Article

El Niño–Southern Oscillation Diversity: Effect on Upwelling Center Intensity and Its Biological Response

Gabriel Santiago Gutiérrez-Cárdenas 1, Enrique Morales-Acuña 2,* Leonardo Tenorio-Fernández 1, Jaime Gómez-Gutiérrez 1, Rafael Cervantes-Duarte 1,* and Sergio Aguñiga-García 1

1 Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz 23096, Baja California Sur, Mexico; ggutierrez2100@alumno.ipn.mx (G.S.G.-C.); itenorio@ipn.mx (L.T.-F.); jagomezg@ipn.mx (J.G.-G.); saguini@ipn.mx (S.A.-G.)

2 Instituto Politécnico Nacional, Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional, Bulevar Juan de Dios Bátiz Paredes, Col. San Joaquin, Guasave 81049, Sinaloa, Mexico

* Correspondence: morales.enrique@uabc.edu.mx (E.M.-A.); rcervan@ipn.mx (R.C.-D.)

Abstract: The influence of El Niño–Southern Oscillation (ENSO) on productivity at upwelling systems has been extensively studied. However, in recent decades, ENSO diversity has been documented; there are more frequent events with anomalies in the central Pacific (CP) causing ecological impacts that are different from the canonical events centered in the eastern Pacific (EP). We hypothesize that ENSO effects on upwelling intensity and its biological response are highly dependent on ENSO diversity. Wavelet coherence was computed for monthly standardized anomalies of Ekman transport and sea surface Chlorophyll-a (Chl-a) concentration from eight upwelling centers located along the west coast of the Baja California peninsula (1993–2022). Ekman transport (ET) showed a non-linear association with ENSO at interannual periodicities between 1.2 and 7 years, as well as semiannual scale variability. Coherence between ENSO and ET showed a reduction in upwelling intensity during CP ENSO events and an increased upwelling intensity after EP El Niño events with regional differences. Our results reveal an influence of northern Pacific circulation that subsequently influences ENSO events during its development and its peak. We detected an influence of SST and wind anomalies on the ENSO–Ekman transport connection associated with the northern Pacific Meridional Mode pattern. The CP shows an important role in sea surface Chl-a concentration anomalies (1998–2022). We highlight the conceptual relevance of distinguishing ENSO diversity, with influential ecological effects associated with CP ENSO events.

Keywords: central Pacific El Niño; equatorial Pacific El Niño; coastal upwelling; northern Pacific meridional mode; California Current System; Mexico

1. Introduction

In wind-driven upwelling systems, economic activities influenced by climate variability typically develop in the most productive coastal regions of the world’s ocean, contributing to over 20% of fish catch around the world and 7% of primary productivity [1,2]. In recent decades, the scientific community has focused its efforts on understanding the genesis and processes that give rise to these climatic-oceanographic events. Although the wind drag is the most relevant mechanism of physical force for upwelling genesis, coastline irregularities, stratification, thermocline depth, bathygraphy, and coastal topography, all have a great influence on the dynamics of the upwelling and influence on related physical, biogeochemical [3,4], hydrological [5], and biological processes [6]. As a result of the irregularities of the coastline and wind fluctuations, these factors are not uniform along the coast, causing the formation of upwelling centers [7], characterized by minimum surface temperatures [8–10], and high primary productivity [11,12].
The coastal upwelling system along the west of the Baja California peninsula, Mexico, located in the southern California Current System, is well known \cite{13–17}. The influence of El Niño–Southern Oscillation (ENSO) is the main interannual timescale variability factor modulating the physical and biogeochemical environment. ENSO’s impacts on particular events have been inferred mostly from sea surface temperature (SST) \cite{18}, salinity \cite{13,19}, upwelling intensity \cite{15,20}, sea surface Chl-a concentration \cite{21–23}, primary productivity \cite{24,25}, and phytoplankton, mostly focusing on data from the El Niño 1997–1998 \cite{13,20,21,24,26}.

One of the main mechanisms that trigger environmental oceanographic changes along the west coast of the Baja California peninsula is atmospheric changes in the Aleutian Low (primary expansion) and northern Pacific High (contraction) during El Niño \cite{27–29}, and the opposite during La Niña events, both of which drive changes in the wind field \cite{30}. In addition, environmental oceanographic changes in the region are influenced by the oceanographic modulation of thermocline anomalies that propagate eastward from the tropical Pacific and then poleward to the northern Pacific \cite{27,31}. Generally, both mechanisms tend to inhibit (rise) the upwelling of nutrients to the euphotic zone during El Niño (La Niña) and trigger reduced (increased) primary productivity with an impact on various trophic levels. However, the relative influence of each mechanism (atmospheric changes and environmental oceanographic changes) is not fully understood yet, and often two seemingly similar events show differential biological impacts. For example, in the 1997–1998 El Niño event, the decrease in upwelling and productivity was attributed to changes in coastal SST \cite{20}; in contrast, in the 2009–2010 El Niño event, southern water advection did not occur, and the atmospheric teleconnection associated with wind stress was widely recognized as a modulating factor \cite{19}.

Two types of ENSO events were recently well-identified according to the position of the maximum SST anomalies, distinguishing between eastern Pacific (EP) and central Pacific (CP) events \cite{32–35}. This ENSO distinction is a key factor in ocean–atmospheric teleconnections that highlights the traditional use of SST anomalies that limit our understanding of the impact of ocean–atmospheric teleconnections \cite{36–39}; thus, the distinction between EP and CP events is necessary to better comprehend ENSO teleconnections.

The CP and EP ENSO events have shown opposite and non-linear effects on the frequency and intensity of tropical cyclones \cite{40}, but also on South American and North American precipitation \cite{41–45}, Eurasian climate, North Atlantic Oscillation \cite{38,39,46,47}, western Pacific subtropical high \cite{48}, and on the biomass of the oceanic phytoplankton \cite{49}, with changes during their development or before their peak. The effects of CP and EP ENSO could be enhanced by global climatic change \cite{50}. Additionally, both types of events do not show the same development and teleconnection patterns; CP variability has a strong connection to subtropics, and in some cases, CP El Niño events are preceded by northeastern Pacific wind and SST anomalies \cite{51–53}.

The extratropical ENSO–atmosphere–ocean teleconnection affects ENSO diversity \cite{33,36,52}. CP El Niño events have been reported more frequent since the 1990s \cite{54–56}, with a distinct regional impact on nutrient, primary productivity, and phytoplankton biomass in the northern EP \cite{49}. It is thus expected that ENSO diversity will have different effects on the intensity of upwelling centers and phytoplankton biomass along the west coast of the Baja California peninsula, a region located in the southern sector of the California Current System with profitable economic, biological, and environmental relevance.

We tested two hypotheses: (1) Ekman transport at upwelling centers will be reduced in EP El Niño and will be increased during both CP El Niño and La Niña events, with no substantial effect from EP La Niña; and (2) a substantial sea surface Chl-a reduction response is expected during the development of EP El Niño events, and similar effects during CP ENSO events. To address both hypotheses, we analyzed the diversity of ENSO effects on upwelling centers, using Ekman transport as a measure of upwelling intensity. We also analyzed the biological response of upwelling centers, using the concentration of sea surface Chl-a to distinguish between CP and EP ENSO events. The present study aims
to establish the baseline of coastal upwelling centers and ENSO diversity on ocean and atmospheric regional scales along the west coast of the Baja California peninsula, Mexico.

