Interannual Spatial Variability of the Western Hemisphere Warm Pool and the Impacts on Marine Protected Areas in the Mexican Pacific

Authors: López-Magaña, Jorge, Hurtado-Oliva, Miguel Ángel, Guzón-Zatarain, Oscar, and Manzano-Sarabia, Marlenne

Source: Journal of Coastal Research, 38(2) : 319-327

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-21-00049.1

Journal of Coastal Research	38	2	319–327	Coconut Creek, Florida	March 2022

Interannual Spatial Variability of the Western Hemisphere Warm Pool and the Impacts on Marine Protected Areas in the Mexican Pacific

Jorge López-Magaña, Miguel Ángel Hurtado-Oliva, Oscar Guzón-Zatarain, and Marlenne Manzano-Sarabia*

Facultad de Ciencias del Mar
Universidad Autónoma de Sinaloa
Mazatlán, Sinaloa, México

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

López-Magaña, J.; Hurtado-Oliva, M.A.; Guzón-Zatarain, O., and Manzano-Sarabia, M., 2022. Interannual spatial variability of the western hemisphere warm pool and the impacts on marine protected areas in the Mexican Pacific. *Journal of Coastal Research,* 38(2), 319–327. Coconut Creek (Florida), ISSN 0749-0208.

The Western Hemisphere Warm Pool is the second warmest body of water on Earth and has been highlighted according to its significant influence on ocean and atmosphere components. This study focuses on the comparison of the interannual spatial variability of the Western Hemisphere Warm Pool in the Eastern Pacific (WHWP-EP) according to satellite-derived data from the Advanced Very High Resolution Radiometer. Secondly, the response of chlorophyll *a* (Chl-*a*) as a proxy of phytoplankton was evaluated for Marine Protected Areas (MPAs, which are considered the main tool for conservation of biological diversity) located in the Mexican Pacific with emphasis on anomalous events of the WHWP-EP. The response was predominantly negative, particularly in MPAs located in the Deep Mexican Pacific and southern Gulf of California, while the Midriff islands area (central Gulf of California) was not statistically significant due to the known higher resilience to warm events. Observed trends in the extension of the WHWP-EP and negative response of Chl-*a* in most of the MPAs highlight the need to consider phytoplankton in marine planning and management strategies, particularly in the area known as Deep Mexican Pacific, where MPAs has been reported with a lack of management effectiveness.

ADDITIONAL INDEX WORDS: *El Niño-Southern Oscillation, sea surface temperature, Gulf of California, California Current System, Deep Mexican Pacific.*

INTRODUCTION

Phytoplankton are key communities with enormous relevance for the functioning of aquatic ecosystems and they provide diverse ecosystem services, *e.g.,* supporting production for higher trophic levels and climate regulation (Tweddle, Gubbins, and Scott, 2018). Chlorophyll *a* (Chl-*a*) is commonly used as a proxy for its study, particularly when using remote sensing techniques to investigate the spatial and temporal variability, especially in the context of the impact of global warming and climate variability (Behrenfeld *et al*., 2006; Kahru *et al*., 2012; Mészáros *et al*., 2021). The dynamics of these organisms depend significantly on different physical and chemical processes, *e.g*., marine currents, upwelling, salinity, light, and availability of nutrients, among others (Jeffrey and Vesk, 1997; Jeffrey, Vesk, and Mantoura, 1997; Thomas *et al*., 2017). On interannual scales, the El Niño-Southern Oscillation (ENSO) is one of the main drivers of atmospheric and oceanic changes in the Pacific Ocean and during its warm phase (El Niño) the dynamics of diverse marine species from all trophic levels—including phytoplankton—are generally negative affected (McPhaden, Zebiak, and Glantz, 2006).

DOI: 10.2112/JCOASTRES-D-21-00049.1 received 25 March 2021; accepted in revision 12 October 2021; corrected proofs received 17 November 2021; published pre-print online 6 December 2021.
*Corresponding author: mmanzano@uas.edu.mx

On the other hand, warm pools are bodies of water with temperatures equal or higher than 28.5°C (Flores-Morales, Parés-Sierra, and Marinone, 2009; Misra *et al*., 2016; Wang and Enfield, 2001; Wang and Enfield, 2003). The Western Hemisphere Warm Pool (hereafter referred as WHWP; Figure 1) is considered the second warmest body of water on Earth (the bigger one corresponds to the Western Pacific Warm Pool). Its seasonal signature involves the Eastern Pacific, Gulf of Mexico, and the Caribbean Sea. On the other hand, large warm pools have been linked to El Niño (*e.g*., 1957–1958, 1969, 1972, 1982–1983, 1987, 1990–1991, 1992–1993, and 1997–1998 (Wang and Fiedler, 2006), although some ENSO years are not related to anomalous WHWP events (*e.g*., 1966, 1973, 1977, 1992) (Enfield, Lee, and Wang, 2006). Recently, it has been discussed that the WHWP is a precursor of ENSO with a 17-month lead time (Park *et al*., 2018). While the dynamics of the WHWP have been studied previously (its onset, seasonality, and interannual variability; *e.g.,* Wang and Enfield, 2001; Wang and Enfield, 2003), the impacts on phytoplankton are not widely reported yet; *e.g*., Manzano-Sarabia *et al*. (2008) discussed the response of satellite-derived sea surface temperature, Chl-*a*, and net primary productivity during the El Niño-linked large warm pool of 1997–1998, and the likely signature on higher trophic levels using fishery landings as a proxy of biological compartments in the southwestern Gulf of Mexico. The most important ENSO events in the last decades took place from

