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RESEARCH ARTICLE

Long Term Variability of Extreme Sea Surface Temperature in the Gulf of Tonkin, China

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ABSTRACT

Till date, no study on trends in extreme sea surface temperature (SST) for different return periods has been done over the Gulf of Tonkin (GoT). Based on a 84-year (1940–2023) ERA5 Reanalysis data sets, this study for the first time, examined the spatio-temporal pattern in extreme SST for different return periods. Findings showed that more significant moderate to fast warming trends (0.1–0.16 °C per decade (dec^{-1})) only existed for the 2 year return period. Temporal trends in the 99th percentile SST are insignificant for all return periods. By using the linear regression method, the variability in extreme SST was obtained. Results showed that moderate warming trends dominated a large portion of GoT. Stronger trends, up to 0.018 °C yr^{-1} are noticed near Guangdong, Haikou and southern Sanya in south China. Extreme SST exhibited a slow warming trend of 0.008 °C per year (yr^{-1}) all through the study years. The SST is most stable in most waters in the southern GoT and few waters surrounding Dongfang. Temporal warming rates of SST revealed that 1940–1958, 1976–1994 and 2003–2012 were years of more coastal upwelling and could affect aquatic lives. The strongest warming rate of 0.07 °C dec^{-1} occurred during 1994–2003. The GoT appeared warmer during spring. Spatial decadal variability of SST revealed that moderate warming trends occurred in few regions in the southern GoT and in larger portion of the central and northern GoT. The rise in SST between 1980 and 2020 in the GoT is not limited to increased anthropogenic activities.

Keywords: Significant; Trends; Return Periods; Spatio-Temporal; Decade; Index

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1. Introduction

The entire planet is believed to be impacted by climate change, and concerns regarding its direction and effects have grown over time. Unfortunately, little is known about how climate change is affecting a few coastal areas. The development of solutions for climate change adaptation is a challenge for spatial planning, management, and conservation methods[1, 2] Over the past century, the rate of global warming has accelerated dramatically due to rising concentrations of greenhouse gases in the atmosphere, including CO_2[3]. According to[4], the total linear trend of global warming from 1906 to 2005 was roughly (0.07 ± 0.02) °C each decade; between 1956 and 2005, this nearly doubled to (0.13 ± 0.03) °C per decade. According to recent studies, the global mean surface temperature warmed at a pace of about 0.07 ± 0.08) °C per decade between 1997 and 2013[5, 6]. The term "hiatus" on global warming refers to the slowing in the rate of warming[7, 8]. But since 2014, the average worldwide temperature has risen[9–11]. In 2016, the world temperature hit a record high that hadn't been seen since the mid-to-late 1800s[12]. Furthermore, the global ocean reached its warmest point in 2017[13].

Despite a significant increase in the global mean surface temperature over the past few decades, the rates of change at various locations varied greatly[4]. However, within the same time frame, a cooling tendency was seen in several places. For instance, a linear trend of −0.2 °C per decade is observed at the coastal stations in central Chile[14]. For more than three decades, the northeastern Gulf of Mexico cooled, yet the western Gulf of Mexico and the Caribbean saw a warming trend throughout same time[15]. Assessing the SST trend at the regional level is crucial, especially considering the stark geographical variations in the warming trend.

While various studies have revealed that SST effects breeding characteristics and survival rates, ecologically speaking it is regarded to be an indicator of nutrients availability in the marine environment[16–18]. The coral reef is one of the well-known instance of an ecosystem on earth, experiencing large-scale mortality, which is directly linked to severe SST and high irradiance[19, 20].The marine system of the Arabian/Persian Gulf, has already experienced significant damage as a result of increase in SST[21, 22].

Reference[23] examined Confirmed the monthly, seasonal and yearly SST changes in the coastal area of Hai Phong (West of Tonkin Gulf) based on the observations from Hon Dau Station from 1995 to 2020. They did this by using the Mann-Kendall test and Sen's slope method. The findings indicate a trend of sea surface warming of 0.093 °C/year (significant level $\alpha = 0.05$) for the period of 2008–2020 and 0.02 °C/year (significant level $\alpha = 0.1$) for the period 1995–2020. For the years 1995–2020, the monthly SSTs in June and September grew by 0.027 °C and 0.036 °C, respectively; for the years 2008–2020, they increased by 0.080 °C and 0.047 °C, respectively. Winter, summer, and other month-specific SST trends were either not substantial enough or varied across the two eras. This could be due to El Nino Southern Oscillation (ENSO), which produced two intrinsic mode functions (IMF) signals with a duration of approximately two years (IMF3) and approximately five years (IMF4), causing interannual SST fluctuation in the Hai Phong coastal region. When combined, these signals showed a maximum correlation of 0.22 with the 8-monthly-delayed Ocean Niño Index (ONI). During 1995–2020, ENSO episodes took about eight months to impact the SST in the Hai Phong coastline area, resulting in a 1.2 °C fluctuation in SST. Reference[24] examined monthly SST data in Vietnam's coastal waters from MODIS satellite pictures obtained by the National Aeronautics and Space Administration (US NASA) over a 16-year period (7/2002–12/2017). The findings demonstrated a distinct pattern of ENSO effects on SST in Vietnam's coastal waters. The tendencies progressively grew northward. In the northwest of the Gulf, notably in Kuwait Bay, reference[25] provided comprehensive in situ SST observations for five consecutive years (2016, 2017, 2018, 2019, 2020). When the data analysis results were compared to the historical records for the area, it became clear that the SST in the Gulf had reached an unprecedentedly high level. The records presented in their study may provide evidence to the effects of global warming, aid further research, and encourage the concerned international government bodies to deliver urgent environmental policies such as understanding biogeochemical cycles (i.e., CO_2, H_2O, SO_2), which can help us to mitigate the impact of the antrophogenetic gas in the atmosphere, or better to understand how we should behave and relate with the massive production of gas (CO_2). This information is extremely important for decreasing the CO_2 budget like during the industrial revolution.

