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Research Article

Response of phytoplankton biomass to sea surface temperature fluctuations in the Bay of La Paz, Southern Gulf of California: a 17-year satellite study

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ABSTRACT. Phytoplankton biomass is a vital indicator of ecosystem health, yet its dynamics are increasingly sensitive to thermal variability and large-scale climatic events. Utilizing a 17-year satellite-derived dataset (2002 to 2018) from the Moderate Resolution Imaging Spectroradiometer (MODIS), this study investigates the relationship between chlorophyll-*a* (Chl-*a*) concentration and sea surface temperature (SST) in the Bay of La Paz, Gulf of California, with a focus on the influence of the El Niño-Southern Oscillation (ENSO). Our findings reveal a pronounced seasonal cycle. Chl-*a* peaked at 1.5 mg m^{-3} during winter cooling (<22°C) and dropped to minimum values of 0.2 mg m^{-3} during summer warming (>30°C). Interannual variability was closely coupled with ENSO phases. Notably, the intense 2015-2016 El Niño drove record-high SSTs that suppressed phytoplankton biomass, whereas the 2011-2012 La Niña fostered cooler conditions and elevated Chl-*a* levels. Wavelet analysis confirms that while seasonal cycles remain the dominant temporal component, spectral distortions occurred during major thermal anomalies. These results identify ENSO-driven thermal shifts as primary determinants of localized SST and Chl-*a* variability, underscoring the critical role of long-term remote sensing in monitoring marine ecosystems where traditional *in-situ* observations are logistically constrained.

Keywords: satellite observations; sea surface temperature; chlorophyll-*a*; ENSO events; Bay of La Paz; Gulf of California

INTRODUCTION

Phytoplankton comprise a diverse group of microorganisms inhabiting the ocean's euphotic zone. These organisms drive over 45% of global net primary production (Simon et al. 2009) and generate more than 50% of Earth's atmospheric oxygen (Grigoratou et al. 2025). As a pigment present in all phytoplankton species, chlorophyll-*a* (Chl-*a*) serves as the primary proxy for estimating biomass (Davies et al. 2018). Consequently, Chl-*a* is a well-established indicator of aquatic ecosystem health and productivity (Yunusa-Ugya 2025), and its concentrations are highly sensitive to environmental shifts, particularly thermal variations (Gomez-Castillo et al. 2023).

Ocean temperatures fluctuate significantly across the water column, driven by a complex interplay of seasonal surface irradiance, mesoscale eddies, coastal upwelling, and large-scale oceanographic processes (Mann & Lazier 2008). These thermal variations profoundly impact phytoplankton populations (Chavez et al. 2011). Since the early 1990s, the scientific community has closely examined how sea surface temperature (SST) fluctuations shape these communities. In the Equatorial Pacific, for instance, researchers documented a direct link between cooling temperatures and diatom abundance, noting that abnormally cold waters trigger surges in pennate diatoms and enhance primary production (Chavez et al. 1990). Furthermore, a large-scale study spanning from

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the Peruvian coast to 170°W in the Pacific demonstrated that temperature fluctuations drive changes in thermocline depth; this alters nutrient availability and, consequently, causes significant shifts in phytoplankton biomass concentration (Chavez et al. 1996).

A chief driver of hydrographic changes within the water column is the El Niño-Southern Oscillation (ENSO), a primary determinant of SST variability. By altering thermal structures worldwide, ENSO shapes the physical environment that defines marine habitats (Jin 2022).

The process operates through two distinct phases that fundamentally reshape marine ecosystems. During La Niña, the advection of cold, nutrient-rich water masses increases Chl-*a* levels, fueling a surge in primary productivity. Conversely, El Niño is marked by the influx of abnormally warm water, which suppresses Chl-*a* concentrations and stifles overall biological production. Regardless of the specific phase, these processes drive critical seasonal and interannual variability in phytoplankton biomass, impacting the entire oceanic food web (McPhaden et al. 2021). This phenomenon has been documented extensively since the 1990s, notably during the extreme 1997-1998 El Niño event, which established a precedent for coupled physical-biological studies. During this period, researchers recorded a 2°C increase in SST anomalies, the advection of nutrient-poor water masses, and profound disruptions in Chl-*a* concentrations (Chavez et al. 1998).