2. Materials and Methods

2.1. Study Area

The west coast of the Baja California peninsula is in the southern California Current System (22°–32° N, and 109.5°–117° W), a transitional region in the northeastern Pacific characterized by the influence of three sea surface water masses: Subarctic Water (California Current), Subtropical Surface Water, and Tropical Surface Water. This region has a pronounced seasonal cycle that transports the northern coolest water along the west coast of the Baja California peninsula during the winter-spring seasons and the tropical and subtropical seawater masses during the summer-fall seasons [13,14,57]. Oceanographic variability separates the area into two regions divided by Punta Eugenia (~27.5° N); the northern Baja California region has subarctic characteristics, while the southern Baja California has warmer tropical/subtropical conditions. These differences result in a spatio-temporal complex transition region [13,18,21] with intense upwelling activity [20], and complex patterns of filaments, meanders, and mesoscale structures [58] that carry nutrients from coastal waters to offshore regions driven by a high variable seasonal and interannual variability in physical and pelagic biological characteristics [59].

The seasonal wind field along the west coast of the Baja California peninsula is controlled by the position and intensity of the northern Pacific High cell pressure [60,61], triggering prevailing northwest winds for the entire region with maximum intensity during spring and summer, and minimum intensity during autumn and winter[20]. Due to northwest winds, Coriolis force, and coastline orientation, upwelling is the primary nutrient input to the euphotic zone with a seasonal cycle that follows the changes in the wind stress field [20]. There are previously identified upwelling regions along the west coast of the Baja California peninsula, two in the north (Ensenada and northern Punta Eugenia) and two in the south (Punta Eugenia and Bahía Magdalena) [20]. Figure 1 shows the characteristics of the study area and the location of the eight upwelling centers recorded so far.
2.2. ENSO Diversity

ENSO events were identified using three distinct indices to represent ENSO diversity, and also the differences between CP and EP ENSO events for El Niño and La Niña phases. The indices were based on the SST of Niño 3 and Niño 4 regions (map details shown in: https://www.cpc.ncep.noaa.gov; accessed on 30 April 2024) to capture inherent differences in the maximum (minimum) longitudinal position anomaly of ENSO, as a key factor in the global effects of ENSO diversity [39,45]. Specifically, EP El Niño (EP La Niña) events are characterized by the warmest (coldest) anomalies located in the Niño 3 region; on the other hand, CP El Niño (CP La Niña) events are characterized by the maximum (minimum) anomalies located in the Niño 4 region [38–62].

We used the monthly Extended Reconstructed SST (ERSST V.5), which was calculated using 1991–2020 climatology data for each region and was normalized using the following equation [63]:

$$Z_i = \frac{(SSTA_i - \bar{X})}{SD}$$

Figure 1. Main upwelling centers (red stars) identified along the west coast of the Baja California peninsula. The bathymetry (m) is shown. The dotted black line corresponds to the 200 m isobath.
where \( Z_i \) and \( \text{SSTA}_i \) are the standardized anomaly and the SST anomaly for each month \( i \), respectively. \( \bar{X} \) and \( SD \) are the mean and the standard deviation of the SST anomalies. The EP and CP SST anomalies indices were calculated following these equations [62]:

\[
\text{EP} = Z_{\text{Niño}3} - 0.5 \times Z_{\text{Niño}4} \\
\text{CP} = Z_{\text{Niño}4} - 0.5 \times Z_{\text{Niño}3}
\]

where \( Z_{\text{Niño}3} \) and \( Z_{\text{Niño}4} \) represent the normalized SST anomalies of Niño 3 (5° S–5° N, 150°–90° W) and Niño 4 (5° S–5° N, 160°–150° W) regions, respectively [62]. Figure 2 shows the EP ENSO and CP ENSO indices, comparing indices (black line) with Niño 3.4 normalized SST anomalies (colors). Table 1 shows EP and CP El Niño/La Niña events that are higher than one \( SD \). When the EP or CP index is higher than one \( SD \) for December–February, the event is classified as an EP or CP ENSO, respectively. The ENSO composites for each type of ENSO are shown in Figure A1.

Figure 2. El Niño–Southern Oscillation index in the 1993–2022 period for (A) eastern Pacific (EP, black line) and (B) central Pacific (CP, black line). Niño 3.4 standardized anomalies region denoting El Niño (red), La Niña (blue), and the neutral phase of ENSO (green).

Table 1. ENSO events for EP and CP. The table shows the events in which the EP or CP index was higher than one \( SD \) for the ENSO peak in December–February.

<table>
<thead>
<tr>
<th></th>
<th>El Niño</th>
<th>La Niña</th>
</tr>
</thead>
</table>

2.3. Wind Data and Ekman Transport

We used the Cross Calibrated Multiplatform 10 m wind monthly data from 1993 to 2022 from the NASA Physical Oceanography Distributed Archive Center. The data were calibrated using Variational Analysis Methods to produce a complete grid with high-resolution (0.25° × 0.25°) zonal wind (u) and vector wind (v) data sets. The data fit in a vector difference of 0.8 m s\(^{-1}\) to QuikSCAT with no wind direction bias and 0.6 m s\(^{-1}\) to high-quality TAO buoys. This data set is capable of revealing ocean surface wind field features
that have been described in previous studies and provides high-spatial-resolution time averages of ocean surface winds [64]. This data set is available at https://www.remss.com/measurements/ccmp/ (accessed on 30 September 2023).

Eight upwelling centers on the west coast of the Baja California peninsula were selected to calculate alongshore wind stress and Ekman transport as a measure of upwelling intensity for each upwelling center. For calculations, we used a standardized method [65] that allows for (1) a systematic approach for Ekman transport estimation via the simplification of a high-resolution coastline without losing accurate determination of coastal angles, and (2) a higher Ekman transport spatial resolution calculation, allowing for the highest precision available for each coastal upwelling center.

The coastal angle estimation and Ekman transport method were applied separately for each upwelling center section. For this purpose, a Douglas–Peucker simplification method was used with $\varepsilon = 0.25$ by matching the wind spatial resolution. The coastal angle was estimated perpendicularly to the approximate coastline pointing offshore. Once the coastal angle was estimated, the wind stress was computed as follows:

$$\tau_{xy} = -\left(\frac{\text{lat}}{\text{lat}}\right)\left(\tau_x \cos(\theta - 90^\circ) + \tau_y \sin(\theta - 90^\circ)\right),$$  

where $\tau_{xy}$ is the alongshore wind stress, $\theta$ is the coastal angle, and lat represents latitude in the $[-90, 90]$ interval; all parameters were computed for each upwelling center. The Ekman transport (ET) is calculated as follows:

$$\text{ET} = \frac{\tau_{xy}}{\rho f},$$

where $\rho$ is the average density of seawater (1025 kg m$^{-3}$) and $f$ is the Coriolis parameter computed using the latitude of each upwelling center. These parameters were computed for each upwelling center shown in Figure 1.

2.4. Sea Surface Chlorophyll-a Concentration

The sea surface Chl-a concentration was obtained from the Copernicus Climate Change Service (C3S) v. 5.0.1 (doi:10.24381/cds.85b319d), which contains daily composites of sensors including VIIRS, OLCI, MODIS Aqua, SeaWiFS, and MERIS. A more complete spatial coverage is thus obtained than when data from independent sensors are used. Data were taken for the period 1998–2022 with a 0.0416° × 0.0416° spatial resolution (data are available at https://cds.climate.copernicus.eu; accessed on 30 May 2024). Monthly time series of sea surface Chl-a concentration in mg m$^{-3}$ were extracted for the location of each of the eight upwelling centers.

