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Short Communication

Phytoplankton biomass in a Ramsar-listed coastal lagoon of the southern Gulf of Mexico during La Niña 2022 and El Niño 2023 events

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ABSTRACT. Coastal lagoons are sites recognized for their high biomass and primary productivity levels and are critical habitats for environmental changes. This study evaluated the phytoplankton biomass in the Términos Lagoon (TL), a Ramsar-listed site in the southern Gulf of Mexico, during the 2022 La Niña and 2023 El Niño events. Four systematic sampling expeditions were carried out in April and October of 2022 and 2023 to acquire high-resolution hydrographic data and collect water samples for spectrophotometric determinations of chlorophyll-*a* (Chl-*a*) as an indicator of phytoplankton biomass in 11 sites distributed along the TL, while values of the Multivariate ENSO Index (MEI) were used to identify the phase during each sampling expedition. The results showed variations, both seasonally and interannually. MEI values reflected a strong La Niña event during 2022, while in 2023, the ENSO phase moved from neutral (April) to El Niño conditions (October). Consequently, in 2023, the maximum values of the surface temperature and salinity increased by 2.9ºC and 9.2, respectively, compared to 2022. Besides, the maximum values of Chl-*a* decreased to 0.55 mg m^{-3} between 2022 and 2023. The horizontal distribution of these parameters displayed interesting gradients along the study area related to each event. Our results demonstrate the impact of La Niña and El Niño events on the hydrographic conditions and phytoplankton biomass of a region recognized for its high species richness contribute to understanding physical-biological coupling processes. This aspect remains poorly understood in the region.

Keywords: hydrography; phytoplankton biomass; chlorophyll-a; ENSO events; Términos Lagoon; Gulf of Mexico

Biomass is a pivotal indicator of biological production in any aquatic ecosystem, and in the case of phytoplankton, it is also recognized as a proxy of primary productivity (Odum & Barret 2005, Keerthi et al. 2022).

Phytoplankton includes a highly heterogeneous group of microorganisms which, due to the photosynthesis processes that they perform, release a significant portion of the total oxygen available in the atmosphere around the world and contribute significantly to the capture and sequestration of CO_2, making the carbon pump work properly (Basu & Mackey 2018). As a ubiquitous pigment in all photosynthetic species, chlorophyll-*a* (Chl-*a*) is considered a proxy of phytoplankton biomass whose quantification is carried out through extremely sensitive and precise standardized chemical techniques (Cullen 2015, Davies et al. 2018).

Currently, it is relatively well-known that the worldwide phytoplankton biomass levels are closely related to changes that occur in the physical environment at different spatial and temporal scales, from turbulence processes to the confluence of large-scale phenomena such as the El Niño Southern Oscillation (ENSO). Characterized by a cold phase (La Niña) and a warm phase (El Niño), ENSO events have strong repercussions on biological productivity throughout the

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entire food chain, and the phytoplankton, being positioned at the lowest trophic level, represents one of the first groups to be affected (Racault et al. 2017). The direct impact of ENSO events on the phytoplankton communities changes depending on its phase. At the same time, La Niña is related to a decrease in sea surface temperatures, increasing phytoplankton biomass rates; conversely, El Niño events are related to the advection of warm and low-nutrient water masses that induce a decrease in biomass in oceanic and coastal environments (McPhaden et al. 2021) (Table 1).

Coastal environments are key sites around the globe because they represent refuge, growth, and feeding habitats for numerous emblematic species, many of them of high ecological and economic value. Besides, coastal environments are recognized worldwide for their high diversity, biomass, and primary productivity levels (Kennish & Paerl 2010).

In the southern Gulf of Mexico, the Términos Lagoon (TL) is a highly dynamic system and one of the largest coastal lagoons in the Mexican territory (Fig. 1). The site is separated from the open waters of the Gulf by Del Carmen Island, which hosts Del Carmen City, a locality in continuous population growth whose population exceeds 190,000 (INEGI 2023).

Surrounded by an extensive mangrove forest, TL represents a refuge, breeding, and feeding habitat for numerous species, many of which are endangered, threatened, or subject to special conservation status (Castellanos-Pérez et al. 2020, Soria-Barreto et al. 2023). Therefore, TL was declared by the Mexican authorities as a protected natural area with the status of a flora and fauna protection area. In 2004, UNESCO declared it a Ramsar site. In addition, the lagoon is also recognized as the recruitment habitat for some high commercial value species, such as pink and white shrimps (Gómez-Ponce et al. 2021).

Climatically, TL is highly dynamic with three distinctive and contrasting seasons: 1) the dry season between February and May, 2) the wet season from June to October, and 3) the locally named "Nortes" season characterized by extremely strong winds (>80 km) that cross the Gulf of Mexico between November and January (Contreras-Ruiz et al. 2014). Dynamically, TL is complex due to the freshwater discharge by three main rivers: Palizada, Chumpán and Candelaria, and the input of seawater from the open Gulf of Mexico through two inlets (Puerto Real and Del Carmen) which generates strong gradients and high hydrodynamic heterogeneity inside the lagoon (Paz-Ríos et al. 2023). Besides, TL is surrounded by a dense mangrove forest that represents a refuge for numerous birds, some of them migratory (Canales-Delgadillo et al. 2019), and in its interior, extensive multi-species seagrass meadows are present (Coria-Monter & Durán-Campos 2015). Economically, the region is crucial for the country's economy because numerous platforms that extract oil and gas are located here. Also, the region is an important exploitation point for white and pink shrimp (Gómez-Ponce et al. 2021); together, both industries provide employment and security for thousands of its inhabitants.

Studies on the phytoplankton composition inside TL are scarce. However, it is known that the lagoon hosts 45 species, including 34 diatoms, 4 dinoflagellates, 3 chlorophytes, 2 cyanophytes, and 2 rhodophytes, whose composition and abundance depend on the year's season. Genera such as *Rhizosolenia*, *Skeletonema*, *Nitzchia*, *Chaetoceros*, *Cocinodiscus*, and *Thalassiothrix* are dominant in the dry season, *Oscillatoria* and *Gomphosphaeria* dominate phytoplankton composition the rest of the year (Gómez-Aguirre 1974, Rojas-Galaviz et al. 1992).

Studies on the phytoplankton biomass inside TL are also scarce, highlighting some works that reported Chl-*a* concentrations ranging from 0.3 to 15.9 mg m^{-3}, with lowest values (<1 mg m^{-3}) during the dry season (from February to May) and highest values (>5 mg m^{-3}) during and after the rainy season (from June to January) (Yáñez-Arancibia & Day 1982, Rojas-Galaviz et al. 1992, López-Mejía et al. 2022). Some authors noticed that Chl-*a* values increase in regions with low salinity, near the rivers that flow into TL (Day et al. 1982) and that there are strong Chl-*a* gradients derived, among other things, from the interaction between the freshwater discharge from the rivers that flow into the lagoon and the seawater input from the Gulf of Mexico through its two inlets (López-Mejía et al. 2022). Studies on the phytoplankton biomass in adjacent environments to TL, such as the Pom-Atasta Lagoon (Fig. 1), have shown seasonal patterns contrary to what has been reported in TL, with the highest concentrations (>19 mg m^{-3}) during the dry season and lowest concentrations (<3 mg m^{-3}) during the rainy season (Barreiro-Güemes & Aguirre-León 1999).

