Latin American Journal of Aquatic Research, 52(4): 637-645, 2024
DOI: 10.3856/vol52-issue4-fulltext-3169

Short Communication

Sea surface temperature differences between *in situ* and GHRSST (L4) records in a socio-ecological critical area of the northeastern Pacific Ocean May 2015 to July 2016

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ABSTRACT. Using satellite sensor data for studying sea surface temperature (SST) provides advantages over *in situ* information, such as obtaining data from large areas and remote access regions in short periods. However, differences between the SST values recorded *in situ* and those by satellite sensors are due to the intrinsic nature of both methods and meteorological factors. The present study aims to search the difference between SST values from *in situ* and satellite sensor data of 1×1 km resolution (type L4) from the Group of High-Resolution Sea Surface Temperature (GHRSST) for an annual cycle in a socio-ecological critical area known as the Gulf of Ulloa (GU). The linear regression, linear spline regression, and logic models showed an overestimated SST by satellites compared to *in situ* data, particularly at temperatures below 20°C. The overestimation can be attributed to the oceanic-atmospheric variations, which are consequences of upwelling and the time lag between the data record morning by *in situ* and night by satellite sensors. This finding may be relevant in decision-making for marine resource management and conservation in the GU. The information may help to seek the sustainability of this social-environmental system.

Keywords: sustainability; monitoring; systems; bycatch; management; marine ecology

Temperature and its variations are fundamental for understanding physical-biological interactions on the planet. In marine environments, the absorption of sun shortwave radiation increases water temperature to an amount directly proportional to the energy absorbed. Likewise, as the temperature increases in the surface layers, the absorption is greater and decreases rapidly at depth (Mann & Lazier 2005). Compared with air, the sea has a greater heat capacity; that is, more energy and time are needed to change or increase the temperature in water. This conservative property is related to all the biotic processes in an oceanic biome. Thus, knowing thermal environmental variations has been part of scientific work and has been of interest for a long time. Although the reliable instrumental records of surface temperature with quasi-global coverage started in 1850 (Brohan et al. 2006), temperature measurements in the ocean were not extended until the 20th century exponentially from then on to these days.

Because the oceans cover a great planet extension, obtaining systemized and consistent *in situ* sea surface temperature (SST) measurements is complicated and extremely costly (Casey & Cornillon 1999). Thus, much of the information comes from punctual observations in space and time recorded on board research expedition vessels, such as the World Meteorological Organization (WMO) of the United Nations, which has worked to achieve global coverage

Associate Editor: Andrea Piñones

of the ocean to get adequate coastal management, a record of the anthropogenic impact to the oceans, good use of marine resources and foresee the impact of the ocean over global climatology (Johnson 2005). The WMO gets 7000 ships, 100 anchored buoys, 1000 drifting buoys, 3000 commercial aircraft supporting the measurement of the ocean surface, and the effort of 20 nations collecting global oceanographic information, including SST, and oceanographic buoys including other than oceanographic vessels taken voluntarily. However, some challenges, such as equipment maintenance, information improvement, and expanding the buoy network in the Pacific, need to be adequately monitored. All this indicates that even nowadays, these tools poorly monitor regions (Casey & Cornillon 1999, Johnson 2005).

However, although many instruments have been installed currently in different seas and oceans and oceanographic cruisers are conducted in vast regions, these methods are not effective if very extensive regions or simultaneously with difficult access require characterization (Casey & Cornillon 1999, Cerdeira-Estrada et al. 2015) although satellite observations starting in 1979 (Spencer & Christy 1990) allowed a global thermal field practically in real time, widening the collection of thermal measurements in large databases available on internet, increasing the synoptic capacities to evaluate actions that are impossible to perform with traditional methods and despite the wide use given to SST satellite information, differences among them and *in situ* measurements have been observed (Parra et al. 2011), which is not all unexpected because of the intrinsic difference of both measurement methods or some other source of variation such as the results of the algorithms used for transforming radiometric measurements to temperature values, particles in the atmosphere that may interfere in the radioactive field of the measurement instrument or including deterioration of the sensors installed in the different satellites (Williams et al. 2014).

