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ARTICLE

Comparative analysis of spatiotemporal trends in sea surface temperature in the major marine protected areas of the Eastern Tropical Pacific

Análisis comparativo de las tendencias espaciotemporales en la temperatura superficial del mar en las principales áreas marinas protegidas del Pacífico Oriental Tropical

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Resumen.- El Pacífico Oriental Tropical (POT) se caracteriza por presentar una dinámica oceanográfica compleja que afecta la temperatura superficial del mar (TSM), un parámetro clave que influye los ecosistemas marinos. Hasta la fecha no se han realizado estudios comparativos de las variaciones espaciotemporales de la TSM entre las distintas áreas marinas protegidas en el POT. Esta investigación utilizó sensores remotos para evaluar las variaciones mensuales, anuales y decadales de la TSM desde 1982 a 2019 en el Parque Nacional Coiba (Coiba), Parque Nacional Isla del Coco (Coco), Santuario de Fauna y Flora Isla Malpelo (Malpelo), Parque Nacional Natural Isla Gorgona (Gorgona), Reserva Marina de Galápagos (Galápagos) e Isla de La Plata (La Plata). Se observó una tendencia creciente en la TSM en la mayoría de los sitios estudiados, excepto en el oeste de Galápagos. Se registró una disminución en la anomalía de la TSM durante los meses de febrero a abril en Malpelo, Coiba, Gorgona y La Plata. Las diferencias observadas son probablemente en respuesta a la corriente de Humboldt y eventos de afloramiento en la cuenca del Pacífico colombiano. Se recomienda emplear series de tiempo de mayor resolución temporal para determinar si las tendencias anuales, mensuales y decadales observadas en este estudio responden a cambios locales, regionales o globales. El monitoreo constante de las tendencias en la TSM es una práctica estratégica para comprender y planificar los cambios actuales y proyectados en el ambiente marino.

Palabras clave: Sensores remotos, Pacífico Oriental Tropical, TSM, áreas marinas protegidas, cambio climático

Abstract.- The Eastern Tropical Pacific (ETP) is characterized by complex oceanographic dynamics that affect the regional sea surface temperature (SST), a key parameter driving marine ecosystems. To date no comparative studies have been conducted on the spatial and temporal variations of SST among the several marine protected areas in the ETP. The present study used remote sensing to evaluate the monthly, annual, and decadal variations in SST from 1982 to 2019 in Coiba National Park (Coiba), Cocos Island National Park (Cocos), Malpelo Fauna and Flora Sanctuary (Malpelo), Gorgona Island National Park (Gorgona), Galápagos Marine Reserve (Galápagos) and La Plata Island (La Plata). An overall increasing trend in SST was observed across all study sites, except for West Galápagos. A decrease in SST anomaly was observed from February through April at Malpelo, Coiba, Gorgona and La Plata. These observations are likely in response to the Humboldt Current and upwelling events in the Colombian Pacific Basin. Using a longer SST dataset is recommended to determine if the annual, monthly and decadal trends observed here are driven by local, regional or global processes. Consistent monitoring of SST trends is a strategic practice in understanding and planning for current and projected changes in the marine environment.

Key words: Remote sensing, Eastern Tropical Pacific, SST, marine protected areas, climate change

INTRODUCTION

In the last 100 years global average sea surface temperature (SST) has warmed noticeably, increasing on average 0.3 to 0.6 °C (Tangang *et al.* 2006, Kashkooli *et al.* 2019). This increase in SST is not homogeneous across all oceans and differs both regionally and geographically (Levitus *et al.* 2005, Kashkooli *et al.* 2019). For example, Belkin (2009) determined that semi-closed ecosystems such as the North Atlantic, European and East Asian seas have a high warming rate (0.6-0.9 °C), the Indian, Caribbean, Australian and Indonesian seas showed moderate warming rates (0.0-0.6 °C), while the Humboldt and California upwelling ecosystems showed cooling rates (< 0 °C).

Changes in SST can modify the dynamics of the ocean, patterns or intensity of marine currents, and depth of the thermocline (*e.g.*, Zhu *et al.* 2015, Carvalho & Wang 2020, Yang *et al.* 2020). These effects on the dynamics of the ocean generate variations in marine populations, especially in the distribution and abundance of lower trophic level organisms (*e.g.*, Huete 2016). By affecting primary producers and consumers, the transfer of matter and energy from marine ecosystems is also adversely affected, harming many migratory and vulnerable species (Murillo-Murillo *et al*. 2013, Jiménez 2016), and subsequently, related commercial activities. For example, a decrease in tuna catches per unit of effort has been related to increasing water temperatures along the equatorial Pacific (Lehodey 2000, Torres 2004).

The Eastern Tropical Pacific (ETP) is a marine ecoregion with biological and oceanographic characteristics that enhance the local indices of diversity, endemism, and productivity. SST in the ETP plays an important role in global climatic conditions by generating modifications in rainfall throughout the tropics (Karnauskas *et al.* 2009, Rústico *et al.* 2015, Coats & Karnauskas 2017). During the twentieth century, SST in the Tropical Pacific (6°N, 162°W) has presented warming trends ranging from 0.36 to 0.74 °C (SST anomalies from Hadley and ERSST datasets, see Nurhati *et al.* 2011). However, various studies mention that at the beginning of the 21st century, the ETP went through a cooling stage, which has contributed to the slowdown of global SST warming (Rústico *et al.* 2015, McGregor *et al.* 2018). According to Karnauskas *et al.* (2015), SST in the ETP showed a cooling trend of 0.3 °C during 1982-2014, while the temperature in the Western Pacific exhibited a warming trend of 0.6 °C (Optimal Interpolation Gridded SST dataset). It is suggested that this cooling process is a product of equatorial trade winds increase and sea level rise, allowing the ETP to cool and contribute to the slowdown of globally averaged SST warming (Chikamoto *et al.* 2016).