2.5. Wavelet Transform

The wavelet transformation analysis allows the estimation of the phase and amplitude of each component of a time series simultaneously [66], and follows the evolution of the distinct form of each signal. The modern wavelet analysis uses a convolution of the real-time series $x_t$ with multiple functions $\Psi(t: \tau, a)$ derived from a complex “mother” wavelet $\Psi(t)$ by scaling by $a$, and converting time in $\tau$:

$$T_x = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \Psi^*[a^{-1}(t - \tau)]x_t dt.$$

The complex conjugate is represented by the symbol *. For the $\Psi(t)$ selection, it will have a similar pattern and $x_t$ characteristics. Higher $T_x$ values denote that $x_t$ follows the desired form. For the current study, the Morlet wavelet is selected as follows:

$$\Psi(t) = \pi^{-1/4}e^{-t^2/2}e^{iwt}. $$

This mother wavelet is selected according to (1) improved localization and detection of scale and (2) better frequency resolution. Additionally, the Morlet wavelet splits the wavelet into the part that describes the characteristics of an oscillatory times series and
another part that retains the phase information required for coherence with another time series [67], which is the main purpose of the present study.

2.6. Wavelet Coherence

The wavelet-based coherence is the method selected to compare ENSO indices with the Ekman transport and sea surface Chl-a concentration time series. The wavelet-based coherence evaluates the frequency and phase synchronization of signals [67,68], which in turn is based on cross-wavelet analysis concepts. The cross-wavelet transform was calculated according to the following equation [69]:

$$ T_{x,y}(\tau, a) = a^{-1} T_x(\tau, a) \cdot T_y(\tau, a), $$

where $T_x(\tau, s)$ and $T_y(\tau, s)$ follow Equation (6)’s form. To compare both time series the energy density was calculated producing the cross-wavelet power spectrum that is useful to compare both time series:

$$ P_{x,y}(\tau, a) = |T_{x,y}(\tau, a)|. $$

Therefore, the cross-wavelet power spectrum depends on the units of the time series. The wavelet coherence that avoids an erroneous interpretation of the results is defined as follows:

$$ C(x_t, y_t) = \frac{aT_{x,y}}{\sqrt{a(a^{-1}|T_x(\tau, a)|^2) a(a^{-1}|T_y(\tau, a)|^2)}} $$

The wavelet coherence is defined as follows:

$$ C^2(x,y) = \frac{|a(a^{-1} T_x(\tau, a) T_y^*(\tau, a))|^2}{a(a^{-1}|T_x(\tau, a)|^2) a(a^{-1}|T_y(\tau, a)|^2)} $$

In Equation (11), $C^2(x,y)$ varies between 0 and 1, where 0 indicates no coherence between both time series, and 1 indicates that the coherence between both time series is the maximum [67].

To obtain information of phase and synchronization in terms of phase, the phase difference was calculated, indicating which signals lead the other [66,70]:

$$ \phi_x(\tau, a) - \phi_y(\tau, a) = \text{Arg} \left( T_{x,y}(\tau, a) \right) = \tan^{-1}\left( \frac{\text{Im}(T_{x,y}(\tau, a))}{\text{Re}(T_{x,y}(\tau, a))} \right), $$

where $\phi_x(\tau, a)$ and $\phi_y(\tau, a)$ are phases of each individual signal. The series moves in-phase (anti-phase) if the phase difference defined in Equation (12) has an absolute value below (greater than) $\pi/2$. The leading time series is defined by the sign of the difference between the phases. Both wavelet coherence and phase difference are displayed in the spectrum; $C^2(x,y)$ is represented by colors and $\phi_x(\tau, a) - \phi_y(\tau, a)$ by arrows [68]. The phase difference (Equation (12)) varies from $-\pi$ to $\pi$. For a given period (P) (for example, P = 2 years), a difference of phase of $\pi/2$ between x and y time series is equal to 0.5 years lag. Where the ENSO index shows a decrease and negative value (that represents La Niña), and the phase difference shows in-phase, a decrease in Ekman transport index occurs; whereas, when La Niña has an anti-phase, Ekman transport increase occurs. The sign represents which time series lead the other. Figure A2 helps to interpret phases and arrows.

The statistical significance of wavelet coherence was tested using the theoretical red noise wavelet power spectrum for the null hypothesis (“no joint periodicity”) through a Monte Carlo simulation using 1024 repeats. The cone of influence, contour lines, and arrows delimit the areas with >95% confidence interval (see [67–71] for details).
3. Results

The selected upwelling centers along the west coast of the Baja California peninsula show different Ekman transport intensities and seasonal cycles (Table 2 and Figure 3). The highest monthly mean upwelling intensity and the highest long-term variability were observed in the Bahía Magdalena region. The boxplot shows that the >75% monthly mean was \(-0.4 \times 10^{-9}\) m\(^2\) s\(^{-1}\) for the spring. Punta Eugenia and the north of Punta Eugenia showed similar interannual variability and a median between \(-0.2 \times 10^{-9}\) and \(-0.5 \times 10^{-9}\) m\(^2\) s\(^{-1}\). Ensenada upwelling centers showed the lowest Ekman transport of the study area, with lower interannual variability in comparison with other upwelling centers, mainly during winter. In December, the Ekman transport was below \(-0.5 \times 10^{-9}\) m\(^2\) s\(^{-1}\) in 75% of the recorded years.

Table 2. The mean and standard deviation of Ekman transport (m\(^2\) s\(^{-1}\)) calculated at each coastal upwelling center located along the west coast of the Baja California peninsula, Mexico.

<table>
<thead>
<tr>
<th>Region</th>
<th>Upwelling Center</th>
<th>Long Term Mean (m s(^{-1}))</th>
<th>Standard Deviation</th>
<th>Month (Minimum Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahía Magdalena</td>
<td>Isla Santa Margarita</td>
<td>(-3.82 \times 10^{-9})</td>
<td>(1.82 \times 10^{-9})</td>
<td>June (-5.58 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>Puerto Magdalena</td>
<td>(-4.18 \times 10^{-9})</td>
<td>(1.96 \times 10^{-9})</td>
<td>June (-5.94 \times 10^{-9})</td>
</tr>
<tr>
<td>Punta Eugenia</td>
<td>San Pablo</td>
<td>(-2.34 \times 10^{-9})</td>
<td>(0.97 \times 10^{-9})</td>
<td>April (-3.43 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>Clambey</td>
<td>(-3.12 \times 10^{-9})</td>
<td>(1.24 \times 10^{-9})</td>
<td>April (-4.71 \times 10^{-9})</td>
</tr>
<tr>
<td>North of Punta Eugenia</td>
<td>Maria</td>
<td>(-1.95 \times 10^{-9})</td>
<td>(0.79 \times 10^{-9})</td>
<td>April (-2.85 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>Punta Prieta</td>
<td>(-3.38 \times 10^{-9})</td>
<td>(1.35 \times 10^{-9})</td>
<td>April (-4.85 \times 10^{-9})</td>
</tr>
<tr>
<td>Ensenada</td>
<td>San Antonio del Mar</td>
<td>(-1.85 \times 10^{-10})</td>
<td>(4.13 \times 10^{-10})</td>
<td>December (-1.98 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>La Bocana</td>
<td>(-4.21 \times 10^{-10})</td>
<td>(2.73 \times 10^{-10})</td>
<td>December (-1.37 \times 10^{-9})</td>
</tr>
</tbody>
</table>
Figure 3. Boxplot showing the monthly mean and standard deviation of Ekman Transport, calculated between 1993 and 2022 for upwelling centers located along the west coast of the Baja California peninsula, Mexico. The median (blue line), quantile one (Q1) and three (Q3; box limits), interquartile range (IQR; length of the box), Q1 − 1.5 × IQR (lower boundary), Q3 + 1.5 × IQR (upper boundary), and outliers (circles) are shown.

