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Research Article

Spatial distribution of nutrients and chlorophyll-*a* in the deep waters of the southern Gulf of Mexico and its relationship with hydrography during the summer season

Héctor Mauricio Alexander-Valdés[1], Elizabeth Durán-Campos[2], Ruth Luna-Soria[1] Adolfo Gracia[1] & Erik Coria-Monter[1]
[1]Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México
Ciudad de México, Mexico
[2]Escuela Nacional de Ciencias de la Tierra, Universidad Nacional Autónoma de México
Ciudad de México, Mexico
Corresponding author: Erik Coria-Monter (coria@cmarl.unam.mx)

ABSTRACT. Chlorophyll-*a* (Chl-*a*) is widely regarded as a proxy for phytoplankton biomass. In marine environments, the concentration of Chl-*a* and its vertical and horizontal distributions are closely linked to the water column hydrography and nutrient availability. This study aimed to assess the spatial distribution of Chl-*a* in the deep waters of the southern Gulf of Mexico and evaluate its relationship with hydrography and nutrient concentrations during the summer season. A multidisciplinary research cruise was conducted in August and September 2018 to collect high-resolution hydrographic data and water samples at various depths (surface, 10, 20, 50, 100, and 150 m). These samples were analyzed for nutrient content and Chl-*a* concentration. The results revealed significant horizontal and vertical variability. Notably, a low-temperature, high-density core was identified at 50 m depth, indicating the presence of a cyclonic eddy. Within this cold, dense core, nutrient levels increased, while Chl-*a* concentrations peaked at depths of 50 m and below. Principal Component Analysis confirmed that temperature and nutrients were the primary drivers of Chl-*a* concentrations, particularly at 50 m depth, and below. While previous research has explored Chl-*a* distribution in the southern Gulf of Mexico, few studies have used in situ observations to examine deeper regions. This study demonstrates how hydrographic conditions regulate nutrient and Chl-*a* dynamics in an area where deep-water sampling remains operationally and economically challenging.

Keywords: chlorophyll-*a*; horizontal distribution; vertical distribution; hydrography; nutrients; southern Gulf of Mexico

INTRODUCTION

Phytoplankton is a diverse group of microorganisms that plays a crucial role in marine ecosystems. Most of these organisms are photosynthetic, meaning they absorb significant amounts of atmospheric carbon dioxide (CO_2) and release substantial amounts of oxygen into the atmosphere (Reynolds 2006).

As the base of the marine food web, phytoplankton is essential for transferring carbon and energy, which sustains the functioning of the biological carbon pump (Nowicki et al. 2022). Furthermore, phytoplankton serves as a primary food source for many fish species, including several commercially important species that support various fisheries (Gittings et al. 2021), underscoring their ecological and economic significance.

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Chlorophyll-*a* (Chl-*a*) is a pigment present in all autotrophic phytoplankton. It is commonly used as an indicator of phytoplankton biomass and the overall health of these communities (Theodorou et al. 2025). Researchers usually quantify Chl-*a* using highly sensitive standard chemical analytical techniques. These methods allow for the assessment of both vertical and horizontal distribution patterns of phytoplankton across various global environments (Roy et al. 2011). These distribution patterns are closely associated with physical, chemical, and biological factors, including hydrodynamic processes at different scales that supply nutrients to the euphotic zone, thereby enhancing phytoplankton biomass. Such processes encompass internal waves, fronts, upwellings, and eddies (McGillicuddy 2016).

Current scientific evidence underscores the significant influence of hydrography and environmental conditions on the horizontal and vertical distribution of Chl-*a* in various interior seas. For instance, in the Gulf of Oman and the Persian Gulf, nutrient levels and Chl-*a* concentrations exhibit marked seasonal variations, closely linked to changes in hydrographic conditions, primarily driven by upwelling events (Ghaemi et al. 2021). In the Gulf of Guinea, the presence of cold, upwelled waters is a crucial factor in elevating Chl-*a* concentrations (Nieto & Mélin 2017). Furthermore, in the Gulf of Alaska, mesoscale eddies play a vital role in altering the hydrographic characteristics of the water column and nutrient levels, thereby promoting phytoplankton blooms and increasing Chl-*a* levels in the area (Crawford et al. 2005).

In the Gulf of Mexico, the largest interior sea in the northern region of the American continent, researchers have studied how environmental factors influence Chl-*a* concentrations, primarily using satellite observations. In coastal areas of the gulf, river discharges and wind-driven upwelling are the main factors affecting nutrient levels and Chl-*a* concentrations (Nababan et al. 2011). On the continental shelf, eddies play a crucial role in transporting both nutrients and Chl-*a* across different areas (Jones & Wiggert 2015). In the deeper areas of the gulf, satellite observations have not shown significant fluctuations in phytoplankton biomass across various climatic seasons (Li et al. 2022).

Research on nutrient and Chl-*a* variations based on *in situ* observations in the southern Gulf of Mexico is limited. Signoret et al. (2006a) examined the vertical distribution of Chl-*a* in continental shelf waters of the southern gulf using *in vivo* fluorescence data. They found a strong correlation between Chl-*a* values and several factors, including thermal gradients, light availability, freshwater plumes, and circulation patterns.

In waters deeper than 500 m, few studies are based on *in situ* observations. However, Chl-*a* concentrations in the region are closely linked to circulation patterns, particularly the presence of cyclonic eddies in the Bay of Campeche. This circulation leads to high Chl-*a* values that vary with depth, including a deep peak between 95 and 110 m, associated with the euphotic layer. Additionally, there are maximum peaks that correlate with the thermocline and the presence of thin layers (Signoret et al. 2006b). Moreover, it has been reported that phytoplankton smaller than 10 µm contribute more than 50% of the total Chl-*a* (Signoret et al. 1998). Recently, research has shown that mesoscale eddy circulation dynamics significantly impact picoplankton communities. These dynamics influence the aggregation, dispersal, and transport of these organisms within the euphotic zone (Linacre et al. 2024).

The vertical distribution of Chl-*a* in the Campeche Canyon has been studied, revealing two distinct distribution patterns. The first pattern shows a maximum peak associated with the thermocline, where diatoms and silicoflagellates are predominant. The second pattern features a peak at the limit of the euphotic layer, dominated by coccolithophorids (Durán-Campos et al. 2017). Recent research in the deep waters of the southern Gulf of Mexico has documented the presence of cyclonic eddies. These eddies significantly influence the vertical and horizontal distributions of nutrients and Chl-*a*, leading to a higher proportion of dinoflagellates than other groups. This phenomenon is attributed to specific hydrographic and chemical conditions (González-Fernández et al. 2025).

While previous studies have significantly advanced our understanding of how hydrography affects the vertical and horizontal distribution of Chl-*a*, comprehensive research remains limited, particularly in the gulf's deepest region. This gap is primarily due to logistical and resource constraints in conducting expeditions at these depths.