All of these studies have identified a marked variability in the phytoplankton biomass values within TL depending on the climatic season and the proximity to the rivers, which have been very useful in identifying the high dynamism of the region. However, the impact of large-scale processes (such as ENSO events) on the phytoplankton biomass of the region still needs to be addressed. Very few reports on this topic centering more on El Niño than La Niña. Indeed, Conan et al.

Table 1. Chlorophyll-*a* values (mg m^{-3}) reported under El Niño and La Niña scenarios in different domains worldwide.

	El Niño events	La Niña events	Region	Authors
Chlorophyll-*a* concentration (mg m^{-3})	1.50	3.50	Gulf of Faralliones, California, USA	Wilkerson et al. (2002)
	0.13	0.62	Southern region of California, México	Lavaniegos et al. (2002)
	<1.00	>4.00	Mazatlán Coastal region; México	Durán-Campos et al. (2023)
	0.60	--	Southern Gulf of California, México	Coria-Monter et al. (2018)
	<1.00	>2.00	Bay of Bengal, India	Devi & Sarangi (2017)
	1.00	--	West of the Baja California coast, México	Durazo et al. (2005)
	0.25	--	Off Baja California, México	Lavaniegos et al. (2003)
	<1.00	--	Términos Lagoon, southern Gulf of México	Conan et al. (2017)

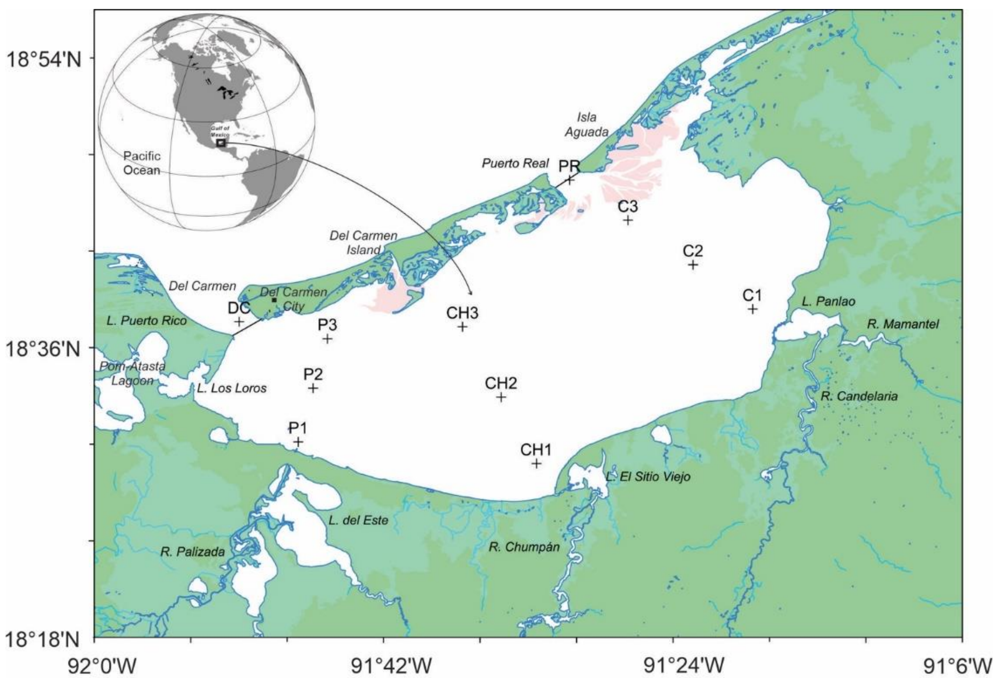

Figure 1. The Términos Lagoon is located in the southern Gulf of Mexico. The signs (+) represent the stations where surface hydrographic data and water samples for chlorophyll-*a* determinations were obtained under different ENSO phases, La Niña 2022 and El Niño 2023. P: Palizada, CH: Chumpán, and C: Candelaria.

(2017) analyzed the biogeochemical cycling and their relationship with the phytoplankton biomass, showing evidence that the 2009/2010 El Niño event generated exceptionally dry conditions and that the highest phytoplankton biomass was aggregated in the Palizada River area. These authors emphasized the need to conduct more research by considering the changes in the hydrographic conditions inside the lagoon associated with other ENSO events, such as the case of La Niña. In a collateral study, Fichez et al. (2019) confirmed the exceptional deficit in the freshwater supply to the lagoon during the 2009/2010 El Niño event, inducing strong salinity gradients which in turn impacted the trophic conditions inside the lagoon, shifting from mesotrophic to oligotrophic.

The period between the second half of 2020 to 2023 has been extremely dynamic. Indeed, from June 2020 to January 2023, the US National Oceanic and Atmospheric Administration recorded a long and strong La Niña event that later, in a quick transition, became an El Niño event beginning in February 2023, whose intensity increased throughout the year; this quick transition between contrasting ENSO phases represents a window of opportunity to evaluate their impact in the physical configuration of the water column and the values of phytoplankton biomass.

Under this scenario, this short communication aimed to report phytoplankton biomass values (expressed as Chl-*a* concentrations) and their relationship to the hydrographic parameters in the TL in La Niña 2022 and El Niño 2023 events. The above advances the scientific understanding of this region, recognized for its high diversity and Ramsar site, considering that studies on physical-biological coupling are still scarce.

For this study, we implemented four systematic sampling expeditions: two during maximum drought and maximum rain in 2022 (April and October, respectively) and two outings in the months of maximum drought and maximum rain in 2023 (again, April and October). In each expedition, 11 sampling sites were selected, which were distributed throughout TL, including the connections with the open waters of the Gulf of Mexico (Puerto Real and Del Carmen) and the regions close to the three main rivers that flow into the lagoon (Palizada, Chumpán, and Candelaria) (Fig. 1).

The geographic position of each site was achieved with a handheld GPS (Garmin 64sx). Once there, surface hydrographic data (at 0.5 m depth) were recorded with a multiparametric probe (YSI EXO1) calibrated before each sampling. Immediately after data acquisition, surface water (at 0.5 m depth) for Chl-*a* determinations was collected using a water sampler bailer (UWITEC, 5 L capacity), from which sub-samples of 1 L were extracted and contained in polypropylene bottles previously rinsed with distilled water, keeping them at environment temperature and in darkness until processing. The water sampler was rinsed with distilled water before each collection to avoid contamination between sampling sites. Additionally, useful information was acquired in each sampling site to interpret the results, including the depth of disappearance of the Secchi disk from which we estimated the diffuse attenuation coefficient (k) and the depth of the photic layer.

