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Research Article

Impact of "the Blob" 2014 and 2019 in the sea surface temperature and chlorophyll-*a* levels of the Gulf of California: a satellite-based study

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ABSTRACT. In 2014, an unexpected and unusual warm patch of ocean water was discovered in the northeast Pacific Ocean (PO) that moved south, reaching the Mexican coasts; this patch, returning in 2019, was nicknamed "the Blob". This paper aimed to assess the impacts of this phenomenon on the sea surface temperature (SST) and chlorophyll-*a* (CHLA) levels in the Gulf of California (GC), a high-productivity region. Daily satellite images of SST and CHLA with a spatial resolution of 1 km/pixel were obtained for 2014, 2017, and 2019 from the Moderate Resolution Imaging Spectroradiometer (MODIS). Two disc-shaped areas of around 25 km in diameter were selected in the southern portion of the GC to assess the variability of both parameters quantitatively. An additional site was selected in the PO for comparison and, thus, to better characterize and have a complete vision of these events. The results showed that in the PO, during the periods in which the Blob occurred, the SST values were higher concerning the neutral year (2017), and the levels of CHLA were very low (barely 0.15 mg m^{-3}). Within the GC, the results showed the presence of a strong seasonal variability, with maximum values of SST (>30°C) and the lowest concentrations of CHLA (<2 mg m^{-3}) during the summer, with maximum concentrations of CHLA (~10 mg m^{-3}) observed during the winter months. Contrary to expectations, no dramatic changes in SST and CHLA were observed during the years impacted by the Blob. This apparent absence of negative impacts could be related to different mechanisms in the gulf that "protect" to avoid climate disruptions. The presence of complex geomorphology and hydrodynamic processes at different scales induce mixing and fertilizing of the euphotic layer. Could these factors protect the southern gulf from the negative impacts of the Blob?

Keywords: the Blob; chlorophyll-*a*; sea surface temperature; Gulf of California

INTRODUCTION

The Gulf of California (GC) is a large marginal sea that extends more than 900 miles between the Baja California Peninsula and the mainland of Mexico (Coria-Monter et al. 2018) (Fig. 1). The GC is recognized as a sea with high productivity, mainly due to the confluence of several hydrodynamics processes which support an immense diversity of marine life, including emblematic, endemic, and endangered species such as sea turtles, sharks, the totoaba, and the vaquita (Lluch-Cota et al. 2007, Álvarez-Borrego 2012, Paéz-Osuna et al. 2017, Durán-Campos et al. 2019). As a whole, the GC hosts 39% of the total number of species of marine mammals in the world and one-third of the marine cetacean species (García-Morales et al. 2017a). The GC also contains more than 244 islands and islets, representing refuge and alimentation habitats for several species of seabirds (Lluch-Cota et al. 2007, Velarde et al. 2013). For these reasons, the GC is recog-

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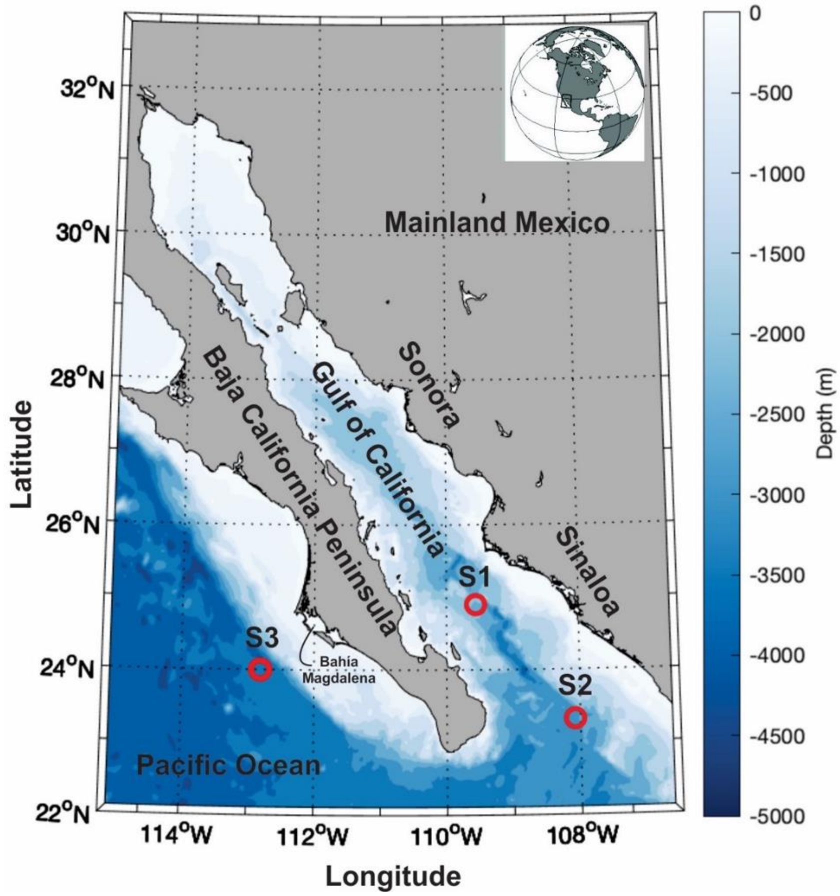

Figure 1. The Gulf of California study area. The red circles (S1, S2, and S3) represent areas roughly 25 km in diameter from which pixels/data were extracted from satellite images (see details in the Material and Methods section).

nized as the largest marine ecosystem in Latin America (Sherman & Hempel 2009), and in 2005 it was added to the World Heritage List of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

The GC is only not unique in terms of biodiversity, but it also has economic importance due to its support of high-value commercial species for the fishery industry, including tuna, sardines, squid, and shrimp, together totaling 60% of Mexico's annual catch (Arreguín-Sánchez et al. 2017). Additionally, the GC attracts over a million tourists yearly due to the pristine beaches, reefs, and wildlife (Johnson et al. 2019).