This study aims to enhance understanding of the deepest sections of the southern Gulf of Mexico by providing observational data on the vertical and horizontal distributions of Chl-*a* and by exploring its relationship with hydrographic conditions. We also include measurements of nutrient concentrations at various depths. We hypothesize that the distribution of Chl-*a*, both horizontally and vertically, is influenced by nutrient concentrations, which are affected by hydrodynamic processes, specifically cyclonic eddies. These findings contribute to a greater understanding of phytoplankton dynamics in the deepest waters of the Gulf of Mexico.

MATERIALS AND METHODS

Study area

The Gulf of Mexico is situated on the North American continent, spanning 18-30°N and 80-98°W. This large inland sea covers more than 1.5 million square kilometers and is shared by three countries: Mexico, Cuba, and the USA (González-Fernández et al. 2025) (Fig. 1).

The gulf features a highly variable bathymetry, characterized by an extensive continental shelf along both the Mexican and the USA coasts. It includes submarine canyons, escarpments, and abyssal plains that reach depths exceeding 3,500 m (Goff et al. 2016). Various hydrodynamic processes occur within the gulf across different spatial and temporal scales, including internal waves, upwellings, eddies, and the Loop Current (Durán-Campos et al. 2017). The Loop Current is a dynamic system that plays a crucial role in transporting energy and heat among the Caribbean Sea, the Gulf of Mexico, and the Atlantic Ocean (Morey et al. 2024).

Biologically, the gulf is home to numerous species of ecological significance, many of which are threatened or endangered. Additionally, it supports valuable fisheries that harvest a variety of fish species across the Gulf of Mexico's diverse ecosystems (Gracia et al. 2020, López-Cabello et al. 2025).

Sampling

A multidisciplinary research cruise, SOGOM-4, was conducted from August 29 to September 20, 2018, aboard the R/V Justo Sierra operated by the National Autonomous University of Mexico (UNAM, by its Spanish acronym). The cruise involved collecting high-resolution hydrographic data at 63 stations across the deep regions of the southern Gulf of Mexico (Fig. 1).

At each station, data were collected using a conductivity, temperature, depth (CTD) sonde (SeaBird 9 Plus) that had been manufacturer-calibrated before the cruise. The sonde was set to collect data at 24 Hz. The CTD was connected to an Oceanographic Rosette (General Oceanics) outfitted with 12 Niskin bottles (10 L capacity) designed to collect water samples at depths 10, 20, 50, 100, and 150 m, as well as at the surface.

After the CTD/Rosette system was retrieved on board, subsamples were taken for various analyses. For nutrient determination, 100 mL of water was collected and filtered through cellulose membranes (Merck Millipore, 0.22 and 0.45 µm) arranged in series. These subsamples were placed in polypropylene containers that had been thoroughly washed with an acid solution and then stored frozen at -20ºC until laboratory analysis.

To determine Chl-*a* levels, 2 L of water were filtered through GF/F membranes (Merck Millipore, 0.45 µm) using a stainless-steel filtration system with a vacuum pressure of less than 10 psi. After the filtration was completed, the membranes were placed in Eppendorf safe-lock tubes, covered with aluminum foil, and frozen in liquid nitrogen until laboratory analysis. Throughout the filtration process, low-light conditions were maintained to prevent sample degradation.

Laboratory analyses

All chemical analyses were performed immediately after the cruise. The concentrations of nitrate, nitrite, soluble reactive phosphorus (SRP), and soluble reactive silicon (SRSi) were measured using a flow injection Analysis system 300 equipped with a PerkinElmer Lambda 25 spectrophotometer. The procedures adhered to the protocols established by Grasshoff et al. (1983).

Chl-*a* concentrations were determined using fluorometric analysis with a Trilogy Laboratory Fluorometer (Turner Designs) equipped with a non-acidified module. To extract the pigment, 10 mL of 90% HPLC-grade acetone was utilized, and the samples were stored at 4°C for 24 h. Special precautions were taken during the readings to ensure the samples were analyzed in a low-light environment.

Data analyses

The data collected with the CTD were processed using the manufacturer's software (SBE Data Processing 7.26.7), with values averaged to one decibar. The data were used to construct conservative temperature–absolute salinity diagrams for water mass identification and to generate horizontal distribution maps of hydrographic variables. These maps, created using standard ArcGIS procedures, correspond to the specific depths at which discrete water samples were collected for nutrient and Chl-*a* analyses.

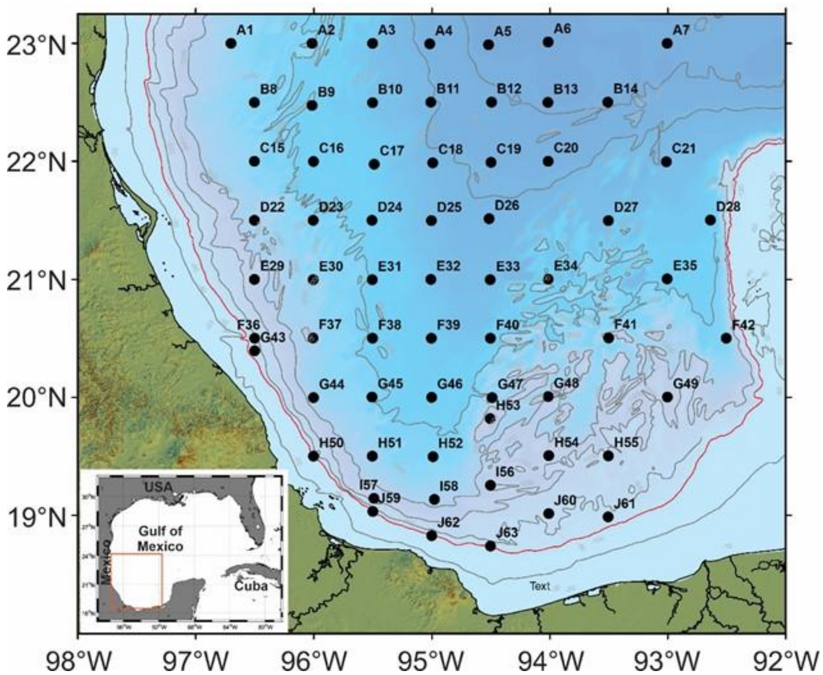

Figure 1. Study area: the Gulf of Mexico. Black dots represent the sites where hydrographic data along the water column and water samples at various depths were collected for chemical analysis of nutrients and Chl-*a* levels.

In this study, we applied a multi-step statistical framework to the dataset. Following initial correlation tests to assess significance, we used Principal Component Analysis (PCA) to examine the physical variables influencing Chl-*a* concentration and distribution. PCA is a multivariate ordination technique that transforms correlated variables into orthogonal principal components (Hotelling 1993, Jolliffe 2002). This approach is essential for managing complex data matrices where physical, chemical, and biological parameters exhibit high multicollinearity (Legendre & Legendre, 2012). By projecting samples onto a lower-dimensional space, PCA identifies latent structures and dominant forcing factors, providing a holistic understanding of marine ecosystem dynamics that univariate analyses often miss (Everitt & Hothorn 2011). PCA was performed for each depth considered in this study using standard routines in PRIMER v6.