To identify the ENSO phase and its intensity in each sampling expedition, we used the ENSO Multivariate Index version 2 (MEI v2), openly available from the NOAA Physical Sciences Laboratory server (https://psl.noaa.gov/enso/mei). This index considers oceanic and atmospheric variables for its calculation, making it a more robust index than other available products. MEI v2 values at or above +0.5 reflect an El Niño event, while values at or below -0.5 reflect the La Niña phase. In terms of their intensity, values from 0.5 (-0.5) to 1.0 (-1.0) are considered weak events, values between 1.0 (-1.0) and 1.5 (-1.5) are considered moderate, values from 1.5 (-1.5) to 2.0 (-2.0) are considered as strong, while >2.0 (-2.0) are considered as very strong events (Wolter & Timlin 2011).

The surface water samples collected at each site were processed immediately after arrival at the port in the Institute of Marine Sciences and Limnology (Del Carmen station) laboratory facilities of the National Autonomous University of México. Each sample was filtered within nitrocellulose membranes (Merck Millipore, 47 mm of diameter, 0.45 µm of pore size) using a 6-place stainless-steel manifold system (Merck Millipore) attached to a vacuum pump (Merck Millipore, at <10 psi). Immediately after filtration, membranes were removed from the manifold system with stainless-steel tweezers (Merck Millipore) and placed in acid-washed and rinsed with distilled water plastic centrifuge tubes covered with aluminum foil to avoid light degradation. The Chl-*a* extraction time was 24 h in 90% acetone, frozen at -20ºC in darkness. Later, the tubes were centrifuged at 4,500 rpm (Eppendorf centrifuge model 5840) for 30 min. Subsequently, the acetone was deposited in quartz cells, which were analyzed (in three replicates) using a spectrophotometer (Thermo Fisher Scientific Genesys 10S UV-VIS) at 630, 647, 664, and 750 nm. Finally, the Chl-*a* concentration (in mg m^{-3}) was calculated with the expression:

$$Chl\text{-}a = \frac{\left(11.85 \times (E664 - E750) - 1.54 \times (E647 - E750) - 0.08 \times (E630 \times E750)\right) \times Ve}{L \times Vf}$$

where E is the absorbance at the specific wavelength (630, 647, 664, and 750 nm), Ve is the extraction volume (expressed in milliliters), L is the thickness of the quartz cell (expressed in centimeters), and Vf is the filtered volume (expressed in liters) (Strickland & Parsons 1972, Parsons et al. 1984). It is important to note that during all laboratory analyses (both filtering and lecture processes), special precautions were taken to work in low-light conditions to prevent any possible degra-dation of the samples.

To test whether differences between Chl-*a* from the two contrasting seasons were statistically significant, we performed the Wilcoxon signed-rank test; this test does not assume a normal distribution and is appropriate for paired measures where the same subjects are evaluated under two different conditions (Legendre & Legendre 2012).

Furthermore, the congruence between the similarity matrices of the two contrasting seasons was evaluated using the Mantel test. By permuting each element in a calculated matrix of dissimilarity indices, this test derives a distribution of correlation values by evaluating the goodness-of-fit between two multivariate datasets (Mantel 1967, Clarke & Ainsworth 1993, Fall &

Olszewski 2010, Legendre & Legendre 2012). The resulting R-statistic is comparable to Spearman's correlation coefficient (r); the Mantel R-statistic goes to 1 as the dissimilarity matrices get more similar (Forcino et al. 2015). We performed additional Mantel tests to determine whether seasonal differences existed in the environmental data. To do this, we intra-annually compared the environmental conditions (e.g. April and October 2022 and April and October 2023).

The results showed that the MEI v2 values were quite different during the sampling expeditions considered in our study. During April 2022, the value was -1.9, while in October 2022, it was -1.7, reflecting that a strong La Niña event occurred in both months. In contrast, the MEI v2 value during April 2023 was -0.1, while during October 2023, it was +0.6, reflecting neutral conditions and an El Niño event, respectively. Concerning the above, our study's hydrographic values and Chl-*a* concentrations displayed clear seasonal and interannual differences.

During April 2022, the surface temperature ranged from 28.3 to 30.2ºC, the surface salinity ranged from 9.4 to 45.9, the total dissolved solids ranged from 27.4 to 43.9 g L^{-1}, the Secchi disappearance depth rose in a range from 35 to 110 cm, the dissolved oxygen displayed values from 5.7 to 7.5 mg L^{-1}, and Chl-*a* values ranged from 0.41 to 26.98 mg m^{-3} (Fig. 2). Values of k ranged from 1.5 to 4.8 m^{-1}, while the depth of the photic layer ranged from 0.94 to 2.97 m. In October 2022, the surface temperature rose from 25.5 to 30.4ºC; the surface salinity ranged from 7.8 to 25.5, reflecting the effect of the freshwater discharge during this season. The total dissolved solids ranged from 17.1 to 32.1 g L^{-1}, the Secchi disappearance depth ranged from 50 to 270 cm, the dissolved oxygen rose into a range from 5.4 to 7.7 mg L^{-1}, and the Chl-*a* showed values from 0.62 to 3.57 mg m^{-3} (Fig. 2). Values of k ranged from 0.62 to 3.4 m^{-1} and the depth of the photic layer rose into a range from 1.35 to 7.29 m.

For 2023, both hydrographic and the Chl-*a* values presented differences compared to 2022. During April 2023, the surface temperature varied from 27.9 to 29.0ºC; salinity values ranged from 23.1 to 40.4; the total dissolved solids ranged from 22.5 to 39.2 g L^{-1}, the Secchi disappearance depth ranged from 30 to 160 cm, the dissolved oxygen rose into a range from 7.5 to 9.4 mg L^{-1}, while the Chl-*a* levels decreased considerably showed values from 0.93 to 4.74 mg m^{-3} (Fig. 2). Values of k ranged from 1.06 to 5.66 m^{-1}, and the depth of the photic layer displayed values from 0.81 to 4.32 m. During October 2023, the surface temperature showed a marked increase compared to the other samplings, ranging from 27.8 to 33.1ºC. Salinity values ranged from 15.4 to 35.2, considerably more saline compared to October 2022, probably due to the increased temperature observed. The total dissolved solids ranged from 19.1 to 34.2 g L^{-1}, the Secchi disappearance depth ranged from 65 to 205 cm, and the dissolved oxygen rose into a range from 5.5 to 7.2 mg L^{-1}, slightly lower compared to October 2022, which can be attributed to the increase in temperature observed. Finally, the Chl-*a* values ranged from 0.40 to 2.90 mg m^{-3}, representing a decrease compared to those observed in October 2022 (Fig. 2). Values of k ranged from 0.83 to 2.61 m^{-1} while the depth of the photic layer ranged from 1.75 to 5.53 m.

After comparing the mean values, the differences observed in the four sampling expeditions during different ENSO phases are shown (Fig. 2). It is important to note the differences observed in the maximum values of Chl-*a* between April 2022 (26.98 mg m^{-3}) and April 2023 (4.74 mg m^{-3}). Besides, it is important to note the differences between October 2022 and October 2023, mainly the temperature, the salinity, and the Chl-*a* values (Fig. 2); while in October 2022, the mean temperature was 28.9ºC, in October 2023 was 31.8ºC, representing an increase of 2.9ºC (Fig. 2a). Mean salinity values also displayed marked differences, with 18.7 in October 2022 and 27.9 in October 2023, a difference of 9.2 between both periods (Fig. 2b). Subsequently, Chl-*a* values (Fig. 2f) showed a marked decrease between both months; in October 2022, the mean value was 2.17 mg m^{-3}, and in October 2023, the mean value was 1.62 mg m^{-3}, representing a decrease of 0.55 mg m^{-3}.