We successfully identified 20 ENSO events using the EP and CP indices (Table 1), achieving effective differentiation between EP and CP events for both El Niño and La Niña events. The composites are shown in Figure A1. The wavelet coherence between ENSO and monthly Ekman transport shows a similar coherence structure for the upwelling centers of the same region; however, there is a difference in coherence and phase between different regions and EP or CP indices (Figures 4–8).

In Ensenada, the periods with interannual significant coherence ranged between 1 and 2 years for both ENSO indices (Figure 4). For the EP ENSO, the interannual coherence of ~2 years indicates anti-phase coherence during 1997, 2007–2009, and 2014–2017 years, with a 2- to 5-month lag. The CP ENSO and Ekman transport wavelet coherence showed anti-phase coherence in the 1.2- to 2-year periods for La Niña events of 2000–2001 and 2010–2011, but also in-phase coherence for the 2016–2022 period, both with a lag between 0 and 4.5 months.

Figure 4. Wavelet coherence $c_{xy}^2(x,y)$ (colors) and phase difference $\text{Arg}(T_{xy}(\tau,a))$ (arrows) for ENSO index and monthly Ekman transport for Ensenada upwelling centers during EP and CP El Niño events: (A) EP San Antonio del Mar, (B) EP La Bocana, (C) CP San Antonio del Mar, and (D) CP La Bocana. Right arrow represents in-phase and the left arrow represents anti-phase.

Differences in coherence between ENSO and Ekman transport indices in the north of Punta Eugenia are shown in Figure 5. Periods of 3 to 4 years show Ekman transport lead coherence between 1996 and 1998 with a 2-month lag. For 1.5- to 2-year periods, the 2015–2016 El Niño shows anti-phase lead Ekman transport. These observations imply an increase in Ekman transport during this El Niño event. In the case of CP ENSO, anti-phase
coherence for 4 to 7 periods shows lead Ekman transport time series with a lag of 9 to 12 months.

Additionally, the coherence of CP and Ekman transport anomalies shows two periods of anti-phase lagging at 1.5 years. The annual periodicity of wavelet coherence, under multi-year CP La Niña conditions for the 1997–2002 period, shows 3 months lead Ekman transport. The 2015–2021 period shows ENSO events with predominantly positive anomalies at CP (Figure 2), and an ENSO lead with ~2–3 months lag upwelling reduction for both upwelling centers. In 2021–2022, CP La Niña events show in-phase coherence.

Figure 5. Wavelet coherence ($C_{xy}(x,y)$) (colors) and phase difference $\text{Arg} \left( T_{xy}(\tau,a) \right)$ (arrows) for the ENSO index and monthly Ekman transport for north of Punta Eugenia upwelling centers during EP and CP El Niño events: (A) EP María, (B) EP Sta. Prieta, (C) CP María, and (D) CP Sta. Prieta. Right arrow represents in-phase and left arrow represents anti-phase.

The coherence in Punta Eugenia shows differences between EP and CP ENSO with Ekman transport (Figure 6A–D). The EP ENSO wavelet coherence shows in-phase coherence in ~2- to 2.6-year periods between 1995 and 2008, and anti-phase coherence for a 2 year period between 2013 and 2016 for both upwelling centers (Figure 6A,B). The CP ENSO and Ekman transport wavelet coherence for Punta Eugenia shows a 4- to 7-year periodicity lead Ekman transport, with a lag around 8 to 14 months. A ~2.5-year periodicity shows a CP ENSO lead between 2009 and 2010 with a lag of around 5 months. Additionally, periods around 1.2 to 1.5 years show a CP index lead coherence between 2016 and 2020, a predominantly positive CP anomaly period with a lag of 3 to 5 months with upwelling reduction (Figure 2).
Figure 6. Wavelet coherence ($C^2_{xy}(x,y)$) (colors) and phase difference $\text{Arg} \left( \tau_{xy}(\tau,a) \right)$ (arrows) for ENSO index and monthly Ekman transport for Punta Eugenia upwelling centers during EP and CP El Niño events: (A) EP San Pablo, (B) EP Clambey, (C) CP San Pablo, and (D) CP Clambey. Right arrows represent in-phase and left arrows represent anti-phase.

The coherence spectra of EP ENSO in Bahía Magdalena (located in the southern region of our study site) showed two main periods with interannual periodicity (Figure 7): ~2-year periodicity and the period of 1997–1998 showed an EP ENSO lead during a period with predominantly positive EP anomalies with upwelling intensity reduction and a lag response of around 4 months. The CP index did not show coherence during interannual periods.
Figure 7. Wavelet coherence ($C_{xy}^2(x, y)$) (colors) and phase difference $\text{Arg} \left( T_{xy}(\tau, a) \right)$ (arrows) for the ENSO index and monthly Ekman transport for Bahía Magdalena upwelling centers during EP and CP El Niño events: (A) EP Isla Sta. Margarita, (B) EP Pto. Magdalena, (C) CP Isla Sta. Margarita, and (D) CP Pto. Magdalena. Right arrows represent in-phase and left arrows represent anti-phase.

The wavelet coherence in Ensenada at annual and semiannual timescales showed in-phase coherence with a lag of 2–3 months, predominantly under the conditions of CP La Niña in the year 2000. In 1995 the coherence showed an EP lead by ~2 months. In contrast, the CP showed an opposite direction of coherence. The same phenomenon was observed in 1998, with anti-phase coherence for EP and in-phase coherence for CP. Similarly, the periods 2007–2008, 2010–2011, 2013–2014, and 2022 showed both EP and CP indices lead. The lag response of the Ekman transport in relation to the ENSO index was between 0 and 2 months (Figure 4). In the north of Punta Eugenia, the coherences with a periodicity below 1 year showed anti-phase and in-phase coherence with a lag of 0 to 2 months. There was also an opposite coherence with EP and CP events for 1995, 1997, 1998, 2004–2006, 2012–2013, and 2022. The EP ENSO index showed a 3-month lag in Ekman transport response in 2003 (Figure 5).

Similarly, in Punta Eugenia, at annual and semiannual periodicities, the coherence between ENSO and Ekman transport showed an opposite direction for EP and CP indices in 1994–1995, 2019–2020, and 2022. The periods 2005–2006 and 2012–2013 showed an EP ENSO lead and Ekman transport leading above CP for the same period (Figure 6). In Bahía Magdalena, a 0.5-year periodicity was observed, with opposite coherence for EP and CP indices in 1998, 2009–2010, 2011–2013, 2015–2016, and 2019–2020. Additionally, the periods 2007–2008 and 2011–2012 showed coherence with the CP index. The lag response was between 0 and 3 months.
4. Discussion

4.1. ENSO and Upwelling Intensity: Interannual Coherence

The present study reveals an upwelling intensity response to ENSO diversity, with differences in ENSO and Ekman transport coherences for eight upwelling centers located along the west coast of the Baja California peninsula. We identified differences between EP and CP ENSO on the Ekman transport response in the time and periodicity domains for the 30-year period of study (Figures 4–7). Our results show that not all ENSO events show coherence and that not all El Niño events with an Ekman transport anomaly response show a canonical El Niño and La Niña pattern in upwelling. These canonical patterns have been reported previously, and include a decrease (increase) in upwelling for El Niño (La Niña) [22,23], coupled with changes in primary productivity [24]. These observations imply that other factors that have not been analyzed in detail may affect the diversity of El Niño events and have not been properly conceptualized.