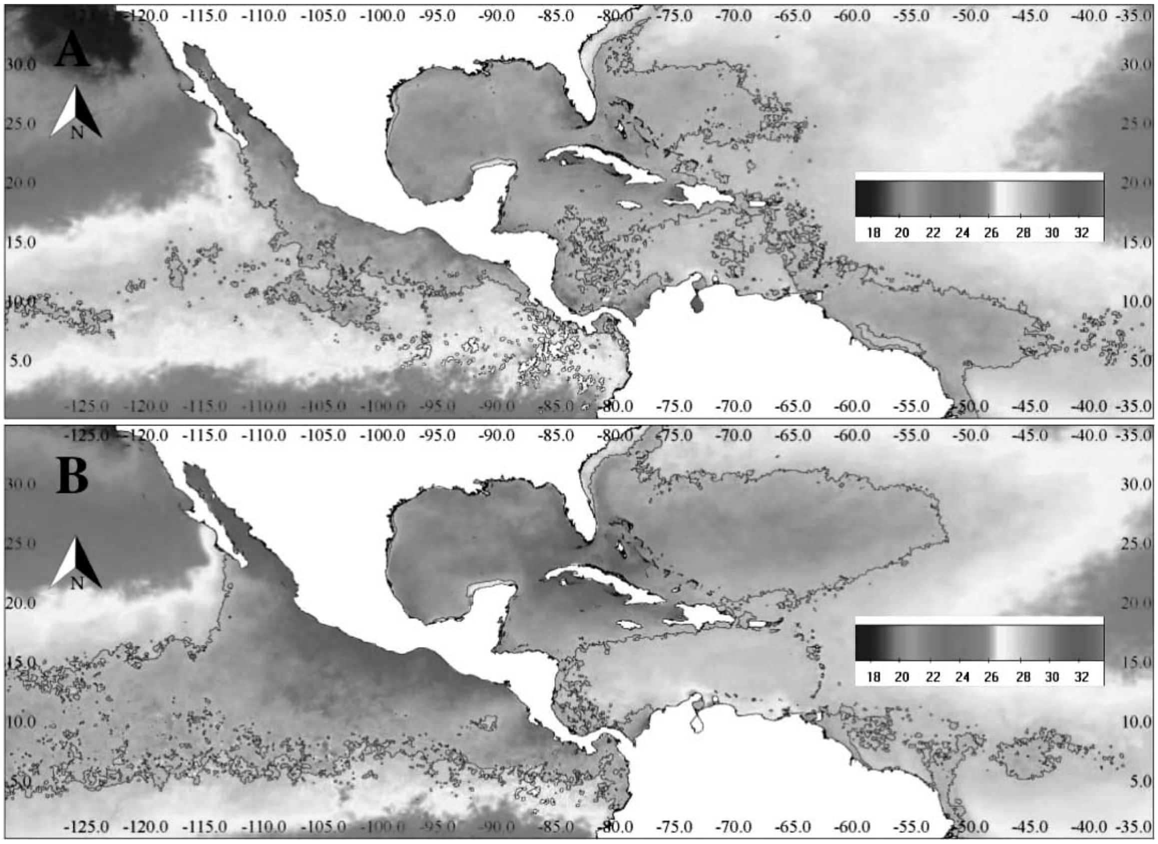

Figure 1. Sea surface temperature: composite image for July, August, and September from AVHRR; (A) 2008 (neutral year) and (B) 2015 (strong ENSO year). The isotherm indicates SST ≥28.5°C which defines the extension of the WHWP-EP.

1982–1983 and 1997–1998, which together with the development of the WHWP led to reductions in Chl-*a* and net primary productivity in the Pacific Ocean (Behrenfeld *et al.*, 2006), predominantly in tropical and subtropical zones (Racault *et al.*, 2017). More recently, the 2015–2016 ENSO is considered one of the strongest on record and the first extreme El Niño of the 21st century, with total heating rates similar to the 1982–1983 ENSO but weaker than the 1997–1998 event (Santoso, McPhaden, and Cai, 2017). Its great development was not just related to a single aspect, but to various forcings, *e.g.*, the development of a warm anomalous event that occurred in the northeast Pacific, also known as the warm Blob (Xue and Kumar, 2017), which developed from 2013–2015 and has been linked as a trigger of the 2015–2016 ENSO (Bond *et al.*, 2015; Jiménez-Quiroz *et al.*, 2019; Tseng, Ding, and Huang, 2017).

Natural Protected Areas (NPA) are defined spatial boundaries established to protect marine and terrestrial ecosystems and related ecosystem services from human activities and/or climate variability (Havard, Brigand, and Cariño, 2015; Heinze *et al.*, 2015; Ortiz-Lozano, Guitiérrez-Velázquez, and Granados-Barba, 2009). In Mexico, NPA are regulated by the National Commission for Natural Protected Areas (Comisión Nacional de Áreas Naturales Protegidas or CONANP by its Spanish acronym) and have increased in the last years from 53 recorded from 1917–1979 to 182 in 2021 (90,838,011 ha), and 37 of them correspond to Marine Protected Areas (MPAs) with 69,458,613 ha (Comisión Nacional de Áreas Naturales Protegidas, 2021). However, MPAs are affected by multiple pressures, *e.g.,* climate (ENSO, sea level rise, storms) and non-climate stressors (pollution, tourism, fragmentation processes, aquaculture, population growth) which may compromise the structure, conservation of biodiversity, and ecosystem services in general (Alban, Appéré, and Boncoeur, 2006; Solandt *et al.*, 2014). Oceanic-atmospheric variability at multiple scales might be affecting the different biological compartments in MPAs, like those associated with anomalous events of the WHWP; therefore, the knowledge about its impact on phytoplankton as an indicator of biological productivity is required for accurate management and conservation strategies. This study discusses the interannual temporal and spatial variability of the Western Hemisphere Warm Pool in the Eastern Pacific (WHWP-EP) throughout the analysis of time series from the Advanced Very High Resolution Radiometer (AVHRR), with focus on its impact on satellite-derived Chl-*a* concentration as a proxy of phytoplankton biomass in MPAs located in this region.

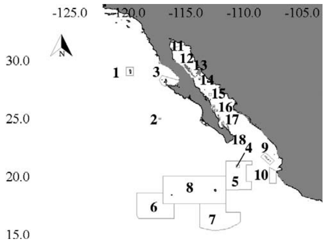

Figure 2. Marine Protected Areas in the Mexican Pacific. Source: MPAs polygons were downloaded from http://sig.conanp.gob.mx/website/pagsig/info_shape.htm. 1: Guadalupe island; 2: Los Alijos island; 3: Vizcaíno Bay-Cedros island; 4: East Pacific rise-hydrothermal vent; 5: Deep Mexican Pacific Deep-NE; 6: Deep Mexican Pacific-W; 7: Deep Mexican Pacific-S; 8: Revillagigedo Biosphere Reserve; 9: Marias islands; 10: Deep Mexican Pacific-Submarine canyon of Banderas; 11: Upper Gulf of California; 12: Angel de la Guarda island; 13: San Lorenzo archipelago; 14: San Pedro Mártir island; 15: Guaymas hydrothermal vent; 16: Loreto Bay; 17: Espiritu Santo island; 18: Cabo Pulmo.

METHODS

The spatial variability of the WHWP was assessed for the Eastern Pacific (hereafter referred as WHWP-EP; extending from the equator to 35° N and extending from the continent to 130° W; Figure 1) and additionally for the Gulf of California (according to its defined boundary as a large marine ecosystem [LME; Large Marine Ecosystems Hub, 2021). Monthly satellite-derived sea surface temperature (SST; 4 km resolution) from the AVHRR (dataset v5.3 from 1982–2018; National Centers for Environmental Information, 2021) were analyzed with the Windows Image Manager software (WIM, 2021) in order to calculate the area (km^2) with SST $\geq$28.5°C, *i.e.* the corresponding area to the WHWP-EP. According to López-García (2020), AVHRR data based on monthly images and a spatial resolution of 4 km are considered a robust product in relation to cloud cover. In addition, an improved algorithm was implemented starting from Version 4 to better eliminate cloud-contaminated pixels (Casey *et al*., 2010). Monthly area anomalies were calculated as deviation from the mean and expressed as percentage.

