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Short Communication

Early signals of El Niño 2023 in the Gulf of California?

Elizabeth Durán-Campos[1] & Erik Coria-Monter[1]
[1]Instituto de Ciencias del Mar y Limnología
Universidad Nacional Autónoma de México, México
Corresponding author: Erik Coria-Monter (coria@cmarl.unam.mx)

ABSTRACT. After a long La Niña event (2020-2023), the US National Oceanographic and Atmospheric Administration warned of a quick transition to an El Niño phase. As a monitoring of sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*) levels in the Gulf of California, Mexico, this study aims to show the evolution of both parameters during the first seven months of 2023. It compares them with the first seven months of 2015 when an extreme El Niño event occurred. Satellite data from the Moderate Resolution Imaging Spectroradiometer were obtained from which maps of both variables were constructed to quantitatively assess the changes in the SST and the Chl-*a* levels during the selected periods. Satellite data/pixels were extracted from the southern region of the gulf, in the connection between the gulf and the open Pacific Ocean. The results showed a gradual increase in the SST values from February to July of 2023 with 20.43, 22.29, 22.77, 27.88, 28.72 and 31.64ºC, respectively (a thermal variation of 11.21ºC), while Chl-*a* levels showed a decrease over the same period, from 1.81, 1.10, 0.78, 0.24, 0.19 mg m^{-3} to unusually low values of 0.11 mg m^{-3}, respectively (a reduction of 1.70 mg m^{-3}). A similar pattern was found in 2015, with increased SST and decreased Chl-*a*. Were the observed patterns in 2023 the early signals of El Niño in the Gulf of California?

Keywords: sea surface temperature; chlorophyll-*a*; satellite products; El Niño; southern Gulf of California

The El Niño Southern Oscillation (ENSO), one of the most noteworthy events in the Earth's climate system, has become a phenomenon that has received crucial attention in the last decades (McPhaden et al. 2021). Characterized by a warm phase known as El Niño and a cold phase known as La Niña, its effects have been well characterized in different environments around the world, and to date, the relationship between El Niño conditions and the advection of warm and oligotrophic waters that suppress the chlorophyll-*a* (Chl-*a*) levels is well established. Conversely, La Niña conditions have been associated with a cooling of the waters that promotes phytoplankton productivity (Park et al. 2011, 2014, Stramma et al. 2016).

In the Gulf of California, one of the ecosystems with the highest biological production levels on Earth and recognized for being an oasis of marine life, ENSO events have been studied in different phases, and there are still controversies about their impact on biological production. While some studies reported strong repercussions by the incursion of warm and oligotrophic waters inside the gulf by El Niño, other studies have postulated that its effects may not be so strong due to the multiple fertilization mechanisms that the gulf presents and "protect" it against the negative effects of El Niño. Indeed, collapses in the primary production levels have been reported by the advection of warm and oligotrophic waters related to El Niño (Zamudio et al. 2001). Besides, it has been reported that the phytoplankton distribution is affected by the advection of warm surface waters into the gulf, which induces a decrease in the silicoflagellates community structure (Pérez-Cruz & Molina-Cruz 1988). Dramatic SST increases of >4°C that caused a strong water column

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stratification and affected the marine organisms in the southern Gulf of California have also been reported (Obeso-Nieblas et al. 2004). More recently, an increase in SST levels (>27°C) impacted the phytoplankton biomass, inducing low Chl-*a* levels (<1 mg m^{-3}) (García-Morales et al. 2017). Conversely, some studies have reported that SST levels do not increase significantly. Chl-*a* does not decrease dramatically during El Niño events because the gulf presents several fertilization mechanisms (e.g. internal waves, eddies, upwellings, among others) than it does "protect" against the negative effects of El Niño (Coria-Monter et al. 2018). Additionally, no dramatic changes in the total fish larvae abundance have been reported during El Niño events (Sánchez-Velasco et al. 2017).

The period between 2020 and 2023 was characterized by a high dynamism in the Earth's climate system, going from neutral to cold (La Niña) to warm (El Niño) conditions. For example, the period between the second half of 2020 and the first three months of 2023 was characterized by a strong and long La Niña event. However, it was noticed that the climate system, in a quick transition, headed into a powerful El Niño event (Witze 2023), confirmed last June by the US National Oceanographic and Atmospheric Administration (NOAA); their consequences are still unknown.

