Net primary productivity in the Gulf of California: spatio-temporal patterns and drivers in a warming climate (2003–2024)

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Abstract. The Gulf of California is a highly productive and biodiverse marine ecosystem that supports nearly 70 % of Mexico's fisheries. Despite its ecological and socio-economic importance, the basin-scale ~~analysis~~ patterns and drivers of seasonal and interannual variability in net primary productivity (NPP) remain incompletely understood. ~~This study~~Here, we analyse~~s~~ 22 years (2003–2024) of satellite-derived NPP data to identify ~~its main~~the principal spatio-temporal patterns ~~and environmental drivers~~of NPP and their environmental controls. ~~The m~~Monthly climatology ~~reveals~~ shows that the cold season (December–May) ~~accounts for~~contributes 68 % of ~~the~~ annual NPP, wh~~ile~~reas the warm season (June–November) ~~contributes~~ accounts for only 32 %. To characteri~~z~~e regional variability, we applied the k-means^{++} clustering algorithm, selected the optimal number of clusters using the elbow and silhouette criteria (Fig. A1), and validated the result~~ant~~ing classification ~~using~~ through discriminant analysis. This procedure ~~robustly~~ identified three distinct productivity zones: low-productivity (LPZ; < 900 mg C m^{-2} d^{-1})~~high (HPZ; > 1700 mg C m^{-2} d^{-1})~~, mid-productivity (MPZ; 900–1700 mg C m^{-2} d^{-1}), and high-productivity (HPZ; > 1700 mg C m^{-2} d^{-1})~~low (LPZ; < 900 mg C m^{-2} d^{-1})~~. Interannually, ~~the HPZ contributes 61.4 % of total NPP despite occupying only 30 % of the gulf's area, whereas~~ the LPZ ~~covers~~ covered 36 % of the area but produces ~~just~~ only 16.9 % of total NPP, whereas the HPZ contributes 61.4 % of total NPP while occupying only 30 % of the gulf's area. A ~~significant~~ pronounced NPP negative anomaly ~~between~~ during 2013~~ and~~–2019 ~~led~~ reduced ~~to a~~ NPP by approximately 9 % ~~decline in NPP~~ relative to the long-term mean (124 Tg C y^{-1}). This decline~~,~~ ~~a period~~ coincided with ~~intense~~ sustained ocean warming ~~episodes~~, including multiple marine heatwaves and the strong 2015–2016 El Niño event. ~~A p~~A partial recovery ~~occurred~~ was observed ~~between~~ during 2020~~ and~~–2024. Nitrate availability and water-column stratification were the dominant predictors of NPP, but their effects differed among productivity zones: nitrate was negatively associated with NPP and stratification positively associated with NPP in the LPZ, whereas the opposite relationships were observed in the MPZ and HPZ. Wind forcing, sea-

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surface salinity and phosphate availability exerted additional zone-specific effects. The dominant environmental drivers of NPP differ among zones: sea surface temperature and mixed layer depth control NPP in the HPZ, temperature and euphotic zone depth in the MPZ, and euphotic depth and phosphate availability in the LPZ. Overall, our analysis demonstrates results indicate that anomalously warm years conditions compress reduce the spatial extent of HPZ productive zones and favour the . Continued warming and stratification are therefore likely to expandsion of oligotrophic conditionsareas, . Continued warming and enhanced stratification are therefore expected to increasing increase the area extent of low productivity watersLPZ, with profound potentially significant ecological consequences for the Gulf of California.

1 Introduction

The Gulf of California is a highly biodiverse ecosystem that supports approximately 70 % of Mexico's fisheries (Lluch-Cota et al., 2007). This gulf is influenced by multiple atmospheric and oceanic processes that complicate the characteriszation of this complex marine system (Kahru et al., 2004, ; Bustos-Serrano and Castro-Valdez, 2006; López-Martínez et al., 2023; Marin-Enriquez et al., 2024). Among these processes, prolonged anomalous warming of the surface ocean exerts widespread negative impacts on marine ecosystems, with large-scale repercussions for ecological and biogeochemical functioning (Somavilla et al., 2017). Such events can alter particulate carbon flux (Xie et al., 2019), reduce biodiversity (Wernberg et al., 2016; Jones et al., 2018), and affect fisheries and aquaculture (Mills et al., 2013; Oliver et al., 2017). Enhanced ocean–atmosphere heat exchange during warming events strengthens water-column stratification (Jacox et al., 2016; Somavilla et al., 2017), disrupting nutrient supply and driving changes throughout marine food webs (Cavole et al., 2016). For instance, reductions in phytoplankton biomass and primary productivity have been documented during anomalous warming episodes such as El Niño events (Jacox et al., 2016).

Despite ongoing global warming, the responses of oceans and marine ecosystems to changing sea-temperature patterns remain uncertain (Somavilla et al., 2017). In recent decades, anomalous warming events, including the positive phase of El Niño-Southern Oscillation (ENSO) and the marine heatwaves, have increased in frequency across multiple ocean regions (Di Lorenzo and Mantua, 2016; Oliver et al., 2019). These events produce positive sea-surface temperature (SST) anomalies over a range of spatial and temporal scales and are generally associated with declines in primary productivity (Wernberg et al., 2016; Oliver et al., 2017). Concurrently, global ocean heat content has risen over the past five decades (NOAA, https://www.ncei.noaa.gov/access/global-ocean-heat-content/), suggesting that marine ecosystems may be approaching resilience thresholds with potentially irreversible consequences (Frölicher et al., 2018).

The northeastern Pacific Ocean represents a transitional marine ecosystem (Fiedler and Talley, 2006; Cepeda-Morales et al., 2013), where warming events across diverse spatiotemporal scales have been reported in the Gulf of California (Sánchez-Cabeza et al., 2022; López-Martínez et al., 2023). Notably, the combined influence of the Blob in the North Pacific, strong equatorial El Niño event and overlapping marine heatwaves between 2013 and 2016 produced persistent warm anomalies in northwestern Mexico (Joh and Di Lorenzo, 2017; Jiménez-Quiroz et al., 2019; Joh and Di Lorenzo, 2017; García-Fernández

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et al., 2023). These anomalies propagated through mid- and upper-trophic levels, altering species distributions, including euphausiids, copepods, pelagic crabs, and tunas, in the Eastern Tropical Pacific (Cavole et al., 2016; García-Fernández et al., 2023). As global temperatures rise, such anomalies are expected to disrupt the biological carbon pump, reducing oceanic carbon storage and increasing atmospheric carbon concentrations (Cavole et al., 2016; Xie et al., 2019). These changes will likely reshape community structures and ecosystem functioning (Cavole et al., 2016).

The Gulf of California (20–32º N, 105–115º W) is among the most diverse and productive marine regions in Mexico (Fig. 1), characterisz~~z~~ed by high net primary productivity (NPP, defined as gross primary productivity minus respiration) and phytoplankton biomass ~~{~~expressed as chlorophyll-*a* concentration (Chl-*a*)~~}~~ (Lluch-Cota, 2004; O'Reilly and Sherman, 2016). Its elongate geometry, steep bathymetry, and pronounced orographic relief modulate regional pressure-gradient forcing and orographic channelling of the winds, generating seasonally coherent along-gulf winds whose wind-stress curl drives Ekman upwelling, coastal divergence, and vertical mixing that inject nutrient-rich subsurface waters into the euphotic zone (Miranda-Alvarez et al., 2020; Robles-Tamayo et al., 2020). However, anomalous warming associated with the positive phases of ENSO and Pacific Decadal Oscillation (PDO) reduce mean Chl-*a* concentration in the gulf (Hakspiel-Segura et al., 2022; López-Martínez et al., 2023). *In situ* NPP measurements in the region remains scarce, particularly during winter, limiting our understanding of latitudinal gradient and seasonal cycles (Zeitzschel, 1969; Álvarez-Borrego and Lara-Lara, 1991; Mercado-Santana et al., 2017). Remote-sensing estimates of NPP and Chl-*a*, based on ecological models incorporating light-use efficiency and absorbed photosynthetically active radiation, have partially addressed these gaps. However, most studies have focused on local variability rather than ~~basin~~ basin-~~scale~~ scale-dynamics. Furthermore, while satellite-derived Chl-*a* is often used as a proxy for NPP, it reflects biomass within the first optical depth, whereas NPP integrates production across the entire euphotic zone and daylight period (Balch et al., 1992; Behrenfeld and Falkowski, 1997).

In this study, we investigate the response of NPP in the Gulf of California to recent anomalous warming events, using a 2003–2024 satellite record to establish the seasonal and interannual baseline against which anomalies are assessed. We specifically focus on the 2013–2024 period, encompassing the 2014–2016 warming event, to evaluate how elevated SSTs and enhanced stratification modify the spatial distribution of productivity and its environmental controls. We hypothesize that anomalous warming events intensify water column stratification, restricting the flux of nutrient-rich water to the euphotic zone and thereby reducing NPP. By combining satellite observations with reanalysis-based water-column variables, we identify the key drivers that modulate NPP under anomalously warm conditions.

2 Materials and methods

2.1 Study area

The Gulf of California (20–32º N~~32–20º N~~,105–115º W) is a marginal subtropical sea of the eastern Pacific located in ~~the~~ northwestern Mexico (Fig. 1). It extends ~1,500 km from its northernmost limit to Bahía de Banderas in the south and is 150–

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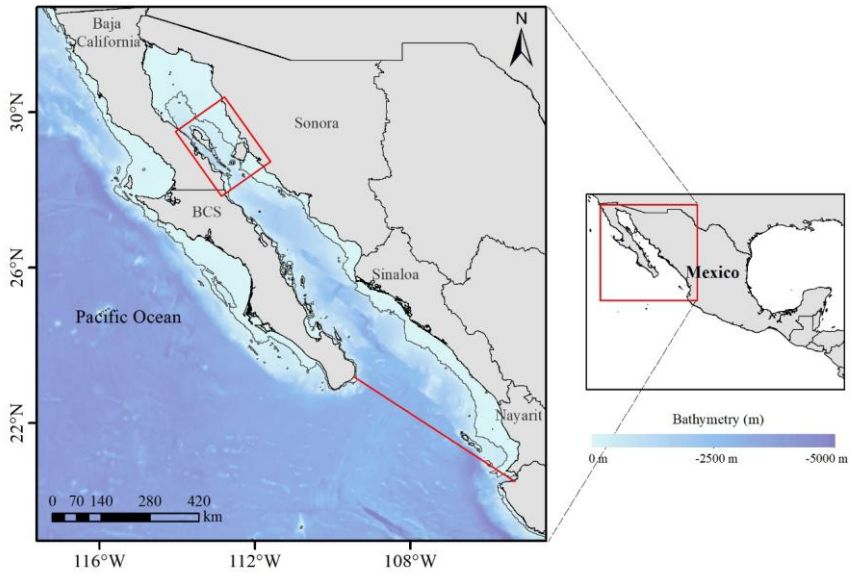
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200 km wide. South of 28º N, the gulf comprises a series of deep basins separated by bathymetric sills (Álvarez-Borrego and Lara-Lara, 1991). The region exhibits dynamic and heterogeneous conditions driven by tidal currents, wind momentum transfer, bathymetrically controlled and wind-driven coastal upwelling, and intense solar heating (~~A~~Álvarez-Borrego, 2007). In the Midriff Archipelago, bathymetric upwelling maintains low temperatures year-round. From December to May, northwesterly winds induce strong coastal upwelling along the eastern coast, transporting nutrient-rich subsurface waters into the euphotic zone, ~~that~~ fuelling phytoplankton growth. In contrast, from July to October southeasterly winds are generally weaker and insufficient to disrupt the pronounced thermal stratification that develops during summer. June and November are considered transitional months between the cold-warm and warm-cold seasonal regimes (Santamaría-del-Á~~A~~ngel et al., 1994~~;~~, Hidalgo-González and Á~~A~~lvarez-Borrego, 2004). The Baja California mountain ranges block low-lying clouds from the Pacific, resulting in predominantly clear skies over the gulf except during summer monsoon incursions (Badan-Dangon et al., 1985). For this study, the southern boundary of the Gulf of California was defined by a line connecting Cabo San Lucas on the Baja California peninsula (23° N) to Cabo Corrientes in Nayarit (~20º N; Fig. 1).