Vectorial data (shape format) corresponding to eighteen MPAs in the Mexican Pacific (Figure 2) were downloaded from Comisión Nacional de Areas Naturales Protegidas (CONANP, 2021) and monthly time series and related percent anomalies ($100 \times (\text{Anomaly} - 1)$) of Chl-*a* (1 km pixel resolution; multisatellite merged data were provided by Dr. Mati Kahru (Kahru, 2021) were calculated for those polygons and correlated (Pearson correlation) with the WHWP-EP area anomalies. Although differences exist between individual sensors, *e.g.,* instrument calibration and data processing algorithms, merged multisensor data has provided several benefits; for instance, an improved coverage and lower uncertainties in the retrieved products (Kahru *et al*., 2012; Maritorena *et al*., 2010; McClain, 2009). In addition, the algorithm for detection of regime shifts was applied on time series of Chl-*a* anomalies (Rodionov, 2004). This sequential t-test algorithm permits the monitoring of changes in its magnitude over time and need no initial visual inspection of time series and handling incoming data as anomalies or absolute values (Rodionov, 2004).

The area with SST $\geq$28°C in the Mexican Pacific and Gulf of California was compared by means of a one-way ANOVA (Zar, 1999) using as independent variables the analyzed years (*i.e.* 1982 to 2018), followed by a Tukey test to determine the significant differences ($P < 0.05$) between means (Statistica v13; TIBCO Software Inc.).

RESULTS

The spatial and temporal coverage of SST $\geq$28.5°C is shown for data derived from AVHRR sensor (1982–2018) in order to characterize the seasonal signature of the WHWP (Figures 3 and 4). As a whole, *i.e.* considering the Eastern Pacific, Gulf of Mexico, and Caribbean Sea regions, the WHWP showed the maxima extension in September (9,400,557 km^2) and separately during April (3,254,546 km^2) and August (1,961,743 km^2) for the WHWP-EP (Figures 3 and 4). On the other hand, the WHWP-EP is well developed from July until October in the Gulf of California (GC) and disappears November–June (Figure 3), although its signature may occur in previous months as recorded during anomalous years; *e.g*., an area of $\sim$850 km^2 with SST $\geq$28.5°C was observed on May 2014, in the southeastern region of the polygon of the Gulf of California LME, *i.e.* southern Sinaloa coast (not shown).

Interannual variability corresponding to the area of the WHWP-EP derived from AVHRR is shown in Figure 5. According to these time series, the highest extension of the WHWP-EP has occurred during strong ENSO events, *i.e.* 1982–1983, 1997–1998, and 2015–2016. Differences between years in the estimated area of the WHWP-EP according to the one-way ANOVA test were significant ($P < 0.05$).

Although not statistically significant, an increasing trend was observed in the area with SST $\geq$28.5°C in the Gulf of California mainly in June and November (not shown), *i.e*. the decaying period in the Eastern Pacific, but the onset and ending seasonal expansion of the WHWP-EP in the GC, respectively (Figure 3). As discussed later, this suggests that threats of warmer areas in the GC are increasing and therefore in MPAs.

The highest area anomalies of the WHWP-EP (>100% in comparison to the climatological mean) were observed during 1982–1983, 1997–1998, and 2015–2016 (Figure 6). In order to analyze the impact of the WHWP-EP in the upper biological compartment, time series of Chl-*a* anomalies on 18 polygons corresponding to MPAs (Figure 7) were performed and correlated with area anomalies of the WHWP-EP (Table 1). Chl-*a* anomalies corresponding to Guadalupe and Alijos islands located in the California Current System (CCS) showed a positive and significant correlation with the WHWP-EP ($r \leq 0.24$; $P < 0.05$). On the other hand, MPAs located in the central and northern GC showed no significant impact from the WHWP-EP, while the Upper GC (Area 11) and areas 15, 16, 17, and 18 corresponding to the southern GC showed a weak but still significant negative correlation ($r \leq -0.27$; $P < 0.05$). As discussed later, this response in the central GC might be associated to the great ocean dynamics found in the Midriff islands zone allowing a good mixing that maintain a stable

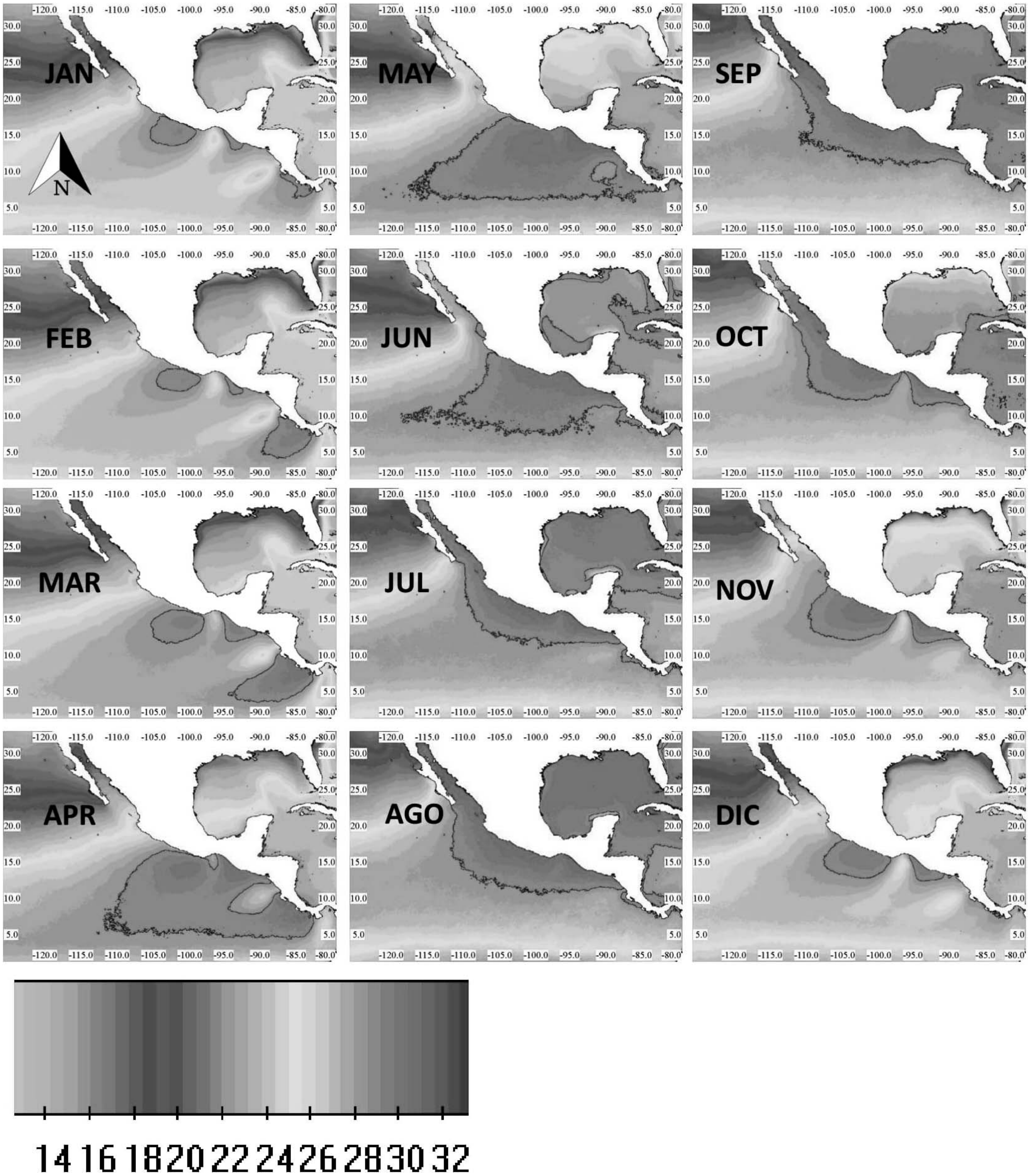

Figure 3. Seasonal spatial variability of the Western Hemisphere Warm Pool (SST ≥28.5°C) according to the AVHRR sensor (1982–2018).