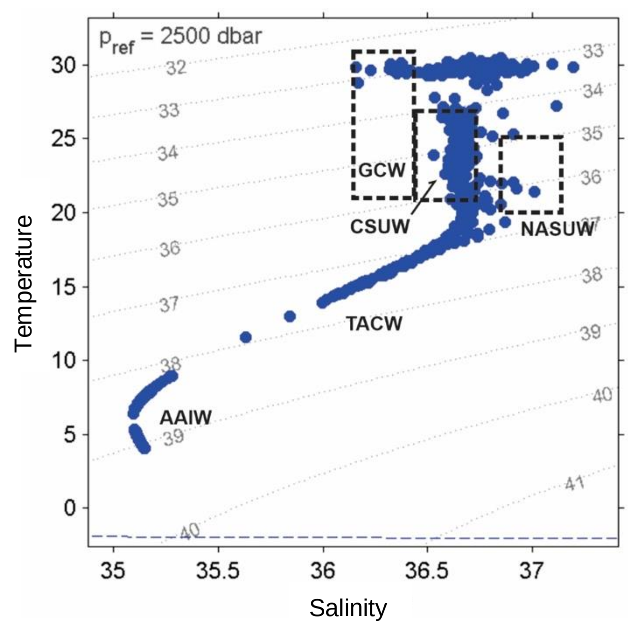

Figure 2. Temperature-salinity diagram. GCW: Gulf Common Water, CSUW: Caribbean Subtropical Underwater, NASUW: North Atlantic Subtropical Underwater, AAIW: Antarctic Intermediate Water, TACW: Tropical Atlantic Central Water.

RESULTS

Hydrography

Based on the classification for the southern Gulf of Mexico by Durán-Campos et al. (2017), five distinct water masses were identified (Fig. 2): 1) Gulf Common Water (GCW) characterized by $22 < T < 28$°C, and $36.2 < S < 36.4$ g kg^{-1}, 2) Caribbean Subtropical Underwater (CSUW) with $22 < T < 26$°C and $36.4 < S < 36.6$ g kg^{-1}, 3) a low proportion of North Atlantic Subtropical

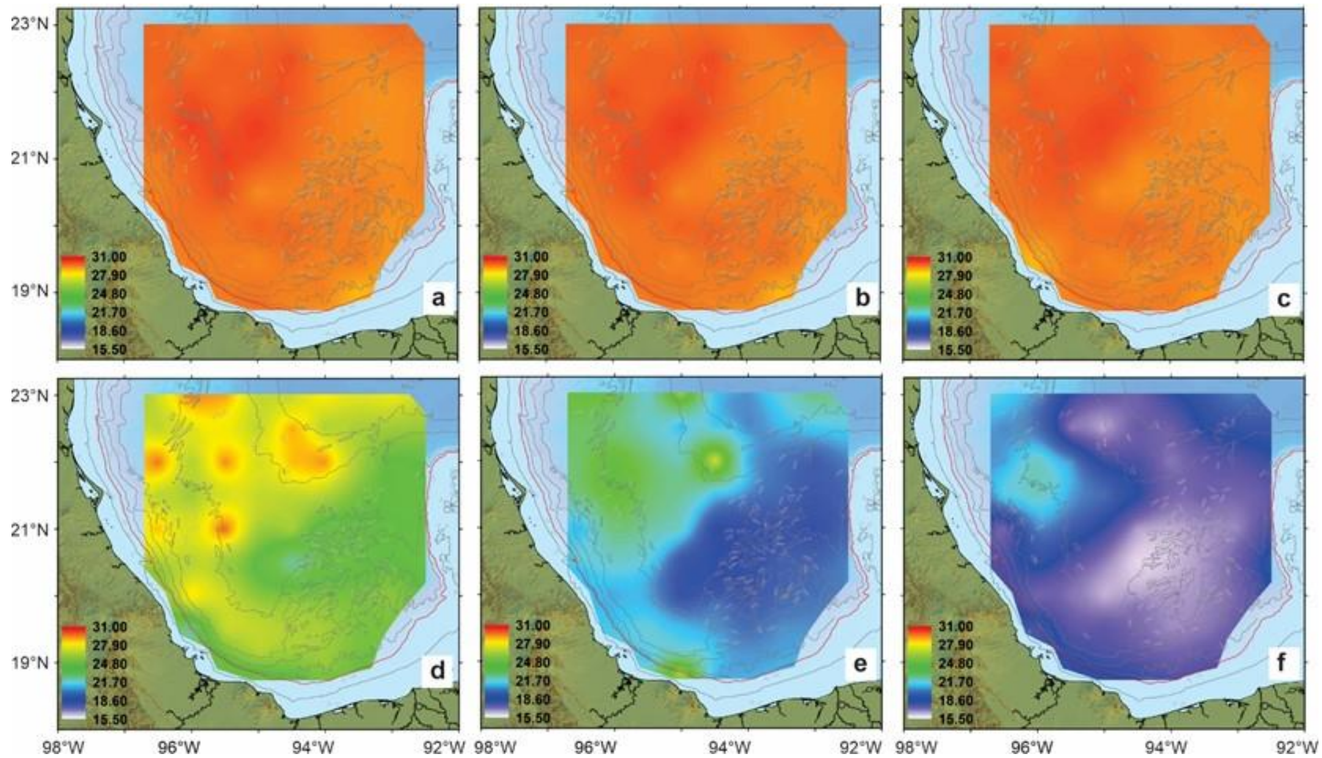

Figure 3. Horizontal distribution of conservative temperature (ºC) at different depths: a) surface, b) 10 m, c) 20 m, d) 50 m, e) 100 m, and f) 150 m.

Underwater (NASUW) characterized by 20 < T < 25ºC and S > 36.8 g kg^{-1}, 4) a low proportion of the Antarctic Intermediate Water (AAIW) characterized by 5.5 < T < 6.5ºC and 35.0 < S < 35.1 g kg^{-1}, and 5) Tropical Atlantic Central Water (TACW) characterized by 8 < T < 20ºC and 35.1 < S < 36.6 g kg^{-1}. The identification of these five water masses is consistent with previous studies in the southern Gulf of Mexico during both summer (e.g. Durán-Campos et al. 2017) and winter (e.g. Torres-Martínez et al. 2020) seasons.

The horizontal distribution of conservative temperature varied with depth. In the first three levels, surface (Fig. 3a), 10 m (Fig. 3b), and 20 m (Fig. 3c), temperatures were uniformly high, exceeding 30ºC. However, at a depth of 50 m (Fig. 3d), temperatures ranged from 24 to 28°C, with higher-temperature cores primarily located in the northern part of the study area. At a depth of 100 m (Fig. 3e), there was a significant decrease in temperature, with values dropping below 18ºC in a large core that spanned the eastern portion of the area. At a depth of 150 m (Fig. 3f), the cold core in the eastern part of the study area became more pronounced, with temperatures falling below 15ºC.