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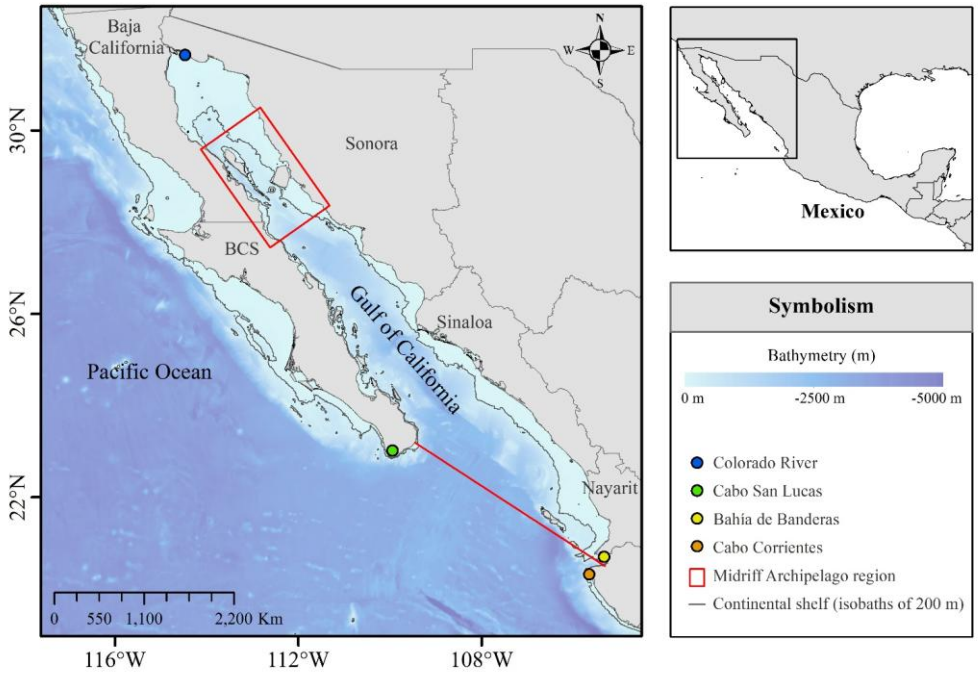


Figure 1: . Bathymetric map of the Gulf of California, conceptually delimited from the Pacific Ocean by a red line. The gulf is a large and deep pull-apart basin formed by right-lateral strike-slip motion along faults associated with the San Andreas system. ~~Tectonic opening on the order of 3–6 cm y^{-1} has shaped the oceanic crust underlying most of the basin.~~ The resulting geological configuration supports oceanographic processes that sustain high phytoplankton productivity, with contrasting dynamics along the opposing coasts. ~~Gray line: continental shelf (isobaths of 200 m); Red square: Midriff Archipelago region.~~

2.2 Data collection

Net primary productivity (NPP) was obtained from the satellite-based VGPM product distributed through NOAA ERDDAP. This product was selected because it provides spatially coherent NPP fields for the Gulf of California and reproduces the expected seasonal cycle of regional productivity, with enhanced winter–spring production and reduced summer productivity under stronger stratification. Reanalysis products were used only for subsurface and water-column variables, including satellite observations of mixed-layer depth, nutrients, salinity, temperature profiles, and the derived stratification index, for which long-term basin-scale observational datasets with consistent spatial and temporal coverage are not currently available in the Gulf of California. ~~The study combines satellite observations and ocean reanalysis products to characterize the spatial and temporal~~

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~~variability of net primary productivity and its environmental drivers in the Gulf of California.~~ The following subsections summarize the datasets used for NPP, physical, biogeochemical, and climate variables.

2.2.1 Satellite variables

Monthly sea surface temperature (SST) and Chlorophyll-*a* concentration (Chl-*a*; OCI algorithm) were obtained from Aqua-MODIS Level 3 global composites (4 × 4 km) spanning January 2003 to December 2024, downloaded from NASA Ocean Colour (https://oceancolor.gsfc.nasa.gov/l3/).

Euphotic-zone depth (EZD) was derived from Chl-*a* using the chlorophyll-*a* dependent bio-optical parameterisation with piecewise power-law relationships for different trophic regimes (Morel and Berthon, 1989; Morel and Maritorena, 2001). Net primary productivity (NPP) at the same nominal resolution (4 × 4 km) was obtained from monthly Level-3 products of the Vertically ~~Generalized~~ Generalised Production Model (VGPM) via NOAA CoastWatch (https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMH1ppmday.graph). Monthly 10-m wind components (*u*, *v*) were taken from Remote Sensing System (RRS) CCMP V3.1 Level-3 dataset (25 × 25 km) for 2003–2024 (https://data.remss.com/ccmp/v03.1/). ~~The~~ To account for the gulf's orientation, the coordinate axes were rotated by 40º, aligning the total *u*-component with the gulf's axis and the rotated *v*-component perpendicular to it. The along-gulf wind *u*-component (URT) was used in statistical analyses.

Daily sea current components (*u*, *v*; Level 4; 12.5 × 12.5 km) were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS, https://doi.org/10.48670/moi-00148). Monthly means were computed for 2003–2024, and rotated analogously to the winds; only the along-gulf *u*-component (UAR) was used in statistical analyses.
Monthly global gap-free Level-4 (L4) sea surface salinity (SSS) analyses at 12.5 km spatial resolution were obtained from CMEMS (https://doi.org/10.48670/moi-00051) for the period 2003–2024 and included in the statistical analyses.

2.2.2 Reanalysis variables and derived parameters

Monthly Global Ocean Biogeochemistry Hindcast reanalysis (GLOBAL_REANALYSIS_BIO_001_029) for nitrate (NO_3), phosphate (PO_4^{-3}) and silicate (SiO_2) concentrations were downloaded from CMEMS (https://doi.org/10.48670/moi-00019). These ~~Level-4~~Level 4 products are provided on a 25 × 25 km grid with 75 depth levels. Mixed layer depth (MLD), potential temperature (θ), and practical salinity (PSU) were obtained from the Global Ocean Physics Reanalysis (GLOBAL_REANALYSIS_PHY_001_030; ~8 × 8 km horizontal resolution, 50 standard depth levels; https://doi.org/10.48670/moi-00021~~https://doi.org/10.48670/moi-00021/~~).

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2.2.3 Data rRegridding homogenization

To ensure consistency, NO_3, PO_4^{-3}, SiO_2, MLD, and the stratification index (Section 2.3.2) were bilinearly interpolated to the 4 km grid used for NPP, SST, and EZD. Only grid cells within the Gulf of California domain (Fig. 1) were retained for analyses.

2.3 Data processing

2.3.1 Identification of warm events, climate indices, and spatial trends

Anomalous warm periods were identified using SST anomalies (SSTa), and marine heatwaves (MHWs) were detected following Hobday et al. (2016) who define MHWs as periods when SST exceeds a seasonally varying 90th-percentile threshold for ≥ 5 consecutive days.

ENSO evolution and strength were tracked at a two months with the (bi-monthly) resolution (Dec-Jan, Jan-Feb, etc.) using tThe Multivariate ENSO Index version 2 (MEI.v2) was used to represent ENSO variability during the study period. MEI.v2 is an index for overlapping two-month periods (Dec-Jan, Jan-Feb, etc.) based on the leading combined empirical orthogonal function of five ocean–atmosphere variables over the tropical Pacific:, which integrates sea-level pressure, SSTsea surface temperature (SST), zonal and meridional surface winds, and outgoing longwave radiation using empirical orthogonal function (EOF) framework over the tropical Pacific (30° S to 30° N) (Wolter and Timlin, 2011; Kobayashi et al., 2015). The index is calculated for 12 overlapping two-month seasons, which allows the seasonal structure of ENSO variability to be represented more appropriately. MEI MEI.v2 data values were obtained from National Oceanic and Atmospheric Administration (NOAA,) Physical Sciences Laboratory webpage (https://psl.noaa.gov/enso/mei/) for the entire study period. ENSO influence was assessed by comparing SST anomaly (SSTa) time series with MEI.v2 (Fig. 2).

In addition, the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) indices were included to evaluate the potential influence of large-scale Pacific climate variability on productivity patterns in the Gulf of California. The PDO index represents the dominant mode of monthly sea surface temperature anomaly variability in the North Pacific. It is calculated as the leading EOF of monthly sea surface temperature anomalies between 20°N and 70°N, after removing the monthly climatology and the global mean sea surface temperature anomaly. Monthly PDO values were downloaded from the NOAA Physical Sciences Laboratory climate time-series database: https://psl.noaa.gov/data/timeseries/month/PDO/.

The NPGO index represents the second dominant mode of sea surface height variability in the Northeast Pacific. It is derived from an EOF analysis of sea surface height anomalies and reflects changes in the intensity of the central and eastern branches of the North Pacific gyre circulation. The NPGO is also associated with variability in salinity, nutrients, and chlorophyll-*a* in the Northeast Pacific. Monthly NPGO values were downloaded from the North Pacific Gyre Oscillation webpage (https://o3d.org/npgo/).

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Spearman's rank correlation coefficients were calculated to evaluate the relationships among hydrographic variables, climate indices, and NPP across gulf regions. To account for temporal autocorrelation, statistical significance was assessed using an effective sample size correction following the method of Pyper and Peterman (1998). Monotonic trends were assessed using the Mann–Kendall test to determine their statistical significance and the Theil–Sen slope estimator to quantify their magnitude. Both analyses were performed using the Mann–Kendall and Theil–Sen functions implemented in the Climate Data Toolbox for MATLAB (**Greene** et al., 2019).

2.3.2 Calculation of stratification index

Water-column stratification was quantified with a density-based index calculated from vertical profiles of potential temperature (θ) and practical salinity (PSU). The stratification index (SI; kg m^{-3}) was defined as:

$$SI = \sigma\theta, MLD - \sigma\theta, surface \quad (1)$$

where: $\sigma\theta$ is potential density anomaly referenced to 0 dbar. Practical ~~salinity~~ Salinity was ~~first~~ converted to ~~absolute~~ Absolute ~~salinity~~ Salinity (g kg^{-1})~~, accounting for~~using latitude, longitude, and pressure~~; p.~~ Potential density anomaly ~~was then evaluated at the surface (0 m)~~referenced to 0 dbar ~~and at~~was subsequently calculated at the surface and at the mixed-layer depth (MLD)~~, using~~ following the Thermodynamic Equation of Seawater 2010 (TEOS-10 ~~equation of state~~ () (IOC ~~et al.~~, SCOR, and IAPSO, 2010). With this definition, positive SI values indicate stable stratification (lighter surface waters overlying denser subsurface waters), whereas values near zero denote well-mixed conditions. This metric represents the physical barrier to vertical mixing and links surface warming to reduced nutrient supply (Jacox et al., 2016).