Our results show that the eight upwelling centers in the four main regions of the coast of the Baja California peninsula show similar responses in terms of the direction to ENSO at interannual wavelet coherence periodicity. The Ekman transport response was opposite for EP El Niño and CP El Niño in some cases, with differences in the periods where coherence between ENSO and Ekman transport was detected. In Ensenada, the 1997–1998 and 2015–2016 EP El Niño events were the strongest El Niño events of the last century [72] and the only two EP El Niño of last three decades [38,73]. Both EP El Niño events showed anti-phase coherence which led to an Ekman transport increase 1–4 months later, in the spring before the ENSO peak (~December). This is consistent with observations of upwelling favored by atmospheric forcing during the spring of 1998, attributed to the ending of EP El Niño [22]. Our results thus reveal a consistent response of Ekman transport to EP El Niño. The same coherences were observed in upwelling centers in the north of Punta Eugenia (Figure 5A,B).

The EP ENSO index anti-phase coherence of 2007–2009 at 2-year periodicity coincides with the 2007–2008 La Niña event, which was an event with multiple location minima throughout the year, and minimum values of the EP index developing from May–March 2006 and extending into December 2007 [56]. According to our results, the 2007–2008 La Niña event led to a decrease in upwelling with a lag of 1–4 months, with Ekman transport standardized anomalies >1 during November (0 years) and January (1 year). Furthermore, in the spring of 2008, the Ekman transport showed a standardized anomaly of ~2, with a higher increase in upwelling during this period. The CP ENSO index, which showed minimum values in February 2008 (Figure 2) led to an increase in upwelling with a lag of 3 months (Figure 4C,D), which suggests an opposite role of CP and EP negative anomalies on Ekman transport. Monthly anomalies in Ensenada in April 2007 reported upwelling with increased intensity, coinciding with changes in thermohaline conditions in surface and subsurface coastal sea waters [74].

In 2001–2002, there was an increase in upwelling during December–February, but it was not reported as an El Niño event in the eastern tropical Pacific. In this period, both CP and EP indices showed opposite coherence. Interestingly, this period was characterized by abrupt oceanic and atmospheric changes with westerly anomalies in December 2000; the SST became warmer in the CP which might have led to an El Niño event by early spring with a different development relative to a canonical El Niño pattern [75]. Both CP and EP indices not only show opposite coherence during this period but also opposite directions with positive CP anomalies and negative EP anomalies (Figure 2), which suggests non-El Niño upwelling anomalies, possibly related to opposite CP and EP indices and a prominent tropical Pacific gradient. Another significant period with a CP ENSO event that led to a 2–5-month lag coherence was in 2016–2021 (Figure 4C,D). In spite of the presence of multi-year La Niña events in 2017 and 2018, the CP index of the period 2016–2020 showed predominantly positive anomalies. During this period, upwelling centers in Ensenada showed multiple months with decreased Ekman transport, suggesting...

In the north of Punta Eugenia, coherence showed that the Ekman transport led 4–5 months during 1997–2001 in a ~3.5-year periodicity. Initially, the Ekman transport on the west coast might not have led to an ENSO event. Furthermore, changes in Ekman transport before the peak period of the ENSO event suggest changes in the wind field during or prior to ENSO development, which in turn controls Ekman transport. It is well known that the seasonal and annual wind stress variability along the west coast of the Baja California peninsula is controlled by the Aleutian Low and the northern Pacific High cell pressure [13,60,61]; thus, ENSO events could trigger variations in both atmospheric systems [29,37]. Recent studies demonstrated that the strengthening and weakening of the spring Aleutian Low (developing ENSO year) could lead to Pacific warming in the following year [76]. This is in keeping with the lag of the ENSO–Ekman transport coherence. On the other hand, the North Pacific Oscillation, the second source of variability of the northern Pacific could trigger an ENSO event [36,77]. The same lag of ENSO–Ekman transport coherence was observed in a ~1.5 periodicity, with a 2–3-month lag in 1997, which is the period of EP El Niño development.

Our results highlighted the conceptual relevance of EP and CP indices distinction. A previous study reported a non-significant correlation between the coastal upwelling index and the Multivariate El Niño Index (MEI; \( r = -0.13 \)) [18]. However, the coherence in our results shows a non-linear Ekman transport response at upwelling centers, which could result in lower linear metrics of correlation analysis. Our results also reveal that the use of a single index for ENSO limits our understanding of their impacts [36–39]. For instance, in the north of Punta Eugenia, there is an anti-phase lag of the La Niña multi-year event (1997–2003 and 2011–2013) (Figure 5C,D), which suggests an increase in upwelling in response to negative CP anomalies during both La Niña events.

The increase in upwelling was evident after 1997–1998. However, in 2000–2002 there were two CP La Niña events during which the decrease in upwelling was evident. After the El Niño event of 2010, there were multiple years with CP La Niña events, during which the anti-phase coherence was higher, suggesting a decrease in upwelling as a response to negative anomalies. Another period with CP ENSO coherence in the north of Punta Eugenia was 2016–2020 (Figure 5C,D); it was characterized by sustained positive anomalies in the CP (Figure 2). The coherence observed in 2016–2020 suggests an atmospheric northern Pacific response to tropical Pacific CP anomalies with a ~2-month lag and upwelling decreasing in the north of the Baja California peninsula. These differences in Ekman transport response validate the importance of addressing the impact of ENSO diversity on atmospheric impact on the Baja California peninsula.

Both Punta Eugenia and Bahía Magdalena showed an in-phase ~2–4-month lag response in Ekman transport. The maximum coherence was observed in 1996 (Figure 2) when the EP index showed predominantly negative anomalies (Figures 6A,B and 7A,B). In spite of EP La Niña conditions, the conditions of the northern Pacific were unusual, showing positive SST anomalies that extended around the northeast Pacific and persisted well into the 1997–1998 El Niño event showing western tropical-northeastern Pacific positive anomalies and anomalous cyclonic wind anomalies [78]. On the other hand, both Punta Eugenia and Bahía Magdalena regions showed EP and Ekman transport anti-phase coherence from 2013 in the southern region to 2015 or 2016 (Figures 6A,B and 7A,B). In 2013–2016, the oceanographic–atmospheric conditions in the northern Pacific were predominantly associated with “The Blob” (2013–2015) that originated in the north CP, a sustained multiple-year warming event in the northeast that was not driven by either ENSO or a positive North Pacific Meridional Mode (NPMM) pattern. Both the coherence of ENSO and Ekman transport suggest that the initial perturbations that trigger upwelling anomalies started in the north EP.

Both the 1996 and 2015 ENSO events had a similar winter warming of the northern Pacific [53] but with the difference that the predominant anomalies in the tropical Pacific
were negative in 1996 and positive in 2015. After October 2013, there was a decrease in upwelling and it remained ET below normal until 2015 [15], similar to what we observed during the La Niña event of 1996 in the present study. The opposite tropical Pacific anomalies and the positive northern Pacific anomalies suggest an Ekman transport anomaly that is not driven by ENSO and is possibly associated with the NPMM and local atmospheric interannual changes in the northern Pacific. There is evidence that the northern Pacific anomalies could be triggered by a wind–evaporation–SST feedback [79], triggered in turn by westward wind anomalies in the western Pacific that are identified as ENSO precursors [53]; these anomalies are related to a third Pacific variability mode [80]. This event is not typically considered to be driven by atmospheric-oceanographic anomalies in local studies carried out along the west coast of the Baja California peninsula, Mexico.