Once the concentration of these parameters was analyzed, noticeable changes were observed between 2022 and 2023, and it was interesting to assess their horizontal distribution. During the 2022 sampling expeditions, the surface temperature showed interesting gradients along the study area. In April, it was observed a core in the central portion of the lagoon was ~30ºC (Fig. 3a), while in October, a less warm influx of water (~26.8ºC) from the Gulf of Mexico to the interior of the lagoon was observed through the Puerto Real connection (Fig. 3b).

In terms of salinity, during April, their horizontal distribution showed high values (>40) in the region closest to Del Carmen Island, while the lowest values were observed near the connection of Palizada (~10) (Fig. 3c). As expected, salinity values were lower in October (Fig. 3d), reaching maximum values of 25.5, related to this month's rainy season. Also, the contribution of freshwater from the three rivers that flow

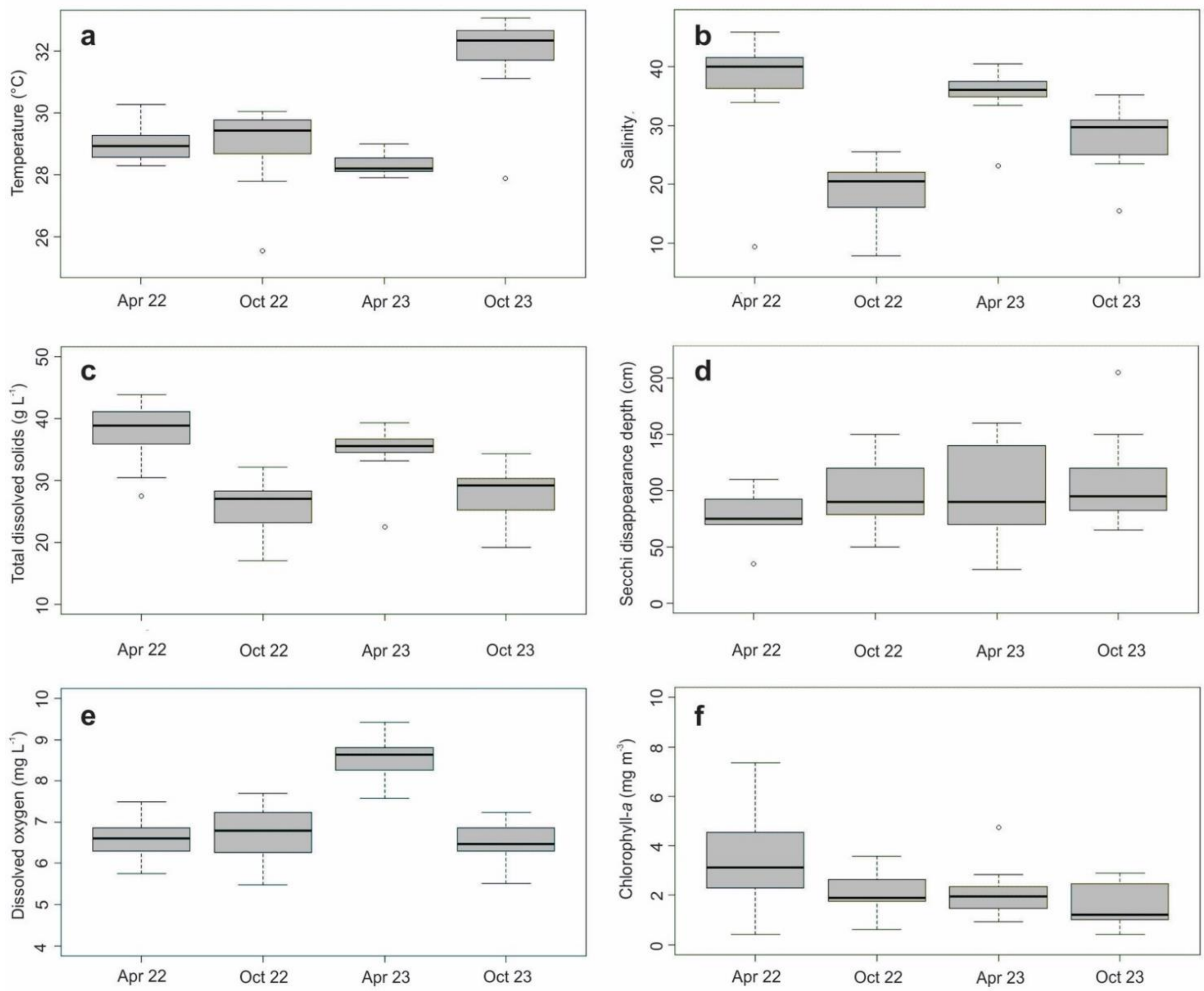

Figure 2. Box-and-whisker plots of the surface hydrographic parameters and chlorophyll-*a* values recorder in Terminos Lagoon, southern Gulf of Mexico, in two months of 2022 and 2023, under different ENSO phases, La Niña and El Niño, respectively: a) temperature (ºC), b) salinity, c) total dissolved solids (g L^{-1}), Secchi disappearance depth (cm), e) dissolved oxygen (mg L^{-1}) and f) chlorophyll-*a* levels (mg m^{-3}). The line inside the box represents the median.

into the lagoon is notable, considerably reducing the salinity levels. In terms of Chl-*a*, during April, a core of maximum concentration (26.98 mg m^{-3}) was observed in the central portion of the lagoon (Fig. 3e), which decreased considerably in October, reaching values of 3.57 mg m^{-3} (Fig. 3f).

The horizontal distribution of the temperature, salinity, and Chl-*a* levels during 2023 was quite different compared to 2022. In this case, during April, the horizontal temperature distribution was uniform throughout the lagoon, with values ranging between 27.9 and 29ºC (Fig. 4a). In contrast, during October, the temperature inside the lagoon increased considerably, exceeding 30ºC practically throughout the study area (Fig. 4b). Regarding salinity, interesting gradients were observed throughout the lagoon between both periods. In April, higher concentrations were observed in the region near Del Carmen Island (~38) (Fig. 4c), while in October, the salinity (Fig. 4d) increased considerably compared to what was observed in 2022. The concentration of Chl-*a* during April and October 2023 was considerably lower compared to 2022, with maximum values of 4.74 mg m^{-3} in April and 2.90 mg m^{-3} in October. This condition of higher temperature, higher salinity, and lower concentration of Chl-*a* could be closely related to the El Niño conditions prevailing during 2023.