The present study aims to report the SST and Chl-*a* levels in the Gulf of California during the first seven months of 2023. It compares them with the first seven months of 2015 to show possible similarities with the extreme El Niño event. The present study was primarily conducted using satellite data with a spatial resolution of 1 km/pixel obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS), intending to identify if was an early signal of El Niño 2023 in the SST and Chl-*a* levels of the Gulf of California and how was their evolution; our intention is also to establish a comparison criterion with the 2015 event to identify possible similarities.

The Gulf of California is the largest elongated interior sea of the North American Continent, encompassing more than 10º of latitude (Fig. 1a). It is delimited by the states of Sonora and Sinaloa (in the mainland of Mexico) to the east and by the Baja California Peninsula to the west with a widely variable bathymetry (Fig. 1b). The gulf is recognized as one of the most biodiverse seas around the world and for being the refuge, breeding, and feeding habitat of numerous emblematic species, many of them subject to special protection due to the threatened status of their populations. Due to its vast species richness, complex bathymetry, and high levels of biological production, the gulf is recognized as one of the main Large Marine Ecosystems in the world (Sherman & Hempel 2009). Currently, it is included in the World Heritage List of the United Nations Educational, Scientific and Cultural Organization.

The high biological diversity that the gulf supports is related to its hydrodynamics, which is characterized by the confluence of several processes that occur at different scales, linked to the supply of nutrients to the euphotic layer, benefiting the phytoplanktonic populations, and then, positively impacts the higher trophic levels (Álvarez-Borrego 2012). These processes include the propagation of internal waves (Gaxiola-Castro et al. 2002), intense tidal mixing (Salas-de-León et al. 2011), the presence of mesoscale cyclonic eddies (Serrano & Valle-Levinson 2021), and upwelling processes whose generation mechanisms are closely linked to wind pattern of the region (Lluch-Cota et al. 2000).

This study used satellite products at 1 km/pixel resolution obtained from the MODIS database (https://oceancolor.gsfc.nasa.gov). We selected the least cloudy days of the first seven months of the year 2023; we also selected the days with less cloudiness of the first seven months of 2015 to establish a comparison with the El Niño event that occurred in that year. Following the protocols described in Coria-Monter et al. (2018, 2019), data/pixels of SST and Chl-*a* were extracted using a standard algorithm and SeaDas 7.3.2 software (Baith et al. 2001). Finally, maps of both variables were constructed with MATLAB routines.

We also selected a polygon in the southern gulf defined by the coordinates 23-24ºN and 107-109ºW (rectangle in black in Fig. 1b) from which data/pixels of both variables were extracted to assess their variation in the indicated months and years quantitatively. Recent research (e.g. Coria-Monter et al. 2018, 2019, Durán-Campos et al. 2022) has confirmed that this methodology represents a good approach to monitoring ocean conditions in the Gulf of California and the Pacific Ocean because it is reliable, capable, and has a high resolution (1 km/pixel).

The satellite products selected in this study allowed us to observe interesting changes in the SST and Chl-*a* levels. Although cloudy conditions occurred on some days, observing their distribution patterns along the Gulf of California was possible. The selection of the polygon in the southern portion of the gulf also allowed us to assess the levels of both variables quantitatively.

In 2023, the SST values presented an interesting behavior during the first seven months of the year with an upward pattern since February (20.43ºC), March

