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Sea Surface Temperature Variability in NHA Trang Bay, Viet Nam: Patterns and Mechanisms

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Authors' contributions

This work was carried out in collaboration among all authors. Author TVC designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors NMT, NHTK and LCT collected data and managed the analyses of the study. Author PM-T managed the literature searches, and wrote the first draft of the manuscript and revised version. All authors read and approved the final manuscript.

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ABSTRACT

Sea surface temperature (SST) serves as a fundamental parameter influencing numerous oceanic processes, and its measurement is facilitated by various remote sensing platforms operating at different scales. In Nha Trang Bay, SST emerges as a pivotal state variable for scrutinizing climate change dynamics by using dataset of Multi-scale Ultra-high Resolution Sea Surface Temperature (MUR SST). Over recent years, the annual mean SST in Nha Trang's waters has exhibited an upward trend, registering a notable increase of 0.4°C from the period spanning 2008-2013 to 2014-

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2018. However, beginning in 2019 up to the present (July 2023), SST has displayed marked fluctuations, characterized by considerable complexity and heightened values. These fluctuations are largely attributed to El Niño-Southern Oscillation (ENSO) events, which exert a substantial influence on SST patterns in Nha Trang Bay. Consequently, these shifts in SST have had significant consequences for the bay's biota. Understanding and mitigating these effects are crucial for safeguarding the ecological integrity of Nha Trang Bay amid ongoing climatic variability.

Keywords: Sea surface temperature (SST); multi-sensor; multi-scale; remote sensing; climate change.

1. INTRODUCTION

The Global Mean Surface Temperature (GMST) has increased by 1.09°C between 1850–1900 and 2011–2020 [1]. However, the 20th century was the hottest century in over 1000 years, and the highest temperature increase has occurred since 1970s. The past two decades (2001–2020) have been warmer than the previous century, with the decade 2011–2020 being the warmest on record [2]. Among the warmest years recorded by NASA and NOAA (considering 2015–2020), 2016 and 2020 were the hottest, 1.02°C above the 1951–1980 baseline average [3]. From 1880 to 2012, global average land and ocean surface temperatures increased by 0.85°C (0.65 to 1.06°C) [4]. The highest overall temperatures were observed after 2000, with 2010 coinciding with 2005 when the warmest global land and ocean surface temperature increased annually by 0.62 ± 0.07°C [5].

Water temperatures in the world's estuaries and oceans are also increasing [6,7,8]. Nevertheless, water temperatures have increased significantly less than on land; for example, during the period from 1850–1900 to 2011–2020, GMST increased by 0.88°C on the ocean surface compared to 1.59°C on the land [1,9-12]. Most of the warming of the oceans (0.60°C) has occurred since 1980, with the rate of ocean warming more than doubling since 1993 [1,13]. Marine heatwaves (which are prolonged periods of unusually high near-surface temperatures that can lead to severe and persistent impacts on marine ecosystems) are becoming more frequent, doubling in number since the 1980s [7]. Sea surface temperatures (SST) are predicted to increase further in the 21st century (an average of 0.86°C between 1995–2014 and 2081–2100 in the best scenario case (Shared Socioeconomic Pathway SSP1-2.6) and 2.89°C in the worst scenario (SSP5-8.5)) [7]. According to Varela et al. [14], SST in coastal waters were higher and more variable than other marine regions, in which SST could increase by 1°C, and some nearshore regions may see a rise of up to 2°C during the period 2031-2050.

According to Maslin [15], a continuous record of global SST from 1880 to 2020 was produced, showing observed warming ranging from 1.0°C to 1.3°C, with a potential peak increase of 1.1°C during this period (Fig. 1). These observations are supported by 60 years of data from balloons and satellites. Temperature records also indicate that land is warming faster than the oceans. Since 1850, land has warmed by 1.44°C and oceans by 0.89°C (Fig. 2).