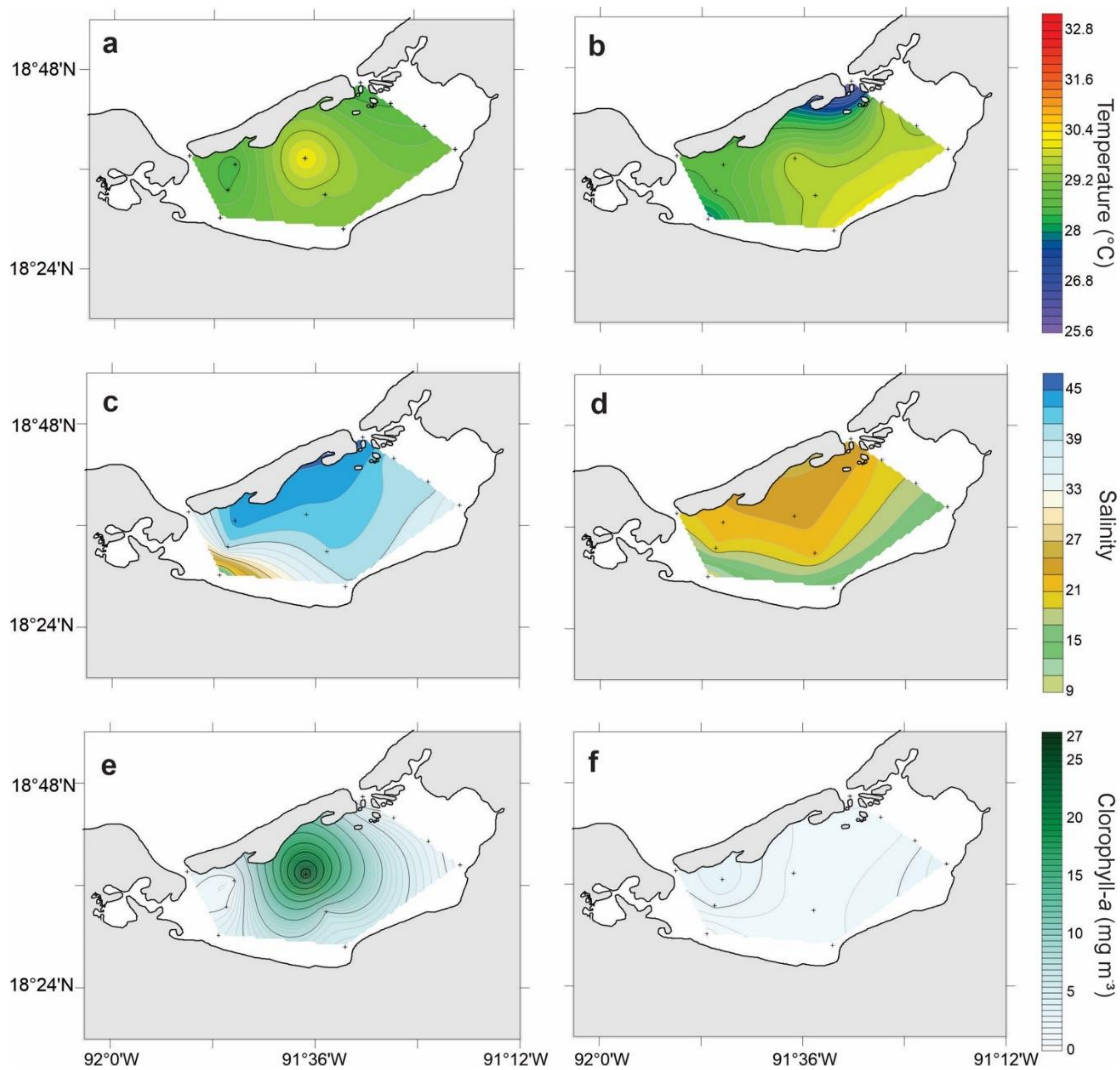

Figure 3. Horizontal distribution of selected hydrographic parameters recorded in 2022: a) temperature (ºC) in April, b) temperature (ºC) in October, c) salinity in April, d) salinity in October, e) chlorophyll-*a* levels (mg m^{-3}) in April, and f) chlorophyll-*a* (mg m^{-3}) levels in October.

Results of the Wilcoxon's sign-ranked tests showed that Chl-*a* concentrations were significantly different between April 2022 and April 2023 (V = 57.5, $P < 0.05$) and between October 2022 and October 2023 (V = 57, $P < 0.05$). In addition, Mantel tests performed between distance matrices showed low correlations between the two contrasting seasons. Mantel's r between April 2022 and April 2023 was 0.404 ($P < 0.05$), while for October 2022 and October 2023, Mantel's coefficient was 0.437 ($P < 0.05$). These results show that both sampling periods significantly differed between the two contrasting seasons; this suggests that Chl-*a* concentrations and the environment significantly differ between the two contrasting seasons. Results for the intra-annual Mantel test performed between environmental distance matrices showed no correlation. Mantel's r between April 2022 and October 2022 was 0.177 ($P = 0.231$), while for April 2023 and October 2023, Mantel's coefficient was 0.00628 ($P = 0.459$). These results show that the two seasons' environmental conditions significantly differed.

Coastal lagoons are ecosystems recognized by their very high complexity and sensitivity to the fluctuations in their physical and chemical conditions throughout the year (León et al. 2013). Besides, they are considered critical habitats of environmental changes (Kennish & Paerl 2017). In the case of TL, an environment recognized