In Punta Eugenia and Bahía Magdalena, the CP ENSO index and Ekman transport showed coherence in 2008–2010. In 2008–2010, in California [19], the importance of atmospheric teleconnection and the lack of tropical Pacific seawater advection to the region was high, which indicates that atmospheric teleconnection is a relevant mechanism for El Niño effects on the California Current System. Like in the northern regions, the CP positive anomaly period of 2016–2020 showed an interannual reduction response in Ekman transport upwelling centers with a 2–5-month lag. At this point, our results highlight the difference in coherence between EP and CP anomalies, and the non-linear teleconnection; we found quasi-opposite coherences between both EP and CP indices for the same anomaly direction at warm events in the tropical Pacific. These findings have great conceptual relevance to distinguish between EP and CP types of ENSO events, and also for tropical Pacific gradient of SSTs, in order to better address the atmospheric impact of ENSO events on the study area.

4.2. Annual and Semiannual Coherence: ENSO and Ekman Transport

The semiannual and annual coherence periods found in the present study could be related to (1) ENSO interaction with other quasi-oscillatory processes, (2) changes in northern Pacific pressure gyres triggered by tropical–extratropical Pacific anomalies, or (3) ENSO precursor processes driven by the main modes of variability (for example, northern Pacific SST [51], Aleutian Low [81] and North Pacific High/NPMM [53,82]). Our results indicate that neither the strongest ENSO events, nor the weaker ones, necessarily trigger SST anomalies in the California Current System that drive changes in atmospheric circulation, wind, and Ekman transport [19,31]. We showed ENSO and Ekman transport wavelet coherence for seven El Niño (La Niña) events along the west coast of the Baja California peninsula. Most of the semiannual coherence estimated between the ENSO and Ekman transport was observed in the spring and summer. In 1996 and 2000, there was a negative CP index and a positive EP index in Ensenada. In contrast, in the ENSO events of 1998, 2007, 2019, and 2022 (Figure 4C,D), coherence was the opposite. Moreover, 1998, 2005, 2008, 2013, and 2021 were opposite in the north of Punta Eugenia (Figure 5C,D), highlighting an opposite response at semiannual timescales to CP and EP events, apparently impacting the tropical Pacific gradient in the Ekman transport response in the study area. Several studies suggest a complex non-linear connection of the atmosphere response to ENSO diversity [27,37] that leads to opposite atmospheric and biological responses [49].

Punta Eugenia and Bahía Magdalena had the same opposite coherence as EP and CP in 1995, 1997, 2009, 2011, 2013, 2015, and 2019; and some coherences show Ekman transport leading to ENSO anomalies, suggesting the existence of changes in the northern Pacific circulation changes that precede the tropical SST variability, which could be captured by the time series variability of both EP and CP. This tropical–extratropical teleconnection was previously documented [36,83], and is in keeping with our results. It should be pointed out that the interaction between ENSO and atmospheric-oceanic circulation systems is not unidirectional; instead, ocean–atmospheric processes occurring in the northern Pacific can also lead to the development of ENSO events [76]. This explains why previous studies found opposite effects of ENSO on upwelling along the coast of
California during El Niño events [31]. Our results show that this does not necessarily mean that the state of the tropical Pacific–northern Pacific teleconnection does not generate a local effect, even in the presence of an anomaly that is opposite to the canonical effect.

The atmospheric field in the northern Pacific, which is the key parameter driving upwelling, showed coherence in the spring–summer period in some time series. The spring–summer period is the key parameter driving upwelling, as the Aleutian Low and northern Pacific High pressure systems, as well as the northern Pacific circulation, play a critical role in ENSO development [76]. Our results thus suggest a complex one-way linear connection between ENSO and the upwelling response on the west coast of the Baja California peninsula. According to recent studies, this tropical–extratropical teleconnection was stronger in the late 1990s [76], since the CP ENSO became more frequent [33,34,54,56,84].

4.3. ENSO Development and Conditions in Pacific for Coherence Events

To understand why some ENSO events do not show typical canonical patterns on Ekman transport and how the development of previous tropical–extratropical Pacific conditions contributed to upwelling anomalies in the Baja California peninsula, we complemented our analysis with direct evaluation of the composite evolution of SST and 10–wind anomaly fields during ENSO (development year) events with significant wavelet coherence and events without it. Table A1 shows ENSO events and the lag of EP and CP ENSO events and Ekman transport for each region.

The evolution of El Niño events with significant wavelet coherence with Ekman transport in the Baja California peninsula shows positive February–April SST anomalies elongating from the CP to the subtropical eastern northern Pacific, as well as negative SST anomalies in the central subtropical Pacific region (Figure 8A). Additionally, western wind anomalies in CP, the meridional Pacific, and the south of Baja California peninsula are shown. This pattern is similar to the positive NPMM pattern [85], characterized by spring positive CP SST anomalies and negative EP SST anomalies and the weakening of the northern Pacific High [53]. Six El Niño events with significant coherence with upwelling intensity showed an NPMM pattern that was recently described as a key process to trigger northern Pacific variability through SST westerly anomalies and the southwestward extension of the northern Pacific positive SST in the following summer season (Figure 8C) (June–August), which is driven by wind–evaporation–SST feedback [79]. Previously, western anomalies near 170° E (Figure 8A) and northern positive SST anomalies were described as key factors of CP ENSO development [51,52], both of which are characteristics of NPMM. Thus, NPMM’s teleconnection with ENSO implies positive feedback, which excites mutually, especially with CP SST anomalies [51,86].

Additionally, the NPMM is related to the northern Pacific oscillation [27,87] through a seasonal foot-printing mechanism, in which SST anomalies are generated by midlatitude atmospheric variability in the previous winter force tropical atmosphere in the spring and summer [88,89]. This teleconnection possibly modulates wind stress anomalies along the Baja California peninsula via tropical–extratropical ocean–atmosphere interactions at interannual timescales. Additionally, it is possible that the coherence between tropical Pacific anomalies and wind field anomalies that drive Ekman transport is triggered by the development of NPMM associated with a preconditioned state of the northern Pacific and sustained by ENSO development via extratropical teleconnection [27,36]. Furthermore, the difference in coherence between EP and CP has a non-linear Ekman transport response to warm–cold anomalies, highlighting the conceptual relevance of taking into account ENSO diversity and the development of each ENSO event.

In El Niño events that do not show phase coherence with Ekman transport in the study area, the pattern of SST and 10 m wind anomalies are totally different with well-developed SST anomalies in the tropical Pacific in the boreal winter, but with no evident teleconnection in oceanic and atmospheric patterns with the northern Pacific, and an apparent absence of wind–evaporation–SST feedback (Figure 8B,D). These observations
suggest the importance of the El Niño development and the NPMM-ENSO positive feedback to drive an atmospheric response in terms of upwelling intensity in Ekman transport.

Figure 8. Composite of SST and 10 m wind anomalies (arrows) for El Niño development that show coherence with Ekman transport (A,C,E) and ENSO events that do not show significant coherence (B,D,F). SST anomalies are observed in February–April (A,B), June–August (C,D), and October–December (E,F). Light dots represent a 95% confidence level using a t-test for ERSSTv5 NOAA and 1991–2020 climatology. The 10 m wind anomalies below an 80% significant two-tailed test were omitted.

La Niña events that exhibit coherence with Ekman transport were preceded by spring negative CP anomalies elongating from the CP to the subtropical eastern northern Pacific (the positive subtropical central Pacific region, Figure 9A), and also by wind anomalies
towards the equator in the west of the Baja California peninsula, such as a negative NPMM [85].