IPCC [16] defined climate change as regional or global changes in the average state of climate or in patterns of climate change over decades to millions of years typically determined by means

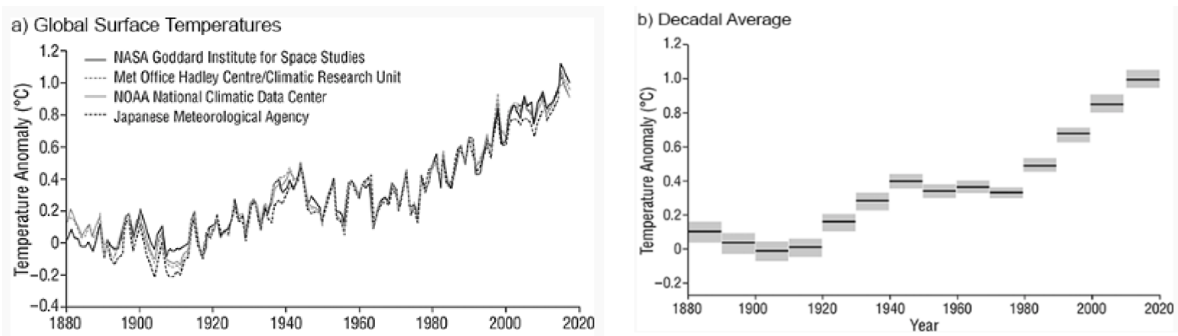

Fig. 1. Change in Earth's surface temperature over the past 150 years [15]

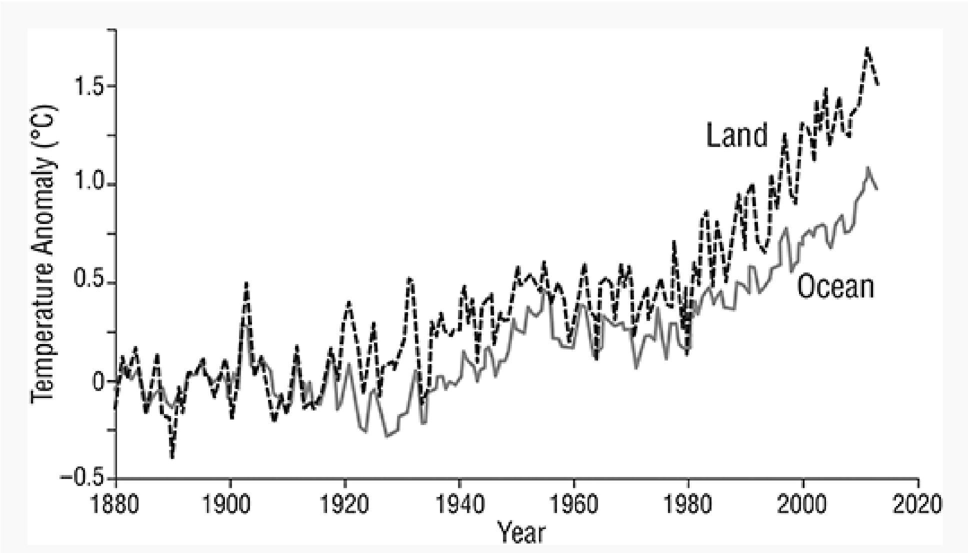

Fig. 2. Land and ocean temperatures since 1880 [15]

of statistical methods and is sometimes referred to as changes in long-term weather conditions. SST is an important state variable for studying and predicting ocean-atmosphere interactions [17] and is a record indicator of change in global climate [18,19].