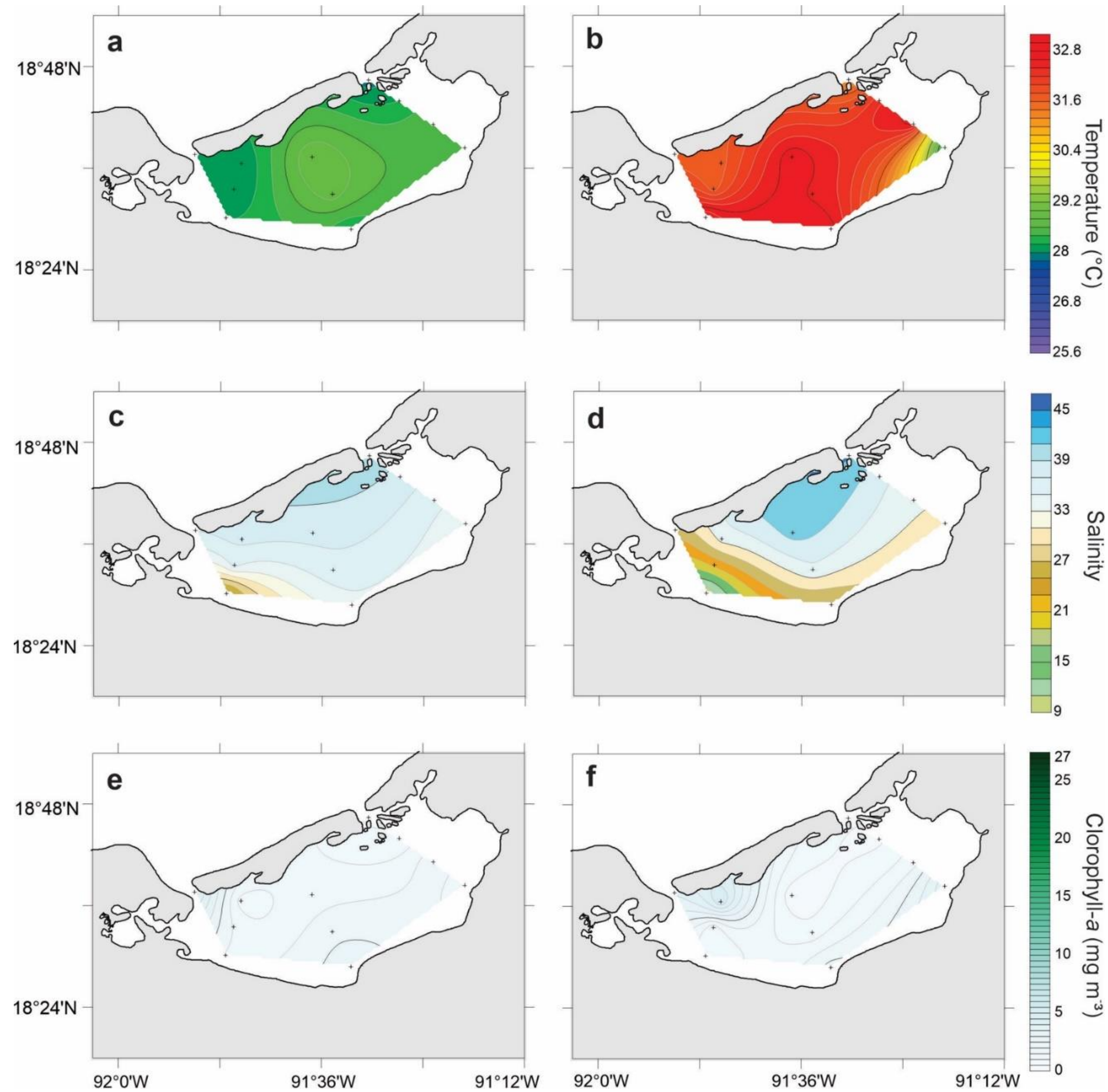

Figure 4. Horizontal distribution of selected hydrographic parameters recorded in 2023: a) temperature (ºC) in April, b) temperature (ºC) in October, c) salinity in April, d) salinity in October, e) chlorophyll-*a* levels (mg m^{-3}) in April, and f) chlorophyll-*a* (mg m^{-3}) levels in October.

as a Ramsar site, it is a priority area for studies that analyze phytoplankton seasonal variability and how it responds to large-scale processes, such as ENSO events. Studies on ecological aspects of phytoplankton inside the lagoon are scarce. However, it is known that the TL hosts a high richness and abundance of phytoplankton, whose variability is linked to changes that occur in the environment throughout the year; furthermore, it is known that phytoplankton biomass inside TL is highly variable, mainly related to changes in salinity and temperature levels (Gómez-Aguirre 1974, Yáñez-Arancibia & Day 1982, Day et al. 1982, Rojas-Galaviz et al. 1992, López-Mejía et al. 2022). Our results showed marked variability in the hydrographic properties of the water column in response to the confluence of ENSO events between 2022 and 2023: a strong La Niña event and an El Niño event, respectively. This transition between cold and warm phases was related to an increase in the temperature levels of 2.9ºC between October 2022 and October 2023. Salinity levels also showed differences, with an increase of 9.2 between October 2022 and 2023, possibly related to higher evaporation due to the increase in temperature and a reduction in the flow of freshwater into the lagoon, as was previously pointed out by Fichez et al. (2019). Chl-*a* values seemed to respond to this dynamic, decreasing their mean values by 0.55 mg m^{-3} between the same periods. Additionally, important differences were observed in the maximum values of Chl-*a* between April 2022 and April 2023, with 26.98 and 4.74 mg m^{-3}, respectively.

The trend observed in our study, with an increase in temperature and salinity levels associated with a decrease in Chl-*a* concentration as a function of the presence of ENSO events, is consistent with previous studies carried out in coastal environments around the globe. Indeed, in the Korea/Tsushima strait (north-western Pacific), strong increases/decreases in the Chl-*a* levels associated with decreases/increases in surface temperature have been reported as a consequence of La Niña/El Niño events, respectively (Jung et al. 2022). In the Río de la Plata estuary (southeastern South America), the presence of El Niño generates changes in the phytoplankton structure, including a significant reduction in diversity values and a noticeable decrease in the phytoplankton biomass (Sathicq et al. 2015). In the Mazatlán coastal region (eastern Gulf of California), the presence of El Niño increases the surface temperature levels (>30ºC), reducing Chl-*a* concentrations to values of barely 0.2 mg m^{-3}; in contrast, the presence of La Niña considerably increases the concentration of Chl-*a* (>10 mg m^{-3}) (Durán-Campos et al. 2023). In the coastal region of the northern Gulf of Mexico, ENSO events have been pointed out as the main agents of disturbances in the salinity levels, which in turn induces strong changes in the seasonal patterns of mixing/stratification along the water column affecting coastal circulation over the Louisiana-Texas shelf, and thus modulate the regional plankton biomass (Gomez et al. 2019).

Our results also showed interesting variability in the horizontal distribution of the temperature, salinity, and Chl-*a* levels during 2022 and 2023 in relationship with La Niña and El Niño events, respectively. Indeed, the temperature was considerably higher in October 2023 (Fig. 4) compared to 2022 (Fig. 3), and salinity levels also showed marked differences between both years. The above impacted the trophic state of the region, generating very low Chl-*a* concentrations in 2023 compared to 2022. A similar trend was observed by Fichez et al. (2019), who documented that during the 2009/2010 El Niño event, the flow of freshwater into the lagoon decreased considerably, which generated changes in salinity, declining Chl-*a* concentrations inside the lagoon, as our case. Although we do not have information on the taxonomic phytoplankton composition during our samplings, it is relatively well-known that diatoms are the dominant organisms in the region. Considering the wide pigment spectrum these organisms host (Jeffrey et al. 2012), it is highly probable that this group of organisms mostly contributed to Chl-*a* in our study.

Wilcoxon's signed rank tests showed that Chl-*a* concentrations significantly differed between La Niña 2022 and El Niño 2023. The Mantel tests further confirmed this, showing that the environmental conditions significantly differed inter- and intra-annually, as they showed poor correlation values.

It is currently recognized that ENSO events, particularly their warm phase (El Niño), present an upward trend. They will become increasingly intense and recurrent due to global warming (Ham 2018). Therefore, it is imperative to increase the oceanographic monitoring capacity and thus be able to identify changes in the productivity of organisms located at the base of the trophic chains, in this case, phytoplankton, which will affect higher trophic levels. Studies on phytoplankton biomass and its relationship with the physical configuration of the water column have gained relevance in recent years around the world, both in coastal and oceanic environments; however, even more are needed. There are still many controversies and gaps to fill about the role that large-scale processes, such as ENSO, play in the phytoplankton biomass of oceanic and coastal environments of the Gulf of Mexico, particularly in their southern portion, owing to the footprint of each ENSO event, whether El Niño or La Niña, is quite different reflecting miscellaneous repercussions (McPhaden et al. 2021). On the other hand, the impact of some events, such as the North Atlantic Oscillation (NAO) on the phytoplankton communities of the Gulf of Mexico, remains unexplored. In this sense, implementing long-term monitoring strategies involving multidisciplinary measurements becomes imperative, intending to get a complete picture of the ecosystems that allow us to establish their current ecological state; this is of high relevance in a context of global change in which numerous environments are threatened and, particularly in those environments recognized for their high species richness as is the case of TL, it becomes even more necessary.