According to Smit et al. (2013), the discrepancy among the obtained SST values is several; for example, hydrodynamic processes, differences in depth among sea layers either from a coastal zone or not, or including the combination factors that may result in a difference of up to 6°C between both measurements. These differences have been attributed to climate by other authors who point out they may generate variations from 4 to 10°C in punctual periods when a strong interaction exists between the ocean and wind, preventing a clear reading by the sensor (Pereira et al. 2020). Al-Shehhi (2022) mentions that the seasonal interactions between the wind and ocean may generate a greater difference in measurement during summer, which is associated with the water column depth and angle of solar incidence as the main elements that may affect estimating SST satellite reading, so they should be considered. Thus, satellite and *in situ* observations are usually complementary since the last ones -despite their limitations- are used to validate satellite sensor data (Xu & Ignatov 2013).

Notwithstanding this, wide spatial coverage offered using satellite sensors has allowed the establishment of oceanographic systems to monitor environments that may be related to the presence of marine organisms of both commercial (Cimino et al. 2019) and ecological interest for the adequate management of natural resources at world level (McCarthy et al. 2017). A case related to the conservation, particularly of sea turtles, is NOAA's Turtle-Watch (https://oceanwatch.pifsc.noaa.gov/turtlewatch.html), still in experimentation, which was proposed as a solution for the bycatch and its socio-ecological consequences in the Hawaiian archipelago, it integrates northern Hawaiian information of SST variations. It generates a map that informs regional longline fleets about areas within the lower thermal limit of the habitat preferred by the loggerhead turtle *Caretta caretta* (17.5-18.5°C). This way, the vessels warn to avoid these areas, mitigating the sea turtle-fleet interaction (Howell et al. 2008).

The sea turtle-fishing interaction is not particular to the Hawaiian archipelago. On the northwest coast of the Mexican Pacific, there is a region locally known as the Gulf of Ulloa (GU). This area is of commercial importance and is used for deep-rooted fishing. Still, according to data from the Federal Environmental Protection Agency (PROFEPA), Mexico's federal government, strandings of sea turtles have been recorded, which, according to some hypotheses, are a consequence of bycatch by the communities' artisanal fishing activities (SAGARPA 2014). As a solution, the government imposed a specific fishing restriction zone. However, this increased the social vulnerability of the communities (Narchi et al. 2018). Based on the ectothermic physiological condition of sea turtles, an alternative hypothesis has been proposed: the accumulation of days below the optimal minimum threshold for sea turtle locomotion can be used to prevent mortality, natural and fishing mortality, of this important species in the ocean ecosystem (Salinas-Zavala et al. 2020, Morales-Zárate et al. 2021). It could serve as a basis for proposing adaptive measures that benefit the conservation of sea turtles, resource management, and the sustainable development of fishing communities.

So, the optimal SST values for *C. caretta* appear to be the same throughout the North Pacific (18°C) (Polovina et al. 2000). The SST could monitor persistently cold events within the GU and thus alert fishing communities of the vulnerability of these chelonians, and this way avoid the sea turtles-fisheries interaction. Therefore, knowing and considering the differences between *in situ* and satellite SST values within this region is important. The objective of this work is to calculate these differences using Multiscale Ultra-high Resolution satellite data that are coincident with *in situ* records in time (days) and space (1 km^2), which could be the first step to generate an early warning system that mitigates the bycatch of sea turtles in this socio-ecological interest region in the Mexican northeastern Pacific.

The GU is on the western coast of the state of Baja California Sur, Mexico, between 25 and 27°N and 112 to 114°W (Fig. 1). The area is completely influenced by the California Current (CC) that flows along the North American coast to the extreme south of the Baja California Peninsula (Lynn & Simpson 1987, Bograd et al. 2001). The dynamics of the area allow the GU to be considered a Biological activity center (Lluch-Belda 2000). High primary production rates are maintained, which allows hosting a greater number of resources, both of economic and ecological interests, highlighting high concentrations of marine turtles, whose eco-thermal nature may be severely affected in abnormally cold conditions (Nichols et al. 2000, Salinas-Zavala et al. 2020).