The horizontal distribution of salinity, as shown in Figure 4, was nearly uniform across all depths examined in this study, with values ranging from 35 to 36.5 g kg^{-1}. This pattern indicates that the oceanic waters are not affected by freshwater discharge. From the surface down to a depth of 100 m (Figs. 4a-e), a low-salinity core was observed, with values between 33 and 34 g kg^{-1}. However, at a depth of 150 m (Fig. 4f), salinity was consistent throughout the study area.

The density distribution (Fig. 5) mirrored the patterns of temperature and salinity, with values increasing in depth. Similar to the salinity distribution, low-density cores were found within the first five depths analyzed (Figs. 5a-e), particularly in the central portion of the study area. At a depth of 150 m (Fig. 5f), the density distribution became relatively uniform, reaching values of 27 kg m^{-3}.

Nutrients

The horizontal distribution of nitrogen, measured as nitrates and nitrites, varied with water depth. In the first four levels (from the surface to 50 m depth), concentrations were low, ranging from 0.10 to 5 µM (Figs. 6a-d). However, at a depth of 100 m (Fig. 6e),

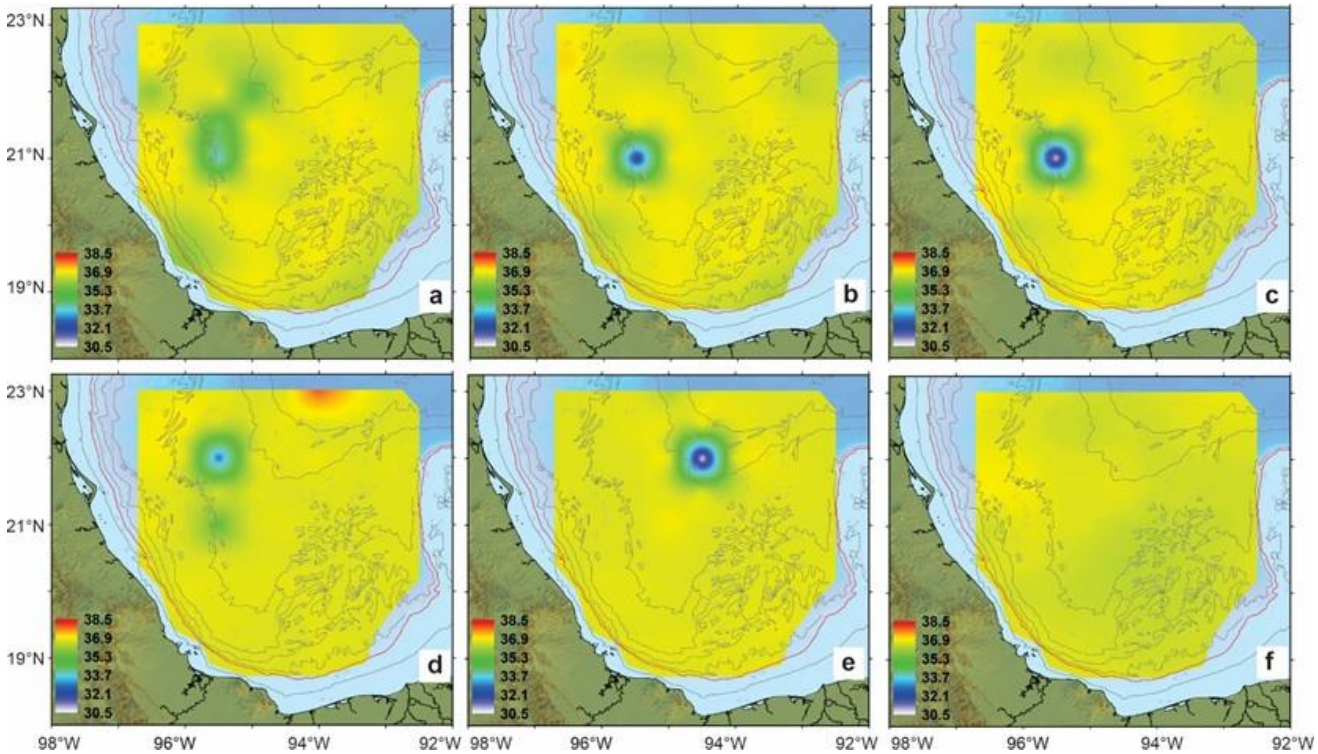

Figure 4. Horizontal distribution of absolute salinity (g kg^{-1}) at different depths: a) surface, b) 10 m, c) 20 m, d) 50 m, e) 100 m, and f) 150 m.

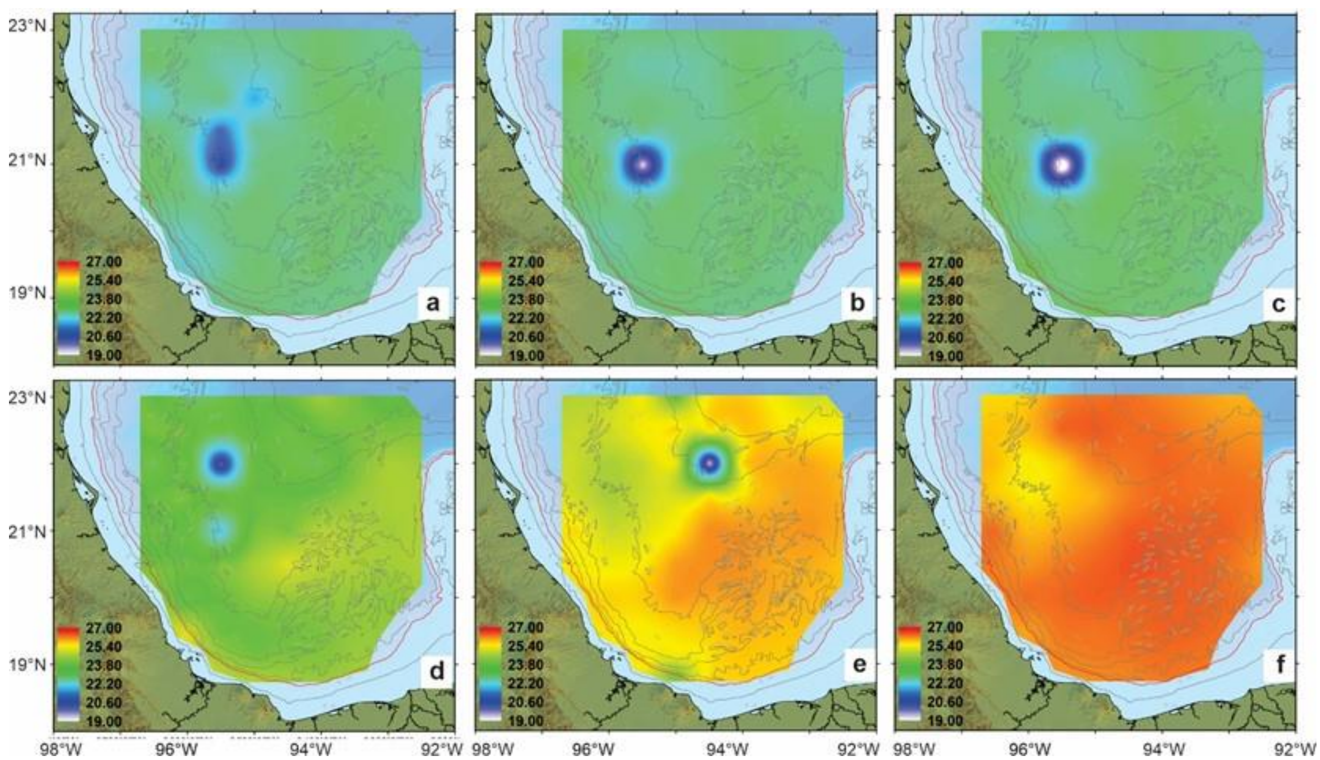

Figure 5. Horizontal distribution of density (kg m^{-3}) at different depths: a) surface, b) 10 m, c) 20 m, d) 50 m, e) 100 m, and f) 150 m.