Credit author contribution

Y. Hernández-Moreno: conceptualization, methodology, formal analysis, writing-original draft, review, and editing; E. Coria-Monter: conceptualization, validation, methodology, formal analysis, writing-original draft, funding acquisition, project administration, supervision, review, and editing; E. Durán-Campos: conceptualization, validation, methodology, formal analysis, writing-original draft, funding acquisition, supervision, review, and editing; M.A. Monreal-Gómez: conceptualization, validation, methodology, formal analysis, writing-original draft, funding acquisition, supervision, review, and editing; D.A. Salas-de-León: conceptualization, validation, methodology, formal analysis, writing-original draft, supervision, review, and editing; B. Quiroz-Martínez: conceptualization, validation, methodology, formal analysis, writing-original draft; funding acquisition, project administration, super-vision, review, and editing.

Conflict of interest

The authors declare no potential conflict of interest in this manuscript.

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REFERENCES

Barreiro-Güemes, M.T. & Aguirre-León, A. 1999. Distribución espacio-temporal de la biomasa fitoplánctica en el sistema lagunar Pom-Atasta, Campeche, México. Revista de Biología Tropical, 47: 27-35.

Basu, S. & Mackey, K.R.M. 2018. Phytoplankton as key mediators of the biological carbon pump: Their responses to a changing climate. Sustainability, 10: 869. doi: 10.3390/su10030869

Canales-Delgadillo, J.C., Perez-Ceballos, R., Zaldivar-Jimenez, M.A., Merino-Ibarra, M., Cardoza, G. & Cardoso-Mohedano, J.G. 2019. The effect of mangrove restoration on avian assemblages of a coastal lagoon in southern Mexico. PeerJ, 7: e7493. doi: 10.7717/peerj.7493

Castellanos-Pérez, P.J., Vázquez-Maldonado, L.E., Ávila, E., Cruz-Barraza, J.A. & Canales-Delgadillo, J.C. 2020. Diversity of mangrove root-dwelling sponges in a tropical coastal ecosystem in the southern Gulf of Mexico region. Helgoland Marine Research, 74: 13. doi: 10.1186/s10152-020-00545-6

Clarke, K.R. & Ainsworth, M.A. 1993. Method and linking multivariate community structure to environmental variables. Marine Ecology, 92: 205-219.

Conan, P., Pujo-Pay, M., Agab, M., Calva-Benitez, L., Chifflet, S., Douillet, P., et al. 2017. Biogeochemical cycling and phyto- and bacterioplankton communities in a large and shallow tropical lagoon (Términos Lagoon, Mexico) under 2009-2010 El Niño Modoki drought conditions. Biogeosciences, 14: 959-975. doi: 10.5194/bg-14-959-2017

Contreras-Ruiz, E.A., Douillet, P. & Zavala-Hidalgo, J. 2014. Tidal dynamics of the Terminos Lagoon, Mexico: Observations and 3D numerical modelling. Ocean Dynamics, 64: 1349-1371. doi: 10.1007/s10236-014-0752-3

Coria-Monter, E. & Durán-Campos, E. 2015. Proximal analysis of seagrass species from Laguna de Términos, Mexico. Hidrobiológica, 25: 249-255.

Coria-Monter, E., Monreal-Gómez, M.A., Salas-de-León, D.A. & Durán-Campos, E. 2018. Impact of the "Godzilla El Niño" Event of 2015-2016 on sea-surface temperature and chlorophyll-*a* in the southern Gulf of California, Mexico, as evidenced by satellite and *in situ* data. Pacific Science, 72: 411-422. doi: 10.2984/72.4.2

Cullen, J.J. 2015. Subsurface chlorophyll maximum layers: enduring enigma or mystery solved? Annual Review of Marine Science, 7: 207-239. doi: 10.1146/annurev-marine-010213-135111

Davies, C., Ajani, P., Armbrecht, L., Atkins, N., Baird, M.E., Beard, J., et al. 2018. A database of chlorophyll *a* in Australian waters. Scientific Data, 5: 180018. doi: 10.1038/sdata.2018.18

Day, Jr., J.W., Day, R.H., Barreiro, M.T., Ley-Lou, F. & Madden, C.J. 1982. Primary production in the Laguna de Terminos, a tropical estuary in the southern Gulf of Mexico. Oceanologica Acta, 5: 269-276.

Devi, K.N. & Sarangi, R.K. 2017. Time-series analysis of chlorophyll-a, sea surface temperature, and sea surface height anomalies during 2003-2014 with special reference to El Niño, La Niña, and Indian Ocean

Dipole (IOD) years. International Journal of Remote Sensing, 38: 5626-5639. doi: 10.1080/01431161.2017.1343511

Durán-Campos, E., Salas-de-Léon, D.A., Coria-Monter, E., Monreal-Gómez, M.A., Aldeco-Ramírez, J. & Quiroz-Martínez, B. 2023. ENSO effects in the southern Gulf of California estimated from satellite data. Continental Shelf Research, 266: 105084. doi: 10.1016/j.csr.2023.105084

Durazo, R., Gaxiola-Castro, G., Lavaniegos, B., Castro-Valdez, R., Gómez-Valdés, J. & Mascarenhas Jr., A. da S. 2005. Oceanographic conditions west of the Baja California coast, 2002-2003: A weak El Niño and subarctic water enhancement. Ciencias Marinas, 31: 537-552. doi: 10.7773/cm.v31i3.43

Fall, L.M. & Olszewski, T.D. 2010. Environmental disruptions influence taxonomic composition of brachiopod paleocommunities in the Middle Permian Bell Canyon Formation (Delaware Basin, west Texas). PALAIOS, 25: 247-259. doi: 10.2110/palo. 2009.p09-091r

Fichez, R., Linares, C., Chifflet, S., Conan, P., Contreras-Ruiz-Esparza, A., Denis, L., et al. 2019. Spatio-temporal variability in Terminos Lagoon (Mexico) waters during the 2009-2010 drought reveals upcoming trophic status shift in response to climate change. Regional Environmental Change, 19: 1787-1799. doi: 10.1007/s10113-019-01519-2

Forcino, F.L., Ritterbush, K.A. & Stafford, E.S. 2015. Evaluating the effectiveness of the Mantel test and Procrustes randomization test for exploratory ecological similarity among paleocommunities. Paleogeography, Palaeoclimatology, Palaeoecology, 426: 199-208. doi: 10.1016/j.palaeo.2015.03.023

Gomez, F.A., Lee, S-K., Hernandez Jr., F.J, Chiaverano, L.M., Muller-Karger, F.E., Liu, Y., et al. 2019. ENSO-induced co-variability of salinity, plankton biomass and coastal currents in the northern Gulf of Mexico. Scientific Reports, 9: 178. doi: 10.1038/s41598-018-36655-y

Gómez-Aguirre, S. 1974. Reconocimientos estacionales de hidrología y plancton en la Laguna de Términos, Campeche, México (1964/1965). Anales del Centro de Ciencias del Mar y Limnología-Universidad Nacional Autónoma de México, 1: 61-82.