SST monitoring allows a greater understanding of physical oceanographic processes, and the impact of global warming on marine ecosystems (Kashkooli *et al.* 2019). It can also provide insight into the effectiveness of marine protected areas (MPAs) for biodiversity conservation (Osgood *et al.* 2021). Although MPAs have been promoted as a tool to mitigate the effects of climate change, actual trends in ocean warming will modify the composition and functioning of protected ecosystems within global MPAs (Bruno *et al*. 2018). Due to the inherent climatic and oceanographic variability of the ETP, a comparatively spatial assessment is necessary to understand and detect SST trends to anticipate and predict future harmful effects within and beyond MPAs.

The present work comparatively evaluated the annual and monthly variations of SST in the ETP using remote sensing. The study's main objectives were to 1) determine the annual average SST trends from 1982 to 2019 for eight MPAs in the ETP, 2) compare the variation in the annual mean SST between sites, and 3) compare the monthly mean SST variability at each site. This study is expected to serve as the basis for long-term research evaluating the effects of climate change on SST and marine ecosystems in the ETP.

Materials and methods

Study area

The ETP is an area of great importance for species conservation and fishery resources sustainable use (Hearn *et al.* 2010). It has an estimated extension of 8,800 km of coastline, and an area of 21 million km^2. It is made up of eleven countries (Mexico, Guatemala, France, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, Colombia, Ecuador, Peru) and extends from southern Magdalena Bay in Baja California (Mexico) to Cabo Blanco (northern Peru) (22°N-10°S; 80°W-150°W), including the oceanic islands of Galápagos, Malpelo, Cocos, Clipperton and Revillagigedo (Fiedler & Lavín 2006). The ETP is characterized by a warm pool that extends along the Pacific Coast of the Americas from southern Baja California to northern Peru, with average annual temperatures of 29 °C. Additionally, there is a tongue of cold surface waters that extends to the west near the equator. It is also influenced by the California Current, Humboldt Current, and Equatorial Countercurrent (Fiedler & Lavín 2017). These currents function as biogeographical barriers that cause a high endemism characteristic of the region (Vega *et al.* 2012). For this research, eight study sites were selected, each one located 10 nautical miles from the intertidal zone of the associated MPAs (Table 1, Fig. 1).

Table 1. Geographic location of the selected study sites and the ETP MPAs to which they belong / Ubicación geográfica de los sitios de estudio seleccionados y las áreas marinas protegidas del POT a las cuales pertenecen

Study sites	Abbreviation	Latitude	Longitude	Range (years)
Coiba National Park	Coiba	7.14	-81.64	1982-2019
Cocos Island National Park	Cocos	5.69	-87.13	1982-2019
Malpelo Flora and Fauna Sanctuary	Malpelo	4.00	-81.76	1982-2019
Gorgona Island National Park	Gorgona	2.97	-78.35	1982-2019
Northern Galápagos Marine Reserve	North Galápagos	1.53	-91.91	1982-2019
Eastern Galápagos Marine Reserve	East Galápagos	-0.25	-89.53	1982-2019
Western Galápagos Marine Reserve	West Galápagos	-0.70	-91.68	1982-2019
La Plata Island	La Plata	-1.26	-81.24	1982-2019

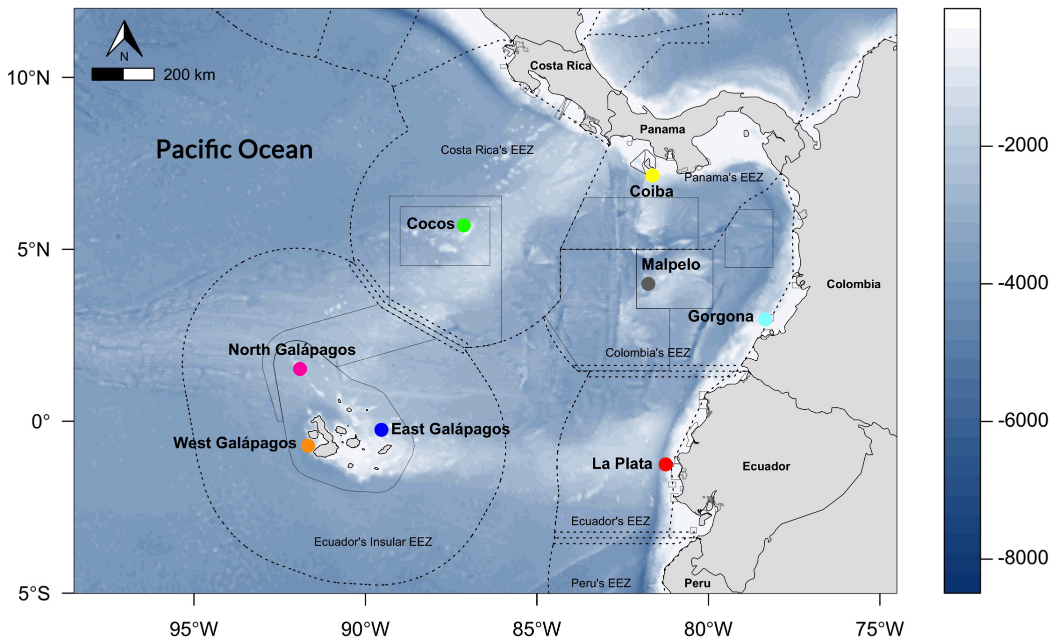

Figure 1. Location of selected study sites in the ETP. Black segmented lines represent national Exclusive Economic Zones (EEZ). Black solid lines represent MPAs / Ubicación de los sitios de estudio seleccionados en el POT. Las líneas segmentadas negras representan las Zonas Económicas Exclusivas (ZEE) de los países. Las líneas negras sólidas representan las AMP

Remote sensing information

SST information was obtained from the Daily Optimum Interpolation SST (OISST) V2.1 dataset provided by the National Oceanic and Atmospheric Administration (NOAA) (Huang *et al.* 2020). OISST's analysis is based on a daily optimal interpolation where *ex situ* and *in situ* observations (satellites, ships, and buoys) are combined to form a spatially complete SST analysis (Bazon *et al.* 2016). The dataset contains information in a daily grid recorded in degrees Celsius (°C), with a spatial resolution of 0.25 geographical degrees (°) from years 1981 to 2019 (access date 2020/01/20). To minimize the influence of measurement errors from the first year, data from 1982 to 2019 were utilized. SST data were extracted using the "rerddapXtracto" v.0.4.5 package of R statistical software (Mendelssohn 2021).