regime in the upper Chl-*a* concentration. In the Deep Mexican Pacific, areas 4, 5, 7, 9, and 10 showed a significant and negative correlation between Chl-*a* anomalies and the WHWP-EP area anomalies (Table 1). On the other hand, the algorithm for regime shift detection (Rodionov, 2004) showed that most of the areas in the GC recorded no abrupt changes during the analyzed period, excepting a period with a dominance of negative Chl-*a* anomalies in the Upper GC (area 11) after 2012 and southern GC after 2009 (area 18) and 2013 (area 17). Areas in the Deep Mexican Pacific (areas 4, 5, 6, 7, 8) showed a negative step after 2012 and/or 2015, with a change to positive anomalies during 2018 for areas 5 and 6.

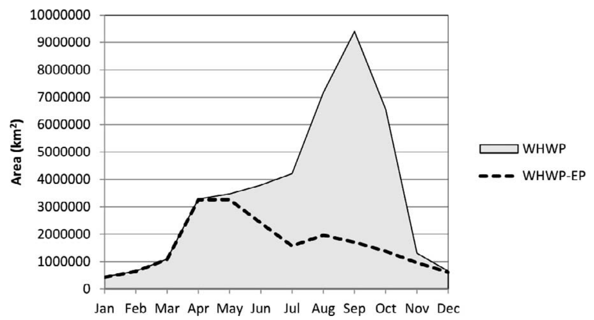

Figure 4. Seasonal comparison of the area of the Western Hemisphere Warm Pool (WHWP) as a whole and the corresponding area in the Eastern Pacific (WHWP-EP).

DISCUSSION

This study focused on describing the changes in Chl-*a* in MPAs from the Mexican Pacific and the likely impact of the WHWP in the Eastern Pacific (WHWP-EP). Changes on sea surface temperature has been an object of study from local to global perspective, *e.g*., trends (An *et al*., 2012; Barbosa, 2011; Dunstan *et al*., 2018) and impacts on biological compartments, *e.g*., the impact on fisheries (Lanz *et al*., 2009; Manzano-Sarabia *et al*., 2008). On the other hand, MPAs in Mexico have been greatly distinctive according to the ecosystem services they provide (Ortiz-Lozano, Olivera-Vázquez, and Espejel, 2017), community involvement (Rodríguez-Martínez, 2008), and social indicators (Morzaria-Luna, Turk-Boyer, and Moreno Baez, 2014) in addition to management issues (Muzquiz-Villalobos and Pompa-Mansilla, 2018; Ortiz-Lozano, 2012; Ortiz-Lozano, Gutiérrez-Velázquez, and Granados-Barba, 2009; Ortiz-Lozano, Olivera-Vázquez, and Espejel, 2017; Stamieszkin, Wielgus, and Gerber, 2009). Nevertheless, the relevance of considering an oceanographic perspective for marine conservation planning and management is still overlooked in most of the studies in Mexico. Particularly, it has been highlighted the importance of considering the establishment of pelagic protected areas (Game *et al*., 2009) and the implementation of an oceanographic background in MPAs (Spiridonov *et al*., 2017).

The seasonal and interannual variability of the WHWP has been discussed by several authors (Enfield, Lee, and Wang, 2006; Misra *et al*., 2016; Wang and Enfield, 2003; Wang and Fiedler, 2006); however, the influence on biological components was not. According to the results from this study, the area of the WHWP-EP is increasing in the last two decades reaching the maxima during the 1997–1998 and 2015–2016 ENSO. Such growth in the extension of the WHWP-EP may increase the threats to phytoplankton and all biological compartments in MPAs from the Mexican Pacific.

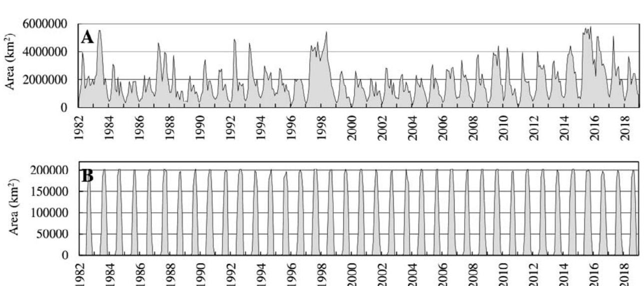

Figure 5. Interannual variability of SST ≥28.5°C (1985–2018) in the (A) WHWP-EP and (B) Gulf of California.

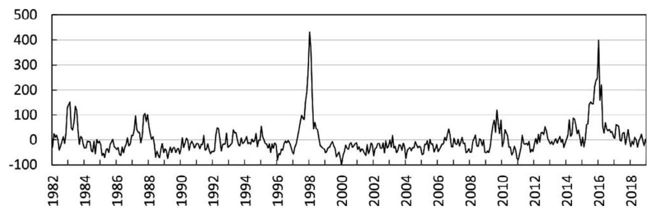

Figure 6. Area anomalies (%) in the WHWP-EP according to AVHRR sensor.

Differences were observed in Chl-*a* anomalies between MPAs, *i.e*. those located in the CCS, GC, and Deep Mexican Pacific. The signature of the WHWP-EP in the CCS was expected to be low as the WHWP-EP limits its northern extension to ~22.8° N (end of the Baja California peninsula; Figure 3), however, a northern incursion of the WHWP-EP has been recorded (SST ≥28.5°C was observed until 24.5° N during September 2009, and even to 29° N during September 2015; Figure 8). Several studies have shown negative trends in global phytoplankton biomass and productivity (*e.g.,* Behrenfeld *et al*., 2006); however, the response of coastal upwelling systems such as the CCS is complex (Xiu *et al*., 2018), as an increasing upwelling intensity is expected (*e.g.,* Bakun hypothesis) and therefore to promote higher productivity. Such complexity is also discussed by Kahru *et al*. (2012), as Chl-*a* fronts in the CCS showed stronger sensitivity to local controls and were less linked to large-scale variability of SST anomalies. Additionally, significant decadal scale trends were detected in the Ensenada front area where front frequencies of both SST and Chl-*a* have increased together (higher Chl-*a* and colder SST). Such evidence may explain significant and positive correlation coefficients for areas 1 and 2 (Table 1). Chl-*a* anomalies in MPAs from the CCS (areas 1, 2, and 3) revealed a negative step after 2007 (Los Alijos, area 2), 2011 (Guadalupe island, area 1), and 2012 (Vizcaino Bay-Cedros island, area 3) (Figure 7), which contrasted with the general state of the CCS, *i.e*. a cool phase (Wells *et al*., 2013). Similarly, a decline in Chl-*a* was previously reported (Bjorkstedt *et al*., 2012) for Punta Eugenia (~28° N, corresponding to area 3 in this study) with an increase in the SST maxima during 1998–2012 (Arroyo-Loranca *et al*., 2015), which was related to different responses of inshore and offshore areas to the Pacific Decadal Oscillation and El Niño events. MPAs in the CCS showed that negative anomalies prevailed after 2011 according to the regime shift detection algorithm (Rodionov, 2004), with no signs of further recovery at the end of the analyzed period (1997–2018) as a likely negative response following the warm Blob of 2013 and the 2015–2016 ENSO. Although the appearance of the warm Blob has been reported for 2013, the step to a poor productive period was recorded even