In its southern portion, the GC merges with the open Pacific Ocean (PO), which holds scientific interest due to the large-scale processes that occur in the eastern PO, and subsequently impact the entire GC. One of the major sources of the interannual and monthly variability in the region has been related to the El Niño Southern Oscillation (ENSO), mainly those events that took place in 1982/1983 and 1997/1998, which induced sea surface temperature (SST) anomalies with negative impacts on the primary productivity levels (Pérez-Cruz 2013). However, while ENSO represents a potential source of variability, the region is also subject to other large-scale processes that could occur along the PO.

In 2014, the National Oceanic and Atmospheric Administration (NOAA) reported an unexpected and unusually warm patch of ocean water in the northeast PO that extended from Alaska to southern California, reaching the Mexican coasts, and lasted for months; it was nicknamed "the Blob" (Bond et al. 2015). This unusual ocean warming was subject to intense research, and several implications for the marine ecosystem have been documented, including changes in the mixed layer depth and anomalies in salinity (Zhi et al. 2019), and net primary productivity rates (Yang et al. 2018), prompting changes in the Pacific bluefin tuna (*Thunnus orientalis*) population (Runcie et al. 2019). Additionally, unusual toxic algae blooms appeared, with fishes and crustaceans vanishing (Cornwall 2019).

In Mexican waters off the west coast of the Baja California Peninsula, changes in planktonic community composition and unusually low zooplankton biomass were documented during the Blob (Gómez-Ocampo et al. 2018, Lavaniegos et al. 2019). In Bahía Magdalena, located on the Pacific coast of Baja California, the Blob was characterized by an increase in the local temperature that abruptly diminished the input of nutrients from the ocean, impacting the planktonic ecosystem (Jiménez-Quiroz et al. 2019).

Eventually, the Blob broke up partly due to the "Godzilla El Niño" event that occurred in the equatorial Pacific in 2015 (Cornwall 2019). However, in 2019, a new marine heat wave appeared over off the west coast of North America, resembling the Blob of 2014.

This paper aims to assess the impact of "the Blob 2014" and "the Blob 2019" using SST and chlorophyll-*a* (CHLA) levels, the latter as a phytoplankton biomass indicator, derived from satellite observations in the southern GC. We hypothesize a clear reduction in the phytoplankton biomass, expressed as CHLA concentrations, due to increased SST in the region over time. This study contributes to the knowledge and understanding of the impacts of sudden extreme events and the responses of marine ecosystems, especially in areas of high biological productivity, such as the GC.

MATERIALS AND METHODS

In order to evaluate the seasonal variability of SST and CHLA in the GC, we used the L1 and L2 level data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) available on the National Aeronautics and Space Administration (NASA) website (www.oceancolor.gsfc.nasa.gov/). The clearest (cloudless) images for each month during 2014, 2017, and 2019 were selected for analysis. We chose 2017 as a control due to its neutral or no-Blob conditions. The images were used to compare and evaluate changes between Blobs' periods and the control year. The images were obtained with a spatial resolution of 1 km/pixel and initially processed using SeaDAS software version 7.4. Different flags/masks were applied to screen out bad or low-quality data, including 1) Cldice, 2) Land, 3) Straylight, and 4) Hilt. 1 and 2 must be applied to any MODIS L2 product, 3 is an indicator of the influence of the brightness of adjacent pixels on pixel reflectance values, while 4 must be flagged if any of the bands reach physical saturation (Prieri et al. 2015).

In order to quantitatively assess SST and CHLA in the target years, based on the satellite images acquired, two circular-shaped sites were selected in the southern GC: site 1 (S1, centered at 24°54'N and 109°33'W) and site 2 (S2, centered at 23°19'N and 108°05'W). An additional site (S3) was selected in the PO and centered at 24°N and 112°48'W to compare with the southern GC. All sites were fixed with an average diameter of around 25 km (red circles in Fig. 1), then values inside these sites were extracted and averaged to construct a time series for both variables. The sites inside the GC were selected in the southern region near its connection with the open PO. The sites were selected to exclude areas along the coastline, which could increase the uncertainties of MODIS-derived CHLA due to high levels of suspended material such as organic matter. This method has been successfully used to evaluate seasonal and interannual variability for parameters derived from satellite observations (Coria-Monter et al. 2018, 2019a).

RESULTS

The GC is a region characterized, in general, by low cloudiness, so satellite observations during the target years revealed a clear signal for both variables. Satellite images in 2014, when the Blob first appeared, showed a clear seasonal variability marked by SST values ranging from 16 to 22°C in winter, which induced high CHLA concentrations reaching 10 mg m^{-3}. During spring and summer, SST reached its maximum value (>30°C), particularly during July, August, and September, when high temperatures extended throughout the gulf. These high SST values correlated with low CHLA concentrations in the gulf, with values <2 mg m^{-3} (Fig. 2). Contrary to expectations, the SST values were not as extremely high as thought, and although CHLA values were low during the warmest months, they did not show a dramatic decline. The presence of CHLA filaments was observed in all images, indicative of the presence of mesoscale processes that occur in the region.