Statistical analysis

SST time series were processed and analyzed in R statistical software (R Core Team 2021). Data for each site was decomposed into its yearly trends, seasonal (monthly) variations and random portion following Kendall *et al.* (1983). To determine upward and downward trends in the raw SST data, the modified Mann-Kendall test for serially correlated data using Hamed & Rao (1998) variance correction approach (MMKH, Mann-Kendall variance corrected approach of Hamed and Rao) was used. MMKH is a variation of Mann-Kendall test that corrects for serial correlation in trend analysis. Data was initially detrended and the effective sample size was calculated using the rank of significant serial correlation coefficient, which was then used to correct the inflated (or deflated) variance of the test. For the analysis interpretation, MMKH parameters Z (presence of positive or negative trend), *P* (significance level), and S (Sen's slope) were separately calculated for the six studied sites. This analysis was performed using the "modifiedmk" v 1.6 statistical package (Kumar & O'Brien 2021). In addition to this, maps for the yearly SST anomalies and MMKH test parameters were created to visually compare the spatial temperature changes across the ETP. This analysis was performed using the statistical package "modifiedmk" v 1.6 (Kumar & O'Brien 2021). In addition, maps for annual SST anomalies and MMKH test parameters were created to visually compare spatial temperature changes across the ETP. To achieve this, all georeferenced SST time series (from 1982 to 2019) found in the area within the latitudes -4° to 12° and longitudes -100° to -75° were extracted and each was analyzed separately for anomalies and MMKH parameters. The results were then gridded and created annual maps for SST anomalies and single maps for Z, P and S values. Finally, correlations analyses were used to compare annual average SST between sites and monthly SST anomalies between sites and decades. To compare annual average SST between sites, a Pearson correlation analysis was used. To compare monthly SST anomalies between sites and decades, a correlation analysis using a Kendall coefficient was used. Monthly SST anomalies per decade were calculated by splitting the time series into four bins: 1982-1991, 1992-2001, 2002-2011 and 2012-2019.

Results

Average SST in the ETP during the period 1982-2019 was 25.92 °C (± 2.40). The highest SST was recorded at Cocos, with a value of 31.88 °C for the second quarter of 1983. The lowest SST was 17.21 °C recorded in the west of Galápagos for the fourth quarter of 2017 (Fig. 2).

SST Trend analysis

The decomposition of the time series showed no clear increase or decrease in SST over the years throughout the ETP (Fig. 2b). However, MMKH test showed an increasing trend for SST in Coiba, Gorgona, North Galápagos and La Plata (MMKH, $P < 0.05$, Z values in Table 2), while a decreasing trend was depicted for West Galápagos (MMKH, $P = 0.004$; Z= -2.85). East Galápagos was the only site where SST did not show any trend (MMKH, $P = 0.56$) (Table 2).

The highest annual average SST (28.22 °C) was recorded in Coiba, while the lowest (22.77 °C) was observed in West Galápagos. Sites such as Coiba, Cocos, Malpelo and Gorgona were characterized as having the warmest temperatures (26-30 °C) and were among the least variable. Sites such as La Plata,

Table 2. MMKH results for the 1982-2019 SST time series trend analysis of the eight study sites in the ETP / Test de significancia Mann-Kendall modificado para la tendencia de las series de tiempo de la TSM de 1982-2019 para los ocho sitios de estudio en el POT

Study sites	*P* value	Z value
Coiba	0.04	1.96
Cocos	0.20	1.25
Malpelo	0.22	1.20
Gorgona	0.00002	4.24
North Galápagos	0.04	1.99
East Galápagos	0.56	0.57
West Galápagos	0.004	-2.85
La Plata	0.03	2.06

North, East, and West Galápagos had low temperatures (25-20 °C), but a higher thermal stress (Fig. 3). The correlation between Gorgona and West Galápagos annual average SST was the weakest of all study sites (Pearson, R^2= 0.26). North and East Galápagos were strongly correlated (Pearson, R^2= 0.95). Further correlation coefficients are detailed in Table 3.

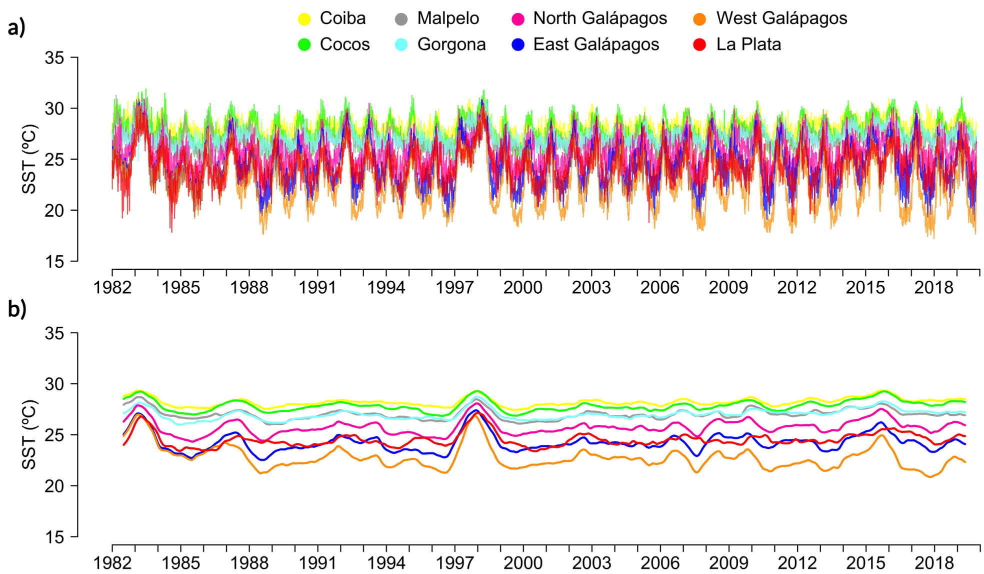

Figure 2. a) Variation in SST time series raw data at the eight study sites in the ETP. b) The decomposed yearly SST trends of the eight study sites in the ETP / a) Variación de los datos en crudo de la serie de tiempo de TSM para los ocho sitios de estudio en el POT. b) Tendencia anual descompuesta de la TSM en los ocho sitios de estudio en el POT

