal fluctuations of the bay are caused by both phases of this phenomenon (El Niño/La Niña), primarily during the warm period of the annual thermal cycle of the bay through the entrance of surface waters from the tropical Pacific. This coincides with observations by [24] [41] [42] [45] [48], who registered tropical waters during both the warm and cold periods of the La Paz Bay annual cycle. However, other studies exist showing that the La Niña effects are also reflected in sea surface temperature decreases in the Gulf of California, such as those by [27] [28]. Based on the sea surface temperature anomalies obtained from satellite records, they showed that during El Niño/La Niña events, the monthly mean temperatures of the Gulf of California vary by up to 3˚C from the normal conditions.

The variability of the mixed layer depth showed a high dependence on the wind conditions during the cold phase of the annual thermal cycle of the bay. [41] [45] showed that when the temperature decreases during the cold phase of the annual thermal cycle of the bay, the north winds velocities gradually rise, thereby increasing the mixed layer depth. Furthermore, [54] mentioned that the wind patterns in the Gulf of California correspond to a large-scale annual cycle of the Northeast Pacific. This was confirmed with the negative correlation obtained between the variability of the mixed layer depth and the NP index, showing that the wind patterns that regulate the depth's dimensions are determined by the atmospheric pressure variability of the Northeast Pacific.

Although the NP fluctuations are the primary factor generating the mixed layer variations, other phenomena must also be taken into consideration, as their indices were not significantly correlated. Such was the case in 1996, 2002, and 2009 when the anomalous mixed layer depths were registered. These were caused by the pressure variations of two or more of the atmospheric phenomena we analyzed that resulted in the changes of the wind magnitude and direction. [40] attempted to relate the large-scale phenomena to the variability of the mixed layer depth at the tropical boundary of the California Current by using CTD observations from 1997-2007. They affirmed that the seasonal and interannual variability of the mixed layer depth was correlated with offshore Ekman transport and that the abrupt mixed layer depth change that occurred between January 1998 and January 2000 was associated with a strong El Niño-La Niña shift.

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