During 2017, the neutral year, cloudiness generated some gaps in the data, but it was possible to visualize a similar pattern as compared to those observed in 2014, with marked seasonal variability of both parameters. The lowest SST values occurred in winter and ranged from 16 to 22°C, correlated with high CHLA values (up to 10 mg m^{-3}). During summer, the maximum values of SST observed ranged from 24 to 32°C, with the highest temperatures recorded during July, August, and September inducing the lowest CHLA values (<2 mg m^{-3}). As observed in 2014, the presence of CHLA filaments was a common feature in the gulf (Fig. 3).

In 2019, the satellite images obtained for both parameters were similar to those observed in previous years, with a strong seasonal variability and the lowest values of CHLA (<3 mg m^{-3}) associated with the warmest months when high SST values (>30°C) were

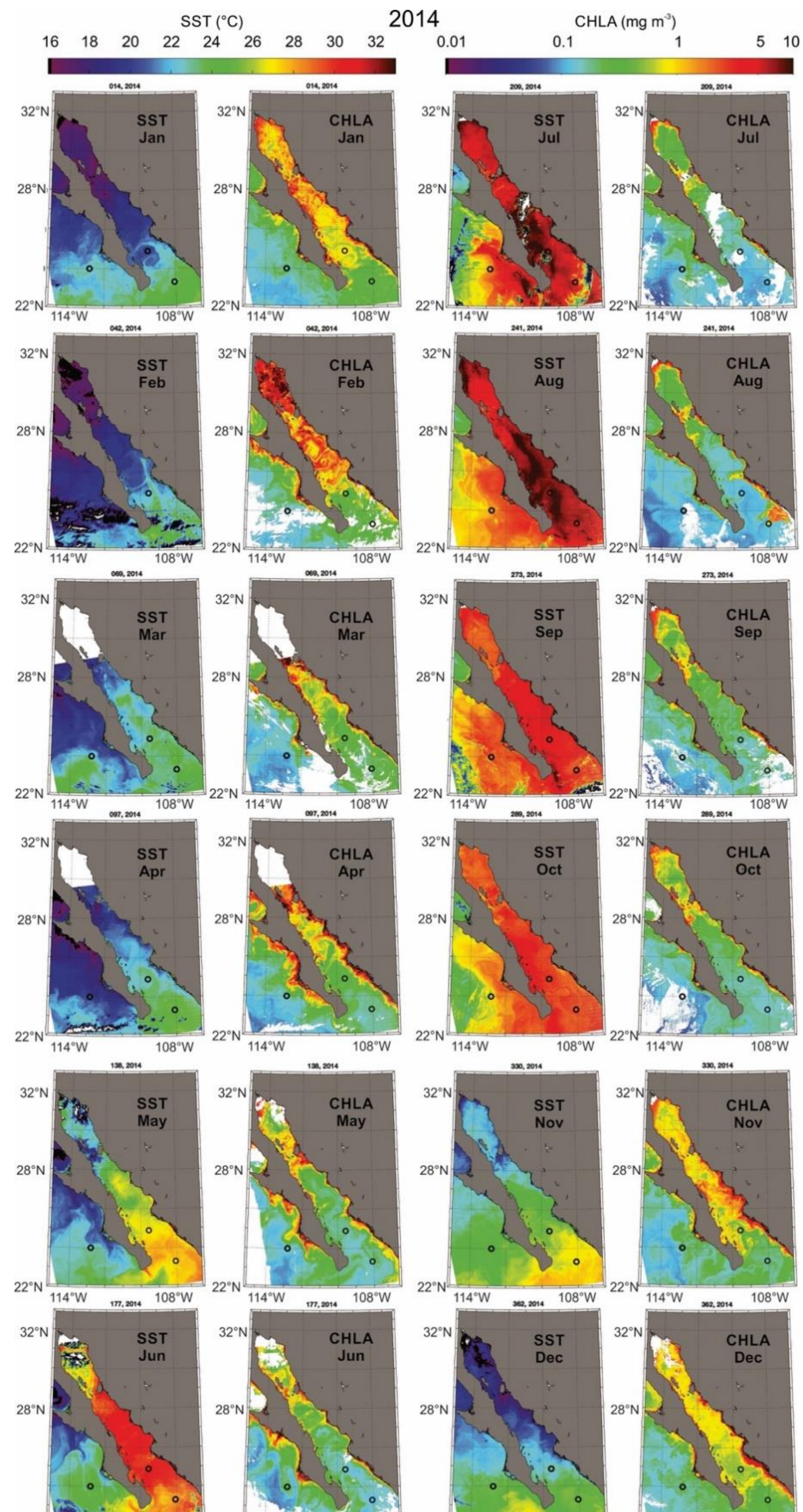

Figure 2. Satellite images of sea surface temperature (SST, °C) and chlorophyll-*a* (CHLA) concentrations (mg m^{-3}) for one cloud-free day each month during 2014.