Nha Trang Bay, located in the center of Vietnam, has an area of about 250 km sq., The Bay has 19 islands, in which the largest is Hon Tre Island with an area of 36 km sq. The islands have successive peaks, the highest being Hon Tre at 482 m and Hon Lon at 414 m. Other smaller islands create an arc running from southwest to north northeast. The natural surface area of the bay is approximately 90 km sq., the main northeast entrance has a width of 16 km, an average length of 25m, and an average depth of 12m. The area with a depth of less than 10 m accounts for about 10 km sq. (11% of the total area of the bay), mainly located in the North of Nha Trang Bay. The slope of the bay bottom varies from 10' - 50' in the northern part, whereas the zone is more than 10' in the southern part of the bay. Nha Trang Bay is becoming a quite attractive beach resort, a beautiful bay in the world and hotpot of biodiversity in the center waters of Vietnam [20,21,22]. Due to this specific nature, daily temperature is significantly strong fluctuation and simultaneously influenced by the monsoon and local winds (land breeze - sea breeze). Wind regime analyses for Nha Trang Bay [23,24] have clearly reflected the properties and distribution rules of local and monsoon winds that have affected the bay. The changes of water temperature also effect on the living organism and biodiversity [20,25,26]. Hence, to evaluate the impact of seawater temperature changes in Nha Trang Bay, the paper aims to analyze SST data that is reliable, spatially detailed, and temporally extensive.

2. MATERIALS AND METHODS

2.1 The Multi-scale Ultra-high Resolution Sea Surface Temperature (MUR SST)

Currently, several satellite devices are available to determine sea surface temperature, and supported data series scientific demand. The Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature (SST) dataset was frequently used to look for the changes of SST. The MUR SST dataset provides daily global analysis divided into grids with a horizontal resolution of 0.01° × 0.01°. The MUR analysis ingests retrievals and aims to capture small-scale SST structures wherever available. The MODIS data are combined with lower resolution SST data from satellite infra-red and microwave sensors (such as MODIS Terra and Aqua, AVHRR, AMSR-E, Windsat, AMRS2, OSI 409 and 401) as well as in-situ measurements [27].

In the case of Nha Trang Bay, the GHRSST level 4 MUR global platform SST dataset were utilized for SST fluctuations. The current version of MUR (Version 4.1, http://dx.doi.org/10.5067/GHGMR-4FJ04, accessed June 1, 2022) combines high-resolution MODIS SST retrievals high spatial resolution of about 1 km, very high-resolution infrared (AVHRR) SST retrievals at intermediate resolutions of 4 to 8.8 km, and microwave SST retrievals at a coarser spatial resolution 25 km. This combination aims to fill data gaps in areas where only infrared or microwave data are available [28]. The approach used in the MUR data maximizes the use of infrared data, where available, from MODIS (level 2 product) and AVHRR. MUR is globally gridded at 1 km resolution and available in daily maps using an interpolation technique based on wavelet resolution [27]. In situ SST observations from NOAA's iQuam project [29], were used for bias correction (Fig. 4). The current version (Version 4.1) of the MUR SST analysis covers the time range from June 1, 2002 to present (July 31, 2023). Its high-resolution SST features have been applied in various scientific studies, including coastal sea-air phenomena and interactions [30-34]; coupled atmosphere-ocean model [35]; tidal mixing [36]; identification and monitoring of surface structures [37-40], and determination of physical indicators for biological productivity [27,41-43]. Accurately extractability SST and its gradients is crucial for studying coastal processes [44] and gaining a better understanding of mesoscale coastal dynamics) and sub-mesoscale processes [45].

2.2 Data of SST in Nha Trang Bay

Nha Trang Bay, Vietnam, covered from Binh Cang Bay in the north and to Cam Lam in the south, with longitude ranging from 109.19°E to 109.40°E and latitude from 12,141°N to 12,303°N. The location of SST distribution points in the study area is shown in Fig. 3. The dataset comprises a total of 308 distribution points collected from June 2002 to July 2023, covering approximately 21 years (254 months). The processed dataset consists of 2,381,148 data points extracted from 7,731 average daily files for analysis.

2.3 Data Analytical Methods

Using traditional statistical methods, calculate the average fluctuation of SST by month, season, year, and over multiple years. Retrieve the extremes and occurrence times from the MUR SST data series for many years, as well as the average value of the data series and the unusually high or low times of SST. Utilize combinatorial analysis to identify changing trends in SST based on average values for months, seasons, years, and periods of the year, and to understand the impact of climate change on SST fluctuations.