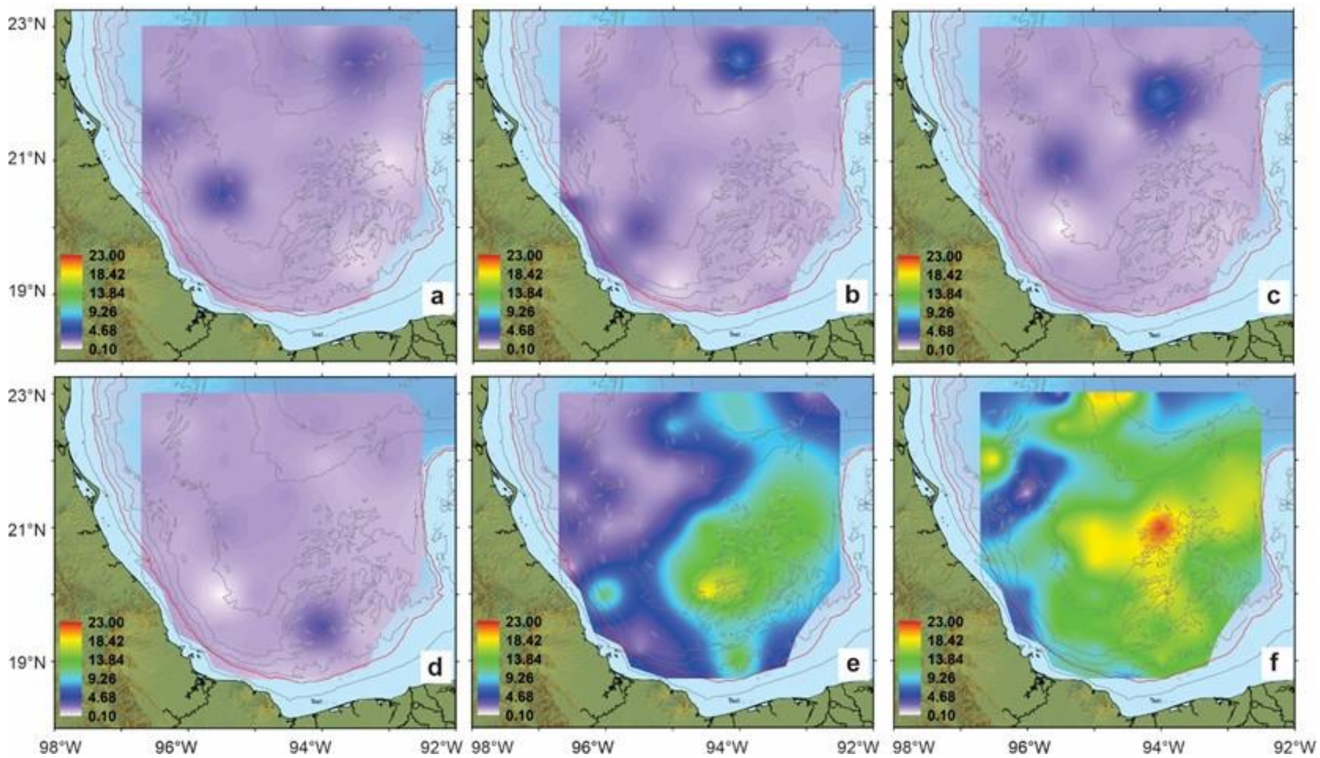

Figure 6. Horizontal distribution of nitrates + nitrites (μM) at different depths: a) surface, b) 10 m, c) 20 m, d) 50 m, e) 100 m, and f) 150 m.

nitrogen values increased significantly, exceeding 15 μM in a core located in the eastern part of the study area. This increase corresponded to the lowest temperature observed (Fig. 3e). The highest concentrations of nitrates and nitrites were recorded at a depth of 150 m (Fig. 6f), exceeding 21 μM, again in a core situated in the eastern region of the study area.

The horizontal distribution of SRP ranged from 0.10 to 2.05 μM. In the initial five depth levels, extending from the surface down to 100 m (Figs. 7a-e), the concentrations were generally consistent, ranging from 0.10 to 1 μM. Notably, at a depth of 10 m in the central part of the study area, a significant concentration peak was observed, exceeding 2 μM (Fig. 7b). At a depth of 150 m (Fig. 7f), higher concentration cores, particularly in the eastern section of the study area, were found to be above 1 μM.

Meanwhile, the horizontal distribution of SRSi exhibited persistently low values (<3 μM) in the upper 50 m of the water column (Figs. 8a-d). However, concentrations began to rise at a depth of 100 m, with localized areas of higher concentration (5 μM) identified in the northern portion of the study area (Fig. 8e). At a depth of 150 m (Fig. 8f), the highest concentrations, reaching up to 13 μM, were detected in a concentrated core located in the northern section of the study area.

Chlorophyll-*a* levels

Chl-*a* levels varied between 0.01 and 0.80 mg m^{-3}, displaying both vertical and horizontal distribution variations. Low concentrations of 0.20 mg m^{-3} were recorded in the upper 20 m of the water column; however, some small areas exhibited higher concentrations of up to 0.40 mg m^{-3} (Figs. 9a-c). The highest concentration was found at a depth of 50 m, where it reached 0.80 mg m^{-3} in two specific cores located in the eastern part of the study area (Fig. 9d). At a depth of 100 m in the western region of the study (Fig. 9e), two cores showed relatively high concentrations of 0.50 mg m^{-3}. Finally, the lowest concentrations, below 0.1 mg m^{-3}, were observed at a depth of 150 m and were evenly distributed across the area of interest (Fig. 9f).

Statistical analyses

Chl-*a* concentrations showed strong statistical significance when correlated with SRSi (p = 0.0002), SRP, nitrates, and dissolved oxygen (p = 0.0001).