Figure 9. Composite of SST and 10 m wind anomalies (arrows) for La Niña events that show coherence with Ekman transport (A,C,E) and ENSO events that do not show significant coherence (B,D,F). SST anomalies are observed in February–April (A,B), June–August (C,D), and October–December (E,F). Light dots represent a 95% confidence level using a t-test for ERSSTV.5 NOAA and 1991–2020 climatology. The 10 m wind anomalies below 80% of a two-tailed Student’s t-test were omitted.

La Niña events without coherence between ENSO and Ekman transport were preceded mainly by the warming of the tropical Pacific (Figure 9B) and reduced wind in the east and north of the Baja California peninsula. On the other hand, La Niña events with coherence showed negative anomalies in the tropical Pacific and equatorward 10-wind
anomalies. These two patterns reveal that during the development of La Niña events, the connection of the tropical Pacific with the eastern northern Pacific is opposite in events with or without coherence. It is important to highlight that in the first scenario, the CP negative anomalies during the development of ENSO and peak event (Figure 9A,C,D) are shown. In contrast, in the no coherence La Niña scenario the predominant anomalies are positive during February–March (Figure 9B). During June–August and October–December, SST anomalies were located mainly in the EP (Figure 9D,F), highlighting the non-linearity of CP and EP events that have been documented in previous studies [39,47].

4.4. ENSO and Biological Response: Interannual Coherence

To analyze whether changes in ENSO diversity that led to changes in the upwelling centers could be predicted from sea surface Chl-a concentration, through an approach similar to that used for Ekman transport, we used satellite sea surface Chl-a concentration values extracted from each upwelling center. Wavelet coherence was calculated for the EP and CP indices, together with sea surface Chl-a monthly standardized anomalies at each upwelling center (Figures A3–A6). To perform this analysis, we only considered coherences for periodicities over 1.2 years. When EP La Niña events occurred that were followed by CP El Niño and mixed-type La Niña events, for the EP index, the coherence analysis was limited to 2006–2009 and a 2-year periodicity in the north of Punta Eugenia, in Punta Eugenia, and in Bahía Magdalena. In 2006–2009, anomalous cold water and high-sea-surface Chl-a concentrations were reported [15,74]. The coherence between Ekman transport and the EP index was only evident during this event in Ensenada, leading to an increase in upwelling. These observations suggest that EP ENSO events might be weakly connected to sea surface Chl-a concentration in upwelling centers. Previously, a low correlation between integrated Chl-a concentration (recorded in the column water) and the Multivariate ENSO Index (MEI.v2) was reported for the Punta Eugenia region [21]. However, our results show the highest coherence between the CP ENSO index and sea surface Chl-a concentration in upwelling centers on the west coast of the Baja California peninsula. The anti-phase coherence suggests that there is linear coherence with increased sea surface Chl-a concentration for CP La Niña events, and decreased sea surface Chl-a concentration for CP El Niño events, with 0- to 4-month lags (Figures A3C,D–A6C,D) for the entire time series. Despite the differences in the non-linearities in ENSO–Ekman transport coherence, the Chl-a concentration shows a linear and consistent response to CP ENSO and a lower influence of EP ENSO on the sea surface Chl-a at upwelling centers in the Baja California peninsula. Differences in Ekman transport and sea surface Chl-a concentrations reflect the conceptual relevance of distinguishing ENSO events according to their development characteristics and diversity.

To complement our analysis, a composite analysis of surface Chl-a anomalies and wind anomalies was implemented for the same scenarios of Section 4.3 (Figures A7 and A8). This analysis shows significant Chl-a anomalies in the coastal zone and in the regions where the upwelling centers are located. The coherence between ENSO and Ekman transport reflects changes in Chl-a only for the spring and summer seasons. Although the peak of ENSO events is usually in the boreal winter and wind anomalies are evident in this period, there was no response in Chl-a. This suggests that differences in Ekman coherence and Chl-a change between events: while ENSO can affect the wind field during other seasons, Chl-a will only respond to changes in wind during the spring and summer.

Furthermore, it is necessary to study not only the effects and impact of the NPMM on the biological response but also the effects on the oceanographic and biogeochemical characteristics that trigger EP ENSO and CP ENSO in the Baja California peninsula, which influence primary productivity and fisheries.
5. Conclusions

The upwelling centers located along the west coast of the Baja California peninsula, Mexico, show non-linearities in Ekman transport standardized anomalies and ENSO diversity in coherence over a time series. EP El Niño events show an increase in upwelling during boreal spring after the peak event, and CP El Niño and La Niña events trigger an Ekman transport decrease with latitudinal region differences. The non-linearities and Ekman transport response show a dependence on ENSO development and diversity, showing coherence between ENSO and Ekman transport when the CP and northeastern Pacific exhibit positive (negative) SST anomalies during the development of El Niño (La Niña) events in the spring and summer. The similarities with the northern NPMM pattern are possibly a key factor of atmospheric teleconnection between ENSO events and wind-forcing upwellings. The semiannual and annual coherences suggest an association with (1) wind speed and direction, (2) changes in northern Pacific pressure gyres triggered by tropical–extratropical Pacific anomalies, or (3) ENSO precursor processes driven by the main variability modes, which are a matter for further study.

The sea surface Chl-a concentration shows coherence mainly with CP ENSO and shows a linear connection at interannual periodicities with anti-phase coherence: increased (decreased) sea surface Chl-a concentration during CP La Niña (CP El Niño) along the west coast of the Baja California peninsula upwelling centers. This suggests that changes in Ekman transport triggered by ENSO events are not the main factor of interannual changes in phytoplankton biomass.

Our results highlight the conceptual relevance of CP ENSO and ENSO diversity driving changes in sea surface Chl-a concentration. Further studies need to address ocean changes that drive ENSO diversity and its effects on upwelling centers in the Baja California peninsula to improve the identification of the impact of EP and CP ENSO on ecosystems and fisheries.


Funding: This research was funded by Consejo Nacional de Humanidades Ciencia y Tecnología (CONAHCyT), Instituto Politécnico Nacional SIP-IPN 20230854 institutional multidisciplinary research project “Perturbaciones ecosistémicas por impactos naturales y antropogénicos en ecosistemas costeros de México” and Instituto Politécnico Nacional SIP-IPN 20240636 institutional research project “Características oceanográficas y calidad del agua en mares y costas del noroeste de México”. Instituto Politécnico Nacional SIP-IPN full supported the Open Access cost of the present publication.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.