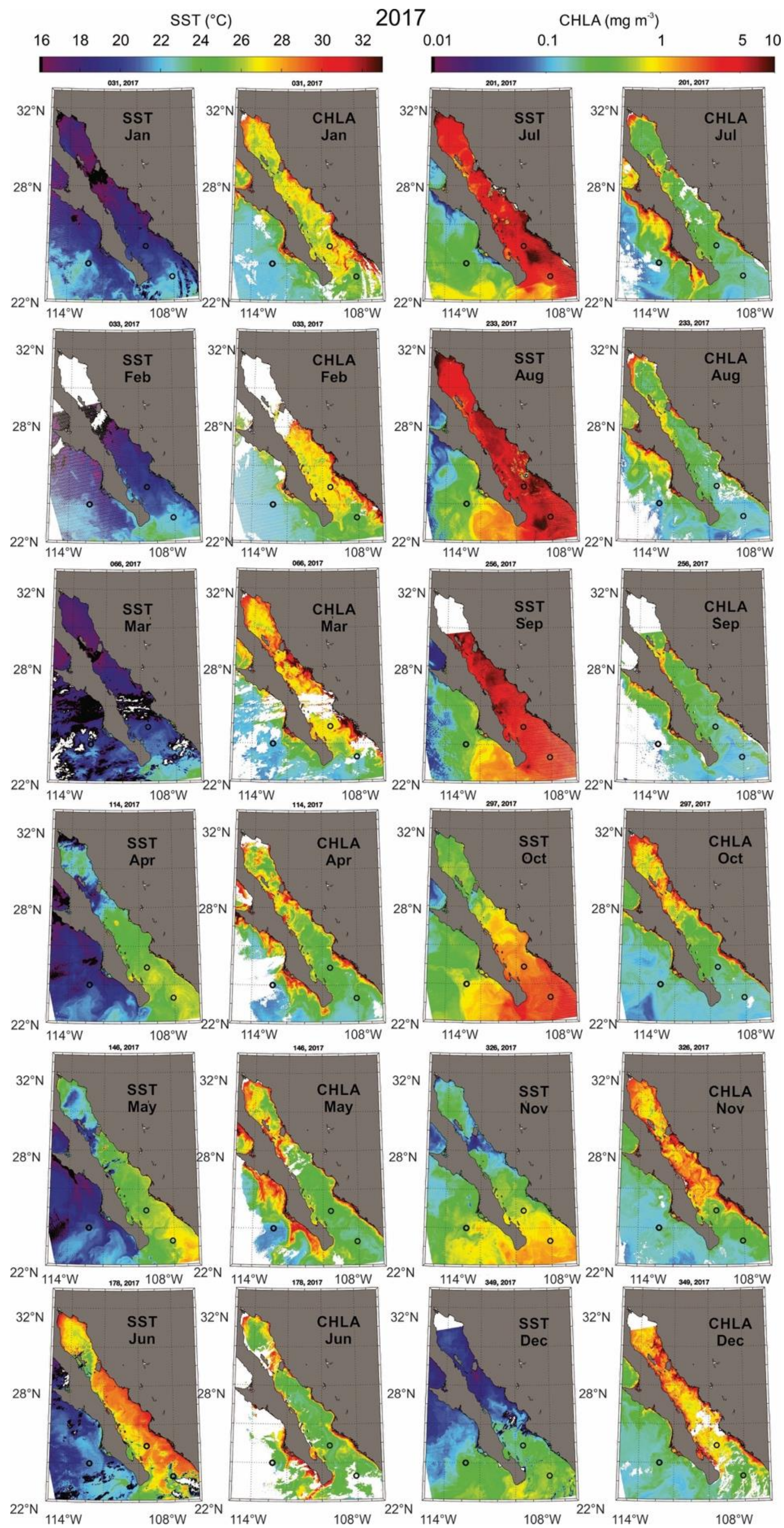

Figure 3. Satellite images of sea surface temperature (SST, °C) and chlorophyll-*a* (CHLA) concentrations (mg m^{-3}) for one cloud-free day each month during 2017.

observed. The CHLA maximum values (~10 mg m^{-3}) were observed during wintertime in association with low SST values. As observed in 2014, the SST values were not as high as expected, and although the CHLA values were low during the warmest months, they did not show a dramatic decline compared to the control year (Fig. 4).

The SST and CHLA values extracted in the three selected sites (S1, S2, and S3) confirmed the seasonal variability observed in the satellite images for the selected years and showed contrasting differences between sites. For example, in the southern GC (S1 and S2), the SST and CHLA values were higher than those observed in S3 because the GC is a semi-enclosed basin in which the SST values tend to increase, and is much more productive than the PO, due to the confluence of different physical processes, as mentioned above. In particular, in S1, higher SST values were observed in the summer months (>30°C), while the minimum values (~20°C) were observed during the winter (Fig. 5a). When comparing the months of August and September (when the Blob occurred) in the three selected years, it was observed that the values were very similar, and no dramatic increases in SST were observed. The CHLA levels showed a similar pattern, and even though during August of 2014, a slight decrease in the CHLA concentration was observed compared to 2017, this was not extreme; during September, the values were very similar (~0.2 mg m^{-3}) in the three selected years (Fig. 5b).