The present analysis is based on two data sources: *in situ* and satellite records. The *in situ* data were obtained through the Gulf of Ulloa Fisheries Regulations (Gulf of Ulloa Fisheries Management Program, SAGARPA-CONAPESCA) for the period from May 2015 to July 2016. Technical assistants on board (TAB) took the *in situ* data during the fishermen's work day. Therefore, there are different measurements on the same day at different points. These points were georeferenced using a portable global positioning system (GPS) model Garmin eTrex 22X (3-7 m of accuracy) in UTM format; at the same points, the SST was taken with an ExStik multiparameter sensor Model EC500 that has a ±1°C of precision, at least 1 m in depth, and the numbers were recorded in full. All data that were poorly georeferenced or outside our area of interest were omitted; thus, to reduce the gaps for the coastline, we only use the records observed below the 10 m isobath and up to 200 m deep; additionally, SST values greater than two standard deviations were eliminated, this was done for the entire study period (from May 2015 to July 2016).

Satellite images were obtained from the Group for High-Resolution Sea Surface Temperature (GHRSST) for the same period (May 2015 to July 2016), particularly from the Jet Propulsion Laboratory of the National Aeronautics and Space Administration (JPL-NASA) data repositories (https://podaac.jpl.nasa.gov/MEaSUREs-MUR). The images used are products with NetCDF format and spatial resolution of 1×1 km Type L4 version 4.1. In other words, they are multiscale ultra-high resolution (MUR) products, one of the complete collections of its type composed of integrated SST nocturnal records captured by several sensors: Advanced Very High-Resolution Radiometer (AVHRR), Advanced Microwave Scanning Radiometer (AMSR-E); Visible Imagine Radiometer Suite (VIIRS) and Moderate Resolution Imaging Spectroradiometer (MODIS). Additionally, the NOAA Institute for Quantitative Asset Management project data incorporates *in situ* records of oceanographic research boats and buoys monitored and corroborated almost in real time for their integration.

The GHRSST satellite SST average (°C) value was obtained for each quadrant of 1×1 km^2 and each date with *in situ* temperature. For this process, the R programming language (R Core Team 2022) and Satin package version 1.0.3 were used (Villalobos & González-Rodríguez 2022). The comparative analysis between both datasets was performed graphically with the time series within the interval they coincide. Additionally, the frequency histograms were calculated in intervals of 1°C to observe the distribution of the time series. A linear model was applied to examine the relationship that both datasets have and can be expressed with the following equation:

$$\text{Satellite } SST = in\ situ\ \ SST \times \text{m} + \text{b}$$

where: m: slope of the straight line; b: intersection with the y-axis.

The linear regression was complemented by a linear spline regression to show a possible non-linear relationship between the two data series and, finally, a logit model was estimated to find the probability of *in situ* sea surface temperatures being below 18°C for any given satellite measurement.

We use 11,101 *in situ* SST values corresponding to a satellite SST value. The time series of both datasets are shown in the upper panel (Fig. 2). This shows discontinuities in the series, which are due to the lack of data in some of the analyzed sets. It shows a similar behavior in both datasets, corresponding to the seasonal thermal pattern. The *in situ* pattern had minimum values of 14°C recorded during spring months and a maximum of 28°C in summer. On the one hand, the set of satellite values showed slightly higher values than those *in situ*, with a minimum of 17°C and a maximum