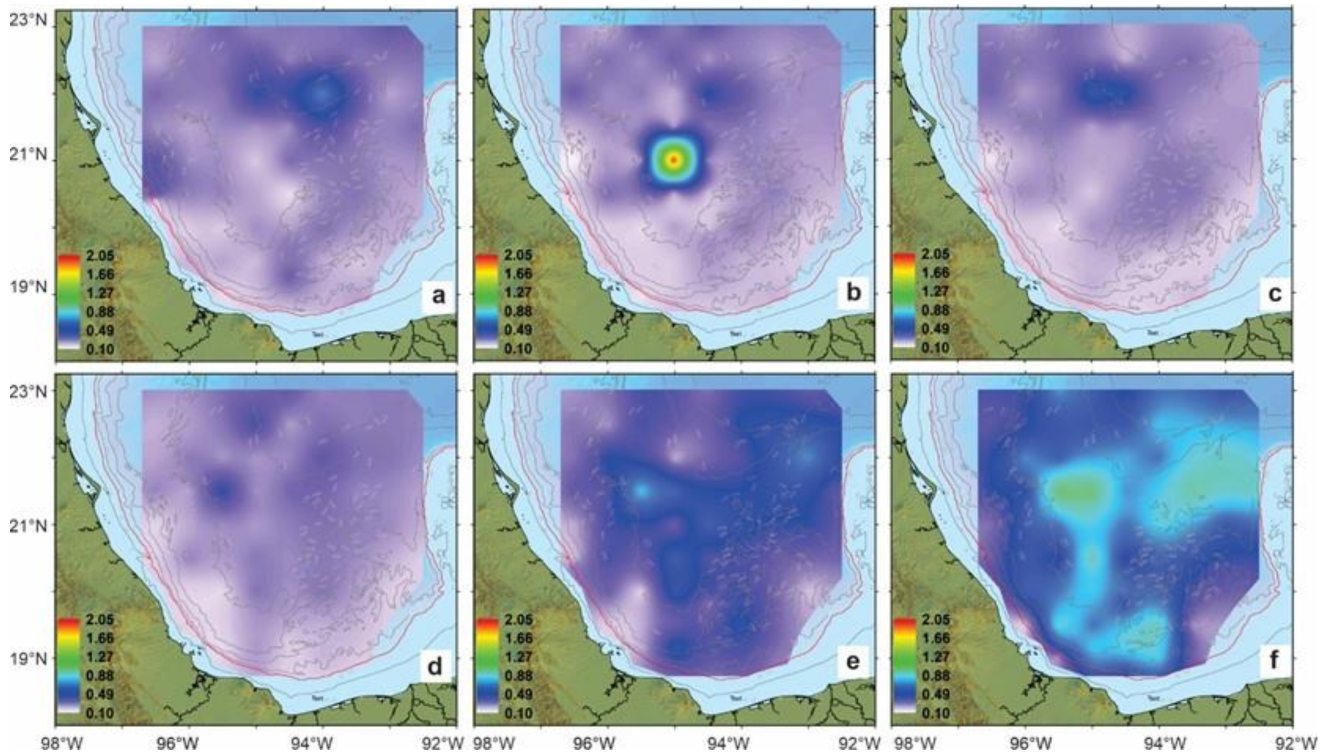

Figure 7. Horizontal distribution of soluble reactive phosphorus (µM) at different depths: a) surface, b) 10 m, c) 20 m, d) 50 m, e) 100 m, and f) 150 m.

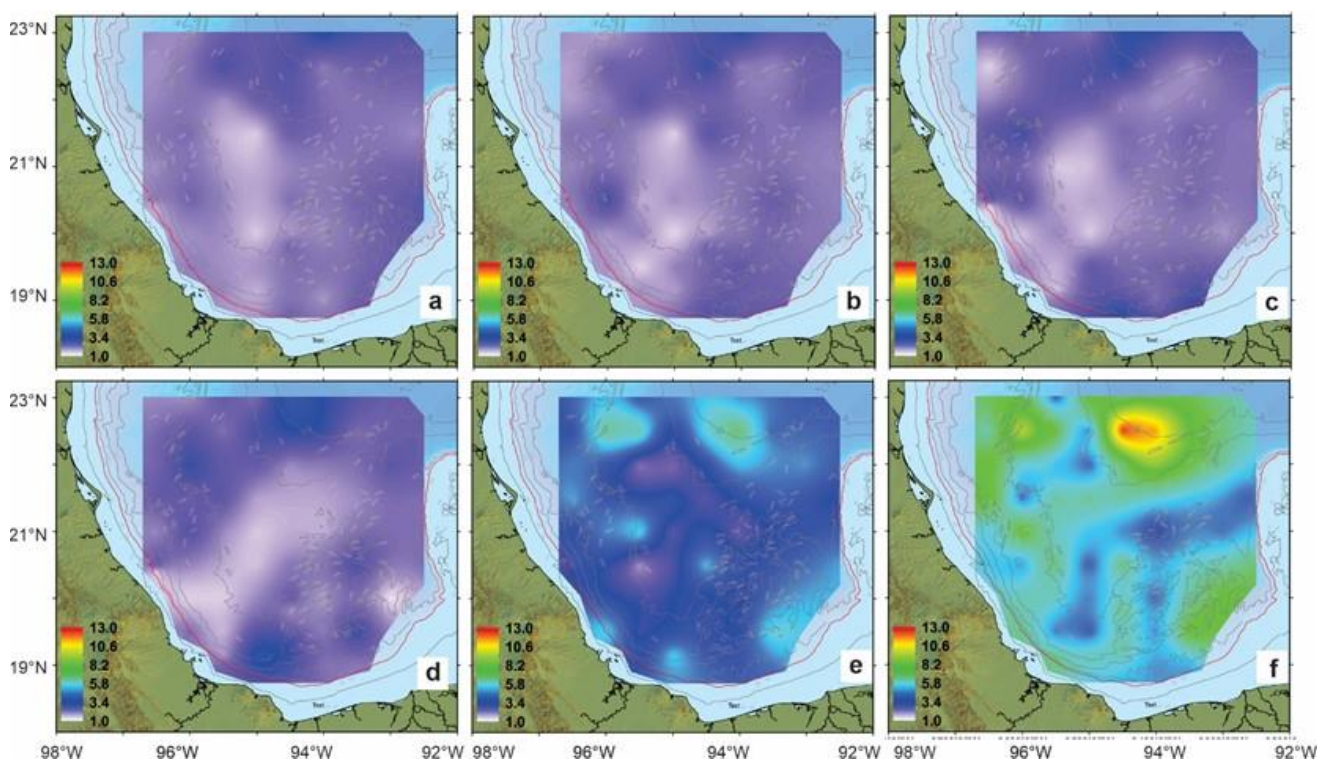

Figure 8. Horizontal distribution of soluble reactive silice (µM) at different depths: a) surface, b) 10 m, c) 20 m, d) 50 m, e) 100 m, and f) 150 m.