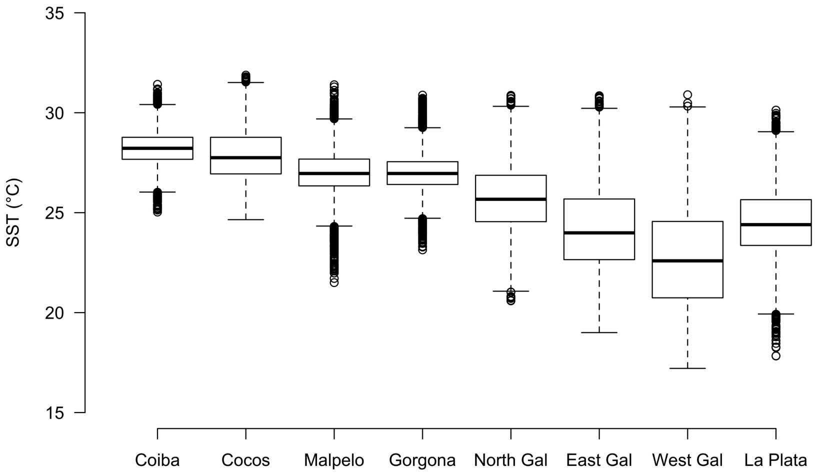

Figure 3. Annual SST variation at the eight study sites in the ETP. Site position on the *y*-axis is ordered based on their latitudinal location within the ETP. North Gal: Northern Galápagos Marine Reserve; East Gal: Eastern Galápagos Marine Reserve; West Gal: Western Galápagos Marine Reserve / Variación anual de la TSM en los ocho sitios de estudio en el POT. La posición de los sitios en el eje *y* depende de su ubicación latitudinal en el POT. North Gal: Reserva Marina Galápagos Norte; East Gal: Reserva Marina Galápagos Este; West Gal: Reserva Marina Galápagos Oeste

Table 3. Pearson's correlations of annual average SST of the eight study sites in the ETP / Test de correlación de Pearson del promedio anual de la TSM para los ocho sitios de estudio en el POT

	Coiba	Cocos	Malpelo	Gorgona	North Galápagos	East Galápagos	West Galápagos
Cocos	0.82[d]	-	-	-	-	-	-
Malpelo	0.67[c]	0.57[c]	-	-	-	-	-
Gorgona	0.52[c]	0.42[c]	0.72[d]	-	-	-	-
North Galápagos	0.71[d]	0.84[d]	0.55[c]	0.41[c]	-	-	-
East Galápagos	0.69[c]	0.83[d]	0.49[c]	0.32[b]	0.95[e]	-	-
West Galápagos	0.67[c]	0.81[d]	0.49[c]	0.26[b]	0.89[d]	0.93[e]	-
La Plata	0.63[c]	0.69[c]	0.47[c]	0.39[b]	0.71[d]	0.72[d]	0.71[d]

a: 0.00-0.10 insignificant correlation, b: 0.11-0.39 weak correlation, c: 0.40-0.69 moderate correlation, d: 0.70-0.89 strong correlation, e: 0.90-1.00 very strong correlation

The spatial distribution of SST anomaly shows the occurrence of warmer waters during the last two decades, and that warm waters located in the northern region of the ETP migrated south towards the equator (Fig. 4). The spatial MMKH analyses show significant cooling trends and negative slopes for the coastal areas close to West Galápagos and north of Peru, yet a significant warming trend and positive slope was observed region-wide north of the equator and next to the coast of Ecuador (Fig. 5). A large area within and around the exclusive economic zone of Costa Rica (around Cocos Island) showed no significant changes in SST, regardless of the observed positive trends and slopes.

SST Seasonal variations

Decomposition of the complete SST time series (1982-2019) per site shows a strong seasonality in SST for all sites excepting Coiba, Malpelo and Gorgona (Fig. 6). For Cocos, Galápagos and La Plata Island, there was a marked warm season occurring from January to May with temperatures up to 3 °C warmer that the site average, while a marked cool season was observable from July to November with temperatures almost 2 °C cooler. Only SST variations in East and West Galápagos were strongly associated, exhibiting very similar temporal changes (Kendall, R^2= 0.97). SST temporal variations in Gorgona were negatively correlated with those of La Plata, North, East, and West Galápagos. SST decreased at Gorgona, while it increased at the other sites (Table 4).