Assessing seasonal and interannual phytoplankton biomass variability is essential for understanding marine ecosystem dynamics, particularly in high-biodiversity regions where maintaining ecosystem integrity and predicting shifts are of critical importance (Zhang et al. 2017). For example, long-term *in situ* time series have enabled the identification of valuable oceanographic variability patterns worldwide. In Monterey Bay, California, for example, a multi-parameter dataset covering temperature, salinity, nutrients, and Chl-*a* from 1989 to 1996 revealed marked seasonal fluctuations: surface waters were coldest and saltiest in spring, warmed in summer, remained warm but freshened in autumn, and cooled and freshened further in winter. Consequently, phytoplankton blooms manifested as distinct pulses of primary production and Chl-*a* during the spring, summer, and occasionally autumn (Pennington & Chavez 2000).

Monitoring Chl-*a* fluctuations alongside large-scale environmental variables remains challenging, as traditional field-based data collection is often cost-prohibitive. However, satellite remote sensing has emerged as a robust alternative, offering the extensive spatial and temporal coverage necessary to analyze the complex relationships between Chl-*a* levels and environmental drivers (Sun et al. 2014).

Over the past decades, satellite-derived products have become instrumental in analyzing the relationship between large-scale Chl-*a* variability and environmental drivers across diverse marine domains. For instance, a 14-year time series in the Gulf of Alaska revealed significant interannual Chl-*a* variability driven by SST fluctuations (Waite & Mueter 2013). Similarly, research in the Kara Sea demonstrated that seasonal Chl-*a* concentrations are closely linked to water temperature and column stratification (Demidov et al. 2017). Furthermore, in the Bohai Sea, observed increases in Chl-*a* levels have been attributed to shifting physicochemical properties within the water column (Zhang et al. 2017).

In recent years, significant efforts to monitor Mexican marine ecosystems have focused on generating satellite-based time series. These studies primarily evaluate fluctuations in SST and Chl-*a* in relation to large-scale climatic events, such as the ENSO. For instance, a 16-year analysis in the southeastern Gulf of California revealed distinct seasonal, semiannual, and interannual variability in these parameters, largely driven by El Niño and La Niña conditions (Durán-Campos et al. 2023). In the central Gulf of California, ENSO events, specifically La Niña, have been shown to intensify wind patterns, enhancing coastal upwelling and the subsequent upward flux of nutrients, which triggers elevated Chl-*a* concentrations (García-Morales et al. 2017). Similar patterns of strong seasonal and interannual variability driven by ENSO phases have been documented across other regional waters (Farach-Espinoza et al. 2021).

While previous research has provided valuable insights into SST and Chl-*a* fluctuations within the open Gulf of California, coastal environments in the gulf remain significantly understudied. These nearshore areas serve as vital refugia, nurseries, and feeding grounds for numerous species of high economic and ecological importance, many of which are currently threatened or endangered (Brusca 2010).

One of the most outstanding coastal ecosystems within the Gulf of California is the Bay of La Paz, a region recognized as a premier marine hotspot. Its high productivity is anchored by organisms at the lowest trophic levels, specifically phytoplankton (Coria-Monter et al. 2024). To date, significant debate persists regarding the impact of large-scale climatic phenomena,

such as El Niño and La Niña, on phytoplankton productivity within the region. Conflicting hypotheses have emerged from existing literature; some studies suggest that local hydrodynamic processes within the bay effectively "mask" the adverse effects of El Niño (Coria-Monter et al. 2019), whereas others argue that El Niño acts as a primary driver of ecosystem change, significantly increasing SST and subsequently depressing Chl-*a* levels (Herrera-Cervantes et al. 2026).

Although substantial efforts have characterized the Bay of La Paz through regular *in situ* sampling, maintaining long-term monitoring via traditional methods presents significant operational and financial challenges. Consequently, satellite observations offer a viable, accessible alternative, providing the robust datasets needed to analyze seasonal and interannual variability over extended periods.

In this context, this study characterizes the seasonal and interannual variability of SST and Chl-*a* concentrations in the Bay of La Paz. Using a 17-year satellite dataset (2002-2018), we investigate how large-scale climatic phenomena (specifically ENSO) modulate these key environmental parameters. We address existing debates regarding the impact of El Niño and La Niña on the bay's thermal and biological state by integrating multi-annual observations with wavelet analysis. We hypothesize that strong ENSO episodes restructure the water column's thermal structure, driving shifts in phytoplankton biomass, here expressed as Chl-*a* concentration. Ultimately, this research identifies the mechanisms through which primary productivity responds to thermal fluctuations, offering a deeper understanding of the bay's ecosystem dynamics.