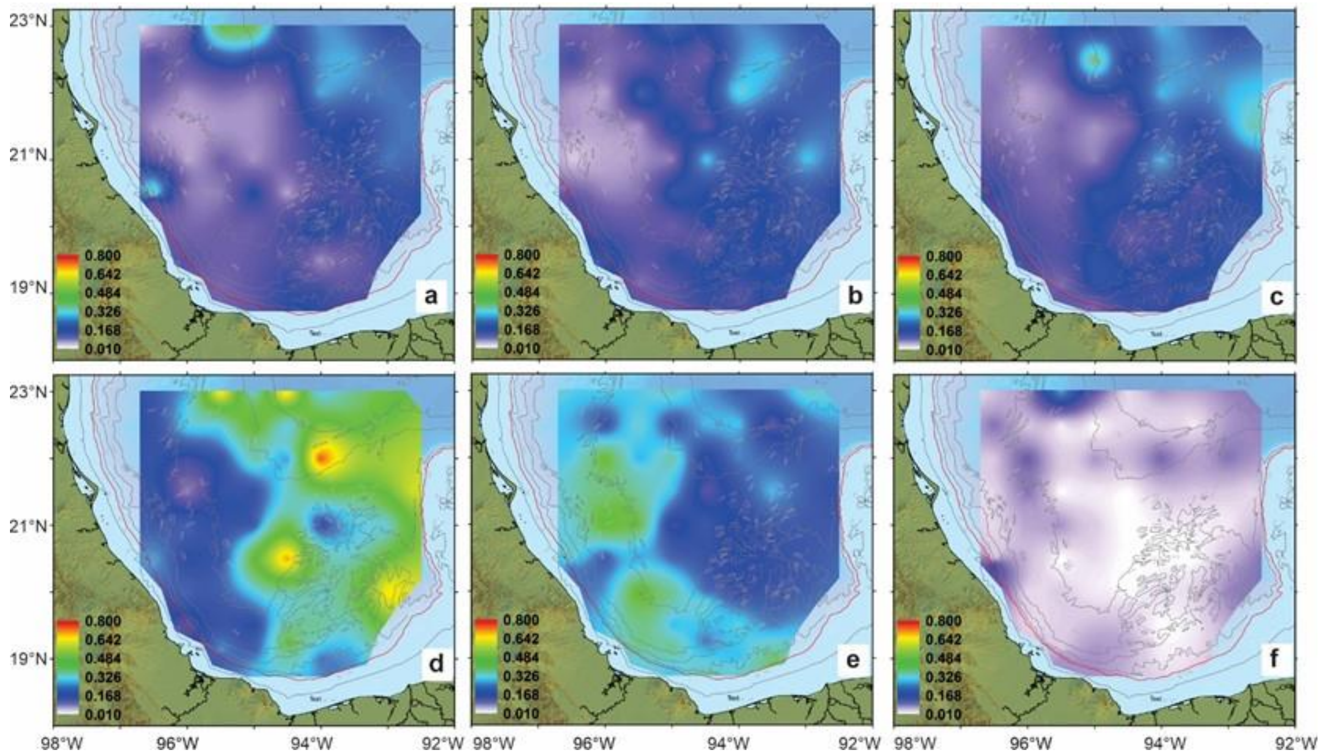

Figure 9. Horizontal distribution of chlorophyll-*a* (mg m^{-3}) at different depths: a) surface, b) 10 m, c) 20 m, d) 50 m, e) 100 m, and f) 150 m.

The PCA performed on this dataset revealed distinct variations across the sampled depths. At the shallower levels, the surface and 10 m depth (Figs. 10a,b), the data remained relatively clustered; no single variable exerted a dominant influence, and no clear spatial trends emerged among the sampling stations.

A shift in environmental dynamics becomes apparent at 20 m depth (Fig. 10c). At this depth, specific variables begin to drive the variance, most notably absolute salinity and SRSi. The alignment of these two variables in the same direction on the PCA biplot suggests a strong positive correlation, indicating they are the primary factors influencing the characterization of the sampling stations at this depth.

At a depth of 50 m (Fig. 10d), the PCA indicates stronger coupling among environmental variables. The biplot reveals that NO_3, NO_2, SRSi, and SRP are closely aligned, signifying a robust positive correlation. Conversely, conservative temperature and dissolved oxygen are positively correlated. Still, in the opposite direction to the nutrient group, suggesting an inverse relationship, as temperature decreases (often indicating upwelling or deeper water masses), nutrient concentrations typically increase. Notably, stations A4, A5, A6, B11, and D24 are strongly associated with the nutrient vectors, indicating that these sites are characterized by higher nutrient enrichment at this depth, particularly nitrites. Finally, at depths of 100 m (Fig. 10e) and 150 m (Fig. 10f), a combined influence of nutrient availability and temperature was observed, suggesting a coupled physical-biological control on Chl-*a* distribution at these depths.

DISCUSSION

The distribution of hydrographic variables in this study indicates a cold, dense core at 100 m, suggesting a cyclonic eddy. Cyclonic eddies are common features in marine environments and are associated with the upwelling of cold, dense, nutrient-rich waters that fertilize the euphotic zone (McGillicuddy 2016). Evidence of these structures has been observed in the southern Gulf of Mexico throughout the year, from summer (Durán-Campos et al. 2017) to winter (López-Cabello et al. 2025). Specifically, in the Bay of Campeche region, it has been noted that the circulation pattern is primarily influenced by a semi-permanent cyclonic eddy (Díaz-Flores et al. 2017), which signifi-