Gómez-Ponce, M.A., Coria-Monter, E., Flores-Coto, C., Canales-Delgadillo, J.C., Cardoso-Mohedano, J.G. & Durán-Campos, E. 2021. Seasonal and interannual variability in the density of the postlarvae of *Litopenaeus setiferus* and *Farfantepenaeus duorarum* in Términos Lagoon, Gulf of Mexico. Crustaceana, 94: 1263-1281. doi: 10.1163/15685403-bja10154

Ham, Y.G. 2018. El Niño events will intensify under global warming. Nature, 564: 192-193. doi: 10.1038/d41586-018-07638-w

Instituto Nacional de Estadística y Geografía (INEGI). 2023. Número de habitantes por municipio. INEGI, Aguascalientes. [https://www.inegi.org.mx/app/areas-geograficas]. Reviewed: October 24, 2023.

Jeffrey, S.W., Wright, S.W. & Zapata, M. 2012. Microalgal classes and their signature pigments. In: Roy, S., Llewellyn, C.A., Egeland, E.S. & Johnsen, G. (Eds.) Phytoplankton pigments, characterization, chemotaxonomy and applications in oceanography. Cambridge University Press, New York, pp. 3-77.

Jung, Y., Park, J-H., Hirose, N., Yeh, S-W., Kim, K.J. & Ha, H.K. 2022. Remote impacts of 2009 and 2015 El Niño on oceanic and biological processes in a marginal sea of the northwestern Pacific. Scientific Reports, 12: 741. doi: 10.1038/s41598-021-04310-8

Keerthi, M.G., Prend, C.J., Aumont, O. & Lévy, M. 2022. Annual variations in phytoplankton biomass driven by small-scale physical processes. Nature Geoscience, 15: 1027-1033. doi: 10.1038/s41561-022-01057-3

Kennish, M.J. & Paerl, H.W. 2010. Coastal lagoons: Critical habitats of environmental change. In: Kennish, M.J. & Paerl, H.W. (Eds.). Coastal lagoons: Critical habitats of environmental change. CRC Press, New York, pp. 1-15.

Kennish, M.J. & Paerl, H.W. 2017. Coastal lagoons: Critical habitats of environmental change. CRC Press, Boca Ratón.

Lavaniegos, B.E., Jiménez-Pérez, L.C. & Gaxiola-Castro, G. 2002. Plankton response to El Niño 1997-1998 and La Niña 1999 in the southern region of the California Current. Progress in Oceanography, 54: 33-58.

Lavaniegos, B.E., Gaxiola-Castro, G., Jiménez-Pérez, L.C., González-Esparza, M.R., Baumgartner, T. & García-Cordova, J. 2003. 1997-98 El Niño effects on the pelagic ecosystem of the California Current off Baja California, Mexico. Geofísica Internacional, 42: 483-494.

Legendre, P. & Legendre, L.F. 2012. Numerical ecology. Elsevier, Amsterdam.

León, V.M., Moreno-González, R., González, E., Martínez, F., Gacría, V. & Campillo, J.A. 2013. Interspecific comparison of polycyclic aromatic hydrocarbons and persistent organochlorine bioaccumulation in bivalves from a Mediterranean coastal lagoon. Science of the Total Environment, 463-464: 975-987. doi: 10.1016/j.scitotenv.2013.06.075

López-Mejía, D., Gutiérrez-Mendieta, F.J., Zavala-Hurtado, J.A., Siqueiros-Beltrones, D.A., Varona-

Cordero, F. & Herrera-Moro-Chao, I.R. 2022. Physicochemical gradients in a coastal lagoon from the southern Gulf of Mexico; a multivariate approach. Regional Studies in Marine Science, 52: 102284. doi: 10.1016/j.rsma.2022.102284

Mantel, N. 1967. The detection of disease clustering and a generalized regression approach. Cancer Research, 27: 209-220.

McPhaden, M.J., Santoso, S. & Cai, W. 2021. Introduction to El Niño Southern Oscillation in a changing climate. In: McPhaden, M.J., Santoso, A. & Cai, W. (Eds.). El Niño Southern Oscillation in a changing climate. American Geophysical Union, Washington D.C.

Odum, E.P. & Barrett, G.W. 2005. Fundamentals of ecology. Thomson Brooks/Cole, Belmont.

Parsons, T.R., Maita, Y. & Lalli, C.M. 1984. A manual of chemical and biological methods for seawater analysis. Pergamon Press, Oxford.

Paz-Ríos, C.E., Sosa-López, A. & Torres-Rojas, Y.E. 2023. Spatiotemporal configuration of hydrographic variability in Terminos Lagoon: Implications for fish distribution. Springer, Berlin.

Racault, M.-F., Sathyendranath, S., Brewin, R.J.W., Raitsos, D.E., Jackson, T. & Platt, T. 2017. Impact of El Niño variability on oceanic phytoplankton. Frontiers in Marine Science, 4: 133. doi: 10.3389/fmars.2017.00133

Rojas-Galaviz, J.L., Yáñez-Arancibia, A., Day Jr., J.W. & Vera-Herrera, F.R. 1992. Estuarine primary producers: Laguna de Terminos - a study case. In: Seeliger, U. (Ed.). Coastal plant communities of Latin America. Academic Press, San Diego, pp. 141-154.

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Sathicq, M.B., Bauer, D.E. & Gómez, N. 2015. Influence of El Niño Southern Oscillation phenomenon on coastal phytoplankton in a mixohaline ecosystem in southeastern South America: Río de la Plata estuary. Marine Pollution Bulletin, 98: 26-33. doi: 10.1016/j.marpolbul.2015.07.017

Soria-Barreto, M., Pérez-Ceballos, R., Zaldívar-Jiménez, A. & Gelabert-Fernández, R. 2023. Assessment of aquatic food web and trophic niche as a measurement of recovery function in restored mangroves in the southern Gulf of Mexico. PeerJ, 11: e15422. doi: 10.7717/peerj.15422

Strickland, J.D.H. & Parsons. T.R. 1972. A practical handbook of seawater analysis. Fisheries Research Board of Canada, 167: 293 pp.

Wilkerson, F.P., Dugdale, R.C., Marchi, C. & Collins, C.A. 2002. Hydrography, nutrients, and chlorophyll during El Niño and La Niña 1997-1999 winters in the Gulf of the Farallones, California. Progress in Oceanography, 54: 283-310.

Wolter, K. & Timlin, M.S. 2011. El Niño/Southern Oscillation behavior since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). International Journal of Climatology, 31: 1074-1087.

Yáñez-Arancibia, A. & Day Jr., J.W. 1982. Ecological characterization of Términos Lagoon, a tropical lagoon-estuarine system in the Southern Gulf of Mexico. Oceanologica Acta, 5: 431-440.