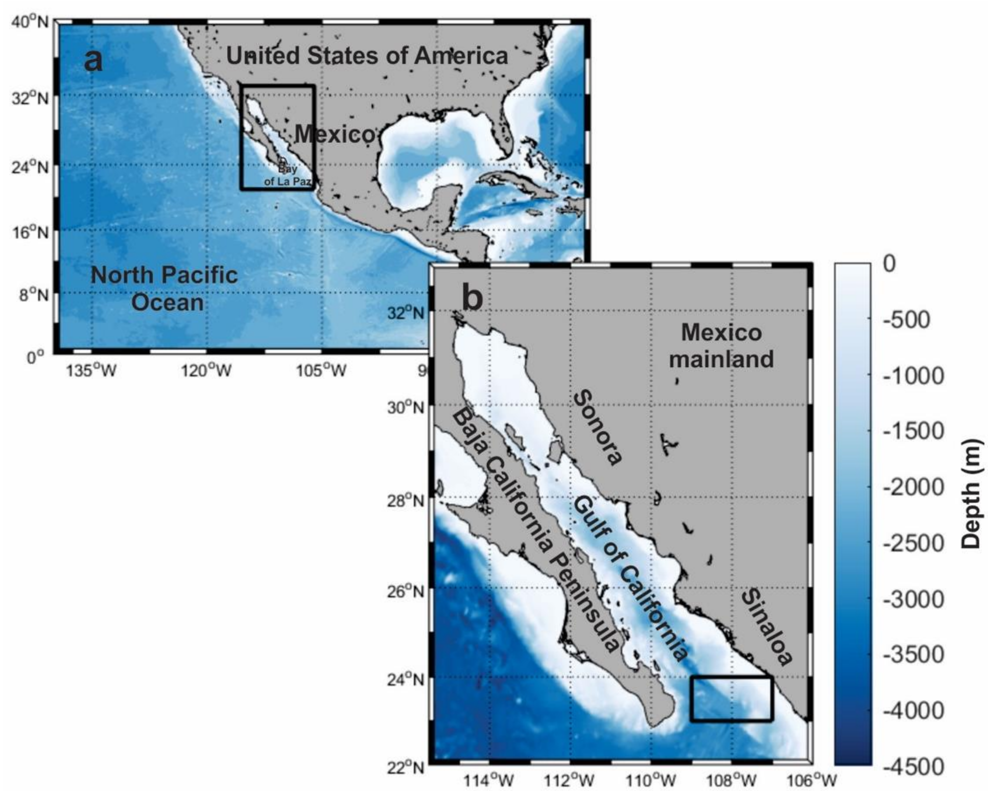

Figure 1. Study area. a) The North Pacific Ocean; the rectangle in black, shows the domain of interest in this study, the Gulf of California. b) The Gulf of California; the rectangle in black, shows the domain in which data/pixels were extracted from the satellite to quantitatively assess changes in sea surface temperature and chlorophyll-*a* levels during the years of interest of this study. Bathymetry is shown in meters.

(22.29ºC), April (22.77ºC), May (27.88ºC), June (28.7ºC) and July (31.64ºC), representing a thermal variation of 11.21ºC. The Chl-*a* levels showed a downward pattern from February (1.81 mg m^{-3}), March (1.10 mg m^{-3}), April (0.78 mg m^{-3}), May (0.24 mg m^{-3}), June (0.19 mg m^{-3}) and unusually low values observed in July (barely 0.11 mg m^{-3}), representing a reduction of 1.70 mg m^{-3} (Figs. 2, 4).

A similar pattern (increases in SST and decreases in Chl-*a*) to that observed in 2023 occurred in 2015, the year in which an extreme El Niño event took place; in this case the increases in the SST values occurred from March (22.96ºC), April (25.90ºC), May (28.25ºC), June (29.15ºC) and July (30.48ºC), with a thermal variation of 7.52ºC. The Chl-*a* levels showed a pattern of decrease from March (0.47 mg m^{-3}), April (0.30 mg m^{-3}), May (0.23 mg m^{-3}), June (0.19 mg m^{-3}), and July (0.17 mg m^{-3}), with a reduction of 0.3 mg m^{-3} (Figs. 3-4).

The satellite observations presented in this study and the approach applied to the generated dataset allowed us to identify very interesting patterns of variation in SST values and Chl-*a* levels during the first seven months of 2023 with a clear pattern towards an increase in the SST and a decrease in Chl-*a*. The thermal variation from February to July 2023 was 11.21ºC, reducing the Chl-*a* levels by 1.70 mg m^{-3}. Particularly in July, high SST values (31.64ºC) and unusually low Chl-*a* (barely 0.11 mg m^{-3}) could be interpreted as an early signal of the El Niño 2023 event. This pattern of variation was very similar to those observed during the first seven months of 2015 (Fig. 4), when an extreme El Niño took place, with a thermal variation in this case from March to July of 7.52ºC and a reduction in the Chl-*a* levels by 0.3 mg m^{-3}.

El Niño 2015 was indeed extreme, with strong repercussions in numerous ecosystems worldwide, and increases in SST and decreases in Chl-*a* due to the presence of this event were reported worldwide, including Mexican waters. Indeed, in the Gulf of Tehuantepec (Pacific Ocean), values higher than 31ºC and atypically low Chl-*a* levels (<0.1 mg m^{-3}) were reported by Coria-Monter et al. (2019). In the Gulf of California, García-Morales et al. (2017) reported high SST values (>27°C) that impacted the phytoplankton biomass, inducing low Chl-*a* levels (<1 mg m^{-3}).