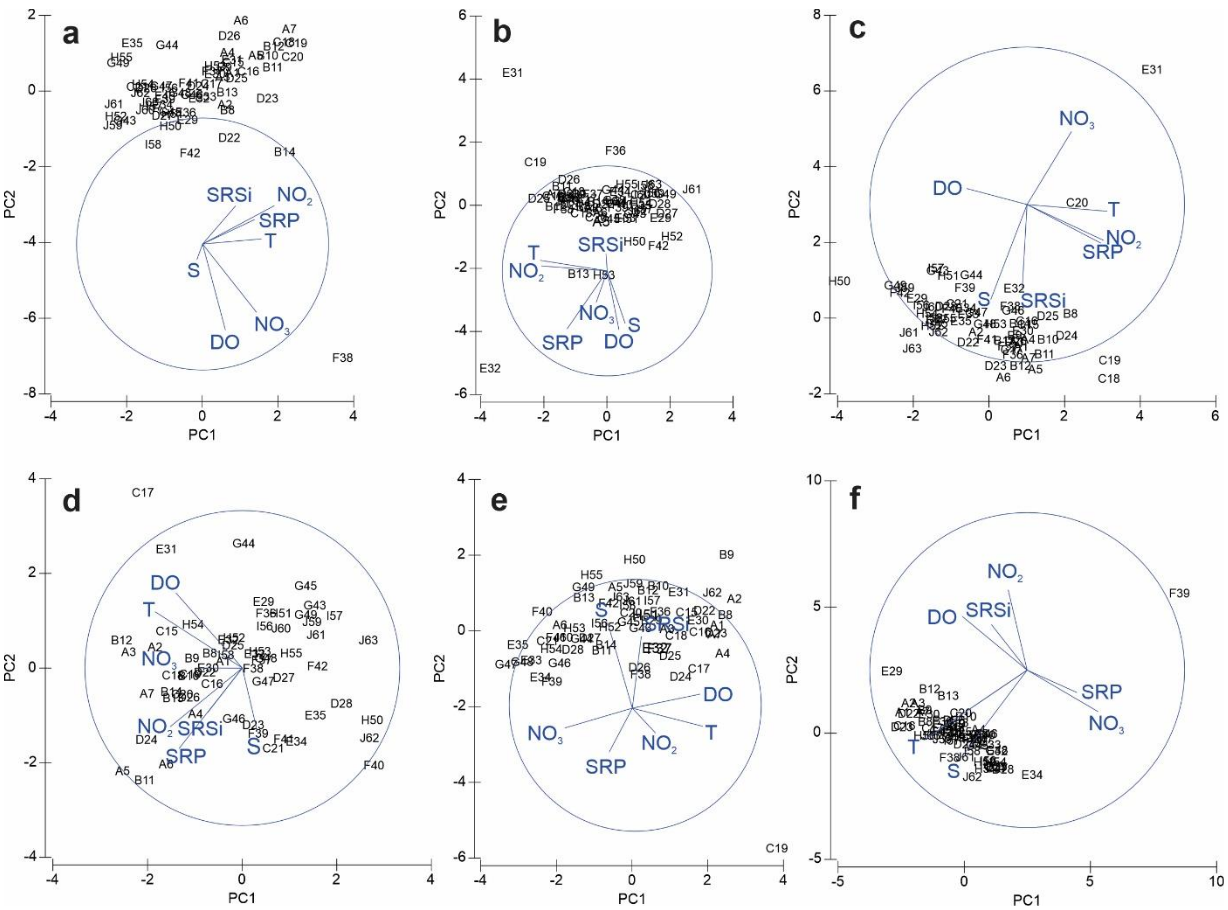

Figure 10. Principal Component Analysis applied to the data set generated in this study: a) at surface, b) at 10 m depth, c) at 20 m depth, d) at 50 m depth, e) at 100 m depth, and f) at 150 m depth. Blue vectors represent environmental variables recorded. Abbreviations are: T: conservative temperature, S: absolute salinity, DO: dissolved oxygen, NO_3: nitrates, NO_2: nitrites, SRP: soluble reactive phosphorus, and SRSi: soluble reactive silice.

cantly impacts the organisms in this region and nearby areas, including the plankton community (Durán-Campos et al. 2017, Linacre et al. 2024).

Cyclonic eddies play a crucial role in determining the vertical and horizontal distribution of nutrients, particularly nitrogen, in the deep waters of the southern Gulf of Mexico. A recent study, based on in situ observations spanning two seasons, found that mesoscale cyclonic eddies increase nitrate and nitrite concentrations in the euphotic zone. These nutrients contribute to a peak in dissolved oxygen levels at depths of 30-50 m, driven by the photosynthetic activity of primary producers (Lee-Sánchez et al. 2022). Our study revealed clear vertical variations in nutrient distribution. The upper water column exhibited low nutrient concentrations (particularly nitrogen) driven by phytoplankton uptake (Libes 2009). Conversely, nitrogen levels increased below 50 m, aligning with the cold, dense cores observed in the eastern study area; this suggests that the cyclonic eddy promotes nutrient enrichment by upwelling deeper water into subsurface layers.

The impact of nutrient fertilization induced by cyclonic eddies is well-documented worldwide. One of the earliest pieces of scientific evidence was found in the Sargasso Sea, where a cyclonic eddy elevated the nutricline, fertilized the euphotic zone, and increased phytoplankton biomass (McGillicuddy & Robinson 1997). Since then, similar observations of nutrient enrichment and increases in Chl-*a* levels due to cyclonic eddies have been reported in various locations, including eastern Australia (Doblin et al. 2016), the northwest Mediterranean (Campbell et al. 2013), the north Atlantic (Li & Hansell 2008), and the southern Gulf of California (Coria-Monter et al. 2017).

In the Campeche Canyon in the southern Gulf of Mexico, research has shown that a dipole eddy, with both cyclonic and anticyclonic components, significantly affects the planktonic ecosystem. The cyclonic component primarily enhances nutrient upwelling toward the euphotic zone, leading to maximum Chl-*a* values at depths below 50 m (Durán-Campos et al. 2017). In our study, we also observed the highest nutrient concentrations and maximum Chl-*a* peaks below 50 m, which supports the findings of previous research. The Chl-*a* concentrations observed in this study (0.01 to 0.80 mg m^{-3}) align with previous summer observations in the region (e.g. Durán-Campos et al. 2017). However, these levels typically increase during the winter, reaching up to 1.5 mg m^{-3} due to the physical dynamics triggered by cold storm seasons in the southern Gulf of Mexico (Torres-Martínez et al. 2020).

The semi-permanent cyclonic circulation in the Bay of Campeche, in the southern Gulf of Mexico, has been linked to increased Chl-*a* levels. Specifically, mixing events at the edge of this circulation lead to elevated nutrient concentrations, which promote phytoplankton biomass growth (Signoret et al. 2006b). It is important to note that this phytoplankton is predominantly comprised of organisms smaller than 10 μm (Signoret et al. 1998). Additionally, strong temperature gradients in the continental shelf waters of the southern Gulf of Mexico are associated with higher phytoplankton biomass (Signoret et al. 2006a). A recent study conducted in the deep waters of the southern Gulf of Mexico, using *in situ* samples collected in late spring, documented the presence of cold and warm cores associated with cyclonic and anticyclonic eddies. These eddies influence the vertical and horizontal distributions of nutrients and Chl-*a* levels. High values of both parameters were observed in regions with cold cores (González-Fernández et al. 2025), consistent with our findings.

While interest in the vertical and horizontal Chl-*a* distribution patterns, and their hydrographic drivers in the southern Gulf of Mexico has grown, comprehensive studies remain scarce, particularly in deep-water environments. Although the physical environment is known to dictate Chl-*a* patterns, previous research has largely focused on shallow continental shelf waters (e.g. Signoret et al. 2006a).

In early 2015, a Mexican government-funded research project expanded its sampling to include deeper regions. This initiative has enabled researchers to better understand how the physical environment influences nutrient and phytoplankton distributions (e.g. Linacre et al. 2019, 2022, 2024, Lee-Sánchez et al. 2022, González-Fernández et al. 2025). However, some aspects remain unclear.

The results of this study demonstrate that the horizontal distribution of nutrients and Chl-*a* is significantly correlated with the presence of a cold, dense, high-nutrient core. Statistical analyses confirm that this nutrient-enhanced core is indicative of cyclonic eddies, in which upward Ekman pumping is likely driving the observed enrichment in nitrogen and phosphate.

These findings, recorded during the summer season, provide a robust baseline for ecosystem dynamics, complementing previous research conducted during different climatic periods (e.g. González-Fernández et al. 2025). Nevertheless, there are still knowledge gaps, particularly regarding ecosystem dynamics during the colder months from January to March. To address these gaps, it is crucial to establish long-term monitoring programs that can identify both seasonal and interannual changes. This focus becomes increasingly important in an era of global change, given the critical role that phytoplankton play in the ocean.

Credit author contribution

All authors contributed equally to this study. All 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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