In S2, similar patterns to S1 were observed. For example, in 2014, high SST values (>30°C) were observed during the summer (Fig. 5c), which induced low CHLA values (~0.2 mg m^{-3}), and the highest CHLA during winter (>0.5 mg m^{-3}) were associated with the lowest SST values (<20°C) (Fig. 5d). Neither variable showed much change between the year of the Blob in 2014 and the control year, 2017. In 2019, the pattern was similar to those observed in the previous years, with maximum values of SST during the summer season associated with low CHLA levels, while the highest values of CHLA were observed during the wintertime, and no dramatic changes in SST values were observed as a consequence of the Blob in the year 2019 (Fig. 5c).

In the S3, which corresponds to the PO region, the SST values were higher during July, August, and September, according to the natural seasonal heating. However, the observed values were much higher during 2014 (>30°C) and 2019 (>28°C) compared to 2017 (~25°C), the neutral year (Fig. 5e). CHLA values were much lower concerning S1 and S2, with values of ~0.2 mg m^{-3} throughout the year. From July through October 2014, the values barely reached 0.15 mg m^{-3} (Fig. 5f).

Once the variability of SST and CHLA levels in the three selected years was quantitatively evaluated, monthly composites images of SST and CHLA were constructed for August 2014, 2017, and 2019 to compare the PO and the GC. August was selected because it was the period in which, based on Figures 2-4, heating in the superficial layer was observed, in agreement with those works that pointed out this period as the maximum overheating caused by the Blob (e.g. Bond et al. 2015).

In 2014, a large patch of warm water (up to 32°C) was observed in the PO region, which covers an important portion of the Baja California Peninsula (Fig. 6a), while CHLA levels showed very low concentrations of barely 0.15 mg m^{-3} (Fig. 6d). Inside the GC, high SST values (up to 32°C) were observed along the gulf, with high CHLA concentrations (>8 mg m^{-3}) in the northern portion and values of 0.5 mg m^{-3} in its southern region.

In 2017, the control year, the warm water patch observed in 2014 in the PO region was not evident. Within the GC, both SST and CHLA levels were very similar to what was observed in 2014, with high SST values (>30°C) and high CHLA concentrations (>8 mg m^{-3}) in the gulf northern portion. Even the SST showed values lower than 28°C (Fig. 6b); CHLA concentrations in this region were higher than in 2014, reaching values of >5 mg m^{-3} (Fig. 6e).

Inside the gulf, a similar pattern was observed for both variables compared to 2014 and 2017. In 2019, although a slight increase in SST was observed, the warm water patch was not as intense as that observed in 2014 (Fig. 6c), and CHLA concentrations presented values of >5 mg m^{-3} (Fig. 6f). Figure 6 confirms that, while marked increases in SST were observed in the PO with a consequent decrease in CHLA (in particular in 2014), no extreme increases in SST levels were observed inside the GC, and the CHLA concentrations were similar in the displayed three years.

DISCUSSION

Using satellite-derived products to analyze seasonal and interannual variability of SST and CHLA at large scales in the world's oceans has become an innovative tool, and to date, it is increasingly common in scientific literature. The use of satellite products to determine the impacts of large-scale hydrodynamic and meteorological processes associated with perturbations in the planktonic ecosystem, such as El Niño, has recently emerged as a tool to analyze, from a synoptic point of view, domains characterized by high biological productivity (Coria-Monter et al. 2018, 2019a). These