MATERIALS AND METHODS

Study area

The Gulf of California (Fig. 1a) and its adjacent waters form a unique, highly productive region recognized as one of the world's large marine ecosystems (Arreguín-Sánchez et al. 2017). In the gulf's southwestern portion, the Bay of La Paz is its largest basin (Fig. 1b) and a critical ecological site. Its exceptional biodiversity and productivity support a wide array of marine megafauna (Durán-Campos et al. 2019). This biological richness is driven by multi-scale hydrodynamic processes, including internal waves, eddies, and fronts, which facilitate water-column mixing and strongly influence the planktonic ecosystem (Coria-Monter et al. 2024). Furthermore, the bay acts as a sensitive recorder of regional climate variability within the subtropical Pacific; specifically, ENSO phenomena modulate SSTs, subsequently driving significant shifts in phytoplankton productivity (Coria-Monter et al. 2019).

The bay exhibits pronounced atmospheric variability that directly modulates its upper-ocean dynamics. During summer, winds have a southeasterly component with relatively low intensities (<5 m s^{-1}). In contrast, the winter season is dominated by persistent, high-velocity (>10 m s^{-1}) northwesterly winds and strong gusts. This seasonal shift in wind stress drives a major transformation in the water column: the mixed layer deepens considerably in winter due to wind-driven turbulence, whereas it becomes highly stratified and shallower in summer (Coria-Monter et al. 2024).

Data analyses

To characterize ENSO events in our study, we obtained Multivariate ENSO Index (MEI) data from NOAA's Earth System Research Laboratory for the period June 2002 to December 2018. The MEI is widely utilized because it integrates both oceanographic and meteorological parameters, offering a more holistic representation of the coupled ocean-atmosphere system than single-variable indices (Wolter & Timlin 2011).

To evaluate the seasonal and interannual variability of SST and Chl-*a*, daily data were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua) for the period from June 2002 to December 2018. Data were extracted from a circular region of interest centered at 24°30'N and 110°33'W in the central portion of the bay (Fig. 1b). Pixels within this ~4.4 km radius were averaged for both variables. This offshore location was specifically selected to reduce potential uncertainties in MODIS-derived Chl-*a* estimates caused by high concentrations of non-algal suspended matter, such as terrestrial organic matter commonly found along the coastline. All data were extracted using standard algorithms and SeaDAS software (version 7.3.2). This methodology has been previously validated for high-resolution (1 km $pixel^{-1}$), long-term monitoring of oceanic conditions in similar domains (e.g. Coria-Monter et al. 2018, Durán-Campos et al. 2023).

Satellite datasets often contain outliers (anomalous values relative to surrounding pixels), mostly caused by undetected clouds or atmospheric contamination (Alvera-Azcárate et al. 2012). To remove these anomalies, we applied the Interquartile Range (IQR) method, a standard statistical approach for identifying outliers in environmental datasets (Kumar-Dash et al. 2023).