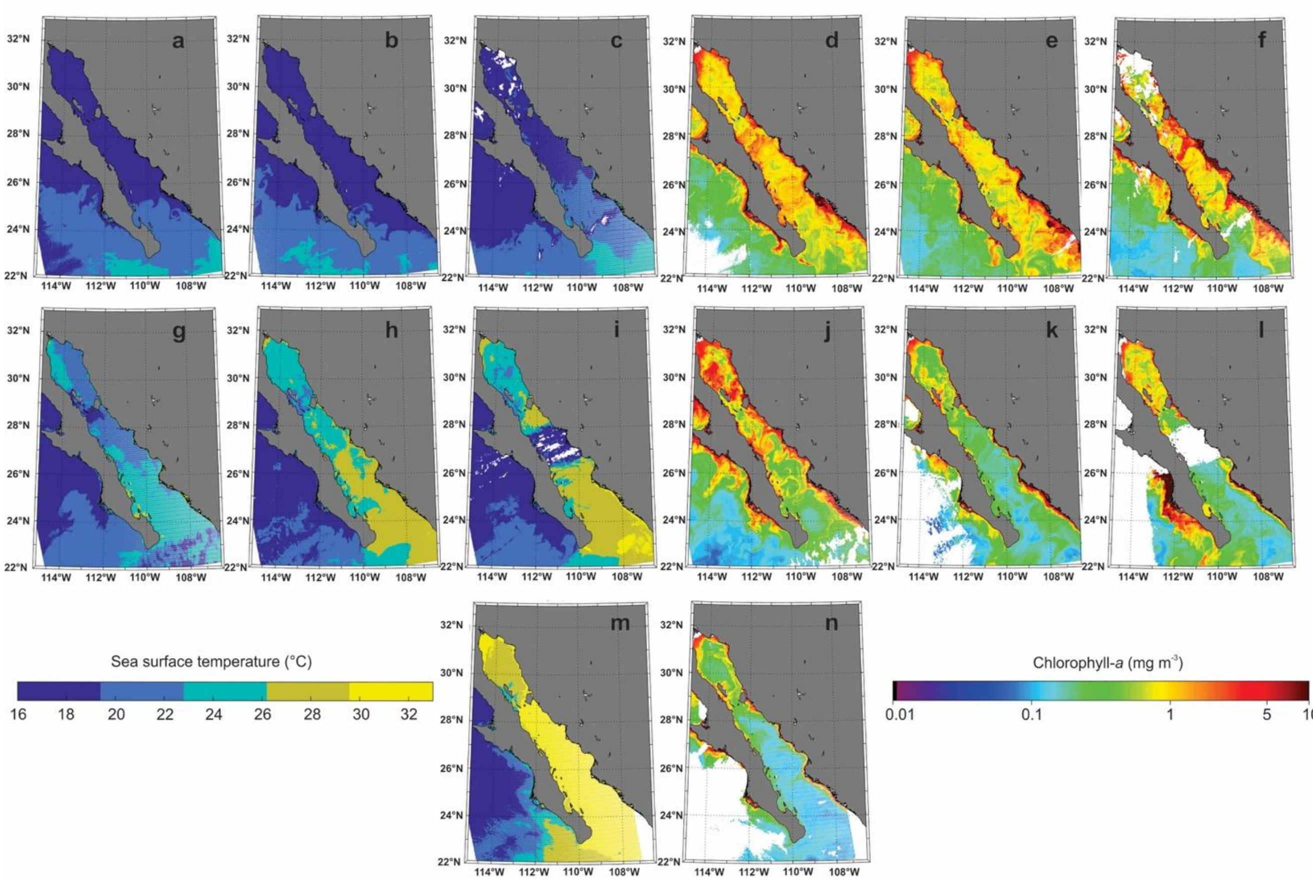

Figure 2. Satellite observations for one day cloud-free in the Gulf of California in the first seven months of 2023. Sea surface temperature (ºC): a) January 21, b) February 8, c) March 11, g) April 22, h) May 22, i) June 12, m) July 06. Chlorophyll-*a* levels (mg m^{-3}): d) January 21, e) February 08, f) March 11, j) April 22, k) May 22, l) June 12, n) July 06.