2.3.3 Regional classification of net primary productivity

To analy~~sz~~e spatio-temporal variability and identify productivity regimes~~. We~~, we ~~sought to~~ classifi~~ed~~ the Gulf of California ~~based on~~according to differences in satellite-derived NPP ~~(~~from January 2003 to December 2024~~)~~. ~~and subsequently evaluate the environmental factors associated with each productivity regime. To do this, the first step was that~~Prior to clustering, outliers were ~~deleted~~removed ~~using~~following the interquartile range (IQR) criterion (1.5 ~~x~~× IQR) ~~following~~of Moore and McCabe (1999)~~, To analyse spatiotemporal variability, monthly NPP fields (January 2003–December 2024) were classified into zones. Then the same~~the resulting filtered dataset was used in all subsequent analyses. ~~for the grouping of~~ NPP was then classified using ~~by using~~ the k-means^{++} algorithm ~~Outlier were removed following Moore and McCabe (1999). NPP was then grouped into three clusters using the k-means^{++} algorithm~~ (Kapoor et al., 2017; Zhang et al., 2025). To ~~further support the selection o~~evaluate the appropriate number of clusters~~f K~~, we ~~evaluat~~compared alternative solutions ~~the number of clusters~~ using the

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elbow and silhouette methods (Fig. A1). These diagnostics indicated that a small number of clusters, particularly K = 2–4, provided the most robust classifications, whereas higher values, K ≥ 5, resulted in lower clustering performance and increased spatial fragmentation. Because NPP varies along a continuous environmental gradient, K = 3 was selected as the most parsimonious and ecologically interpretable solution, resolving three coherent productivity regimes corresponding to low-, intermediate-, and high-productivity waters. ~~We therefore selected the most parsimonious and ecologically interpretable solution.~~

A discriminant analysis was subsequently performed to evaluate whether the NPP-derived productivity classes corresponded to distinct environmental regimes. The productivity classes obtained from the k-means classification were used as the grouping variable, whereas the environmental variables ~~(~~, SST, EZD, MLD, NO_3, PO_4^{-3}, ~~–~~SiO_2, URT, UAR, SI, and SSS~~AL)~~, were includ~~us~~ed as explanatory variables (Johnson and Wichern, 2018). NPP was ~~intentionally~~deliberately excluded from this analysis because it was the variable used to defin~~generate~~ the original k-means classification. Its includ~~ing~~sion would therefore have ~~NPP would have~~ introduced circularity and artificially inflated the classification performance. Th~~erefore~~us, the purpose of the discriminant analysis was not to validate the clustering procedure or the selected number of clusters, but rather to ~~evaluate~~determine whether the resulting NPP-based productivity classes could ~~also~~ be independently distinguished by ~~independent~~ hydrographic and biogeochemical characteristics.

~~The discriminant analysis was applied after the k-means++ classification to evaluate whether the NPP-derived groups corresponded to distinct environmental regimes. The classes obtained from the k-means++ algorithm were used as the grouping variable, while all environmental variables (SST, EZD, MLD, NO3, PO4, SiO2, URT, UAR, SI, and SAL) were included as explanatory variables (Johnson and Wichern, 2018). NPP was intentionally excluded from the discriminant analysis because it was the variable used to generate the original k-means++ classification. Including NPP would have introduced circularity and artificially inflated classification performance. Instead, the objective was to determine whether the resulting NPP-based groups could also be distinguished by independent hydrographic and biogeochemical characteristics.~~

~~Discriminant analysis (Johnson and Wichern, 2018) was applied to all variables except NPP to validate cluster assignments.~~ Spatial distribution and seasonal patterns (cold season: December–May and warm season: June–November) were visualis~~z~~ed (Fig. 3) (Santamaría-del-~~A~~Ángel et al., 1994; Hidalgo-González and ~~A~~Álvarez-Borrego, 2004). The areal coverage for each cluster was calculated by counting grid cells within each class, converting to km^2, and then to percentage coverage (%) per month, season, and year. Monthly anomalies were calculated from the coverage time se~~We agree with the reviewer and have clarified in the Methods that the discriminant analysis was not intended to validate the clustering or the selected number of clusters, but only to evaluate the environmental separability of the NPP-derived productivity classes.~~ries (Kushnir, 1994; Ramos-Rodríguez et al., 2012). Monthly climatological NPP was estimated for each cluster, and cluster contributions were integrated to obtain total monthly productivity. NPP is reported as teragrams of carbon per month (Tg C ~~per~~ month~~-1~~) and per year (Tg C y^{-1}). Annual distribution patterns were visualis~~z~~ed (Figs. 5, ~~S1~~A2–A, ~~S3~~2).

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2.3.4 Assessment of NPP drivers

~~to~~ To explain spatial and temporal variability in NPP, the following biophysical variables were analysed for each NPP zone: SST, EZD, MLD, NO_3, PO_4^{-3}, SiO_2, URT, UAR, ~~and~~ SI, and SSS~~AL~~. Monthly time series were computed by zone for each variable. Nutrients (NO_3, PO_4^{-3}, SiO_2) were vertically integrated from the surface to the EZD prior to analysis. ~~SST, EZD, and MLD were standardized to derive anomalies.~~ Potential collinearity among predictors was evaluated with correlation matrices considering Pearson's correlation > 0.7; highly correlated variables were excluded from the final predictor set (Table A1).

To avoid potential circularity between the response variable and predictor variables, SST, ~~and~~ euphotic zone depth (EZD), and SiO_2 were excluded from the final GLMM because ~~both~~these variables are directly involved in, or derived from quantities used in, the VGPM algorithm employed to estimate NPP. ~~To~~ To identify the environmental drivers of net primary productivity (NPP) and evaluate whether their effects differed among productivity zones, we fitted a Generalis~~z~~ed Linear Mixed Model (GLMM) using a Gamma error distribution and a log-link function, which is appropriate for continuous, positive, and right-skewed response variables such as NPP (Corrales and Cepeda-Cuervo, 2019; Miyamoto et al., 2019). Prior to modelling, all continuous predictor variables were standardis~~z~~ed (z-scores) to facilitate comparison of effect sizes and improve model convergence. Separate ~~The~~models were fi~~x~~etted for each productivity zone; ~~effects structure included productivity zone (categorical factor) and its interactions~~ within each model, ~~the environmental predictors~~ MLD, NO_3, PO_4^{-3}, U~~W~~RT, UAR, SI, and ~~SAL~~SSS were included as fixed effects. To account for temporal dependence among observations and repeated measurements through time, month was included as a random intercept term (1|Month). ~~To evaluate environmental controls on NPP while accounting for spatial heterogeneity among zones, a generalized linear mixed model (GLMM) with Gaussian errors was fitted. Fixed-effect coefficients (estimate, standard error, t-statistic, and p-value) were evaluated with marginal ANOVA to identify significant predictors and interaction terms. Predictors with $p < 0.05$ were considered significant drivers of NPP.~~ The model structure was:

$$NPP_{zone} \sim Zone * MLD + NO_3 + PO_4 + URT + UAR + SI + SSS \quad (2)$$

~~$NPP_{zone} \sim Zone * MLD + NO_3 + PO_4 + URT + UAR + SI + SSS + (1|Month)$~~

~~DAVID, de acuerdo a la IA, el de abajo es el modelo correcto! revisa por favor~~

~~NPP ~ MLD+NO3+PO4+URT+UAR+SI+SSS+(1|Month)~~

~~The same model structure was fitted independently to each productivity class.~~

where ~~Month represents the random effect and Zone and the environmental variables correspond to fixed effects.~~ NPP_{zone} indicates the response variable and the same ~~Separate~~ GLMMs structure w~~ere~~as fitted independently ~~for~~to each net productivity zone class (low-productivity zone (LPZ), mid-productivity zone (MPZ), and high productivity zone (HPZ) as defined in result section~~LPZ, MPZ, and HPZ~~); therefore, ~~Z~~zone was used only to stratify the dataset prior to model fitting

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and was not included as a predictor in the models. MLD = mixed-layer depth, NO_3 = nitrate concentration, PO_4^{-3} = phosphate concentration, UAR = along-gulf (u) sea current component; URT = along-gulf (u) wind component; SI = stratification index, SSS = sea surface salinity, and 1|Month represents the random effect, and the environmental variables correspond to fixed effects.

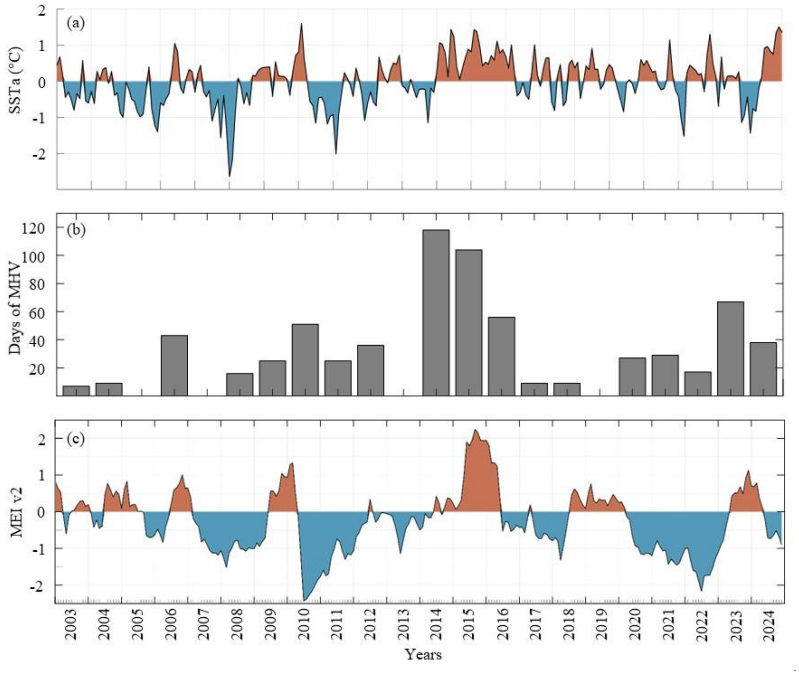
Positive coefficients indicate that higher predictor values are associated with increased NPP, whereas negative coefficients suggest inhibitory or limiting effects. Model fitting was performed using the fitglme function in MATLAB. Model assumptions and goodness of fit were evaluated through graphical and statistical diagnostics. Because a Gamma distribution with a log-link function was employed, diagnostic evaluation focused on the distribution of deviance and Pearson residuals, the absence of systematic patterns in residual-versus-fitted value plots, and the assessment of homoscedasticity across the range of fitted values. Quantile–~~Q~~quantile plots of residuals were also inspected to evaluate departures from normality. The adequacy of the linear predictor was examined by inspecting residual patterns against each covariate, while the inclusion of month as a random effect accounted for non-independence among observations collected within the same temporal group. Model performance was further assessed using Akaike's Information Criterion (AIC) and~~,~~ Bayesian Information Criterion (BIC)~~, and likelihood ratio tests comparing alternative model formulations~~. Fixed-effect coefficients (estimate, standard error, *t*-statistic, and *p*-value) were evaluated with marginal ANOVA to identify significant predictors~~ and interaction terms~~. Predictors with $p < 0.05$ were considered significant drivers of NPP.