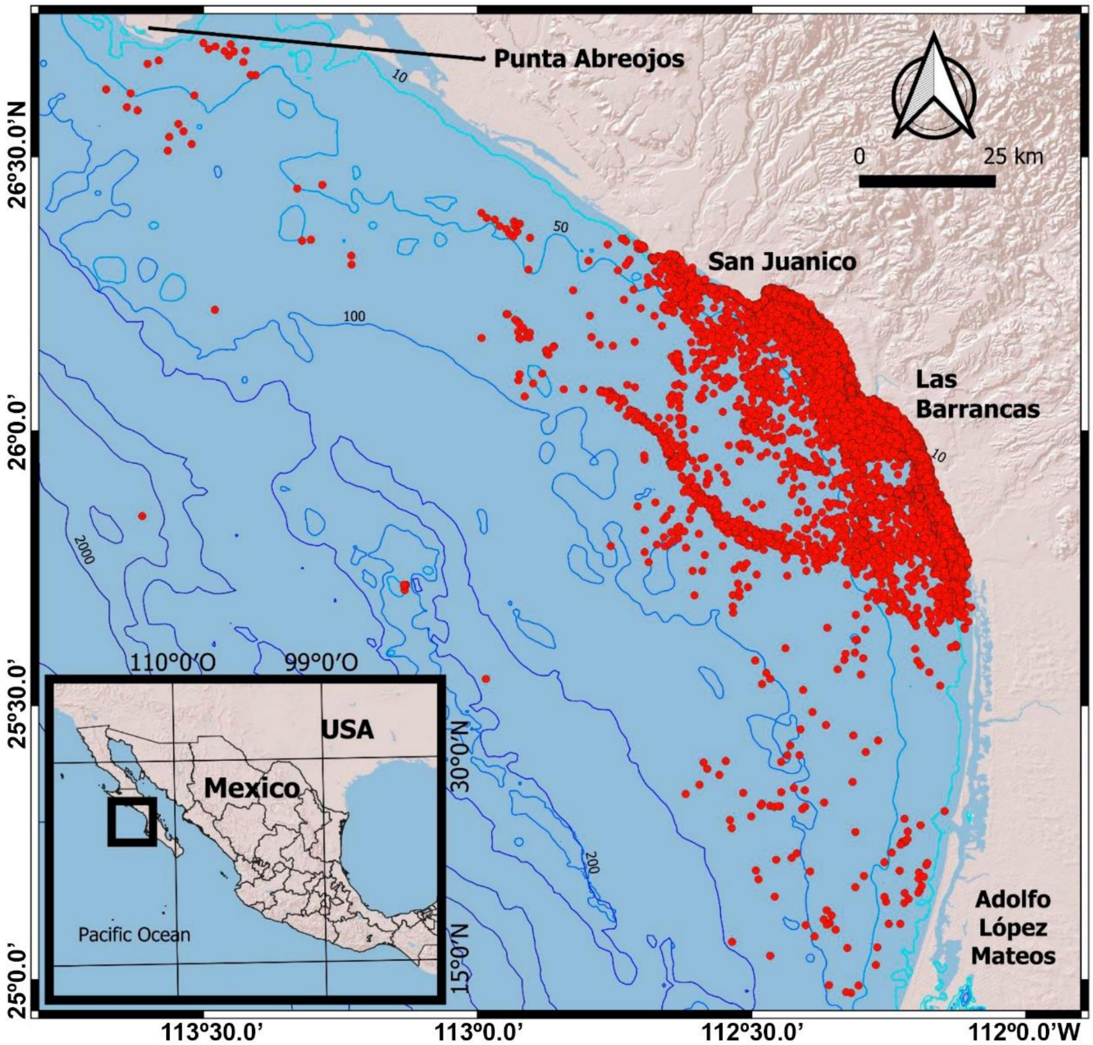

Figure 1. Gulf of Ulloa, on the western coast of Baja California Sur, Mexico. Red points indicate the sites with recorded *in situ* sea surface temperature.

of 30°C during spring and summer, respectively. It is worth highlighting that greater daily variability can be observed *in situ* records than in satellites. The lowest panel shows the frequency histograms of both series. In the case of *in situ* SST, the most frequent values corresponded to 20°C. On the other hand, the satellite frequency distribution datasets veered away from unimodality, showing two maximums at 21 and 27°C. In general, this dataset showed higher SST values than those of the *in situ* records.

Figure 3 presents a weighted scatter plot (blue dots) to visualize the relationship between satellite-derived SST (y-axis) and *in situ* measurements (x-axis). The linear regression model (red line) estimates the linear relationship between the two measurements. The linear spline regression (green dashed line) also captures potential non-linearities. The primary aim is to determine if the measurements move in parallel, indicating that a one-degree change in one measure-ment results in a one-degree change in the other. The linear regression slope (0.9548, [0.944,0.966] 95%-CI) is significantly less than 1 ($P < 0.001$), suggesting that a one-degree increase in the *in situ* measurement corresponds to a smaller increase in the satellite measurement. The linear spline model, segmented into 2-degree intervals, further reveals a non-linear relationship. The slope varies considerably, ranging from 0.237 [0.173,0.295] between 18-20°C to 1.659 [1.605,1.714] between 22-24°C. Notably, at lower temperatures (below 20°C), the spline deviates significantly from the diagonal, indicating a substantial overestimation of SST by satellites compared to *in situ* measurements.