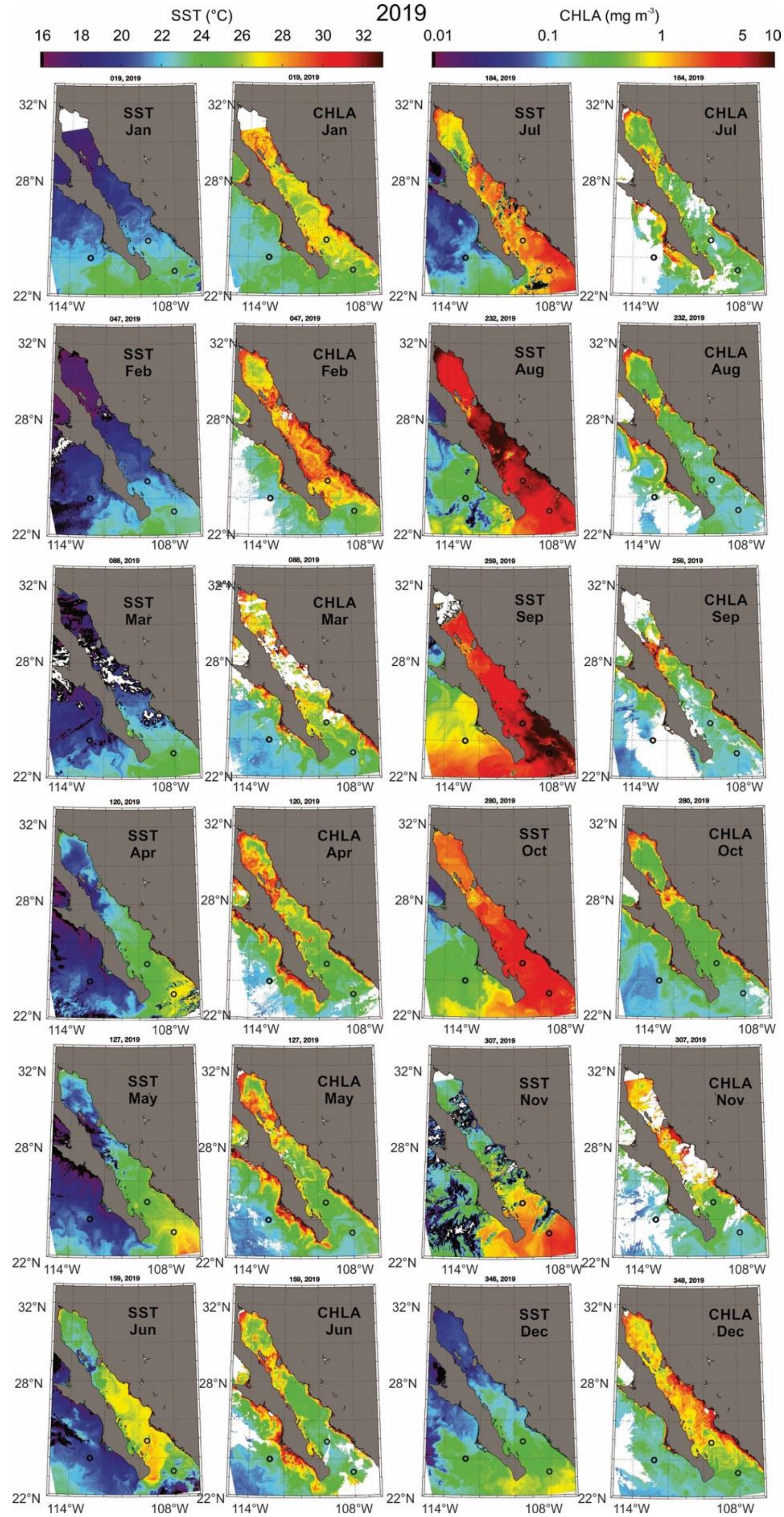

Figure 4. Satellite images of sea surface temperature (SST, °C) and chlorophyll-*a* (CHLA) concentrations (mg m^{-3}) for one cloud-free day each month during 2019.

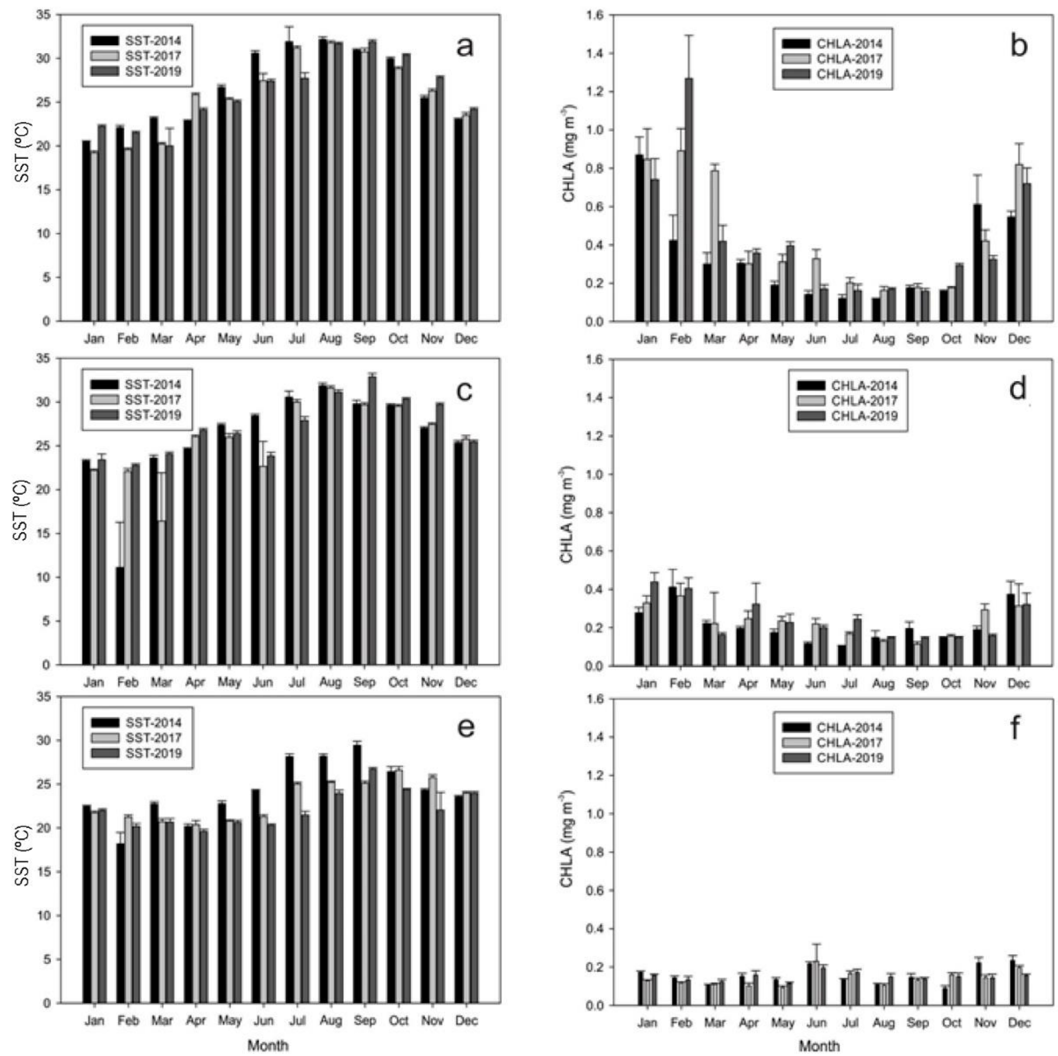

Figure 5. Extracted sea surface temperature (SST, °C) and chlorophyll-a (CHLA, mg m^{-3}) values ± standard deviations from the three selected sites (S1, S2, and S3) for 2014, 2017, and 2019. In S1, a) SST (°C) and b) CHLA (mg m^{-3}). In S2, c) SST (°C) and d) CHLA (mg m^{-3}). In S3, e) SST (°C) and f) CHLA (mg m^{-3}).