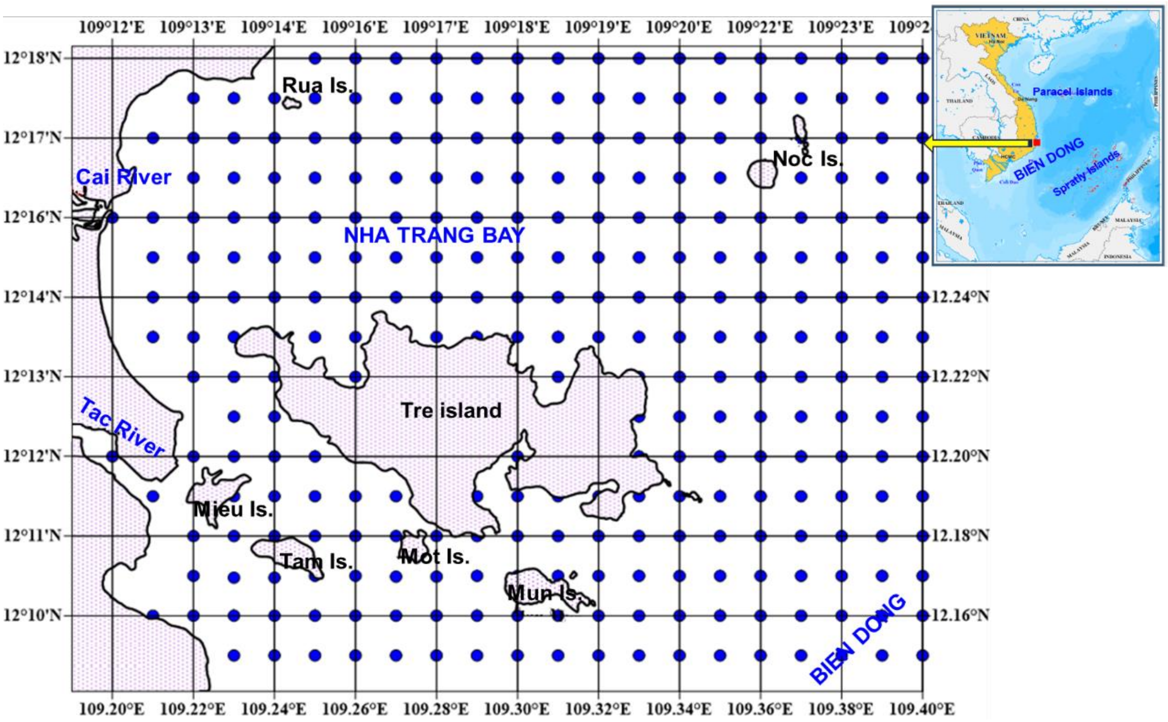

Fig. 3. Extracted MUR SST point distribution for Nha Trang Bay

3. RESULTS AND DISCUSSION

3.1 SST Variation in Nha Trang Bay for the Period of 2002-2023

The results of SST analysis for monthly averages over many years are shown in Fig. 4; The daily SST extremes that occurred are shown in Table 1; According to records in the recent 21 years of research, the hottest SST value in the study area can reach 32.4°C (recorded on June 13, 2019) and the coldest can be 22.3°C (recorded on January 24, 2014). The results in Table 1 show that the hottest SST value per day by month is in the period (2010-2019); with a focus on 2016 with 3 months (January, May, November); and 2015 with 3 months (February, October, December). This heat can be explained by the fact that the period (2015-2016) was a year of a very strong El Niño (https://ggweather.com/enso/oni.htm (updated July 2023)). From ONI information from 1952 to 2023, there are only 03 periods when El Niño is very strong including: (1982-1983); (1997-1998) and (2015-2016). This is also the reason why hot SSTs are focused on (2015-2016) in this analysis. Meanwhile, the coldest SST recorded was largely in 2011, with 5 months including: April, May, June, October, December. This was a very strong La Niña year (the period (2010-2011) had strong La Niña); 2018 also had contributions from 2 months (February and March) (the period (2007-2008) had strong La Niña) details shown in Table 1.