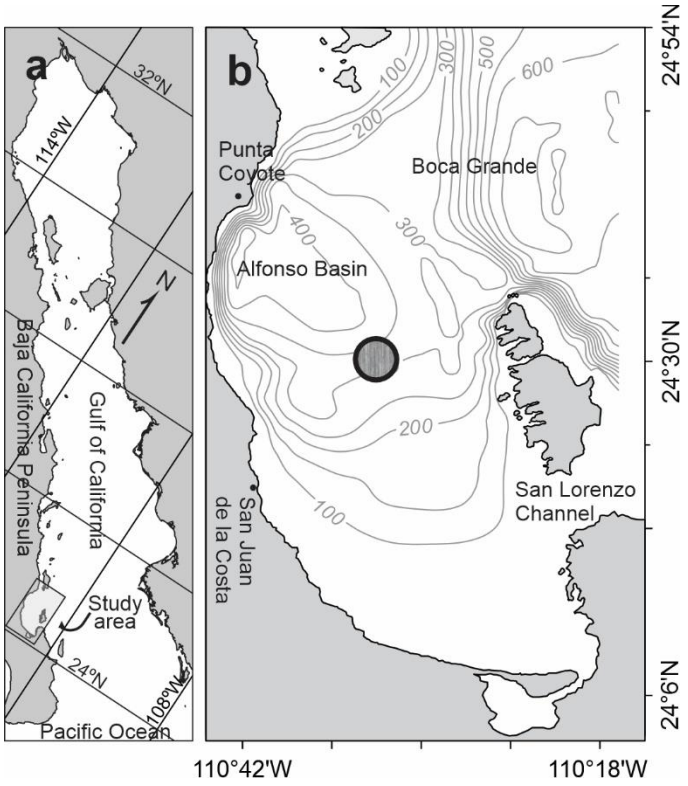


Figure 1. Location of a) the Gulf of California, Mexico; the rectangle represents the location of the Bay of La Paz; and b) the Bay of La Paz. The gray circle is ~4.4 km in diameter and centered at 24°30'N and 110°33'W; bathymetry is shown in meters.

After removing outliers, we constructed time series for both variables, presenting two approximations: one using the cleaned data and another with high-frequency noise filtered out to reveal underlying trends. To do so, we applied a moving average (rolling mean) to smooth short-term fluctuations, enabling clear visualization of long-term patterns in both Chl-*a* and SST over time (Goodell-Brow 2004). Next, we calculated the anomalies for both variables. We did this by subtracting the long-term monthly climatology to mitigate seasonal biases.

Finally, we employed Continuous Wavelet Transform analyses to assess data periodicity and identify seasonal and interannual cycles (Torrence & Compo 1998). To normalize the distribution and isolate seasonal signals from long-term trends, we logarithmically transformed and detrended the data. The wavelet power spectrum was subsequently computed by taking the square of the absolute value of the resulting transform coefficients. We also calculated the cone of influence to identify boundaries affected by finite-length edge effects. Finally, we visualized the spectral power distribution across a time-frequency grid using a logarithmic scale for period and a standardized color scale (Torrence & Compo 1998, Grinsted et al. 2004).

RESULTS

The 17-year analysis revealed significant oceanographic trends and interannual variability. Based on the MEI index, we identified five El Niño and five La Niña events throughout the study period. Notably, the 2014-2016 El Niño was a strong event, with MEI values exceeding 2.0. Conversely, the 2011-2012 period featured a long and strong La Niña events, with MEI values reaching -1.5.

Chl-*a* concentrations fluctuated between 0.1 and 5.8 mg m^{-3} (Fig. 2a). At the same time, SST ranged from 17 to 33°C (Fig. 2b).

These data highlight an inverse relationship between the two parameters, with Chl-*a* peaks consistently coinciding with seasonal SST minima. This pattern underscores a recurring annual cycle in which elevated SST corresponds to reduced phytoplankton biomass. In Figure 2, shaded areas represent ENSO phases regis-