The impact of previous strong El Niño events has also been documented inside the Gulf of California. Indeed, during 1997-1998, El Niño reported increases in SST of >4°C (Obeso-Nieblas et al. 2004), and the phytoplankton distribution was affected by the advection of warm surface waters into the gulf with a decrease in the silicoflagellates community structure (Pérez-Cruz & Molina-Cruz 1988).

Herrera-Cervantes et al. (2010) analyzed historical El Niño events inside the gulf and their influence on satellite-derived Chl-*a*, showing a pattern of decrease in its concentration; the authors also noticed that the El Niño effects inside the gulf are not homogeneous, while the northern region is the most affected, the region of the islands shows the least variability. More recently, Herrera-Cervantes et al. (2020) analyzed the interannual variability of the surface satellite-derived Chl-*a* concentrations inside the Bay of La Paz in the southern Gulf of California, showing that the El Niño suppresses the Chl-*a* levels of the region due to the incursion of warm and oligotrophic waters towards the interior of the bay.

Due to the vast biological diversity that the Gulf of California supports, it becomes imperative to evaluate the effects that the system may present due to the confluence of large-scale processes, in this case, El Niño. Due to the high monetary and logistical costs posed by *in situ* observations, the use of satellite products has become a fundamental tool for synoptically monitoring different oceanographic variables, in this case, the SST and the Chl-*a*, the last because it is an indicator of phytoplankton biomass. It has repercussions in the upper trophic levels of the pelagic trophic web. The consequences of El Niño 2023 are still unknown. However, the pattern observed in this study (a thermal variation of 11.21ºC between February and July and a decline in the Chl-*a* levels by 1.70 mg m^{-3} in the same period) suggests that the 2023 event may be