products can provide useful information to analyze the impacts of abrupt events, such as the Blob.

The Blob 2014 was indeed extreme, and to date, it is well recognized that this sudden phenomenon had strong repercussions on the marine ecosystem in different regions of the North American continent. In the Gulf of Alaska, perturbations in the distribution of different bottom-dwelling species were detected, inducing anomalous movements of these organisms to deeper waters (Yang et al. 2019). Off British Columbia in Canada, abrupt warming of surface waters (~4°C) was observed with significant changes in the composition and abundance of the phytoplankton structure induced by the advection of oligotrophic waters (Peña et al. 2019).

Along the west coast of the USA, particularly the coasts of Washington, Oregon, and California, the SST observed was significantly warmer than usual, reaching a maximum anomaly of 6.2°C and resulting in major disruptions in the California Current ecosystem with massive economic impacts (Gentemann et al. 2017). More than 12 species of copepods occurred in areas not previously observed in shelf waters off Oregon, transforming the lower trophic structure of the food chain. High abundances of doliolids (indicative of oligotrophic ocean conditions) were also recorded, and the occurrence of a toxic diatom bloom (genus *Pseudo-nitzschia*) was detected (Peterson et al. 2017). At Mission Bay (San Diego, CA), fish populations of economic importance were adversely affected (Basilio et al. 2017). In Mexican waters, particularly off the