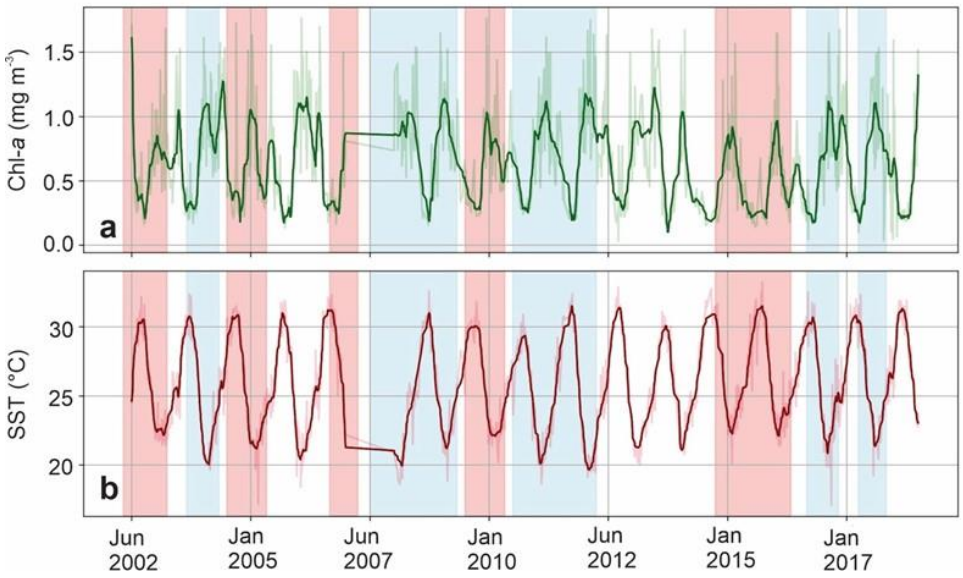


Figure 2. Time series from June 2002 to December 2018 of a) chlorophyll-*a* (Chl-*a*, mg m^{-3}), the smoothed green line represents the outlier-removed time series, whereas the solid green line depicts the filtered data, and b) sea surface temperature (SST, °C), the smoothed red line represents the outlier-removed time series, whereas the solid red line depicts the filtered data. See the Materials and Methods section for details. Shaded areas represent ENSO phases registered during the study period; red regions correspond to El Niño events and blue regions correspond to La Niña events.

tered during the study period; red regions correspond to El Niño events and blue regions correspond to La Niña events. A distinct inverse relationship is evident between ENSO phases and phytoplankton biomass; El Niño events trigger a marked decline in Chl-*a* concentrations due to rising SST, whereas La Niña events, characterized by significantly cooler SSTs, coincide with pronounced increases in Chl-*a* levels.

Analysis of Chl-*a* (Fig. 3a) and SST (Fig. 3b) anomalies confirms an inverse relationship between the two variables. Negative SST anomalies (cooler waters) promote phytoplankton growth, resulting in positive Chl-*a* anomalies. Conversely, positive SST anomalies (warmer waters) correspond to negative Chl-*a* anomalies, reflecting reduced phytoplankton biomass. The images further confirm that peak positive SST anomalies coincide with El Niño events, while La Niña events show the opposite. Consistent with this, El Niño periods show negative Chl-*a* anomalies. In contrast, La Niña periods correspond with positive Chl-*a* anomalies, underscoring the coupling between these climate drivers and regional productivity.

We performed statistical correlations on the filtered data. In particular, a Pearson correlation analysis (Fig. 4) yielded -0.66, indicating that as SST increases, Chl-*a* concentration tends to decrease. The analysis also showed a *P*-value < 0.05, indicating high statistical significance.

The continuous wavelet transform power spectrum for the Chl-*a* dataset (Fig. 5a) illustrates the dominant time-frequency characteristics of the time series.

The analysis reveals a persistent annual cycle, evidenced by a high-power band concentrated strictly around one year across the entire temporal record. While interannual variability is discernible, the seasonal signal remains the most robust feature of the time series.

For SST (Fig 5b), significant variance is similarly concentrated within the seasonal-to-annual band (one year period) throughout the record. Distinct high-power episodes within this annual cycle recur, with strong localized maxima during 2004-2006, 2011-2012, and 2015-2016, suggesting interannual modulations in signal intensity likely driven by ENSO events.

DISCUSSION

Satellite observations revealed distinct seasonal and interannual variability driven by the interplay between thermal thermodynamics and regional atmospheric dynamics. During summer, increased solar irradiance in the northern hemisphere warms the surface layers,