According to the average monthly SST in Nha Trang Bay, high SST values are typically concentrated in May and June. Considering the 10 highest SST values based on the regional average, June accounts for 4 out of these 10 highest values, whereas May accounts for 3 out of 10 (Table 2). Conversely, low SST values are generally concentrated in January and February. Among the 10 lowest SST values based on the regional average, January accounts for 6 out of these 10 lowest values, and February accounts for 3 out of 10 (details in Table 3, sorted from the lowest SST upwards).

According to the analysis results of the average monthly SST across the study area of Nha Trang Bay, high SST values are usually concentrated in May and June; Considering the 10 highest SST values based on the regional average based on the average month, June accounts for out of 10; while May accounts for 3 out of 10. Detailed analysis results can be found in Table 2 sorted by highest SST rank). On the other hand, low SST values are typically concentrated in January and February. Among the 10 lowest SST values based on the regional average, January accounts for 6 out of 10, and February accounts for 3 out of 10 (Table 3).

Analyzing the situation of the annual average temperature, the period from 2008 to 2013 experienced quite high SST fluctuations, with a standard deviation of 0.48°C around an average of 27.1°C. Following this period, from 2014 to 2018, the annual average SST returned to a state of dynamic balance, exhibiting low fluctuations with a standard deviation of 0.057°C around a baseline of 27.5°C. However, after 2018, the average SST has shown high and abnormal fluctuations (Fig. 4).

Table 1. Monthly SST (°C) in averages and extremes in Nha Trang Bay

Month	Average SST	Maximum SST			Minimum SST		
		Year	Date of month	SST	Year	Date of month	SST
January	24.4	2016	16	27.7	2014	24	21.0
February	24.8	2015	25	28.2	2008	29	21.4
March	26.1	2013	24	31.1	2008	2	21.1
April	27.6	2014	30	31.3	2011	5	21.9
May	28.9	2016	5	32.1	2011	15	24.5
June	29.0	2019	13	32.4	2011	28	25.1
July	28.5	2010	16	30.9	2015	20	25.2
August	28.7	2017	2	31.6	2007	18	25.1
September	29.1	2010	27	32.0	2012	12	25.4
October	28.2	2015	5	31.6	2011	8	25.0
November	27.0	2016	7	29.8	2010	29	23.2
December	25.4	2015	1	28.7	2011	27	21.5

Table 2. Ten highest monthly average SST values in Nha Trang Bay

Order	1	2	3	4	5	6	7	8	9	10
SST	30.8	30.2	30.2	30.1	30.0	30.0	30.0	30.0	30.0	29.9
Month	6	9	6	5	6	6	5	7	9	5
Year	2019	2020	2010	2010	2013	2017	2017	2010	2022	2018

Table 3. Ten lowest monthly average SST values in Nha Trang Bay

Order	1	2	3	4	5	6	7	8	9	10
SST	23,2	23,4	23,4	23,5	23,6	23,6	23,7	23,7	23,7	23,8
Month	1	1	2	1	1	1	2	2	1	3
Year	2009	2012	2008	2014	2021	2011	2004	2018	2006	2005