3 Results

3.1 Anomalous warming events

Sea surface temperature anomalies (SSTa) in the Gulf of California were predominantly negative from 2003 to 2013. Beginning in 2014, anomalies transitioned to positive values, with increasing frequency and duration over time. The most intense and persistent positive anomalies occurred between late–2013 and late–2016 (Fig. ~~2a~~2**¡Error! No se encuentra el origen de la referencia.**A). During 2014–2016, the annual number of MHW days reached 118, 95, and 51 days, respectively, amounting to 50.2 % of all MHW days in the 2003–2024 record (Fig. ~~2b~~2B). The MEI.–v2 also showed strong positive anomalies and extreme values during 2015–2016, consistent with the 2015–2016 El Niño ~~event, and~~event and was flanked by prolonged negative anomalies associated with La Niña conditions during 2010–2014 and 2016–2018 (Fig. ~~2c~~2C). ~~together,~~ SSTa, MHW occurrence, and ~~MEI~~ MEI.v2, the warmest period in the study was 2014–2016, followed by 2023–2024, which recorded the second-highest number of MHW~~s~~ days.

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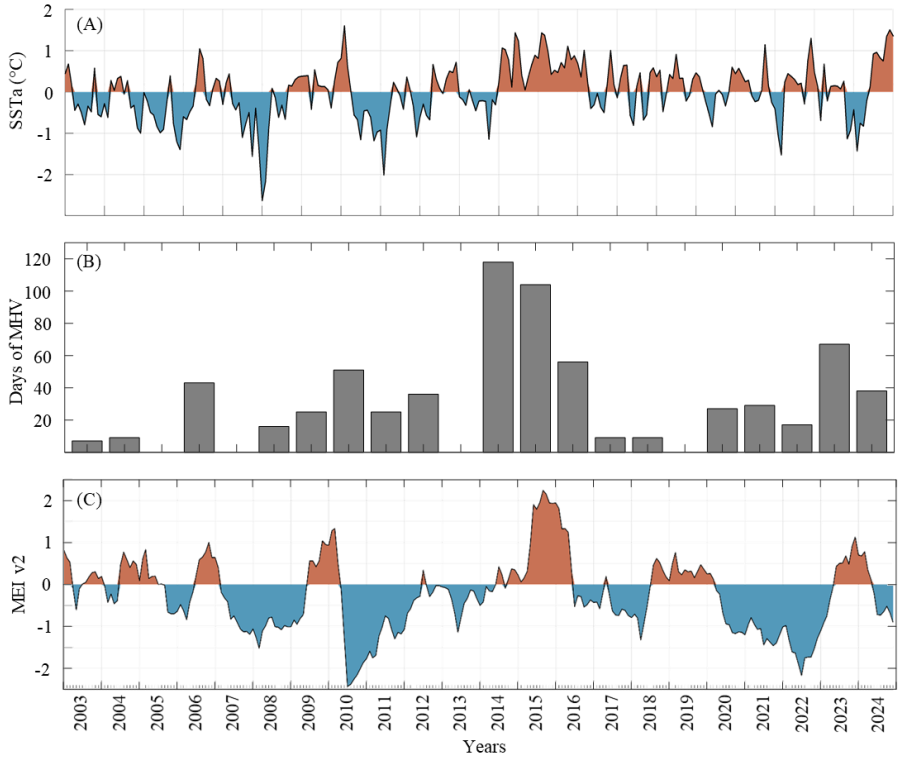


Figure 2. Time series for the Gulf of California of **(a)** monthly sea surface temperature anomaly (SSTa), **(b)** annual number of marine heat waves (MHW) days, and **(c)** multivariate ENSO index version 2 (MEI v2) from January 2003 to December 2024.

3.2 Regional classification of NPP

The k-means^{++} clustering analysis identified three groups. The discriminant analysis indicated clear environmental separation among the NPP-derived productivity classes. The overall misclassification rate was low (8.7 %), while assignment accuracy was high across groups, with values of 92.4 %, 96.1 %, and 80.1 % for Groups 1–3, respectively~~The discriminant analysis showed a low misclassification rate (8.7%) and high assignment accuracy among groups (92.4%, 96.1%, and 80.1% for Groups 1–3, respectively), indicating strong environmental separation among the resulting productivity classes with 8.7 % observations misclassified (51,572 out of 591,836 records). Classification accuracies for the three groups were 92.4 %, 96.1 %, and 80.1 %, respectively~~. Groups were categorized as low-productivity (LPZ, < 900 mg C m^{-2} d^{-1}), mid-productivity (MPZ, 900–1700

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mg C m^{-2} d^{-1}), and high-productivity (HPZ, >1700 mg C m^{-2} d^{-1}) productivity zones (Fig. 3). By dividing the Gulf into three productivity zones, we evaluate how anomalous warming affects their spatial extent, their total carbon contribution, and the physical drivers underlying these changes.~~This regionalization provides the spatial framework to assess how anomalous warming modifies the extent, contribution, and environmental controls of productivity across the gulf.~~

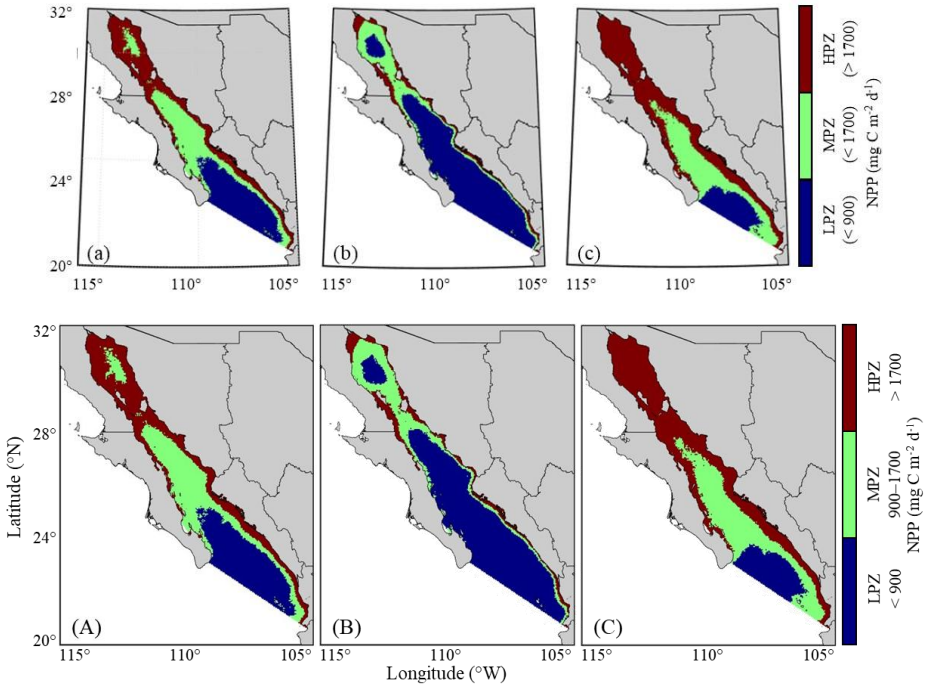


Figure 3. ~~:~~ Regionali~~z~~ation of net primary productivity (NPP) based on (~~a~~A) the k-means^{++} clustering of the January 2003–December 2024 global climatology, (~~b~~B) warm seasonal (June–November), and (~~c~~C) cold seasonal (December–May). NPP classes: low-productivity (LPZ < 900 mg C m^{-2} d^{-1}), mid-productivity (MPZ 900–1700 mg C m^{-2} d^{-1}), and high-productivity (HPZ > 1700 mg C m^{-2} d^{-1}).

3.3 ~~Variability at i~~Intra- and interannual ~~scales~~ variability in primary productivity ~~scale~~

The 2003–2024 NPP mean seasonal cycle ~~climatology~~ ranged from 642 to 3487 mg C m^{-2} d^{-1}. The average annual spatial pattern showed a gulf-latitudinal ~~longitudinal~~ gradient along the continental coast, extending from the mouth (~20° N) to the

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northern gulf (~31.5° N) (Fig. 3aA). The most productive regions (HPZ, >1700 mg C m^{-2} d^{-1}) included the Nayarit, Sinaloa, and Sonora coasts, the Midriff Archipelago (28° N; 1200–2000 mg C m^{-2} d^{-1}), and the Colorado River mouth extending ~40 km offshore (Fig. 3Aa).

Intermediate Mid-productivity (MPZ, 900–1700 mg C m^{-2} d^{-1}) occupied coastal waters near the gulf's mouth and southern sector, forming a coast-shore gradient from the coast to the shelf edge. The MPZ extended from ~25° N to the Midriff Archipelago region and along the entire peninsular coast, with a core in the upper gulf. Low productivity waters (LPZ, < 900 mg C m^{-2} d^{-1}) characteriszed oligotrophic conditions from the mouth to ~26° N (Fig. 3Aa). Seasonality was pronounced during the warm seasonperiod (June–November), HPZ and MPZ coverage decreased, while LPZ expanded northward to ~28° N, forming a core in the upper gulf (Fig. 3b3B). In contrast, during the cold seasonperiod (December–May), HPZ expanded over the upper gulf and along both continental and peninsular coasts (Fig. 3c3C).

Gulf-wide climatological monthly mean NPP over the 22-years period was 8.6 Tg C per month^{-1}. During the cold season, NPP averaged 11.7 Tg C per month, peakeding in March at 14.9 Tg C per month, whereas Dduring the warm season, NPP averaged 5.5 Tg C per month, with a it reached a minimum in August (4.4 Tg C per month^{-1}) (Fig. 4aA). HPZ coverage increased from 34 to 71 % (mean 54 %) in cold season winter but declined to 19 % in warm seasonsummer, reaching ~8 % in July–August (Fig. 3c3C, 4a4A). LPZ covered 8–20 % (~10 %) in cold season winter and expanded to 49 % in warm season summer, peaking ~66 % in July–August. MPZ accounted for ~34 % annually (Fig. 3b3B, 4a4A).

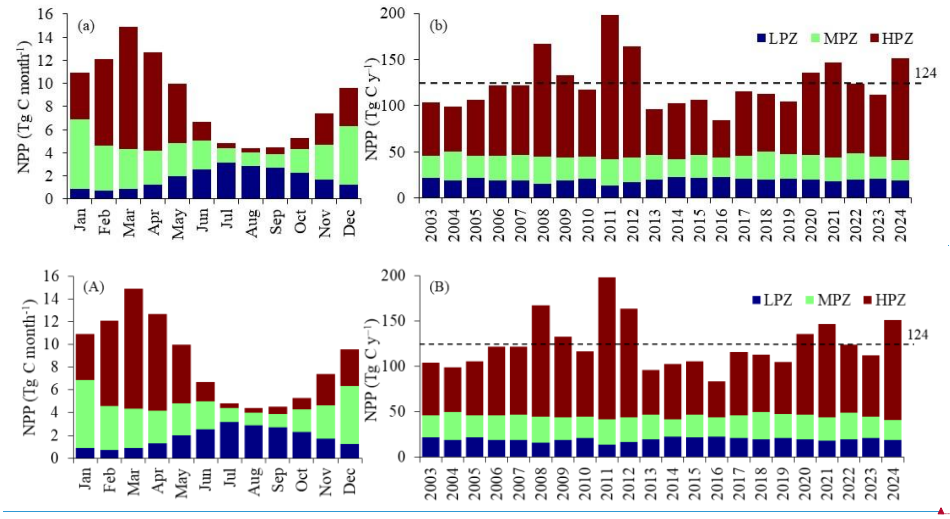


Figure 4. (aA) Monthly mean NPP (bars) for January 2003–December 2024, showing class contribution (%) as stacked bars and total NPP (Tg C per month^{-1}), (bB) mean annual NPP (Tg C y^{-1}) per zone for 2003–2024. The dashed line denotes time series mean.