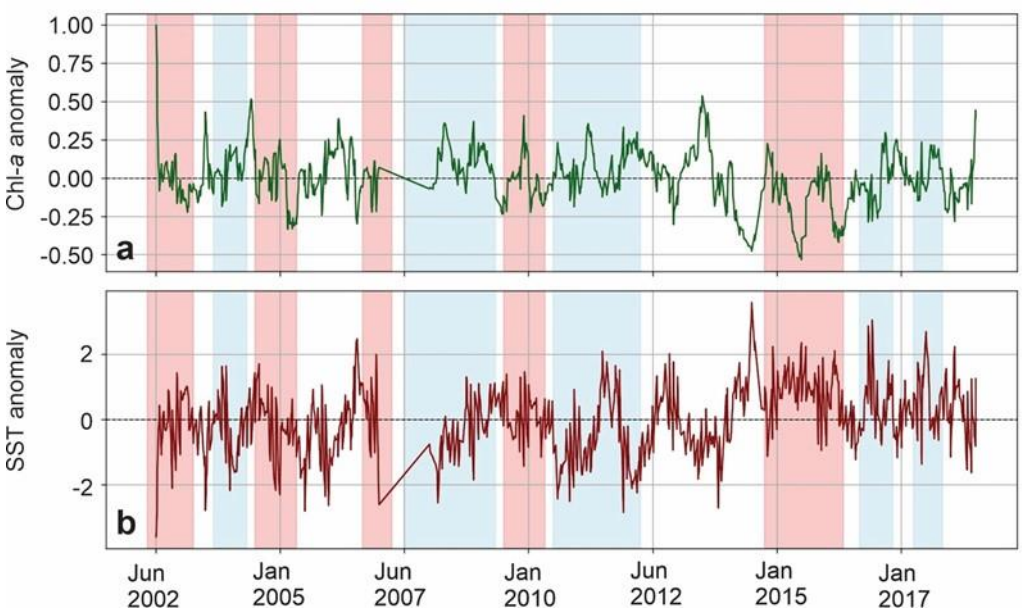


Figure 3. Anomalies calculated for a) chlorophyll-*a* (Chl-*a*) concentration and b) sea surface temperature (SST) from June 2002 to December 2018. Shaded areas represent ENSO phases registered during the study period; red regions correspond to El Niño events and blue regions correspond to La Niña events.

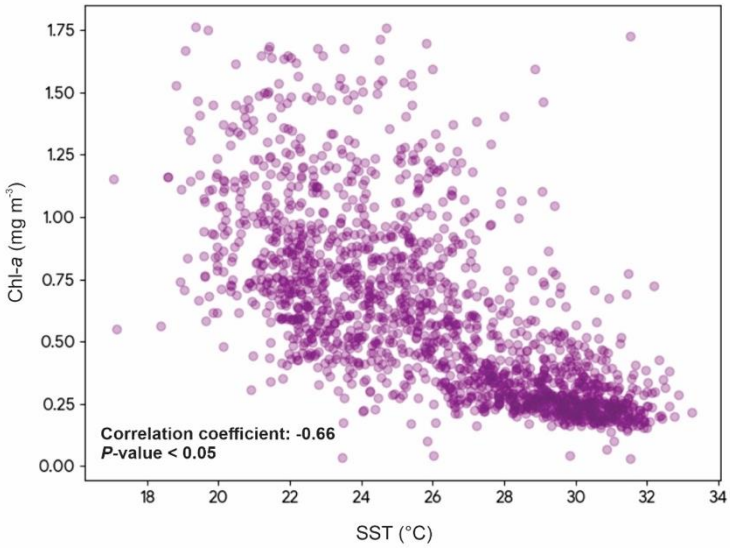


Figure 4. Pearson correlation analysis between sea surface temperature (SST, °C) and chlorophyll-*a* (Chl-*a*, mg m^{-3}) concentration (r =0.66, P-value < 0.05).

strengthening vertical stratification, which aligns with previous *in situ* findings from the Bay of La Paz showing more pronounced summer stratification than in winter using CTD measurements (Molina-Cruz et al. 2022). This stable density gradient acts as a physical barrier that inhibits the upward flux of nutrients into the euphotic zone, leading to a measurable decline in Chl-*a* concentrations. As autumn and winter approach, declining irradiance cools the surface layers, triggering vertical convective mixing (Coria-Monter et al. 2024). This process erodes stratification, facilitating the transport of nutrient-rich deeper waters to the surface and resulting in the observed annual Chl-*a* maxima, a dynamic likewise supported by prior *in situ* observations in the Bay of La Paz (Durán-Campos et al. 2020).