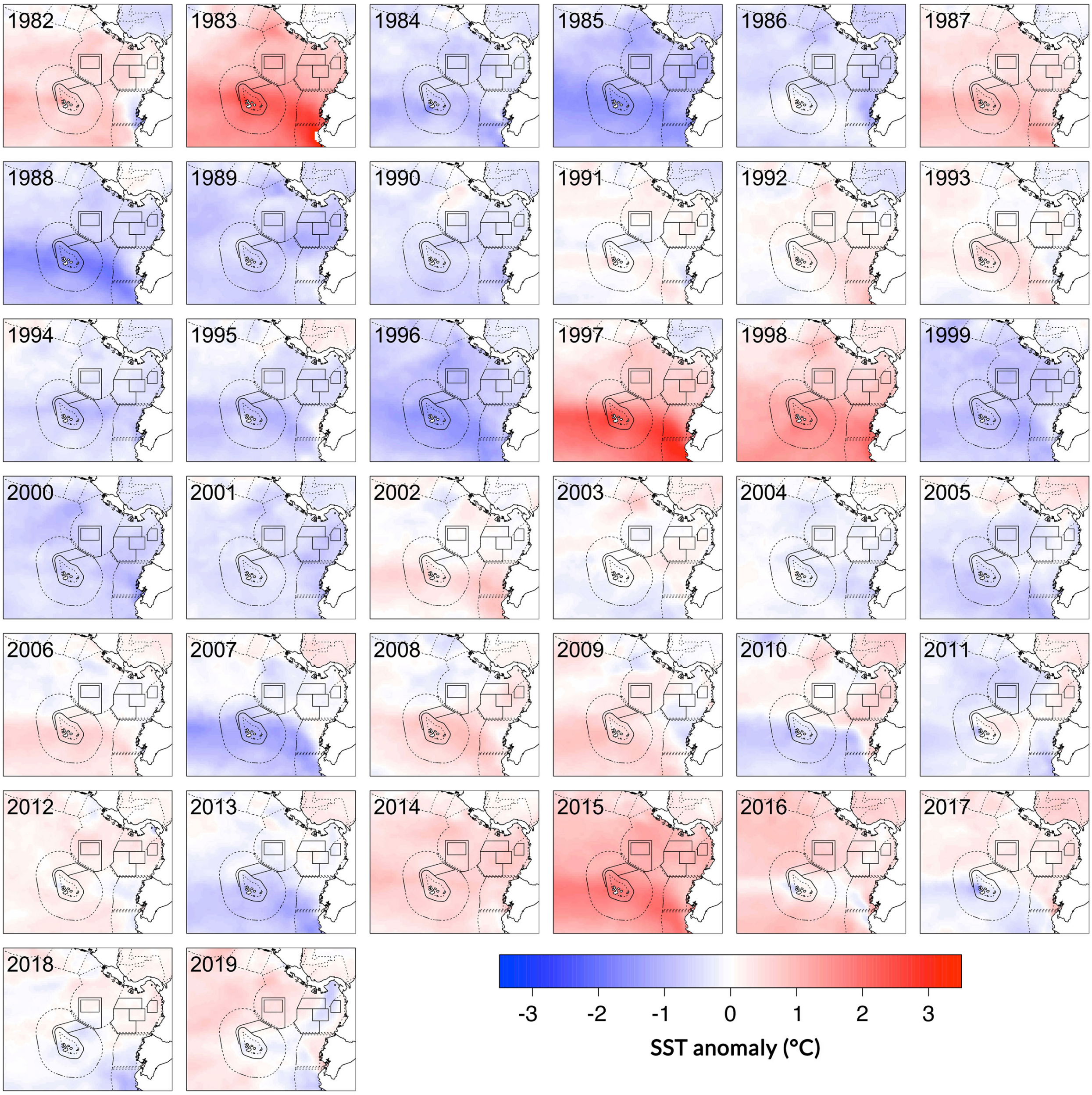

Figure 4. Yearly SST anomaly during the 38-year study period in the ETP. Black segmented lines represent national Exclusive Economic Zones (EEZ). Black solid lines represent MPAs / Variación de la anomalía en la TSM durante los 38 años de estudio en el POT. Las líneas segmentadas negras representan las Zonas Económicas Exclusivas (ZEE) de los países. Las líneas negras sólidas representan las AMP

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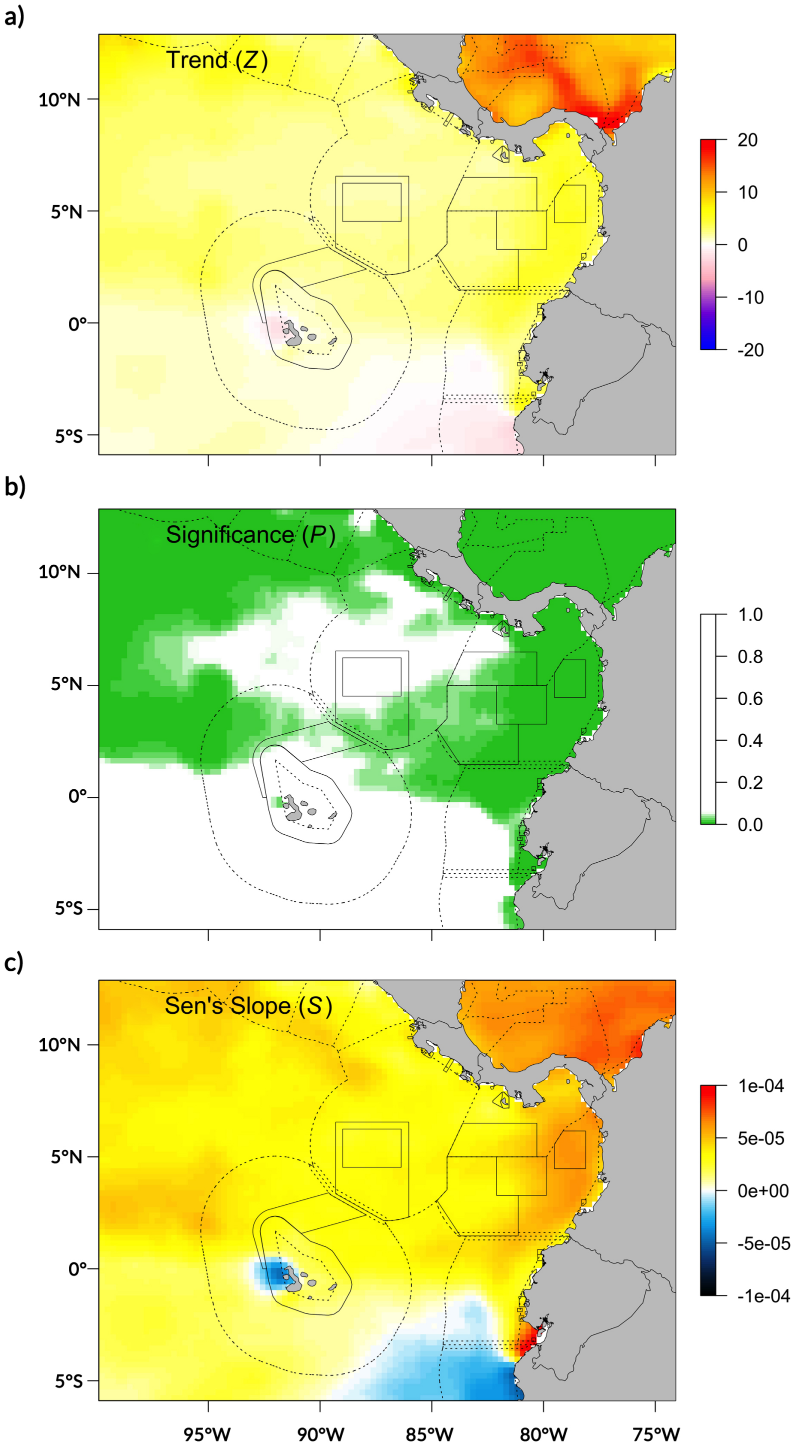