Acknowledgments: GGC thanks CONAHCyT for an MSc scholarship (2022–2024), Instituto Politécnico Nacional and the Programa Institucional de Formación de Investigadores (PIFI) for the BEIFI-IPN scholarship as part of the SIP 20230854 institutional multidisciplinary research project: “Perturbaciones ecosistémicas por impactos naturales y antropogénicos en ecosistemas costeros de México” during August–December 2022, August–December 2023 and January–July 2024. EM-A thanks
“Programa de estancias posdoctorales del CONAHCyT, investigadores e investigadoras por México convocatoria 2022(2)”. LT-F thanks CONAHCYT Catedras Patrimoniales program. JG-G, RC-D, SA-G thank the EDI-IPN and COFAA-IPN fellowships. EM-A, LT-F, JG-G, RC-D, SA-G thank the CO-NAHCYT-SNI fellowship. The authors thank NASA, ECMWF Earth observation component, the Copernicus Marine Service and Remote Sensing Systems for high-resolution data availability. All authors thank the anonymous reviewers for their helpful suggestions.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Figure A1. Composite anomalies of SST during December–February: (A) EP El Niño, (B) CP El Niño, (C) EP La Niña, and (D) CP La Niña from Table 1. Data: ERSSTV5 and 1991–2020 climatology were used.
Figure A2. Phase coherence and interpretation of wavelet coherence phase difference $\text{Arg} \left( T_{x,y}(\tau, a) \right)$ arrows [68]. Shows the arrow (black) directions and their respective interpretation. When the phase shows in-phase (A–C) or anti-phase (D–F). When there is no lag between both series (A,D), when leading $x$ (B,E) and when leading $y$ (C,F).
Figure A3. Wavelet coherence ($C_{xy}^2(x, y)$) (colors) and phase difference $\text{Arg} \left(T_{xy}(\tau, a)\right)$ (arrows) for ENSO index and monthly sea Surface Chl-a concentration in Ensenada upwelling centers: (A) EP San Antonio del Mar, (B) EP La Bocana, (C) CP San Antonio del Mar, and (D) CP La Bocana. Right arrows represent in-phase and left arrows represent anti-phase.
Figure A4. Wavelet coherence ($C_{xy}(x,y)$) (colors) and phase difference $\text{Arg} \left(T_{xy}(\tau,a)\right)$ (arrows) for ENSO index and monthly sea surface Chl-a concentration in north of Punta Eugenia upwelling centers: (A) EP María, (B) EP Sta. Prieta, (C) CP María, and (D) CP Sta. Prieta. Right arrows represent in-phase and left arrows represent anti-phase.
Figure A5. Wavelet coherence ($C_{xy}(x,y)$) (colors) and phase difference $\text{Arg} \left( T_{xy}(\tau, a) \right)$ (arrows) for ENSO index and monthly sea surface Chl-a concentration in Punta Eugenia upwelling centers: (A) EP San Pablo, (B) EP Clambey, (C) CP San Pablo, and (D) CP Clambey. Right arrows represent in-phase and left arrows represent anti-phase.
Figure A6. Wavelet coherence ($C_{xy}(x,y)$) (colors) and phase difference $\text{Arg}(T_{xy}(\tau,a))$ (arrows) for ENSO index and monthly sea surface Chl-$a$ concentration in Bahía Magdalena upwelling centers: (A) EP Isla Sta. Margarita, (B) EP Pto. Magdalena, (C) CP Isla Sta. Margarita, and (D) CP Pto. Magdalena. Right arrows represent in-phase and left arrows represent anti-phase.

Table A1. A classification of ENSO events using the approach of [63] and phase differences of the eastern Pacific (EP) or central Pacific (CP) indices for the boreal winter December–January–February and Ekman transport for upwelling centers in the west coast of the Baja California peninsula. The ERSST v.5 database and climatology 1991–2020 were used to calculate both indices. The time-month lag for coherence between EP Ekman transport and CP Ekman transport are shown for the study regions Ensenada (ENS), the north of Punta Eugenia (NPE), Punta Eugenia (PE) and Bahía Magdalena (BM). * denotes that the type of ENSO and the index were not the same (e.g., 1994/95 are CP ENSO events but showed coherence with the EP index). Bold numbers indicate that ENSO led coherence, and for the opposite, Ekman led in wavelet coherence.

<table>
<thead>
<tr>
<th>Event</th>
<th>Phase</th>
<th>Type</th>
<th>Coherence Lead ET (Time Months)</th>
<th>Coherence Chl-$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>ENS NPE PE BM</td>
<td>ENS NPE PE BM</td>
</tr>
<tr>
<td>1994/95</td>
<td>El Niño</td>
<td>CP</td>
<td>1–2 * (1–2) 0 * 0–4 *</td>
<td>- - - -</td>
</tr>
<tr>
<td>1996/97</td>
<td>La Niña</td>
<td>EP</td>
<td>- - - -</td>
<td>1</td>
</tr>
<tr>
<td>1997/98</td>
<td>El Niño</td>
<td>EP</td>
<td>3–4 0–2 4–5 1–5</td>
<td>2 * (2) 0 * 0 *</td>
</tr>
<tr>
<td>1998/99</td>
<td>La Niña</td>
<td>CP</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1999/00</td>
<td>La Niña</td>
<td>CP</td>
<td>c 2 0–2 1</td>
<td>2 * (2) 0 * 0 *</td>
</tr>
<tr>
<td>2001/01</td>
<td>La Niña</td>
<td>CP</td>
<td>1–2 * (2–3) 2</td>
<td>0 *</td>
</tr>
<tr>
<td>2002/03</td>
<td>El Niño</td>
<td>CP</td>
<td>0 *</td>
<td>1–4</td>
</tr>
<tr>
<td>2004/05</td>
<td>El Niño</td>
<td>CP</td>
<td>1 * (2)</td>
<td>0–2</td>
</tr>
<tr>
<td>2007/08</td>
<td>La Niña</td>
<td>CP</td>
<td>0</td>
<td>1–2 *</td>
</tr>
<tr>
<td>2008/09</td>
<td>La Niña</td>
<td>CP</td>
<td>0 * 0 *</td>
<td>1–2 * 1* 1–4</td>
</tr>
<tr>
<td>2009/10</td>
<td>El Niño</td>
<td>CP</td>
<td>1–4 0–2 0–1 * (4–5) 4</td>
<td>1–2 * (2) 1 (3–4 *)</td>
</tr>
</tbody>
</table>
I confirm 2010/11 La Niña CP 0 1–2 * 21 * 1–2

<table>
<thead>
<tr>
<th>Year/Season</th>
<th>Phenomenon</th>
<th>Type</th>
<th>Chl-a Anomaly (mg m⁻³)</th>
<th>Wind Anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011/12</td>
<td>La Niña</td>
<td>CP</td>
<td>0</td>
<td>1–2 *</td>
</tr>
<tr>
<td>2014/15</td>
<td>El Niño</td>
<td>CP</td>
<td>0 * 4 *</td>
<td>4–5</td>
</tr>
<tr>
<td>2015/16</td>
<td>El Niño</td>
<td>EP</td>
<td>1–2 * 4 *</td>
<td>0–4</td>
</tr>
<tr>
<td>2016/17</td>
<td>La Niña</td>
<td>EP</td>
<td>4–5</td>
<td>1–2</td>
</tr>
<tr>
<td>2018/19</td>
<td>El Niño</td>
<td>CP</td>
<td>1 * 5</td>
<td>0 * (0–1)</td>
</tr>
<tr>
<td>2020/21</td>
<td>La Niña</td>
<td>EP</td>
<td>0 *</td>
<td>0 *</td>
</tr>
</tbody>
</table>

Figure A7. Composite of sea surface Chl-a and 10 m wind anomalies (arrows) for El Niño events that show coherence with Ekman transport (A,C,E) and ENSO events that do not show significant coherence (B,D,F). SST anomalies are observed in February–April (A,B), June–August (C,D), and October–December (E,F). Light dots represent a 95% confidence level using two-tailed t-test. The 10 m wind anomalies below 80% of a two-tailed Student’s t-test were omitted.
Figure A8. Composite sea surface Chl-a and 10 m wind anomalies (arrows) for La Niña development that show coherence with Ekman transport (A,C,E) and events that do not show significant coherence (B,D,F). There are SST anomalies shown for February–April (A,B), June–August (C,D), and October–December (E,F). Light dots represent a 95% confidence level using a two-tailed t-test. The 10 m wind anomalies below 80% are omitted.

References


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.