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NPP per year per productivity zone~~Annual, zone-integrated NPP~~ ranged from 84 to 198 Tg C y^{-1} (mean of 124 ± 27.3 Tg C y^{-1}) (Fig. 4~~B~~b). Contributions over the entire period were HPZ = 61.4 %, MPZ = 21.6 %, and LPZ = 16.9 % (Fig. 4~~B~~b). During 2003–2012 (predominantly negative SSTa), HPZ contributed 63.9 %~~.~~, MPZ = 20.9 %, and LPZ = 15.1 %. During 2013–2024 (positive SSTa), LPZ increased to 18.4 %, while HPZ declined to 59.4 %, indicating a progressive reduction in HPZ extent, MPZ remained ~21.6 %. Years 2006–2012 exceeded the historical mean (124 ± 27.3 Tg C y^{-1}), with 2008, 2011, and 2012 being most productive (167, 198, and 164 Tg C y^{-1}, respectively). In those years, HPZ contributed ~78 % of NPP, while LPZ contributed 14–17 %. In contrast, the anomalously warm interval (2014–2016) recorded the lowest mean NPP (~101 Tg C y^{-1}), with LPZ contributing 21.8 % and HPZ declining to 54.7 % in 2016. MPZ exceeded 25 % of NPP in 2004, 2013, 2018, and 2021 (Fig. 4~~B~~b). The longest below-average period occurred during 2013–2019, followed by recovery in 2020–2024, only 2023 (111 Tg C y^{-1}) remained below the mean. Notably, 2024 ranked fourth (152 Tg C y^{-1}), after 2008, 2011, and 2012.

3.4 Spatial and interannual variability of primary productivity

The annual spatial distribution of the LPZ, MPZ and HPZ (Fig. 5~~4~~) exhibited distinct patterns closely tied to temperature regimes. Here, percentages refer to the spatial extent of each zone. During 2003–2012, when SSTa were predominantly negative, the LPZ was mostly located south of 26° N, covering on average 32.4 % of the gulf. In these years, HPZ was prominent in the upper gulf, the Midriff Archipelago, and along the continental coast, extending > 40 km offshore, and accounting for 33.3 % of the gulf~~the~~ area. In contrast, during 2013–2023, when SSTa were mostly positive, HPZ coverage decreased markedly in coastal areas and the upper gulf (< 26 % of the area), while MPZ expanded to ~33.9 %, occupying much of the basin. The most pronounced spatial ~~reorganization~~ reorganisation occurred during 2014–2016 warm anomaly, when LPZ increased to nearly 50 %, advanced north of 26° N and reached ~28° N in 2016. Years with widespread HPZ coverage (e.g., 2008, 2011, 2012, 2021 and 2024) coincided with positive NPP anomalies > 25 %, whereas~~,~~ 2013–2016 showed LPZ expansions >20 % (Fig. 5).

Seasonality was most pronounced in the cold season~~period~~ (December–May). On average, HPZ covered 44.2 % of the gulf, followed by MPZ (33.5 %) and LPZ (22.2 %). HPZ varied from 22.9 % (2016) to 63 % (2012), MPZ from 25.7 % (2010) ~~and~~ to 42.5 % (2013), and LPZ from 2 % (2021) to 44 % (2016). HPZ exceeded 50 % in 2008 (58 %), 2011 (61.4 %), 2012 (63 %), and 2021 (59.7 %), with LPZ nearly absent (< 10 %) in 2021. Conversely, HPZ fell below the historical average in 2014, reaching 22.9 % in 2016 and 42 % in 2017 (Fig. ~~S1~~A2).

During the warm season ~~period~~ (June–November), interannual variability was lower. LPZ dominated averaging 68.5 % (range 57.9–76.2 %~~), and~~) and shifting northward into the upper gulf. MPZ averaged 19.7 % (15.6–26.9 %), and HPZ averaged 11.7 % (7–22 %) concentrated near the Midriff Archipelago, Colorado River mouth, and along the continental coast,

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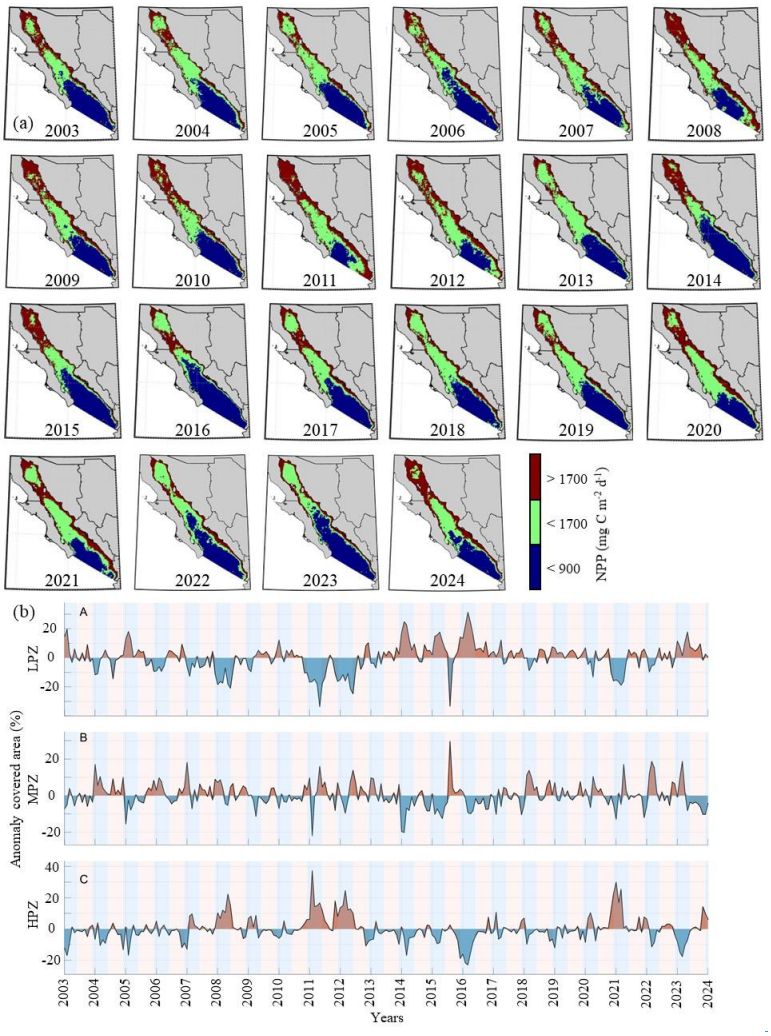
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with limited offshore extent (Fig. A~~S~~23). Additional latitude-time distributions of NPP and anomalies are shown in Figs. ~~S3-S4~~A4. A5.

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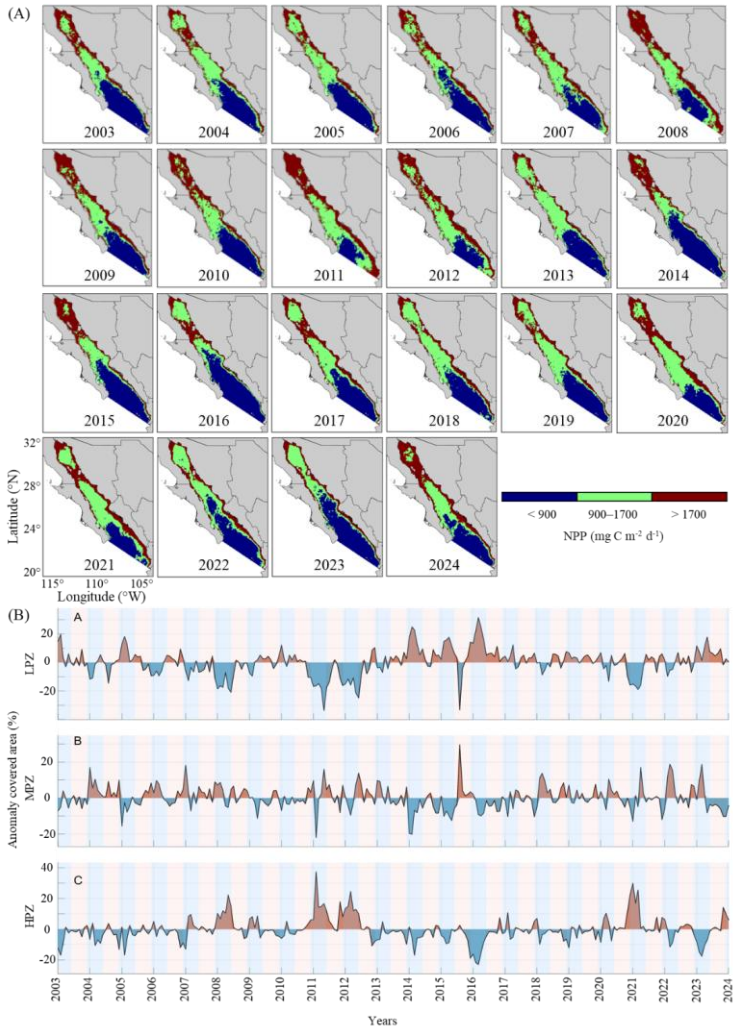


Figure 5: ~~.~~ (~~a~~A) ~~Annual~~ NPP annual maps showing low-productivity (LPZ), ~~high (HPZ),~~ mid productivity (MPZ), and high productivity (HPZ) ~~low (LPZ)~~ (variability during 2003–2024); (~~B~~b) anomalies in class coverage (%) through time for (A) low (LPZ), (B) mid (MPZ), and (C) high (HPZ). Cold (blue) represents a reduction in cover, and warm (red) represents an increase in cover relative to the historical average distribution.

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3.5 Responses of biophysical drivers (GLMM analysis)

Correlation analysis indicated strong collinearity between PO_4^{-3} and SiO_2 (r = 0.88; $p < 0.05$). PO_4^{-3} was retained in the model given its broader relevance to primary productivity, whereas SiO_2 primarily constrains siliceous phytoplankton, like diatoms. Best-fitting ~~g~~Generali~~s~~zed L~~l~~inear Mixed M~~m~~odels (GLMMs) for each NPP class identified the significant environmental drivers (Table 1). The model provided a good fit to the data (AIC = 1057.4, BIC = 1178.9, log-likelihood = −502.69). Month was included as a random intercept to account for temporal dependence among observations, yielding an estimated random-effect standard deviation of 0.504.

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Table 1~~: .~~. GLMM results for main effects of biophysical variables on NPP by productivity zone classification (LPZ, MPZ~~,~~ and HPZ). Coefficients $p < 0.05$ are in bold. Abbreviations: LPZ = ~~Low~~low-productivity zone; MPZ = ~~Mid~~mid-productivity zone; HPZ = ~~High~~high-productivity zone; ~~SST = sea surface temperature; EZD = euphotic zone depth,~~ MLD = mixed layer depth; NO_3 = nitrate concentration; PO_4^{-3} = phosphate concentration; UAR = along-gulf (*u*) sea current component; and URT = along-gulf (*u*) wind component; SI = stratification index, and SSS = sea surface salinity.