Figure 5. Mann-Kendall (a) trend, (b) significance and (c) Sen's Slope parameters for the spatial analysis of SST change during the 38-year study period in the ETP. Trend and Sen's Slope vary from negative to positive values, with zero indicating no trend or slope was detected in the time series. Significance is shown as a gradient of green that varies from 0 (deep green, highly significant) to 0.06 (white, non-significant). Black segmented lines represent national Exclusive Economic Zones (EEZ). Black solid lines represent MPAs / Parámetros de (a) tendencia, (b) significancia y (c) pendiente de Sen para el análisis espacial de los cambios de TSM durante los 38 años de estudio en el POT. La tendencia y la pendiente de Sen varían en valores positivos y negativos, con el cero indicando que no se detectó una tendencia o pendiente en la serie de tiempo. La significancia es representada por un gradiente de color verde que varía desde 0 (verde oscuro, altamente significativo) hasta 0,06 (blanco, no significativo). Las líneas segmentadas negras representan las Zonas Económicas Exclusivas (ZEE) de los países. Las líneas negras sólidas representan las AMP

Table 4. Kendall's correlation test of monthly averaged SST of the eight study sites in the ETP / Test de correlación del coeficiente de Kendall para el promedio mensual de la TSM para los ocho sitios de estudio del POT

	Coiba	Cocos	Malpelo	Gorgona	North Galápagos	East Galápagos	West Galápagos
Cocos	0.88[d]	-	-	-	-	-	-
Malpelo	0.52[c]	0.52[c]	-	-	-	-	-
Gorgona	0.06[a]	0.12[b]	0.36[b]	-	-	-	-
North Galápagos	0.64[c]	0.70[d]	0.21[b]	-0.12	-	-	-
East Galápagos	0.67[c]	0.67[c]	0.18[b]	-0.15	0.91[e]	-	-
West Galápagos	0.64[c]	0.70[d]	0.21[b]	-0.12	0.94[e]	0.97[e]	-
La Plata	0.61[c]	0.67[c]	0.30[b]	-0.09	0.85[d]	0.82[d]	0.85[d]

a: 0.00-0.10 insignificant correlation, b: 0.11-0.39 weak correlation, c: 0.40-0.69 moderate correlation, d: 0.70-0.89 strong correlation, e: 0.90-1.00 very strong correlation

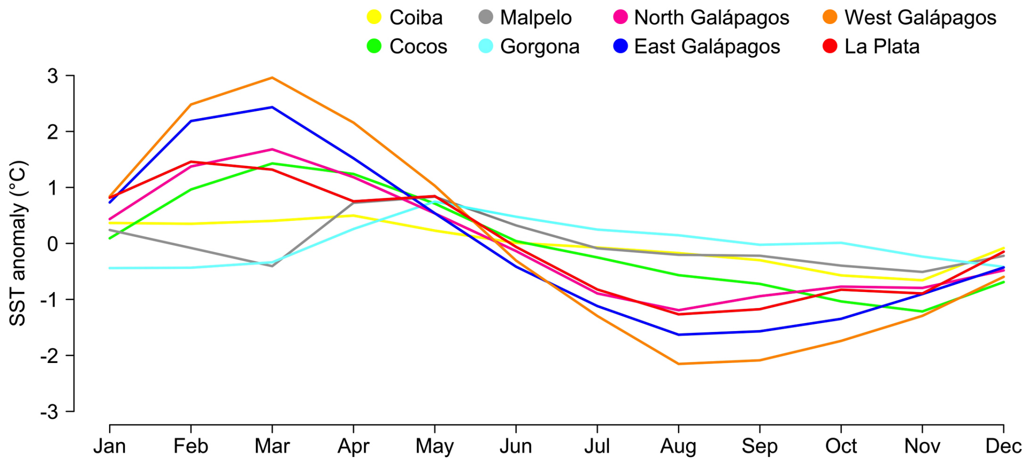

Figure 6. Monthly variations in SST anomaly at the eight study sites in the ETP / Variación mensual de la anomalía de la TSM para los ocho sitios de estudio en el POT

At sites such as Cocos, La Plata, North, East, and West Galápagos same temporal patterns were maintained with no changes in monthly SST across the compared decades (Fig. 7). For Coiba, decades 1992-2001 and 2002-2011 presented warmer temperatures during March and April (+ 0.5 °C), while the decade 2012-2019 presented colder temperatures from February to April (- 0.5 °C) and warmer temperatures from August-November, compared to the other decades. Malpelo exhibited a more pronounced difference in monthly SST across decades, with temperatures progressively becoming almost one degree colder in the last three decades for February through April (Fig. 7c). At Coiba, moderate correlations were observed in SST temporality for decades 1992-2001 and 2012-2019 (Kendall, R^2= 0.58), and strong correlations for decades 1982-1991, 1992-2001 and 2002-2011 (Kendall, R^2= 0.79). At Malpelo, a moderate correlation was observed for decades 1982-1991, 2002-2011, and 2012-2019, and a strong correlation for decades 1992-2001, 2002-2011 and 2012-2019 (Kendall, R^2= 0.79).

Discussion

Temperature is an oceanographic parameter that excerpts one of the greatest impacts on the physiology, behavior, and distribution of marine species (Spalding *et al.* 2007). Through this study, a comparative evaluation of SST in eight coastal and oceanic MPAs of ETP was conducted. The results show there was a significant warming trend in SST across the ETP, apart from Cocos, Malpelo and East Galápagos, and a significant cooling trend in West Galápagos and north of Peru. Temperature changes have been reported to occur whether El Niño events are included or not during these analysis (Wang *et al.* 2019). Additionally, a distinct seasonality was observed for Malpelo and Coiba, where an important temperature drop in the last decades was observed from February to April. The implications of these results are discussed below.