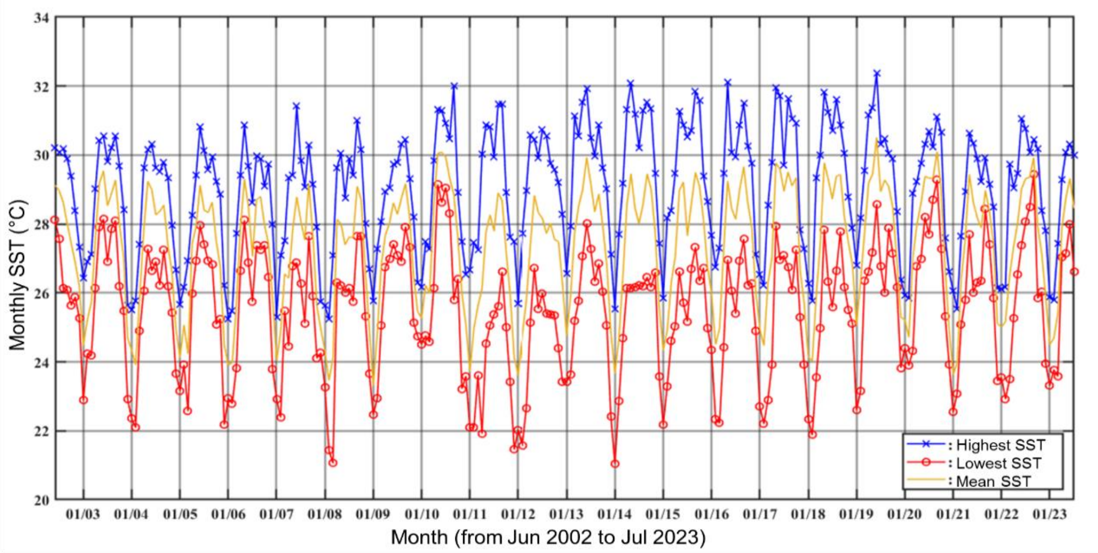

Fig. 4. Changes in sea surface temperature (°C) according to monthly average over many years

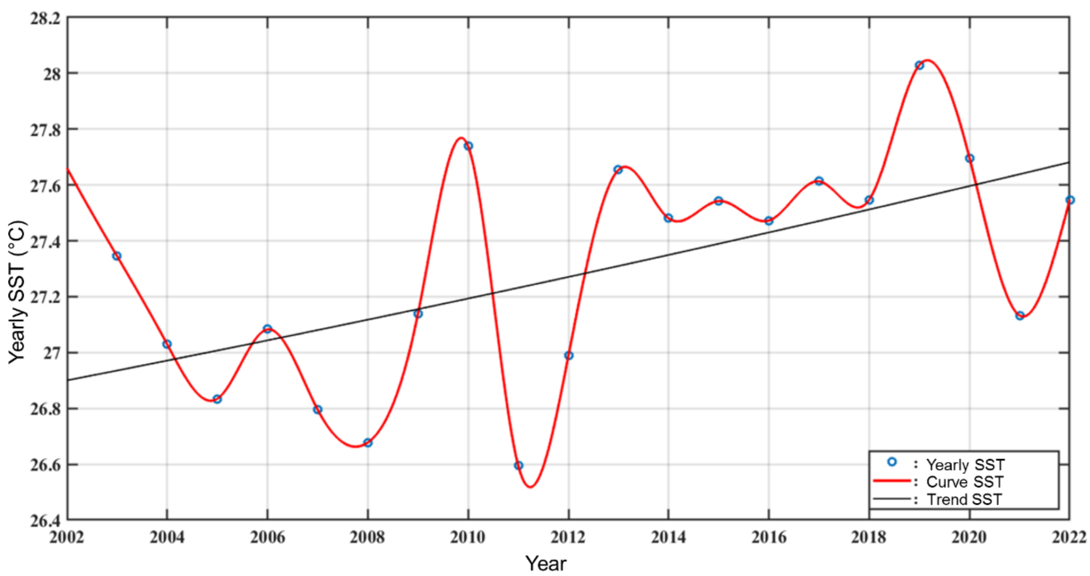

Fig. 5. Average annual SST variation in the waters of Nha Trang Bay

Based on the actual analysis results of the annual average SST in the 21-year study area (Fig. 5), the trend line of SST variation according to the annual average can be represented by the following polynomial equation:

$$y = 0{,}0002029 * x^2 - 0{,}7773 * x + 769{,}9$$
$R^2 = 0.216$

In which: y is the annual average SST trend value (°C); x: is the year to be calculated (using a reasonable analytical function for the period 2002 - 2022).