Productivity z~~Z~~one	**Environmental d~~D~~rivers**	**Estimate**	**Std. Error**	**t-ratio**	***p*-value**
LPZ	Intercept	0.124	0.168	0.737	0.461
	MLD	0.079	0.086	0.921	0.357
	NO_3	-1.841	0.261	-7.063	**3.7~~6~~5×10~~E~~$^{-12}$**
	PO_4^{-3}	-0.091	0.051	-1.772	0.077
	U~~RT~~RT	0.326	0.072	4.504	**7.7~~1~~×10~~E~~$^{-06}$**
	UAR	-0.061	0.050	-1.206	0.228
	SI	1.050	0.105	10.026	**2.6~~0~~×10~~E~~$^{-22}$**
	~~SAL~~SSS	-0.176	0.048	-3.682	**2.4~~7~~5×10~~E~~$^{-4}$**
MPZ	Intercept	0.484	0.089	5.465	**6.~~26~~3×10~~E~~$^{-08}$**
	MLD	0.081	0.094	0.862	0.389
	NO_3	1.926	0.266	7.247	**1.04×10~~E~~$^{-12}$**
	PO_4^{-3}	0.097	0.060	1.620	0.106
	U~~RT~~RT	-0.122	0.090	-1.357	0.175
	UAR	0.033	0.063	0.524	0.600
	SI	-1.116	0.110	-10.109	**1.2~~3~~×10~~E~~$^{-22}$**
	~~SAL~~SSS	0.196	0.055	3.555	**4.0~~1~~×10~~E~~$^{-4}$**
HPZ	Intercept	1.307	0.090	14.502	**2.7~~3~~×10~~E~~$^{-42}$**
	MLD	-0.059	0.106	-0.558	0.577
	NO_3	2.008	0.260	7.720	**3.7~~6~~5×10~~E~~$^{-14}$**
	PO_4^{-3}	0.294	0.057	5.109	**4.1~~0~~9×10~~E~~$^{-07}$**
	U~~RT~~RT	-0.336	0.094	-3.572	**3.8~~7~~6×10~~E~~$^{-4}$**
	UAR	-0.048	0.056	-0.855	0.393
	SI	-1.117	0.105	-10.645	**9.0~~1~~×10~~E~~$^{-25}$**
	~~SAL~~SSS	0.182	0.054	3.370	**~~0.000~~7.~~88~~9×10^{-4}**

Zone	Drivers	Estimate	Std. Error	t ratio	p-value
LPZ	Intercept	-0.527	0.134	-3.936	**8.67E-05**
	SST	0.124	0.065	1.908	**0.057**
	EZD	-0.030	0.086	-0.349	0.727
	MLD	0.021	0.074	0.291	0.771
	NO_3	-0.006	0.226	-0.028	0.977
	PO_4	-0.009	0.043	-0.212	0.832
	UAR	-0.035	1.775	-0.019	0.984
	URT	0.032	0.039	0.812	0.417
	SI	0.242	0.392	0.618	0.536
MPZ	Intercept	0.173	0.149	1.158	0.247
	SST	-0.338	0.094	-3.606	**3.21E-04**
	EZD	-0.023	0.153	-0.147	0.883
	MLD	0.052	0.084	0.617	0.537
	NO_3	0.027	0.232	0.117	0.907
	PO_4	0.014	0.050	0.276	0.783
	UAR	0.000	2.213	0.000	1.000
	URT	-0.011	0.059	-0.194	0.846
	SI	-0.127	0.455	-0.280	0.780
HPZ	Intercept	-0.146	0.208	-0.702	0.483
	SST	-1.189	0.079	-15.092	**3.88E-48**
	EZD	0.775	0.152	5.107	**3.68E-07**
	MLD	-0.453	0.093	-4.885	**1.14E-06**
	NO_3	0.285	0.226	1.258	0.208
	PO_4	0.192	0.048	3.985	**7.06E-05**
	UAR	2.177	1.980	1.100	0.272
	URT	-0.069	0.063	-1.095	0.274

The stratification index (SI), sea surface salinity (SALSSS), and nitrate (NO_3) were significant predictors of NPP across the three productivity zones, although their effects differed in both magnitude and direction (Table 1). In the LPZ, SI was positively associated with NPP ($\beta = 1.050$, $p < 0.001$), whereas salinity ($\beta = -0.176$, $p < 0.001$) and nitrate ($\beta = -1.841$, $p < 0.001$) showed significant negative relationships. In contrast, both the MPZ and HPZ exhibited the opposite pattern. SI was negatively associated with NPP (MPZ: $\beta = -1.116$; HPZ: $\beta = -1.117$; $p < 0.001$), whereas salinity (MPZ: $\beta = 0.196$; HPZ: $\beta = 0.182$; $p < 0.001$) and nitrate (MPZ: $\beta = 1.926$; HPZ: $\beta = 2.008$; $p < 0.001$) were positively associated with productivity. The effect of URTT also varied among productivity zones. URTT was positively associated with NPP in the LPZ ($\beta = 0.326$, $p < 0.001$), whereas a significant negative relationship was observed in the HPZ ($\beta = -0.336$, $p < 0.001$). In contrast, URTT was not a significant predictor in the MPZ. Phosphate (PO_4^{-3}) was significant only in the HPZ, where it exhibited a positive association with NPP ($\beta = 0.294$, $p < 0.001$).

Sea surface temperature (SST) was the dominant predictor across zones. In LPZ the SST coefficient was positive but marginally not significant at $\alpha = 0.05$ ($\beta = 0.124$, $p = 0.057$). In MPZ and HPZ, SST had significant negative effects (MPZ: $\beta = -0.338$, and HPZ: $\beta = -1.189$, $p < 0.01$). In HPZ, NPP increased with greater EZD ($\beta = 0.775$, $p < 0.01$) and higher PO_4 (β

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~~= 0.192, $p < 0.01$), but decreased with a deeper MLD (β = −0.453, $p < 0.01$). NO_3, sea current and wind components (UAR, URT), and SI showed no significant effects in any zone at α = 0.05.~~ These results underscore strong regional differences in environmental controls on NPP across the Gulf of California. The complete anomaly time series for all variables (2003–2024) is provided in supplementary material (Figs. ~~S~~A4~~-S11~~A~~S~~9, Table A1).

4 Discussion

Monitoring net primary productivity (NPP) in the Gulf of California is essential for assessing the impacts of climate variability and anthropogenic pressures, and their ecological and socioeconomic consequences. NPP underpins fisheries, mediates carbon cycling, and contributes to ecosystem resilience, making it a key indicator of ocean health. Despite its importance, long-term NPP records, both in situ and satellite-derived, remain scarce, constraining assessments of variability from seasonal to interannual scales.

The Gulf of California's spatial organi~~s~~zation has been analy~~s~~zed through various regionalization schemes, evolving from early classifications using biological indicators and physical properties to more complex schemes leveraging satellite observations. Initial frameworks identified regions based on phytoplankton (Round, 1967; Zeitz~~s~~chel, 1969), thermohaline structures (Roden and Emilsson, 1979) and bathymetry (Merrifield and Winant, 1989), while later methods introduced detailed classifications based on photosynthetic pigments (Santamaría-del-Ángel et al., 1994) and multivariate variables and machine-learning techniques (Santamaría-del-Ángel et al., 1994; Kahru et al., 2004; Petatán-Ramírez, 2015; Heras-Sánchez et al., 2019; Marín-Enríquez et al., 2024). Recent approaches exhibit increased complexity, ranging from simplified divisions to schemes with up to 22 regions. Nonetheless, effective regionali~~s~~zation should prioritize parsimony and mechanistic understanding to maintain interpretability and enhance insights into productivity controls.

~~The spatial organization of the Gulf of California has been described using diverse regionalization schemes reflecting different criteria. Early classifications relied on biological indicators (e.g., phytoplankton assemblages in sediments (Round, 1967; Zeitzchel, 1969), or on physical properties, including the vertical thermohaline structure (Roden and Emilsson, 1979) and bathymetry (Merrifield and Winant, 1989). With the advent of satellite observations, more detailed schemes emerged, notably the 14-region classification based on photosynthetic pigments (Santamaría-del-Ángel et al., 1994). Recent approaches have increased regional complexity by incorporating multivariate physical-chemical variables and machine-learning techniques ranging from simplified latitudinal divisions (north, central, south, and mouth) to 12–22 region schemes (Santamaría-del-Ángel et al., 1994; Kahru et al., 2004; Petatán-Ramírez, 2015; Heras-Sánchez et al., 2019; Marín-Enríquez et al., 2024). Many relying on satellite chlorophyll-*a*, bathymetry (Lavín and Marinone, 2003), or multivariate environmental datasets. However, regionalization should follow the principle of parsimony, excessive subdivision without a mechanistic basis diminished interpretability. Process-based frameworks that clarify controls on productivity are therefore preferable.~~

We utili~~s~~zed the K-means^{++} algorithm with k-means++ initialisation for its probabilistic centroid selection, enhancing accuracy and convergence in classifying meteorological, hydrographic (Kapoor et al., 2017; Zhang et al., 2025; Zhang and Qian, 2025)

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and primary productivity (NPP) patterns in the Gulf of California. We stablished three NPP categories~~We applied the K-means++ algorithm because this unsupervised method optimizes initial centroid selection probabilistically, improving accuracy, reducing iterations, and enhancing convergence stability (Kapoor et al., 2017; Zhang et al., 2025). This approach is effective for classifying meteorological and hydrographic patterns (Zhang and Qian, 2025) and primary productivity in the Gulf of California. Our regions align with previous classifications and identify areas and periods of high, medium and low NPP. We defined three NPP categories~~: HPZ (> 1700 mg C m^{-2} d^{-1}), MPZ (900–1700 mg C m^{-2} d^{-1}), and LPZ (< 900 mg C m^{-2} d^{-1}). While HPZ covers~~areas occupy~~ ~30 %~~ of the gulf area but~~ and contribute ~61.4 % of total NPP, ~~while~~ LPZ covers ~36 % and ~~yet~~ accounts for only ~16.9 %. These findings align with previous studies indicating a latitudinal gradient in productivity linked to factors such as upwelling and tidal currents, especially in areas with strong mixing along the eastern coast and Midriff Archipelago (Valdez-Holguín and Lara-Lara, 1987; Gaxiola-Castro et al., 1995).~~This latitudinal gradient is consistent with Gaxiola-Castro et al. (1995), who reported averages of 2.94 (1.98–4.17) g C m^{-2} d^{-1} in the southern gulf to 1.70 (0.64–4.57) g C m^{-2} d^{-1} and the Midriff Archipelago. Similarly, Valdez-Holguín and Lara-Lara (1987) reported 1.51–3.12 g C m^{-2} d^{-1} for central and northern regions.~~

HPZ regions are found along the eastern coast, the Midriff Archipelago, and the upper gulf, characteri~~s~~z~~z~~ed by strong mixing and upwelling (Mercado-Santana et al., 2017), particularly during winter when ~~northwesterly~~north-westerly winds influence the coasts of Sonora, Sinaloa, and Nayarit (Santamaría-del-Ángel et al., 1994; Mercado-Santana et al., 2017). MPZ contributes ~21% of total NPP with moderate conditions (SST ~25 °C, salinity ~35 ups, and a mixed layer depth ~24 m), influenced by various water types that enhance productivity through complex interactions of mesoscale (Lavín and Marinone, 2003; Lavín et al., 2013). In contrast, LPZ is the most oligotrophic area of the southern gulf, with historically low NPP, largely due to eastern Pacific influences and warm, low-salinity waters that increase stratification and limit nutrient availability, further complicated by thermohaline structures and mesoscale dynamics (Mercado-Santana et al., 2017; Marín-Enríquez et al., 2024; Trasviña-Castro et al., 2024).