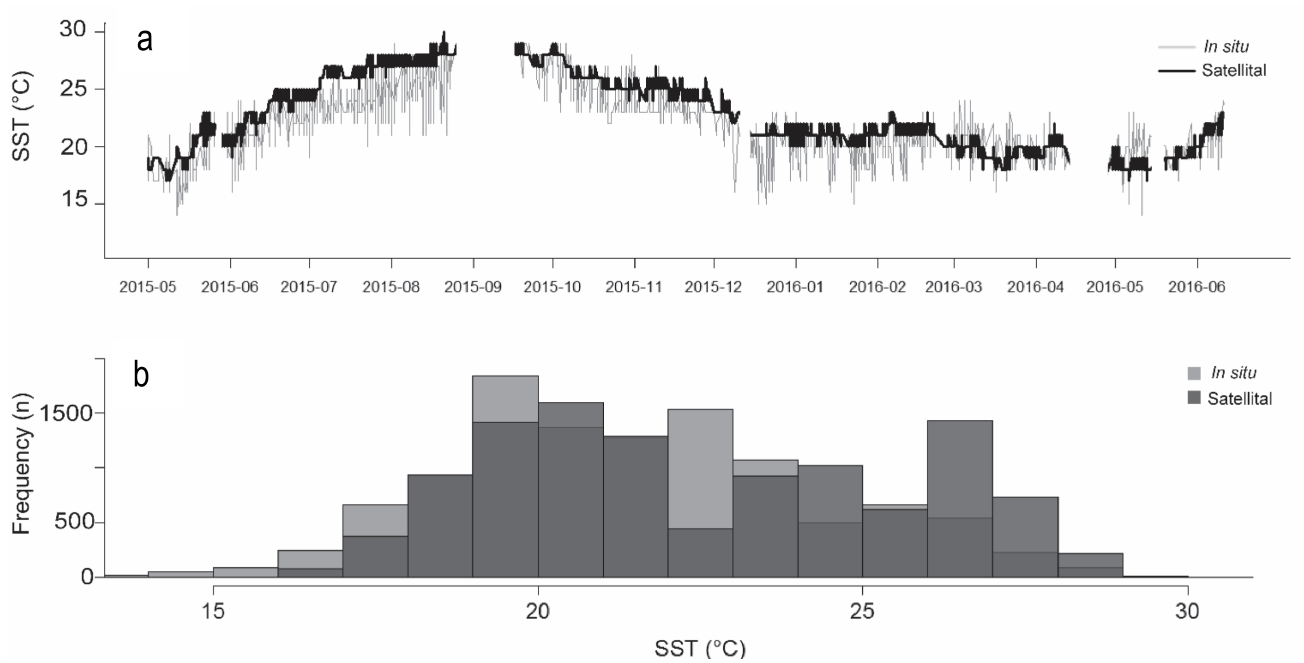

Figure 2. Comparison of *in situ* and satellite sea surface temperature (SST) series in the Gulf of Ulloa. a) General behavior of data during the study period (May 2015-June 2016), b) frequency histograms of both datasets.