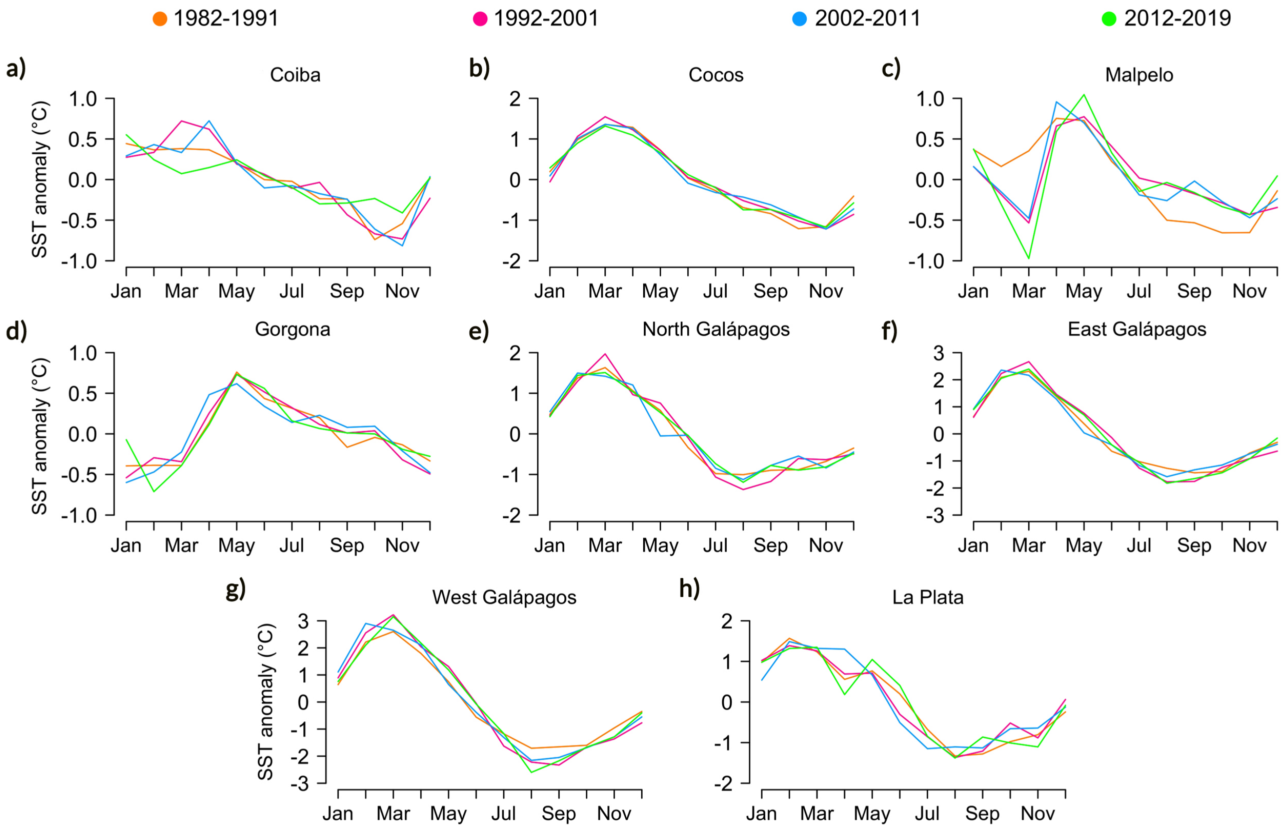

Figure 7. Differences in monthly variation of SST anomaly per decade at the eight study sites in the ETP / Diferencias en la variación mensual de la anomalía de la TSM por década para los ocho sitios de estudio en el POT

SST regional trends

According to the latest Report of the Intergovernmental Panel on Climate Change (IPCC 2021), there is unequivocal evidence of an overall global air temperature and SST warming, and that this warming is under direct influence of human emissions of greenhouse gasses. As reported by other authors, most of the studied MPAs are following the same warming trend that the rest of the world (*e.g.*, Jimenez *et al.* 2018, Lian *et al.* 2018). The observed warming rate in the ETP could be explained by the southward expansion of the Eastern Pacific Warm Pool (EPWP) and the start of the PDO warm phase. The EPWP occurs mainly from March to August, when the heating of the ETP bathes the coasts of Tehuantepec Gulf (Mexico), Guatemala, and Costa Rica with waters with temperatures above 28.5 °C (Misra *et al.* 2016). Significant linear trends suggest the EPWP is increasing in area and peaking earlier in the season compared to a few decades ago. The EPWP expansion could be reducing SST latitudinal gradient and pushing the ocean front (produced in conjunction with the cold waters of the Humboldt Current) several degrees further south. In addition to this, the PDO has been progressively changing from a cold phase that lasted until the early 2000s towards a warm phase during the 2010s (Dong & Zhou 2014). Together, these two factors are potentially influencing Coiba, Cocos, Malpelo, Gorgona, La Plata and North Galápagos, yet they do not explain the cooling trend observed in West Galápagos. There are only two areas in the world where a cooling trend has been reported: Humboldt and California currents (*e.g.*, Belkin 2009, Deser *et al.* 2010, Lian *et al.* 2018). Cooling of Humboldt Current region is regarded to be a result of the Pacific Walker Circulation strengthening and westward mobilization of atmospheric convection over the Pacific Ocean (Sohn *et al.* 2016, Zhao & Allen 2019). Although Galápagos is located far from the South American continent, it is possible these atmospheric forces are also driving the negative trends in SST observed to the west of the islands, particularly since this upwelling area is also influenced by atmosphere-ocean interactions (Forryan *et al.* 2021) and the extension of the Humboldt Current during cold La Niña conditions (known as the Equatorial Cold Tongue) (Fiedler & Lavín 2017).

Spatial difference in SST

The ETP is highly influenced by the dynamics of the trade winds that promote upwelling events both off the coast of Peru and Central America (Fiedler 1992). The Humboldt Current marks the southern limit of the ETP, bathing the region with cold waters reaching an annual average of ~18 °C and ~35 g kg^{-1} in salinity (Amador *et al.* 2016). During the colder months (June to November) this current extends to the north and west of the Equatorial Pacific area, mixing with the waters of Galápagos (Chelton *et al.* 2001), forming a more pronounced ocean front from September to October (Fiedler & Talley 2006, Fiedler & Lavín 2017). The cooling effect of the Humboldt Current could neutralize the warming trend in East Galápagos. This rise in warm and cold temperatures was proposed by Wolff (2010), corroborating what was observed in East Galápagos. The cooling of the Humboldt Current could be associated with the strengthening and displacement of the Equatorial Countercurrent (Karnauskas *et al.* 2015), allowing for the observed annual and monthly latitudinal thermal gradients between the studied MPAs.