~~HPZ typically occur along the eastern continental coast, in the Midriff Archipelago, and in the upper gulf, where strong mixing and persistence upwelling prevail (Mercado-Santana et al., 2017). In the northwest, tidal currents generate jets and cyclonic eddies that further sustains high productivity (Marín-Enríquez et al., 2024). Seasonal upwelling driven by northwesterly winds along the Sonora, Sinaloa, and Nayarit coast during winter reinforces these patterns (Santamaría-del-Ángel et al., 1994; Mercado-Santana et al., 2017).~~

~~MPZ contributes ~21% of total NPP and exhibit intermediate conditions (SST ~25 °C, salinity ~35 ups, and a mixed layer depth ~24 m), with relatively high water-column stability (Marín-Enríquez et al., 2024). This region is influenced by the convergence of Subtropical Subsurface Water (SSW), Tropical Surface Water (TSW), and Gulf of California Water (GCW), which generates fronts, eddies, and mesoscale processes that modulate productivity (Lavín and Marinone, 2003; Lavín et al., 2013).~~

~~LPZ corresponds to the most oligotrophic southern gulf, including the Baja California Sur coast, the gulf's mouth, and areas between the continental coast and the Pescadero Basin. Historically, this region shows low NPP (0.002–0.95 g C m^{-2} d^{-1})~~

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~~(Zeitzchel, 1969; Escalante et al., 2013) due to the influence of the eastern Pacific and the intrusion of warm, low-salinity tropical waters, which intensify stratification and limit nutrient flux to the euphotic zone (Lavín and Marinone, 2003; Mercado-Santana et al., 2017; Marín-Enríquez et al., 2024). The complex thermohaline structure shaped by GCW, TSW, and California Current Water (CCW), together with mesoscale dynamics (eddies, fronts), further constrain productivity (Lavín and Marinone, 2003; Portela et al., 2016; Marín-Enríquez et al., 2024; Trasviña-Castro et al., 2024).~~

The GLMM analysis revealed that the environmental controls on NPP vary markedly among productivity regimes, highlighting the spatial heterogeneity of the mechanisms regulating phytoplankton production across the Gulf of California. Despite these regional differences, NO_3 availability and water-column stratification (SI) consistently emerged as the dominant predictors of NPP. The HPZ and MPZ exhibited the strongest dependence on nutrient availability, with NO_3 representing the most influential positive predictor in both zones, whereas PO_4^{-3} contributed significantly only within the HPZ. In constrast, increasing stratification (SI) exerted a strong negative effect in both zones, indicating that enhanced water-column stability limits the upward transport of nutrients into the euphotic layer. These results are consistent with the hydrographic dynamics of the upper gulf, the Midriff islands region, and eastern continental coast, where seasonal cooling, wind-driven mixing, and tidal processes enhance the upward transport of nutrients and sustain high rates of primary production (Santamaría-del-Ángel et al., 1994; Mercado-Santana et al., 2017; Marín-Enríquez et al., 2024). The MPZ appears to represent a transitional environment where biological production is primarily regulated by nutrient supply, and where stronger stratification restricts the vertical nutrient transport into the euphotic zone (Marín-Enríquez et al., 2024). Although nitrogen is widely recognised as the principal limiting nutrient in the Gulf of California (Álvarez-Borrego, 2012), our results indicate that PO_4^{-3} availability also ~~plays a~~ significantly affects NPP within the HPZ. This pattern is consistent with observations from the Guaymas Basin, where intense summer stratification restricts nutrient fluxes, promoting nitrogen limitation and ~~favoring~~favouring picophytoplankton-dominated communities (Millán-Núñez et al., 2023; Martínez-López et al., 2023). In contrast, the LPZ, influenced by oligotrophic, highly stratified waters entering from the Pacific Ocean, remains persistently low in productivity and is typically dominated by picophytoplankton. Consequently, the LPZ maintains relatively low but persistent productivity, whereas the MPZ exhibits greater seasonal variability associated with winter mixing and episodic nutrient enrichment.

~~3.3 The GLMM analysis identified SST as the most influential variable controlling NPP in the Gulf of California, consistent with the inverse relationship between annual NPP and SST, maximum productivity in the cold season and minima in the warm season (Hakspiel-Segura et al., 2022). In HPZ, NPP was additionally modulated by EZD, MLD and PO_4 concentrations. As expected for a biogeochemical hindcast, MLD strongly covary with nutrient availability (NO_3 and PO_4). These drivers are particularly relevant in the upper gulf, Midriff Archipelago, and along the eastern continental coast, where bathymetry, tidal currents, and strong winter northwesterly winds promote intense mixing and persistent upwelling that sustaining productivity (Santamaría-del-Ángel et al., 1994; Mercado-Santana et al., 2017; Marín-Enríquez et al., 2024).~~

~~Although Álvarez-Borrego (2012) emphasized nitrogen as the primary limiting nutrient in the gulf, our results indicate that phosphate availability also plays a significant role in regulating NPP, despite its lower stoichiometric demand. Millán-Núñez~~

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~~et al. (2023) documented that summer stratification in the Guaymas Basin severely restrict vertical nutrient fluxes, creating nitrogen-limited conditions ($NO_3 + NO_2$) and reducing surface Chl-*a*. These hydrographic conditions favors picophytoplankton dominance due their higher surface-area-to volume ratios under oligotrophic conditions (Millán-Núñez et al., 2023; Martínez-López et al., 2023). Browning et al. (2023) further noted frequent N-P co-limitation in sub-tropical environments, including the eastern North Pacific subtropical gyre and the entrance and southern Gulf of California. Accordingly, LPZ, influenced by oligotrophic, stratified Pacific waters, remains persistently low in productivity and can dominated by picophytoplankton, whereas MPZ shows greater variability, particularly in winter, when nutrient enrichment enhances NPP.~~

At the seasonal scale, NPP peaks in cold season~~winter~~ (December–May), with maxima in February–March (Fig. A2). This increase is driven by prevailing ~~northwesterly~~north-westerly winds and cooling that enhance upwelling along the eastern gulf coast, enriching the euphotic zone and stimulating phytoplankton growth (Santamaría-del-Ángel et al., 1994; Escalante et al., 2013). During this period~~winter~~, HPZ and MPZ together typically cover ~77 % of the gulf~~'s~~. Hakspiel-Segura et al. (2022) reported a negative correlation of SST and meridional wind stress with surface Chl-*a* in the central gulf, reinforcing the role of wind-driven mixing.

Conversely, during the warm season (June–November), oligotrophic conditions dominate: NPP < 900 mg C m^{-2} d^{-1} covers ~68 % of the basin due to weaker southeasterly winds, the intrusion of warm tropical waters, and strong stratification that limits nutrient supply (Fig. A3–A8) (Lavín and Marinone, 2003; Escalante et al., 2013; Mercado-Santana et al., 2017; Trasviña-Castro et al., 2024).

The 2003–2024 NPP time series exhibited significant interannual variability. Spearman's rank correlation analyses indicated that neither the PDO nor the NPGO was significantly associated with the extent of any productivity zone (Table A1). In contrast, MEI.v2 showed a weak but statistically significant negative correlation with the extent of the HPZ ($rs_{[264]}$: −0.136, p_{sCorr} = 0.027), suggesting that ENSO-related variability exerts a measurable, although limited, influence on regional productivity patterns. Consistent with this relationship, La Niña conditions were generally associated with lower SST, intensified ~~northwesterly~~north-westerly winds, a deeper mixed layer, and enhanced nutrient availability (NO_3, PO_4^{-3} and SiO_2) within the euphotic zone, conditions that favour elevated NPP. During the La Niña events of 2008, 2011, 2012, and 2021, the HPZ contributed more than 70% of the total gulf-wide NPP while occupying only 35–44% of the gulf area. This response was most pronounced during the cold season, when the HPZ and MPZ together occupied approximately 95% of the Gulf of California, confining the LPZ primarily to the southern entrance of the basin (Fig. A~~3~~2).

~~The 2003–2024 NPP time series exhibits pronounced interannual variability. A significant negative correlation was found between the MEI.v2 and the HPZ coverage ($rs_{[264]}$: −0.21; $p < 0.05$). Negative MEI.v2 anomalies during 2006–2009, 2010–2012, and 2020–2022, corresponding to La Niña conditions characterized by lower SST, intensified northwesterly winds, and a deeper mixing layer that enhances nutrient concentrations (NO_3, PO_4 and SiO_2) in the euphotic zone and increased NPP. In 2008, 2011, 2012 and 2021, moderate to strong La Niña phases, HPZ contributed > 70 % of total NPP with 35–44 % areal~~

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~~coverage. Seasonal was most evident in winter, when HPZ and MPZ together covered ~95 % of the gulf, displacing LPZ to the mouth (Fig. S1).~~

Stratification index (SI) analysis indicated varying productivity regimes (Fig. A9~~8~~S13): HPZ had low SI (0–0.5 kg m^{-3}) due to mixing processes (upwelling, tidal forcing, and ~~northwesterly~~north-westerly winds), while LPZ exhibited high SI (up to ~2.0 kg m^{-3}), indicating strongly stratified waters. MPZ showed an intermediate SI (0.5–1.1 kg m^{-3}). Notably, from mid–2013, warming trends led to increased stratification, reduced nutrient concentrations (NO_3, PO_4^{-3}), and negative anomalies in NPP (Figs. A5~~–~~–A9). This pattern mirrors global trends of warming-driv~~in~~gen stratification documented in the North Atlantic, North Pacific, and elsewhere (Xie et al., 2019; Fischer et al., 2020; Honda, 2020), with cascading effects on hydrography, primary productivity, phytoplankton functional composition, and coastal carbon fluxes (Xie et al., 2019; Fischer et al., 2020; Honda, 2020; Hakspiel-Segura et al., 2022; Song et al., 2022)

~~Consistent with this physical mechanism, the stratification index (SI) revealed distinct regimes by productivity class (Fig. S13): HPZ showed persistently low SI (0–0.5 kg m^{-3}), indicative of well-mixed conditions maintained by upwelling, tidal forcing, and winter wind-driven mixing. LPZ displayed the highest SI (up to ~2.0 kg m^{-3}), characteristic of strongly stratified oligotrophic waters. MPZ showed intermediate, variable SI (0.5–1.1 kg m^{-3}), reflecting its transitional nature. This mechanistic link was especially evident from mid-2013 onward, when positive SST anomalies, increased stratification, and reduced nutrient concentration (NO_3, PO_4) triggered persistent negative NPP anomalies and shifted pelagic habitat toward warm, oligotrophic conditions (Fig. S4-S8). This pattern mirrors global trends of warming-driving stratification documented in the North Atlantic, North Pacific, and elsewhere (Xie et al., 2019; Fischer et al., 2020; Honda, 2020), with cascading effect on hydrography, primary productivity, phytoplankton functional composition, and coastal carbon fluxes (Xie et al., 2019; Fischer et al., 2020; Honda, 2020; Hakspiel-Segura et al., 2022; Song et al., 2022).~~

The 2014–2016 period marked a significant decline in Net Primary Production (NPP) in the Gulf of California, characteri~~z~~sed by severe negative anomalies. This period was associated with strong atmospheric forcing related to ENSO (MEI.-v2) and coincided with a positive phase of the PDO, a transition toward a negative NPGO, and widespread marine heatwaves. Together, these large-scale climate conditions have been previously linked to changes in the physical and biogeochemical structure of the Gulf of California (Hakspiel-Segura et al., 2022). ~~The 2014–2016 period marked a significant decline in Net Primary Production (NPP) variability in the Gulf of California, characterized by severe negative anomalies. This decline stemmed from high-frequency atmospheric influences (MEI v2), low-frequency climate shifts (a positive PDO and a negative NPGO transition), and concurrent marine heatwaves, which adversely affected the physical and biogeochemical structure of the system, consistent with Hakspiel-Segura et al. (2022).~~ The persistent increase in SST during this period diminished cold season HPZ coverage to below 5% and expanded the LPZ to approximately 50% of the gulf. SST anomalies exceeding +2 °C led to intensified thermal stratification and limited nutrient transport into the euphotic zone, notably impacting HPZ and MPZ relying on vertical mixing and coastal upwelling (Di Lorenzo and Mantua, 2016; Hakspiel-Segura et al., 2022). Stratification increased significantly, reaching oligotrophic conditions, and caused diminished nutrient flux, correlating with declines in PO_4 and a reduction in productive habitats.