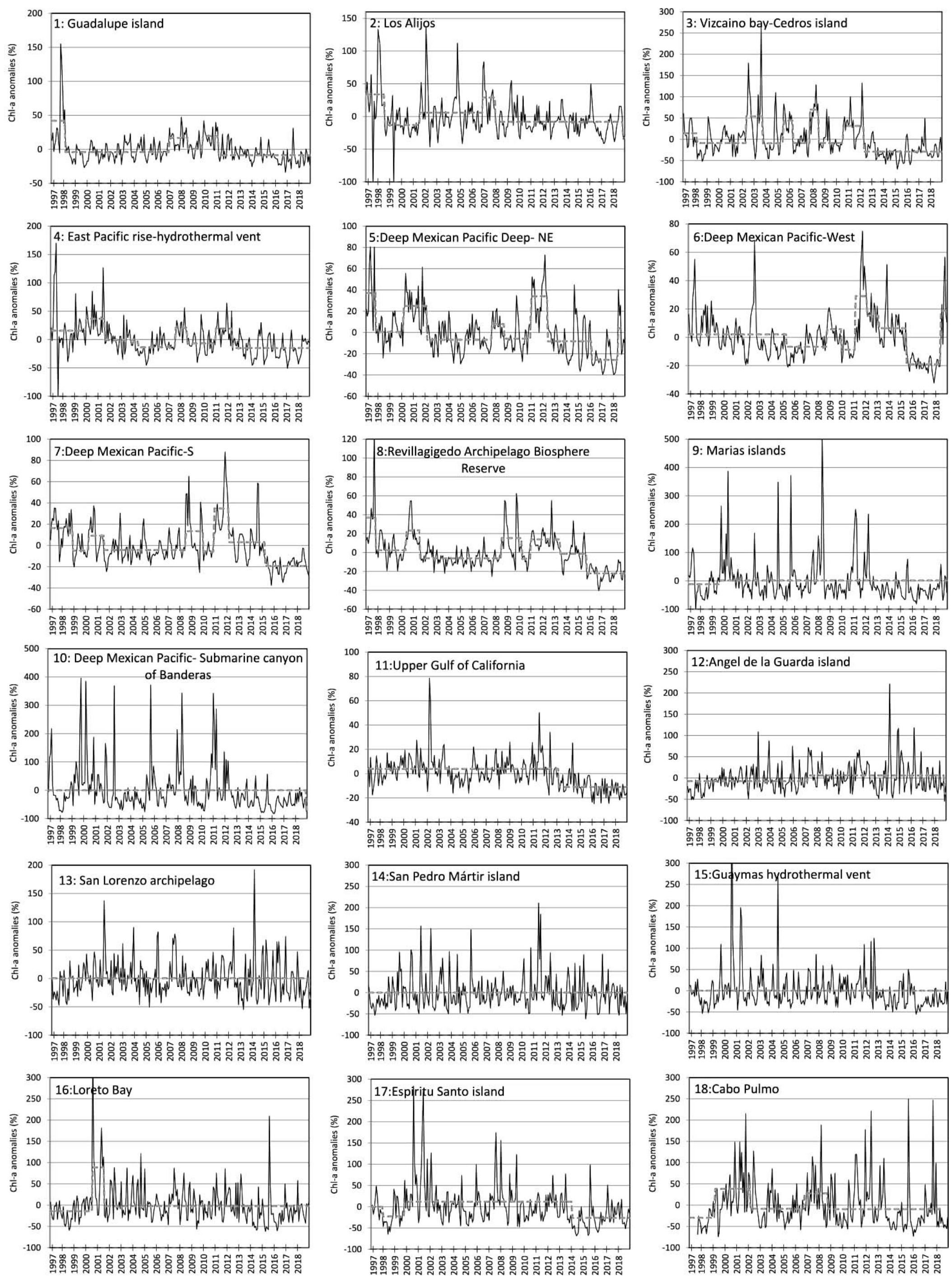

Figure 7. Chl-*a* anomalies corresponding to Marine Protected Areas polygons. The algorithm for regime shift detection (Rodionov, 2004) was applied to detect abrupt changes in time series (1996–2018).

earlier, *i.e*. 2012, which suggested that the biological compartment responded to another forcing factors.

Seasonally, the influence of the WHWP-EP in the GC starts on June and disappears in November (Figure 3). In relation to Chl-*a*, most of the central and northern GC showed no correlation with the WHWP-EP except the Upper GC (area 11) and southern GC, *i.e*. Guaymas hydrothermal vent, Loreto Bay, Espiritu Santo island, and Cabo Pulmo (areas 15, 16, 17, and 18, respectively), recording negative correlation coefficients ($P < 0.05$). This might be related to the known poor

Table 1. *Pearson correlation coefficients between anomalies of the area of the Western Hemisphere Warm Pool in the Eastern Pacific (WHWP-EP) and chlorophyll* a *(Chl-*a*) anomalies for Marine Protected Areas in the Mexican Pacific.*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Correlation coefficient	**0.24**	**0.21**	**−0.22**	**−0.18**	**−0.13**	N.S.	**−0.16**	N.S.	**−0.21**	**−0.28**	**−0.25**	N.S.	N.S.	N.S.	**−0.14**	**−0.2**	**−0.25**	**−0.27**

Bold = P < 0.05; AVHRR = Advanced Very High Resolution Radiometer; N.S. = no significant correlation