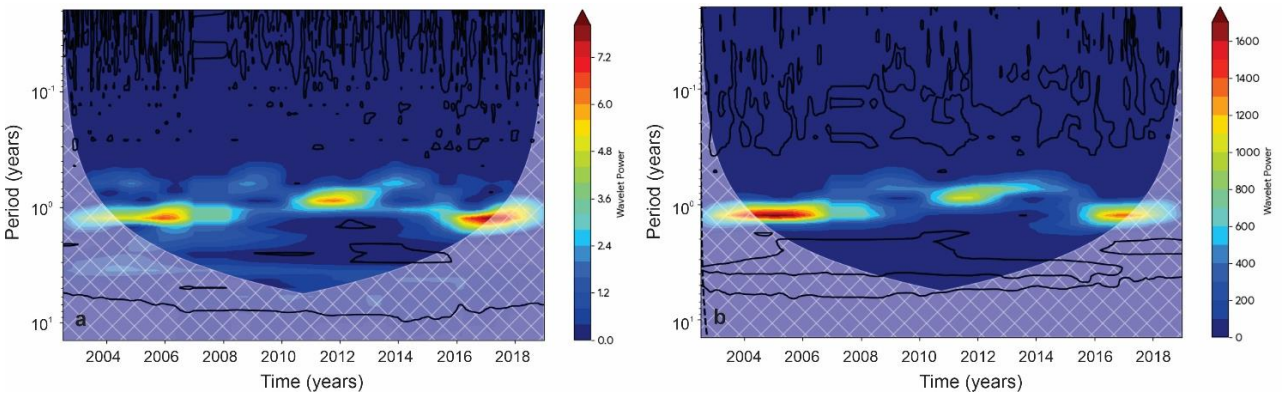


Figure 5. Continuous Wavelet Transform (Morlet) Power Spectrum of a) chlorophyll-*a* and b) sea surface temperature. The color bar represents wavelet power, with warmer colors indicating higher spectral power. The hatched, lighter region at the bottom represents the cone of influence, where edge effects may distort the spectrum. The black contour lines represent the 95% confidence level.

In addition to thermal dynamics, atmospheric forcing plays a critical role in modulating this variability through shifting pressure centers and wind patterns (Barry & Chorley 2009). Winters are characterized by intense, cold, and dry northwesterly winds exceeding 12 m s^{-1}, which enhance mechanical mixing and amplify Chl-*a* levels. Conversely, summer conditions are dominated by weaker southeasterly winds (~5 m s^{-1}) and frequent calms (Velázquez-Aguilar et al. 2024). These stagnant conditions fail to disrupt the stratified water column, preventing nutrient injection into the euphotic zone and maintaining the lower productivity characteristic of warmer months.

The satellite observations presented here align closely with previous *in situ* studies conducted in the Bay of La Paz. Minimum surface Chl-*a* concentrations during the warm season are a direct consequence of strong thermal stratification, whereas winter maxima are driven by vertical mixing processes (Martínez-López et al. 2001). This dynamic was further supported, noting that summer stratification acts as a physical barrier to surface fertilization, thereby suppressing phytoplankton productivity (Reyes-Salinas et al. (2003). Furthermore, this seasonal inverse relationship between temperature and Chl-*a* mirrors findings from the southeastern Gulf of California, where elevated summer temperatures intensify stratification and drive a corresponding decline in Chl-*a* levels (Durán-Campos et al. 2023).

Significant debate persists regarding the impact of large-scale climatic phenomena, such as El Niño and La Niña, on phytoplankton productivity within the Bay of La Paz. Conflicting hypotheses in the literature suggest either that local hydrodynamic processes buffer El Niño's adverse effects (Coria-Monter et al. 2019) or that El Niño drives ecosystem change by elevating SST and suppressing Chl-*a* levels (Herrera-Cervantes et al. 2026). Our results, based on an extensive time series, show a direct and consistent response to ENSO forcing. During El Niño, substantial SST increases are coupled with a decline in Chl-*a*, whereas La Niña conditions promote cooling and a corresponding increase in biomass. Anomaly calculations (Fig. 3a-b), Pearson correlation (Fig. 4), and wavelet analyses (Fig. 5) robustly support this relationship, confirming that local dynamics do not entirely mask large-scale climatic signals.

The global influence of ENSO events on marine phytoplankton is well-established, with La Niña phases typically inducing surface water cooling and elevated Chl-*a* levels (Stramma et al. 2016). Our findings corroborate this, as peak Chl-*a* concentrations were closely linked to La Niña conditions. These results mirror observations across the southern Gulf of California, where regional Chl-*a* variability is heavily influenced by La Niña-induced cooling (García-Morales et al. 2017). Furthermore, a similar coupling between reduced SSTs and enhanced Chl-*a* values along the southeastern coast of the gulf during La Niña events has been documented previously (Robles-Tamayo et al. 2020).

The findings presented here significantly enhance our understanding of the coupled dynamics between SST and Chl-*a* within the Bay of La Paz. Monitoring these parameters across broad spatial and temporal scales presents substantial logistical and financial challenges, mainly because ship-based sampling is

costly. Consequently, implementing alternative methodologies, such as the remote sensing approach used in this study, is paramount. These tools provide a robust and scalable framework for assessing phytoplankton dynamics, particularly in ecologically vital regions recognized for their exceptional biological productivity.

Credit author contribution

Both authors contributed equally to this study. Both authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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