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~~The 2014–2016 period represents a tipping point for NPP variability in the Gulf of California, encompassing the most intense negative anomalies of the record. Unlike shorter warm events, this episode arose from the concurrence of high-frequency atmospheric forcing (MEI v2), low-frequency climate modes (a positive PDO and transition to a negative NPGO), and simultaneous marine heatwaves, which together amplified impacts on the system's physical and biogeochemical structure, consistent with Hakspiel-Segura et al. (2022). The persistent SST increase during 2014–2016 was the primary negative control on NPP, reducing winter HPZ coverage to < 5 %, and expanding LPZ to ~50 % of the gulf. SST anomalies > +2 °C intensified thermal stratification, shoaled the mixed layer, and limited nutrient transport into the euphotic zone. These effects were most evident in HPZ and MPZ, where productivity typically depends on vertical mixing, coastal upwelling, and tidal forcing (Di Lorenzo and Mantua, 2016; Hakspiel-Segura et al., 2022). SI confirmed a basin-wide intensification of stratification during this period (Fig. S13) increasing by ~60–80 % relative to its long-term mean, reaching values typically of oligotrophic conditions (>1.5 kg m^{-3}) and rendering MPZ "LPZ-like" in physical structure. Even HPZ showed enhanced stratification, though It remained within mixing-favorable values. This pervasive increase in stratification, specially the "oligotrophication" of MPZ, created a widespread barrier to vertical nutrient flux, directly explaining the observed PO_4 declines and contraction of productive habitat.~~

A key mechanism affecting the marine ecosystem between 2014 and 2016 was the weakening of ~~northwesterly~~north-westerly winds (~8 m s^{-1} versus climatological values >20 m s^{-1}), which reduced wind speed and coastal upwelling efficiency. This led to a shift in seasonal productivity maximum and a decline in HPZ coverage. Concurrently, Tropical Surface Water intrusion reinforced stratification and limited mesoscale activity, particularly in the southern gulf and at the mouth (Di Lorenzo et al., 2008~~;~~, 2013; Di Lorenzo and Mantua, 2016), resulting in the lowest NPP recorded, with both HPZ and MPZ declining by about 7%, and areal coverages below historical averages. The HPZ remained only in the upper gulf~~A~~, while the MPZ shifted north, and the LPZ expanded ~~by~~to ~26~~ to~~27° N (Fig. ~~S~~A3). Additionally, nutrient records indicated a significant decline in phosphate concentrations, suggesting a N-P co-limitation and highlighting phosphorus's critical role during extreme warm events (Browning et al., 2023).

~~A second key mechanism was the weakening of northwesterly winds during the winters of 2014–2016. Reduced wind stress (~8 m s^{-1} versus climatological values >20 m s^{-1}) diminished the efficiency of coastal upwelling along the eastern margin attenuating the characteristic winter fertilization, shifting the seasonal productivity maximum, and reducing HPZ coverage in 2015–2016. Concurrently, the intrusion of Tropical Surface Water reinforced the stratification and limited mesoscale activity, particularly in the southern gulf and at the mouth (Di Lorenzo et al. 2008; 2013; Di Lorenzo and Mantua, 2016). This period recorded the lowest NPP of the series, with HPZ and MPZ contribution each declining by ~7 % and areal coverages 5–10 % below historical averages. HPZ persisted only in the upper gulf (Fig. S3), MPZ shifted northward, and LPZ expanded by ~6 to 27° N (Fig. S2). The combined influence of warm, low salinity, and nutrient poor waters further restricted vertical exchange and sustained low productivity conditions (Di Lorenzo et al. 2008; 2013; Di Lorenzo and Mantua, 2016). The nutrient record indicates that the 2014–2016 NPP reduction was not purely thermal. PO_4 concentrations decline markedly~~

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~~within the upper 100 m (Fig. S11), especially in HPZ and MPZ, suggesting a N-P co-limitation and underscoring a more prominent role for phosphorus during extreme warm events than traditionally assumed (Browning et al. 2023).~~

Long-term trends derived from this study indicate declining NPP of 50–100 mg C m^{-2} d^{-1} per year in the upper gulf, in La Paz Bay, and in front of~~along Sonora and~~ Nayarit coasts (Fig. ~~S12~~A3), while values at the mouth and near ~28° N remained relatively stable. These patterns are consistent with global trends~~This mirrors global patterns~~ reported by Maishal (2024a,b), who documented ~25 mg C m^{-3} d^{-1} per decade decreases in the Pacific associated with warming of 0.1–0.2 °C per decade, rates slightly lower than those reported for the Gulf of California (0.38 and 0.57 °C per decade; Hakspiel et al., 2022; Sánchez-Cabeza et al., 2022). Maishal (2024a) also noted concurrent decreases in density, salinity, wind stress, MLD, and nutrients (NO_3, PO_4~~$^{-3}$~~) during the past ~~2~~ two decades, in agreement with our findings. Despite this, NPP rebounded strongly after the prolonged low-productivity phase of 2013–2019: 2020–2024 showed recovery, and although 2023, the warmest oceanic year on record (Cheng et al., 2024), did not yield the lowest NPP (that occurred in 2016, 85 Tg C y^{-1}), 2024 ranked fourth (152 Tg C y^{-1}), suggesting resilience potentially linked to the negative PDO that began in late 2019.

Globally, inverse relationship between NPP, Chl-*a* and ocean warming are well documented, along with strong coupling between NPP and climate variability (Behrenfeld et al., 2006; Xie et al., 2019; Fischer et al., 2020; Honda, 2020). Positive phases of climate indices such as MEI.~~-~~v2 and PDO exert negative ~~feedbacks~~feedback on NPP via warm-water intrusion, enhanced stratification, and oligotrophication that alter pressure ~~centers~~centres and wind regimes, reducing upwelling and nutrient supply.

This study advances understanding of regional and phenological mechanisms affecting NPP in the Gulf of California, primarily mediated by SST and its associated processes. The integration of long-term environmental dataset demonstrated the utility of satellite-based and modelled observations for tracking NPP variability. Our parsimonious ~~classification~~ three-zone classification (LPZ~~HPZ~~, MPZ, and HPZ~~-LPZ~~) captures spatial and temporal heterogeneity efficiently. Further research should elucidate the drivers of the LPZ expansion observed over the past decade and its implications for ecosystem structure and fisheries in the Gulf of California.

5 Conclusions

The average total NPP in the Gulf of California during 2003–2024 was 124 Tg C ~~m^{-2}~~ y^{-1}. ~~Classifying~~ Classification of the Gulf of California into three NPP categories with the k-means^{++} algorithm provided an effective, parsimonious framework for explaining spatial and temporal variability. HPZ conditions predominated along the continental coast and in the Midriff Archipelago, contributing 61.4 % of total NPP while covering ~~~~approximately 30 % of the ~~gulf~~Gulf~~'s~~ area. In contrast, LPZ conditions dominated the oceanic region and the entrance to the G~~g~~ulf~~'s entrance~~, covering approximately ~~~~36 % of the area and contributing 16.9 % of total NPP.

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The ~~2014–2016 period showed that the~~ decline in NPP in the Gulf of California during 2014–2016 resulted~~arouse~~ from the non-linear ~~coupling c~~interaction ~~of surface warming (~~El Niño-related surface warming~~)~~, weakened wind forcing, tropical-water intrusion, ~~intensified~~ enhanced thermal stratification, reduced nutrient ~~supply~~availability, and concurrent marine heatwaves. This coupling explains both the magnitude of the productivity ~~collapse~~ decline and the unprecedented expansion of oligotrophic conditions observed during these years.

Seasonal variability was also pronounced: ~~The~~ the cold season ~~(~~, from December to May~~,)~~ accounted for 68 % of annual NPP, whereas the warm season ~~(~~, from June – to November~~),~~ contributed 32 %.

The GLMM results indicate that NO_3 and water-column stratification (SI) ~~SST was~~ were the dominant predictors of NPP overall. In the HPZ, NPP was additionally modulated by the along-gulf ~~wind speed~~, the salinity~~EZD, MLD~~, and the PO_4^{3-} concentrations. Warmer years were associated with reduced coverage of productive zones ~~(~~, including MPZ and HPZ ~~and MPZ,)~~ and with the expansion of oligotrophic LPZ areas.

If regional warming and stratification trends persist, oligotrophic conditions and low productivity are likely to intensify, potentially extending the ~~LPZ~~ influence of LPZ further into the ~~gulf~~Gulf of California. These changes ~~could~~ may have ~~significant~~ important ecological and socioeconomic implications, underscoring the need for continued monitoring and research to anticipate, understand, and mitigate the impacts of climate variability on phytoplankton marine net primary productivity.

Data availability. The datasets supporting the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.18776942.

Appendix A: Supplementary material.

Author ~~Contributions~~contributions. Conceptuali~~z~~sation: EGR, RCD; Data curation: EGR; Formal analysis: EGR, RCD, JDAA; Investigation: EGR, RCD; Methodology: EGR, JDAA; Project administration: EGR, RCD, JGG; Supervision: EGR, RCD, JDAA, JGG; Validation: RCD; ~~Visualization~~Visualisation: EGR, JDAA; Writing –original draft: EGR, RCD, JDAA; Writing – review ~~& amp;~~and editing: EGR, R~~F~~CD, JDAA, JGG.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Administration (NOAA) (https://psl.noaa.gov/enso/mei/) for satellite data set availability. We also thank MacTavish Scientific Editing for English translation services. EGR also thanks the SERVANT laboratory from CICESE UALP for their support.

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Con formato: Punto de tabulación: 3.54 cm, Izquierda + en 8 cm + 16 cm

Código de campo cambiado

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Con formato: Inglés (Reino Unido)

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Código de campo cambiado

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Con formato: Inglés (Reino Unido)

Código de campo cambiado

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Con formato: Inglés (Reino Unido)

Con formato: Izquierda, Sangría: Izquierda: 0 cm, Sangr francesa: 0.5 cm, Punto de tabulación: 0.5 cm, Izquierda No en 0 cm

Código de campo cambiado

Con formato: Inglés (Reino Unido)

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