impact of warm events in the central GC, particularly in the Midriff islands area due to the strong mixing related to winds, tides, hydraulic jump, and currents (Robles-Tamayo *et al*., 2018), overlapping with the reports of no long-term trends on SST (Lluch-Cota *et al*., 2013). Although not statistically significant, the area with SST ≥28.5°C has been increasing in the GC since 1982 for the onset and decaying months of the WHWP-EP in the GC, *i.e*. June and November (not shown), suggesting that the GC would be becoming more sensitive to warmer conditions. For MPAs located in the region known as the Deep Mexican Pacific, a negative step was recorded in all analyzed areas (4, 5, 6, 7, 8, 9, 10) starting on 2012 and followed another negative step in 2015. This region is more affected by diverse events that have a deep signature in the tropical and sub-tropical Pacific, *i.e*. ENSO and anomalous WHWP; therefore, the referred negative steps on Chl-*a* anomalies could be related to the higher influence of such events. The positive trend observed in the area anomalies of the WHWP-EP (Figure 6) followed the response reported for the southern Mexican Pacific, *i.e*. a warming trend after the 1997–1998 ENSO (Lluch-Cota *et al*., 2013). Biological productivity in MPAs from the Deep Mexican Pacific were more susceptible to WHWP-EP anomalies, *i.e*. Chl-*a* anomalies dropped *ca*. –20% for most of the areas following the 2015–2016 ENSO, considered a "Godzilla" or super ENSO, in addition to the events of 1982–1983 and 1997–1998. Management effectiveness evaluation is a key tool to assess how protected areas are being managed (Leverington *et al*., 2008). Mexico, throughout CONANP, has implemented this framework for both terrestrial and marine protected areas and published a first national report about the effectiveness of the management of Natural Protected Areas (Comisión Nacional de Áreas Naturales Protegidas, 2020). In this sense, it is important to highlight that excepting Revillagigedo Biosphere Reserve, all MPAs located in the Deep Mexican Pacific were reported with a poor level on management effectiveness, which in addition to a negative response of Chl-*a* to warm events increases the risks on all biological compartments. Although most of the MPAs located in the GC showed a negative correlation of Chl-*a* and WHWP-EP, it is relevant to mention that those were reported with a high management effectiveness (*e.g.,* Upper Gulf of California-area 11, San Pedro Mártir-area 14, Loreto Bay-Area 16, and Cabo Pulmo-area 18). MPAs located in the California Current System are less sensitive to warm pool events because of their geographical location and their high reported management effectiveness (*e.g.,* Guadalupe island-area 1). According to the overall results, it is strongly recommended that MPAs consider climate forcing, particularly present and future scenarios of warm pool events, in assessments and management of Mexican MPAs. If warm areas and related magnitude continue increasing in the Mexican Pacific, the known high biological productivity of these MPAs may be compromised as their biological richness would also decrease (Muzquiz-Villalobos and Pompa-Mansilla, 2018), *e.g.,* priority species such as whales and other marine mammals may change their distribution outside the current MPAs polygons. This scenario highlights the fact that current boundaries of MPAs in the Mexican Pacific may become obsolete in the near future due to a likely stronger influence of WHWP as phytoplankton biomass decreases.

CONCLUSIONS

This contribution provided a first insight of the response of Chl-*a* in MPAs to anomalous events of the Western Hemisphere Warm Pool in the Mexican Pacific. According to analyzed data from the AVHRR sensor, the area with SST ≥28.5°C is increasing over the last two decades and reached a maximum during the 1997–1998 and 2015–2016 ENSO, raising also the threats of MPAs to warmer conditions. MPAs located in the Deep Mexican Pacific showed a negative

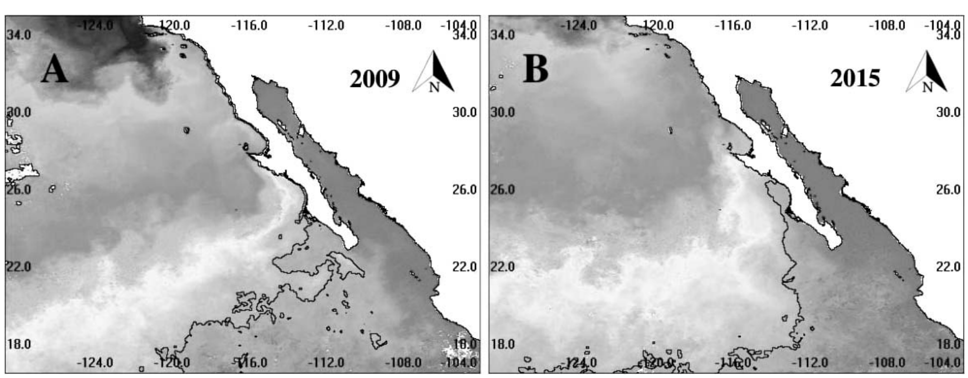

Figure 8. Areas with SST ≥28.5°C in the California Current System and Gulf of California during September 2009 and 2015.

response on Chl-*a* anomalies, which in addition to a low management effectiveness, increases their risk level during warm conditions. Although the sensitivity of the GC to warm events was considered low, the increasing trend of areas with SST $\geq$28.5°C in both the onset and decayed months of the WHWP-EP in the GC suggested that threats to warmer conditions are growing in this Large Marine Ecosystem. Political, social, and economic stressors are commonly evaluated in Mexican MPAs, while the climate and oceanographic background are still missed in most of the studies. According to present results and due to the relevance of phytoplankton for the functioning of ecosystems, primary producers should be considered as priority within marine management strategies.

ACKNOWLEDGMENTS

The authors acknowledge financial support provided throughout PROMEP UAS-NPTC UAS-PTC-039, PROFAPI 2014-121, 2014/089, 2015/124, 2015/164, ECOS Nord-Secretaría de Educación Pública-ANUIES-Consejo Nacional de Ciencia y Tecnología ("Influencia de la variabilidad climática en las comunidades zooplanctónicas en tres zonas costeras de Francia y México: importancia de los observatorios ambientales" Project), Infraestructura-CONACYT INFR-2012-01-188065, and INFR-2017-01-280994. Consejo Nacional de Ciencia y Tecnología provided a doctoral scholarship to J. López-Magaña (No. 568329). We strongly acknowledge the comments and suggestions from four anonymous reviewers who significantly improved this manuscript.

LITERATURE CITED

Alban, F.; Appéré, G., and Boncoeur, J., 2006. *Economic Analysis of Marine Protected Areas. A Literature Review*. European Union: EMPAFISH Project, Booklet No. 3, 51p.

An, S.I.; Kim, J.W.; Im, S.H.; Kim, B.M., and Park, J.H., 2012. Recent and future sea surface temperature trends in tropical pacific warm pool and cold tongue regions. *Climate Dynamics*, 39(6), 1373–1383.

Arroyo-Loranca, R.G.; Álvarez-Borrego, S.; Ortiz-Figueroa, M., and Calderón-Aguilera, L.E., 2015. Spatial and temporal variation of satellite-derived phytoplankton biomass and production in the California Current System off Punta Eugenia, during 1997–2012. *Hidrobiológica*, 25(3), 321–334.

Barbosa, S.M., 2011. Testing for deterministic trends in global sea surface temperature. *Journal of Climate*, 24(10), 2516–2522.

Behrenfeld, M.J.; O'Malley, R.T.; Siegel, D.A.; McClain, C.R.; Sarmiento, J.L.; Feldman, G.C.; Milligan, A.J.; Falkowski, P.G.; Letelier, R.M., and Boss, E.S., 2006. Climate-driven trends in contemporary ocean productivity. *Nature*, 444, 752–755. doi:10.1038/nature05317

Bjorkstedt, E.; Goericke, R.; McClatchie, S.; Weber, E.; Watson, W.; Lo, N.; Peterson, W.; Brodeur, R.; Bograd, S.; Auth, T.; Fisher, J.; Morgan, C.; Peterson, J.; Durazo, R.; Gaxiola-Castro, G.; Lavaniegos, B.; Chavez, F.; Collins, C.A.; Hannah, B.; Field, J.; Sakuma, K.; Satterthwaite, W.; O'Farrell, M.; Hayes, S.; Harding, J.; Sydeman, W.; Thompson, S.A.; Warzybok, P.; Bradley, R.; Jahncke, J.; Golightly, R.; Schneider, S.; Largier, J.; Suryan, R.M.; Gladics, A.J.; Horton, C.A.; Kim, S.Y.; Melin, S.; DeLong, R., and Abell, J., 2012. State of the California Current 2011–2012: Ecosystems respond to local forcing as La Niña wavers and wanes. *California Cooperative Oceanic Fisheries Investigations Reports*, 53, 41–76.