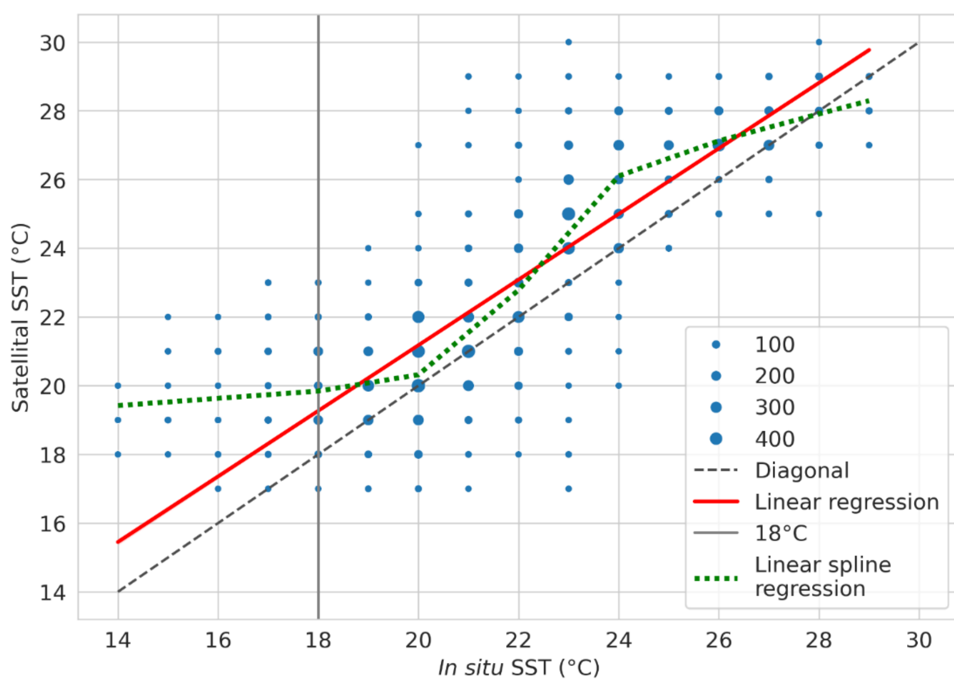

Figure 3. Relationship between satellite and *in situ* data, weighted scatter plot (blue dots), linear regression model (red line), linear spline regression (green dashed line), and the intercept (black dash line). SST: sea surface temperature.

The linear spline model has a higher R-square value (0.786) than the linear model (0.730), suggesting that it can better represent the underlying relationship between the two measurements. Additionally, we estimated two logit models (Fig. 4). We plotted the predicted probability of *in situ* temperatures below (black line) and strictly below (gray line) 18°C as a function of the satellite-derived SST. We can observe

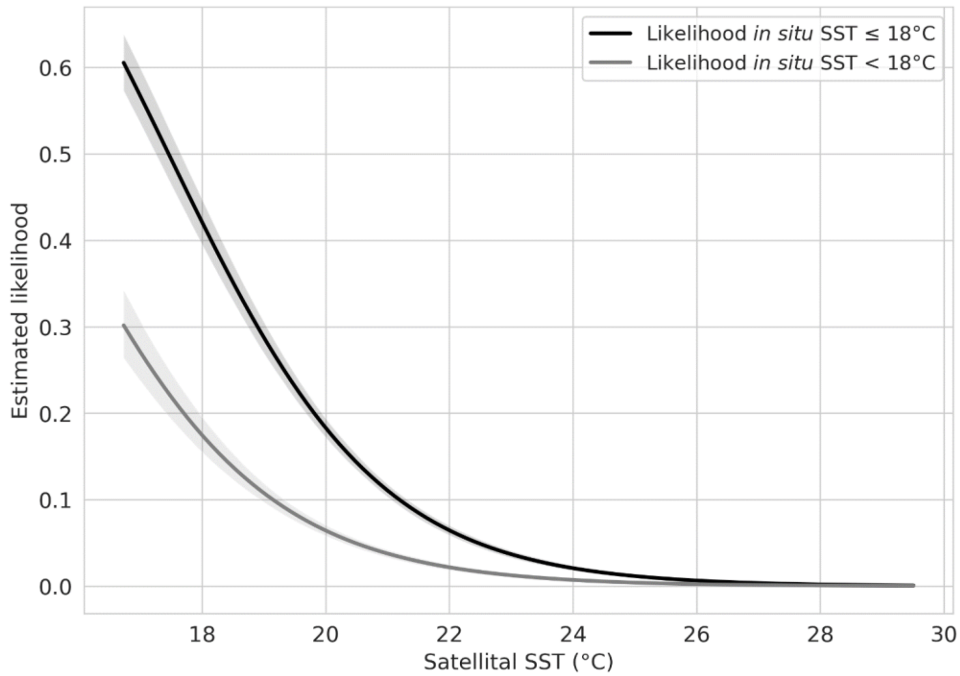

Figure 4. Probability to find sea surface temperature (SST) below 18°C by satellite data in the Gulf of Ulloa.

that the probability of *in situ* temperatures below or equal to 18°C is well above zero, even when the satellite measurements show temperatures between 20 and 24°C. For example, we find a 20% probability of having 18°C or less *in situ* when satellite measurements indicate 20°C.