3.2 Contribution of SST on the Life of Organisms in Nha Trang Bay

Nha Trang bay was established the marine protected area based on abundance of coral reefs and high biodiversity of fauna. According to Vo et al. [46], 800 species of corals, fish, molluscs, echinoderms, crustaceans and macro algae were identified in 754.1 ha of coral reefs [47]. Long and Hoang [21] recorded 266 species of coral reef fishes. The cover rates of hard coral and soft coral were detected to be 22.8±15.9% and 4.73±5.5%, respectively [25]. Most aquatic animals are cold-blooded, so changes in sea water temperature greatly affect their lives and cause stress for them. In this study, SST profiles from the period 2002-2023 indicated strong variations due to climate changes. The shapes and mechanisms of events influenced by ENSO, along with the multi-year SST change trends, have been fully illustrated in the analysis. Analysis of the MUR SST data set for the 21-year period from June 2002 to July 2023 shows that the hottest period in Nha Trang Bay's history often coincided with the very strong El Niño event (2015-2016), whereas the coldest period occurred during the strong La Niña event (2010-2011). The highest SST values are typically concentrated in May-June, and the lowest values are usually in January. According to Glynn and D'Croz [48], when the SST exceeds the highest monthly mean temperature by 1°C, corals begin to experience stress and undergo bleaching. Khen et al. [49] indicated that the coral bleaching was responded differently to thermal stress. As a result, during the El Niño event, coral reef bleaching was significant in Nha Trang Bay. For example, hard corals were the most affected, with 39.5 ± 8.1% experiencing bleaching during the strong El Niño event in 2019 [25]. Chan et al. [26] reported that coral bleaching events were recorded in the years of 1998, 2010 and 2016 that was strong El Niño in South China Sea. Since 2010, many coral bleaching events of varying severity have been reported in the South China Sea [50,51]. This underscores the growing impact of environmental stressors, such as rising SST, coastal urbanization and pollution, on coral reef ecosystems in the region [26]. The diversity of reef assemblages may have mitigated cover declines up to this point, but climate change could endanger reef resilience If current trends continue, the ability of diverse reef assemblages to buffer against environmental changes may be overcome, leading to more pronounced declines in coral cover and overall reef health.

4. CONCLUSION

The notable result in this paper is the comprehensive analysis of SST variations in Nha Trang Bay over the period from 2002 to 2023. This analysis included examining SST profiles based on monthly, seasonal, and annual cycles. Throughout the study period, SST in Nha Trang Bay has demonstrated a discernible increasing trend. Specifically, the period from 2008 to 2013 was marked by significant SST fluctuations, with a standard deviation of 0.48°C compared to the average SST of 27.1°C. In contrast, the years 2014 to 2018 saw a period of dynamic equilibrium, characterized by low SST fluctuations with a standard deviation of just 0.057°C around a baseline of 27.5°C. However, from 2018 to July 2023, the annual average SST exhibited abnormal and significant fluctuations, underscoring a shift in temperature stability. This variation is strongly influenced by El Niño-Southern Oscillation (ENSO) events, which have been shown to have a profound impact on SST variations in Nha Trang Bay. These fluctuations in SST have had considerable repercussions on the bay's biota, particularly affecting coral reef ecosystems. The significant stress on corals due to these temperature changes has led to notable bleaching events, disrupting the marine life balance in the region. Given the frequency and intensity of these changes, there is a clear need for further research to provide detailed quantitative assessments related to weather changes as a consequence of climate change. Such research is critical for understanding and mitigating the impacts of these environmental changes, which have been frequently highlighted in recent years. Understanding these dynamics will be essential for developing strategies to preserve the ecological integrity of Nha Trang Bay amidst ongoing climate shifts.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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