Bond, N.A.; Cronin, M.F.; Freeland, H., and Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, 42, 3414–3420.

Casey, K.S.; Brandon, T.B.; Cornillon, P., and Evans, R., 2010. The past, present and future of the AVHRR pathfinder SST program. *In*: Barale, V.; Gower, J.F.R., and Alberotanza, L. (eds.), *Oceanography from Space: Revisited*. Dordrecht, The Netherlands: Springer, pp. 273–287.

Comisión Nacional de Áreas Naturales Protegidas, 2020. *Evaluación de la Efectividad del Manejo de las Áreas Naturales Protegidas de México: Primer Informe Nacional*. México: Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT, 95 p.

Comisión Nacional de Áreas Naturales Protegidas (CONANP), 2021. http://sig.conanp.gob.mx/website/pagsig/datos_anp.htm

Dunstan, P.K.; Foster, S.D.; King, E.; Risbey, J.; O'Kane, T.J.; Monselesan, D.; Hobday, A.J.; Hartog, J.R., and Thompson, P.A., 2018. Global patterns of change and variation in sea surface temperature and chlorophyll *a*. *Scientific Reports*, 8. doi:10.1038/s41598-018-33057-y

Enfield, D.B.; Lee, S.K., and Wang, C., 2006. How are large western hemisphere warm pools formed? *Progress in Oceanography*, 70(2–4), 346–365.

Flores-Morales, A.L.; Parés-Sierra, A., and Marinone, S.G., 2009. Factors that modulate the seasonal variability of the sea surface temperature of the Eastern Tropical Pacific. *Geofísica Internacional*, 48(3), 337–349.

Game, E.T.; Grantham, H.S.; Hobday, A.J.; Pressey, R.L.; Lombard, A.T.; Beckley, L.E.; Gjerde, K.; Bustamante, R.; Possingham, H.P., and Richardson A.J., 2009. Pelagic protected areas: the missing dimension in ocean conservation. *Trends in Ecology and Evolution*, 24(7), 360–369.

Havard, L.; Brigand, L., and Cariño, M., 2015. Stakeholder participation in decision-making processes for marine and coastal protected areas: Case studies of the south-western Gulf of California, Mexico. *Ocean & Coastal Management*, 116, 116–131. doi:10.1016/j.ocecoaman.2015.06.017

Heinze, C.; Meyer, S.; Goris, N.; Anderson, L.; Steinfeldt, R.; Chang, N.L.Q., and Bakker, D.C.E., 2015. The ocean carbon sink-impacts, vulnerabilities and challenges. *Earth System Dynamics*, 6(1), 327–358.

Jeffrey, S.W. and Vesk, M., 1997. Introduction to marine phytoplankton and their pigment signatures: Phytoplankton pigments in oceanography: guidelines to modern methods. In: Jeffrey, S.W. and Mantoura, R.F.C. (eds.), *Phytoplankton Pigments in Oceanography: Guidelines to Modern Methods*. Paris: UNESCO, pp. 37–84.

Jeffrey, S.W.; Vesk, M., and Mantoura, R.F.C., 1997. Phytoplankton pigments: Windows into the pastures of the sea. *Nature and Resources*, 33(2), 14–29.

Jiménez-Quiroz, M.C.; Cervantes-Duarte, R.; Funes-Rodríguez, R.; Barón-Campis, S.A.; García-Romero, F.J.; Hernández-Trujillo, S.; Hernández-Becerril, D.U.; Gonzáles-Armas, R.; Martell-Bubois, R.; Cerceira-Estrada, S.; Fernández-Méndez, J.I.; Gonzales-Ania, L.V.; Vásquez-Ortiz, M., and Barrón-Barraza, F.J., 2019. Impact of "The Blob" and "El Niño" in the SW Baja California Peninsula: Plankton and environmental variability of Bahia Magdalena. *Frontiers in Marine Science*, 6(25), 1–25.

Kahru, M., 2021. http://spg-satdata.ucsd.edu/

Kahru, M.; Kudela, R.; Manzano-Sarabia, M., and Mitchell, B.G., 2012. Trends in the surface chlorophyll of the California Current: Merging data from multiple ocean color satellites. *Deep-Sea Research II*, 2, 89–98.

Lanz, E.; López-Martínez, J.; Nevárez-Martínez, M., and Dworak, J.A., 2009. Small pelagic fish catches in the Gulf of California associated with sea surface temperature and chlorophyll. *The California Cooperative Oceanic Fisheries Investigations* (*CalCOFI*) *Report*, 50, 134–146.

Large Marine Ecosystems Hub, 2021. https://www.lmehub.net/#gulf-of-california

Leverington, F.; Hockings, M.; Pavese, H.; Costa, K.L., and Courrau, J., 2008. *Management Effectiveness Evaluation in Protected Areas—A Global Study. Supplementary report No.1: Overview of Approaches and Methodologies*. Gatton, Australia: University of Queensland, TNC, WWF, IUCN-WCPA, 192p.

Lluch-Cota, S.E.; Tripp-Valdez, M.; Lluch-Cota, D.B.; Lluch-Belda, D.; Verbesselt, J.; Herrera-Cervantes, H., and Bautista-Romero, J.J., 2013. Recent trends in sea surface temperature off Mexico. *Atmósfera*, 26(4), 537–546.

López-García, M.J, 2020. SST Comparison of AVHRR and MODIS Time Series in the Western Mediterranean Sea. *Remote Sensing*, 12(14), 1–12.

Manzano-Sarabia, M.; Salinas-Zavala, C.A.; Kahru, M.; Lluch-Cota, S.E., and González-Becerril, A., 2008. The impact of the 1997–1999 warm-SST and low-productivity episode on fisheries in the southwestern Gulf of Mexico. *Hydrobiologia*, 610(1), 257–267.

Maritorena, S.; Fanton d' Andon, O.H.; Mangin, A., and Siegel, D.A., 2010. Merged satellite ocean color data products using a bio-optical model: Characteristics, benefits and issues. *Remote Sensing of Environment*, 114(8), 1791–1804.

McClain, C.R., 2009. A decade of satellite ocean color observations. *Annual Review of Marine Science*, 1, 19–42. doi:10.1146/annurev.marine.010908.163650

McPhaden, M.J.; Zebiak, S.E., and Glantz, M.H., 2006. ENSO as an integrating concept in earth science. *Science*, 314 (5806), 1740–1745.