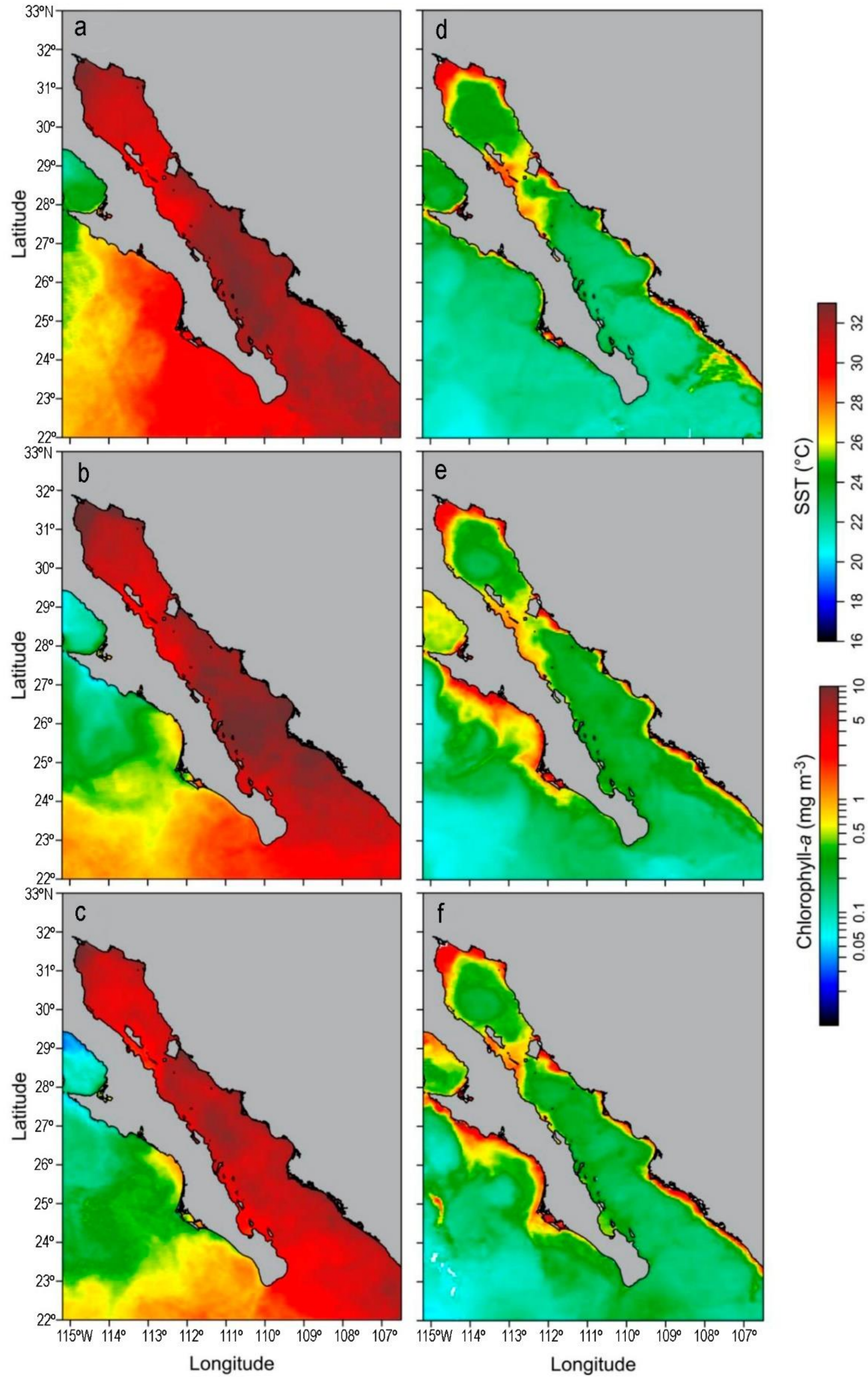

Figure 6. Monthly composite images of August: sea surface temperature (SST, °C) in a) 2014, b) 2017, c) 2019; and chlorophyll-*a* (CHLA, mg m^{-3}) in d) 2014, e) 2017, and f) 2019.

western coast of Baja California, the effects of the Blob were noticed. Dorantes-Gilardi & Rivas (2019) documented the advection of warm oligotrophic waters and low levels of CHLA along with a persistent weakening of the winds that support the upwelling process in the region. Lavaniegos et al. (2019) observed a 95% decrease in the abundance of euphausiids related to a decrease in the phytoplankton biomass. Gómez-Ocampo et al. (2018) reported anomalous warm conditions in the upper layers of the water column, dramatically reducing the phytoplankton biomass. Our results were very close to their values, with SST higher than 32°C and CHLA concentrations barely 0.15 mg m^{-3}.

Although the repercussions of this phenomenon were extreme throughout the North American continent, the results obtained in this study suggest that the Blob had no dramatic impact on the southern portion of the GC, as evidenced in both the analysis of satellite images and the time-series generated for two fixed locations in the southern portion of the gulf. The strong seasonal variability observed in the years analyzed reflects normal heating and cooling periods in the surface layers, which induce mixing and increase the availability of nutrients, leading to high CHLA values (Álvarez-Borrego 2012, Coria-Monter et al. 2018).

The southern GC has been documented as a region in which large-scale phenomena in the tropical Pacific have strong negative repercussions (such as El Niño Godzilla 2015/2016). For example, in the coastal waters of the eastern GC, García-Morales et al. (2017b) reported that during the El Niño 2015/2016 extreme event, an increase in SST levels (>27°C) impacted phytoplankton biomass, inducing low CHLA levels (<1.00 mg m^{-3}). More recently, using monthly 9 km resolution MODIS products in environments located on the eastern coast of the GC, Robles-Tamayo et al. (2018) showed a strong decrease in CHLA levels (<1.00 mg m^{-3}) during El Niño 2015/2016. However, although the region is subject to the advection of warm and oligotrophic water masses associated with ENSO phenomena, sometimes these are not usually as extreme inside the gulf, as was previously noted by Sánchez-Velasco et al. (2017) and Coria-Monter et al. (2018).

However, what makes the GC a productive area while inhibiting certain climate disruptions that could negatively impact it? The gulf is a large marginal sea with variable topography, including the presence of submarine canyons, basins, faults, and a very narrow or nonexistent continental shelf on the west side of the gulf but fairly broad on the east (Álvarez et al. 2009). The gulf contains several islands and islets with channels between them. This particular geomorphology, as a whole, constantly modifies the gulf's water circulation, promoting mixing, which fertilizes the euphotic zone and enhances productivity (Álvarez-Borrego 2012). The gulf also exhibits complex hydrodynamic processes, including strong tidal mixing and fronts (Lavin & Marinone 2003) and the occurrence of mesoscale eddies (Salas de León et al. 2011), and internal waves (Coria-Monter et al. 2019b). These processes have been related to the induction of nutrients into the euphotic zone with a noticeable impact on whole planktonic ecosystems.

Additionally, the GC is subject to wide seasonal and interannual variability in wind patterns, mainly due to the interactive atmosphere-ocean system, with northwesterly winds of high and persistent velocity (≥10 m s^{-1}) prevailing during the winter. In contrast, a southeasterly wind blows at approximately 5 m s^{-1}, with frequent calms during the summer (Monreal-Gómez et al. 2001). These wind patterns generate upwelling along the coasts and significantly impact all levels of the marine trophic web (Lluch-Cota 2000).

CONCLUSION

The satellite information presented in this study made it possible to identify some aspects of the GC's phytoplankton biomass (in terms of CHLA concentration) under sudden warming scenarios such as the Blob that occurred in 2014 and 2019. The evidence suggests that, while in the PO, increases in SST with a consequent decrease in phytoplankton biomass were observed, in the GC, no dramatic increases in SST were observed, followed by a decrease in the CHLA levels. As discussed above, this apparent lack of repercussions could be related to the oceanic dynamics of the GC that can "mask" these events and act as a "defense mechanism" against some potentially damaging processes. Keep in mind that this study assessment comes from satellite observations and corresponds only to the surface layer, the "skin of the ocean", without considering subsurface levels that could have had Blob repercussions. In this sense, to better understand the disruptive climate events significance around the world, such as the Blob, many more detailed observations (both *in situ* as well as derived from satellite) and numerical modeling are required to realistically evaluate the many aspects of these events and their impacts on the hydrographic properties of the water column and food-web dynamics, which is especially important in domains characterized by high biological productivity, such as the GC.

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