Likewise, the Gulf of Panama is influenced by upwelling in the eastern margin of the ETP that is caused by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and wind jets coming from the Gulf of Panama (Belkin & Cornillon 2003). These processes modulate the surface ocean circulation patterns and develop seasonal upwelling through Ekman pumping. Ekman pumping generates a shallow-based thermal dome, increasing local primary productivity and reducing both surface and thermocline temperatures from February through April (Rodríguez-Rubio *et al.* 2007). The present study shows a cooling of the waters surrounding Malpelo, Coiba, Gorgona, and La Plata, particularly from February to April (Fig. 6). These results suggest that there is a strengthening of the Ekman pumping system in the region, which could be reducing the depth of the 15 °C isotherm to less than 70 m, consequently reducing SST. This effect occurs to a lesser degree in Coiba, Gorgona, and La Plata, suggesting that the influence gradient of the Panama upwelling system is latitudinally strengthen, especially in the last decade. If the trend continues, this region could present greater cooling and thus lower average annual temperatures. This could potentially mask effects of global warming in long-term trend studies, as well as exposing marine species to greater thermal stress. More studies are necessary to determine the extent that this thermal stress may affect tropical species inhabiting this region, particularly coral colonies and sessile species between Coiba, Malpelo, and La Plata. It is worth noting that this study does not report the increase in temporal variability found by Wolff (2010) for Galápagos. This could be a result of the differences in spatial resolution, temporal scale, and methodology between studies, as Wolff (2010) focused on *in situ* temperature measurements at a single location for an extended time series (1965-2007).

Potential effects on migratory species

Climate variability impacts both abundance and distribution of migratory marine species (Block *et al.* 2011). Due to ocean warming trends, studying the variability in SST not only allows for improved knowledge of regional oceanography and climate, but also the potential effects that may have SST changes on species of commercial and conservation interest (Reygondeau 2019). It has been predicted that sharks, turtles, tunas and seabirds in the Northeast Pacific Ocean could change their current distribution by up to a 35% due to global warming (Hazen *et al.* 2012). This change could be in response to a structural reorganization of the distribution of these species from the tropics to higher latitudes, in accordance with their temperature preferences (Whitehead *et al.* 2008). Examples of this reorganization have already been reported in commercial species such as North Atlantic tunas, *Thunnus alalunga* (Bonnaterre, 1788) and *T. thynnus* (Linnaeus, 1758), which have modified their arrival times to their feeding areas in response to increasing temperatures in the Atlantic Ocean (Dufour *et al.* 2010). Other marine ecosystems, such as coral reefs, are threatened by ocean warming trends (Heron *et al.* 2016). According to Figueiredo *et al.* (2014), rising ocean temperatures could lead to higher rates of local retention of coral larvae, thus weakening connectivity between populations.

Drastic changes in species distribution could not only cause a structural change in marine ecosystems, but also a reduction in local resource availability, causing a cascading effect on fishing activities (Allison *et al.* 2009) and tourism (Ho *et al.* 2016). MPAs of the ETP host several species of high commercial and conservation interest. For example, West Galápagos is home to one of the most important aggregations and fishing sites for yellowfin tuna *T. albacares* (Bonnaterre, 1788) in the ETP (Bucaram *et al.* 2018). The present study reports that West Galápagos SST was relatively stable compared to other areas in the ETP, suggesting that there is not a heightened risk to fishing activities there. However, significant changes in ETP SST and primary productivity could put at risk an activity that produces several billion dollars annually. The ETP also hosts the largest aggregations of scalloped hammerhead shark, *Sphyrna lewini* (Griffith & Smith, 1834) in the world (Hearn *et al.* 2014). The size of these aggregations changes according to the season, reaching more than 50 to 100 individuals when the SST fluctuates between 24-28 °C (Bravo-Ormaza *et al.* 2023). *S. lewini* is a critically endangered species (Rigby *et al.* 2019) and is highly vulnerable to fishing outside of the protection of MPAs (Gulak *et al.* 2015). Temperatures greater than this range cause the aggregations to decrease in size (Bravo-Ormaza *et al.* 2023) and individuals to migrate to other areas of the ETP (Peñaherrera-Palma 2016).

ETP coastal, oceanic, and abyssal ecosystems host more than 5,000 species of marine invertebrates, more than 1,000 species of fish, 30 species of marine mammals, 123 marine birds, and six marine reptiles (Peñaherrera-Palma *et al.* 2018). Currently, about 18% of all rays, 34% of sharks, 66% of reptiles, 16% of mammals, and 26% of seabirds are in danger of extinction or in a vulnerable state. Changes in the regional SST could worsen these declining population trends and cause local extinction of these and other species. This regional deterioration of biological and ecological diversity could, in turn, threaten the nearly 15 billion USD that the ETP generates annually in ecosystem services. The consistent evaluation of regional SST variations is important in the early detection of oceanographic condition changes that could impact regional biodiversity and species distribution. This information is crucial when developing management measures to mitigate the deterioration of ETP marine ecosystems.

The results of this research showed that a great area of the ETP has experienced a significant increase in SST during the last four decades. Higher latitudes were warmer and showed lesser thermal stress compared to lower latitudes. Despite the gradual increase in regional SST, annual SST latitudinal gradient at most sites in the ETP was maintained in part by the cooling effect of the Humboldt Current (in the south) and the strengthening of the Ekman pumping in the Gulf of Panama and the Colombian Pacific Basin. Specifically located in this area, Malpelo, Coiba, Gorgona, and La Plata show a decrease in SST from February to April. More studies are required to investigate the effects that changes in regional SST within the ETP can have on the thermal stress of marine species. Furthermore, higher resolution data need to be used to determine if annual and monthly trends observed in this study respond to local changes, regional events such as PDO, or global ones such as El Niño Southern Oscillation.

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