Mészáros, L.; van der Meulen, F.; Jongbloed, G., and El Serafy, G., 2021. Climate change induced trends and uncertainties in phytoplankton spring bloom dynamics. *Frontiers in Marine Science*, 8, 1–28.

Misra, V.; Groenen, D.; Bhardwaj, A., and Mishra, A., 2016. The warm pool variability of the tropical northeast Pacific. *International Journal of Climatology*, 36(14), 4625–4637.

Morzaria-Luna, H.N.; Turk-Boyer, P., and Moreno Baez, M., 2014. Social indicators of vulnerability for fishing communities in the Northern Gulf of California, Mexico: Implications for climate change. *Marine Policy*, 45, 182–193. doi:10.1016/j.marpol.2013.10.013

Muzquiz-Villalobos, M. and Pompa-Mansilla, S., 2018. Marine mammals of Mexico: Richness patterns, protected areas, and conservation trends. *Estuarine, Coastal and Shelf Science*, 208, 153–160.

National Centers for Environmental Information, 2021. https://www.ncei.noaa.gov/products/avhrr-pathfinder-sst

Ortiz-Lozano, L., 2012. Identification of priority conservation actions in marine protected areas: Using a causal networks approach. *Ocean & Coastal Management*, 55, 74–83. doi:10.1016/j.ocecoaman.2011.10.013

Ortiz-Lozano, L.; Gutiérrez-Velázquez, A.L., and Granados-Barba, A., 2009. Marine and terrestrial protected areas in Mexico: Importance of their functional connectivity in conservation management. *Ocean & Coastal Management*, 52(12), 620–627.

Ortiz-Lozano, L.; Olivera-Vázquez, L., and Espejel, I., 2017. Legal protection of ecosystem services provided by Marine Protected Areas in Mexico. *Ocean & Coastal Management*, 138(15), 101–110.

Park, J.H.; Kug, J.S.; Li, T., and Behera, S.K., 2018. Predicting El Niño beyond 1-year lead: Effect of the Western Hemisphere Warm Pool. *Scientific Reports*, 8(1). doi:10.1038/s41598-018-33191-7

Racault, M.F.; Sathyendranath, S.; Menon, N., and Platt, T., 2017. Phenological Responses to ENSO in the Global Oceans. *Surveys in Geophysics*, 38(1), 277–293.

Robles-Tamayo, C.M.; Valdez-Holguín, J.E.; García-Morales, R.; Figueroa-Preciado, G.; Herrera-Cervantes, H.; López-Martínez, J., and Enríquez-Ocaña, L.F., 2018. Sea surface temperature (SST) variability of the eastern coastal zone of the Gulf of California. *Remote Sensing*, 10(9). doi:10.3390/rs10091434

Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, 31(9). doi:10.1029/2004GL019448

Rodríguez-Martínez, R.E., 2008. Community involvement in marine protected areas: The case of Puerto Morelos reef, México. *Journal of Environmental Management*, 88(4), 1151–1160.

Santoso, A.; Mcphaden, M.J., and Cai, W., 2017. The defining characteristics of ENSO extremes and the strong 2015/2016 El Niño. *Reviews in Geophysics*, 55(4), 1079–1129.

Solandt, J.L.; Jones, P.; Duval-Diop, D.; Kleiven, A.R., and Frangoudes, K., 2014. Governance challenges in scaling up from individual MPAs to MPA networks. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 24(2), 145–152.

Spiridonov, V.; Solovyev, B.; Chuprina, E.; Pantyulin, A.; Sazonov, A.; Nedospasov, A.; Stepanova, S.; Belikov, S.; Chernova, N.; Gavrilo, M.; Glazov, D.; Krasnov, Y.; Tertitsky, G., and Onufrenya, I., 2017. Importance of oceanographical background for a conservation priority areas network planned using MARXAN decision support tool in the Russian Arctic seas. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27(S1), 52–64.

Stamieszkin, K.; Wielgus, J., and Gerber, L.R., 2009. Management of a marine protected area for sustainability and conflict resolution: Lessons from Loreto Bay National Park (Baja California Sur, Mexico). *Ocean & Coastal Management*, 52(9), 449–458.

Thomas, M.K.; Aranguren-Gassis, M.; Kremer, C.T.; Gould, M.R.; Anderson, K.; Klausmeier, C.A., and Litchman, E., 2017. Temperature–nutrient interactions exacerbate sensitivity to warming in phytoplankton. *Global Change Biology,* 23(8), 3269–3280.

Tseng, Y.H.; Ding, R., and Huang, X.M., 2017. The warm Blob in the northeast Pacific—The bridge leading to the 2015/16 El Niño. *Environmental Research Lett*ers, 12(5). doi:10.1088/1748-9326/aa67c3

Tweddle, J.F.; Gubbins, M., and Scott, B.E., 2018. Should phytoplankton be a key consideration for marine management? *Marine Policy*, 97, 1–9.

Wang, C. and Enfield, D.B., 2001. The tropical Western Hemisphere warm pool. *Geophysical Research Letters*, 28(8), 1635–1638.

Wang, C. and Enfield, D.B., 2003. A further study of the tropical Western Hemisphere Warm Pool. *Journal of Climate*, 16(10), 1476–1493.

Wang, C. and Fiedler, P.C., 2006. ENSO variability and the eastern tropical Pacific: A review. *Progress in Oceanography*, 69(2–4), 239–266.

Wells, B.; Schroeder, I.; Santora, J.; Hazen, E.; Bograd, S.; Bjorkstedt, E.: Loeb, V.; McClatchie, S.; Weber, E.; Watson, W.; Thompson, A.; Peterson, W.; Brodeur, R.; Harding, J.; Field, J.; Sakuma, K.; Hays, S.; Sydeman, W.; Losekoot, M.; Thompson, S.A.; Largier, J.; Kim, S.Y.; Chavez, F.; Barceló, C.; Warzybok, P.; Bradley, R.; Jahncke, J.; Goericke, R.; Campbell, G.S.; Hildebrand, J.A.; Melin, S.R; DeLong, R.L.; Gómez-Valdés, J.; Lavaniegos, B.; Gaxiola-Castro, G.; Golightly, R.T.; Schneider, S.R.; Lo, N.; Suryan, R.; Gladics, A.; Horton, C.; Fisher, J.; Morgan, C.; Peterson, J.; Daly, E.A.; Auth, T., and Abell, J., 2013. State of the California current 2012–2013: No such thing as an "average" year. *California Cooperative Oceanic Fisheries Investigations Reports*, 54, 37–71.

Windows Image Manager (WIM), 2021. https://www.wimsoft.com/

Xiu, P.; Chai, F.; Curchitser, E.N., and Castruccio, F.S., 2018. Future changes in coastal upwelling ecosystems with global warming: The case of the California Current System. *Scientific Reports*, 8(2866), 1–9.

Xue, Y. and Kumar, A., 2017. Evolution of the 2015/16 El Niño and historical perspective since 1979. *Science China Earth Sciences*, 60, 1572–1588.

Zar, J.H., 1999. *Biostatistical Analysis*, 4th edition. Englewood Cliffs, New Jersey: Prentice Hall, 663p.