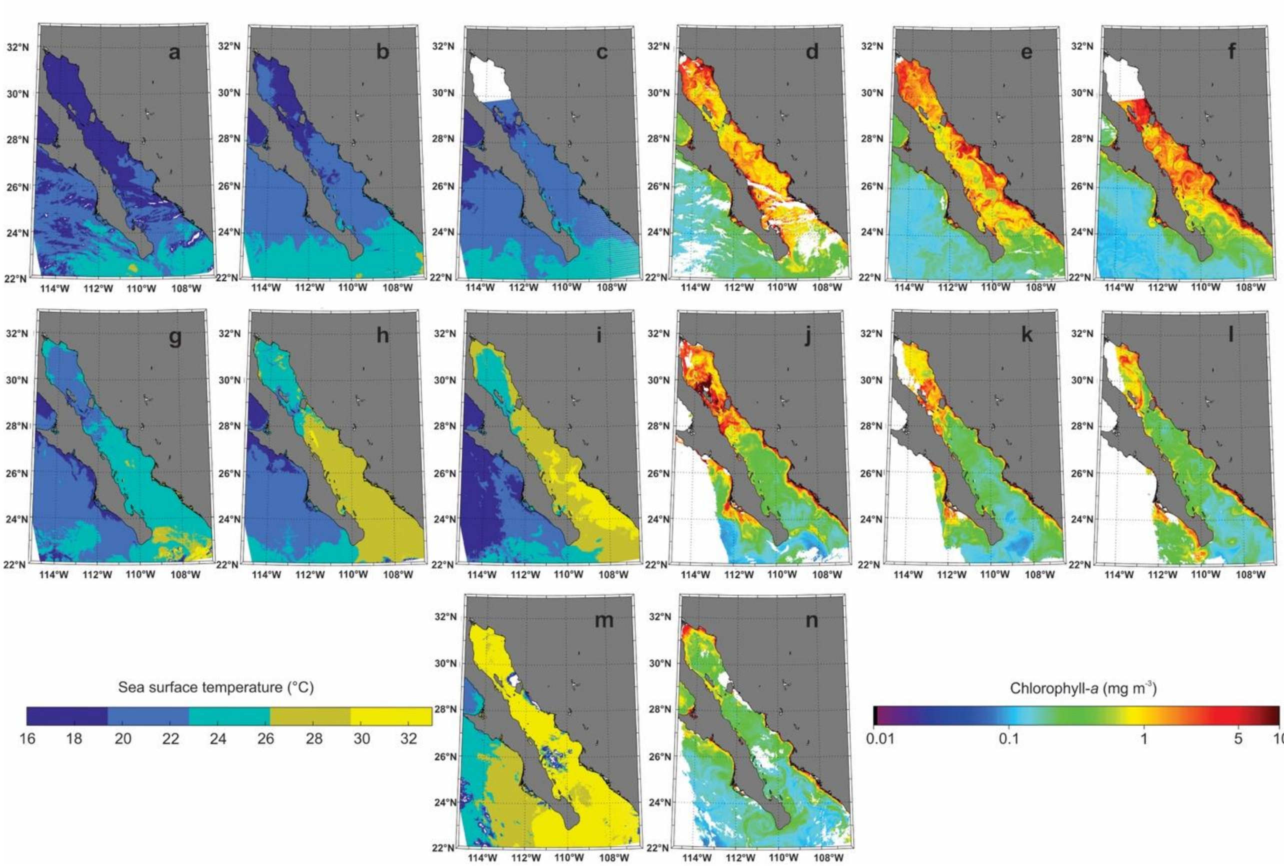

Figure 3. Satellite observations for one day cloud-free in the Gulf of California in the first seven months of 2015. Sea surface temperature (ºC): a) January 22, b) February 07, c) March 09, g) April 28, h) May 30, i) June 15, m) July 24. Chlorophyll-*a* levels (mg m^{-3}): d) January 22, e) February 07, f) March 09, j) April 28, k) May 30, l) June 15, n) July 24.

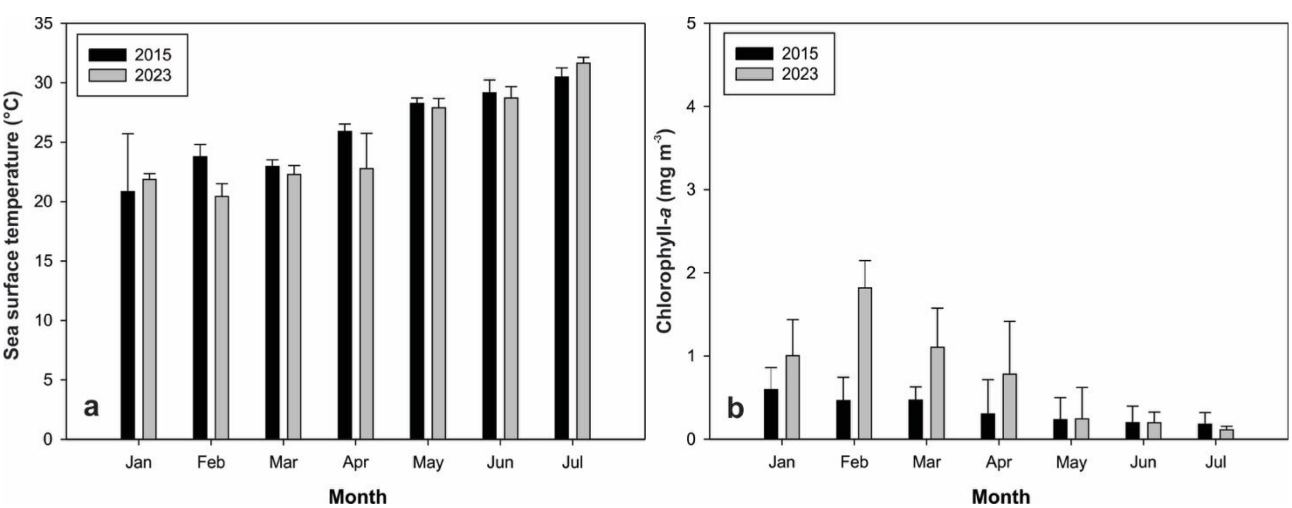

Figure 4. a) Sea surface temperature (°C) and b) chlorophyll-*a* (mg m^{-3}) values ± standard deviations in a domain of the southern Gulf of California (see rectangle in black in Figure 1b).

stronger than that in 2015. In this sense, it is imperative to focus monitoring efforts to identify the potential effects of El Niño 2023 in different environments worldwide, including those recognized for their extreme biological diversity, in this case, the Gulf of California.

Many of the potential consequences of ENSO events remain unknown. In this sense, it is imperative to monitor the evolution in the oceanographic conditions of the Gulf of California and adjacent ecosystems through *in situ* and satellite observations. Furthermore, numerous reanalysis products (e.g. ERA5) currently exist, which could provide valuable information to be compared and thus provide a more robust and complete vision of the impact of El Niño 2023.

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