The seasonal pattern described in Figure 2 for both datasets is consistent with the data reported in the literature. The cold CC influences the GU; thus, punctual temperature records exist from 11 to 24°C (Bakun & Nelson 1977, Lynn & Simpson 1987). This seasonal variability is observed in the behavior of the data that showed the lowest temperatures from March to June, which is coherent with the period described by Lynn & Simpson (1987). These authors mentioned the dominance of cold water from March to June because of the CC intensification and the decrease of the Equatorial Counter Current.

Our findings of discrepancies between *in situ* and SST satellite measurements are consistent with previous research. Cerdeira-Estrada et al. (2015) found an SST difference from 0.2 to 0.3°C between *in situ* and satellite data measurements in northern Cuba and the Yucatan Peninsula, using L3 data from the AVHRR sensor. Pereira et al. (2020) reported differences between the *in situ* and satellite SST of 4°C on average that may reach up to 10°C when oceanic upwelling exists in the Cabo Frio, Brazil region. These authors used the Moderate Resolution Imaging Spectroradiometer (MODIS) data. As with the present research results, the satellite values had an SST overestimation, whereas the in situ data showed greater variation concerning the satellite measurements.

Although an overestimation may exist in satellite sensor measurements above *in situ*, it may result from the influence of different factors individually or jointly. The conditions of the oceanic and atmospheric climates and their variations could be one of the causes. One of the oceanographic processes with greater relevance within the GU is the oceanic upwelling events, which may alter vertical and horizontal oceanic temperature distribution, as well as the stratification of masses of water (Bakun & Nelson 1977). Additionally, the ocean-atmosphere generates low cloudiness during upwellings, which may cause a bias in SST readings since cloudiness at a local scale is not considered for satellite sensor calibration, particularly in those that work in the infrared spectrum (François-Dufois et al. 2012, Pereira et al. 2020).

Another possible variation source that should be considered is datasets with temporal matching since they may coincide in date and hour (Cerdeira-Estrada et al. 2015). The present study searched working with datasets with the same seasonality. However, given that the MUR data is based on information from various satellite sensors, this recommendation was difficult to reach accurately because they mainly constitute nocturnal records. In contrast, the *in situ* methods used in the present research were recollected during daytime hours. Thus, the differences found could be partly due to this time condition.

The MUR data are integrated products from several sources that offer ultra-high-resolution data for any user, apply corrections, and analyze errors in all the data sets to know possible uncertainties. According to Chin et al. (2017) those corrections are consistent with the GHRSST with just a 0.36°C mean gap in synoptic and mesoscale, except for the Arctic areas. Likewise, this product has a standard deviation analysis by every point by the grid to estimate analysis uncertainty (Chin et al. 2017). However, those should not affect our results because of the time-space scale of our study.

Satellite technology has enormous potential for environmental monitoring, especially the oceans; its application provides valuable information, which, with good management and interpretation, could be used in decision-making that supports resource management and species conservation. Thus, the present work represents the first effort to use and apply remote sensing in this socio-ecological interest area in the Mexican Pacific. However, the overestimation found by this study of Ultra High-Resolution satellite SST measurement over the *in situ* data could be considered when managing adaptive management solutions that have SST or its influence as the main element, especially in the case of ectotherm organisms like sea turtles.

Credit author contribution

J.A. López-Ramírez: data curation, validation, methodology, data analysis, writing-original draft; M.V. Morales-Zárate: funding acquisition, project administration, methodology, data analysis, review, and editing; U. Rubio-Rodríguez: methodology, data curation, review, and editing; F. Chavéz-Juárez: methodology, formal analysis, review, and editing; C.A. Salinas-Zavala: conceptualization, methodology, formal analysis, review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

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

ACKNOWLEDGMENTS

All authors acknowledge Project CONACyT: A1-S-43455 "Modelación basada en agentes como herramienta para la evaluación de resiliencia en un sistema socioambiental de uso pesquero" and D. Fischer for translation-edition services.

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Received: November 6, 2023; Accepted: April 19, 2024