Reference [26] used high-resolution satellite data to investigate the trends of the sea surface temperature (SST) in the South China Sea from 2003 to 2017. They found that the average sea surface temperature (SST) in the basin is linearly trending at 0.31 °C each decade, with southeast Vietnam showing the greatest warming. West of the Luzon Strait, the SST trend is marked by a fast summer warming that exceeds 0.6 °C per decade, but a negligible winter warming trend. Southeast Vietnam experiences a stronger warming trend in the winter and a considerably milder warming trend in the summer.

Reference [27] examined the spatio-temporal variability of SST in the Yellow Sea over a 29-year period, from 1981 to 2009, using in-situ measurements and satellite data. They discovered that there was a warming signal in the first empirical orthogonal function mode of SST variability, which accounts for 47.59% of the overall SST variation. They also noted that the Yellow Sea's shallow areas showed more notable rates of increase than the deep areas, and that the Yangtze River's influence was primarily responsible for the spatial patterns of the long-term SST warming trends.

Nearly immediately after the severe SST, the Northwest Arabian Gulf coast began to feel the effects on the environment [25]. As they become more prevalent in the environment, the effects might not be restricted to fish kill incidents, algae development, and coral bleaching; they might potentially endanger the ecosystem's entire cycle. Therefore, the sustainability of the environment is heavily reliant on the capacity for adaptation and change. Studies on the effects of heat and humidity stress on human health have shown that the body can only adapt to a certain degree [28]. Thus, in order to evaluate how climate change is affecting marine resources and the environment on rising water temperatures is crucial.

Return periods for extreme events in the Gulf of Tonkin (GoT), such as high sea surface temperatures (SSTs), may vary depending on the specific event and the kind of analysis used. Typically, return periods are determined through statistical examination of historical data. This category could include seasonal changes as well as more unusual phenomena like El Niño or La Niña events [29–31]. which can have a significant impact on SSTs in the region. Compiling historical SST data for the region is typically the first step in studying the return periods of extreme events, such as high SSTs in the GoT. The return periods of these occurrences can then be determined using statistical methods like frequency analysis and extreme value analysis.

Extreme SSTs have gained a lot of attention recently, but the spatio-temporal trends for the various return periods of extreme SST in the GoT are still unknown. In the calculation of the spatial trend, particularly for different return periods such as 2, 5, 10, 25, 50 and 100-year 99th percentile SST, the question of whether trends in extreme SST over a 84-year period (1940–2023) are statistically significant over the gulf is being investigated. In addition, a long-term warming trends analysis that has not yet been done in the GoT will be investigated, along with its effects on coastal communities and marine ecosystems. This study also seeks to relate the results of the warming rates for 2 different periods, 1940–1980 and 1980–2020 in the GoT to the global SST warming of 0.15 ± 0.04 °C/dec for 1980–2020.

2. Data Source and Methodology

One (1) hourly data of the SST, obtained from ERA5 Reanalysis over a 84 year period (1940–2023), were sourced from https://cds.climate.copernicus.eu/user. The data were downloaded over a box extending from 105.61° E to 110.04° E and 17.08° N to 21.92° N at 0.5° × 0.5° spatial grid resolution, which contains the GoT and neighbouring waters (**Figure 1a**). This parameter was used to examine the spatio-temporal variability of extreme SST in the GoT. The highest SST readings (99th percentile) are referred to in this study as extreme SST. The monthly means for the seasons, Winter (December through February), Spring (March through May), Summer (June through August) and Autumn (September through November), were combined to get the average extreme SST for each season. The yearly mean extreme SST was calculated and recorded as the yearly average extreme SST. For every grid point in the GoT region, linear trends in the seasonal and yearly average 99th percentile SST were determined. The linear least square fitting of the SST time series was used to compute the trend of the year-combined 99th percentile SST climate. The trend's significance was determined by calculating the p values. It was established statistically that trends were significant at 95% confidence (p value < 0.05). Additionally, the annual and seasonal SST patterns spatiotemporal over the GoT were determined. Furthermore, calculations were made to see if the estimates of the extreme SST values for the 2, 5, 10, 25, 50, and 100 year return periods showed any distinct trends. This is accomplished by applying extreme value analysis to each segment of the 10-year period formed by the division of the yearly mean 99th percentile SST. The SST's seasonal variability index (SVI) and monthly variability index (MVI) spatiotemporal patterns are also examined. The SVI and MVI are both expressed in[32] as:

$$SVI = (P_S1 - P_S4)\,/Pyear \tag{1}$$

$$MVI = (P_M1 - P_M12)\,/Pyear \tag{2}$$

where P_S1 and P_S4 are respectively the maximum and minimum seasonal mean SST, P_M1 and P_M12 are respectively the maximum and minimum monthly mean SST and Pyear is the annual mean SST.

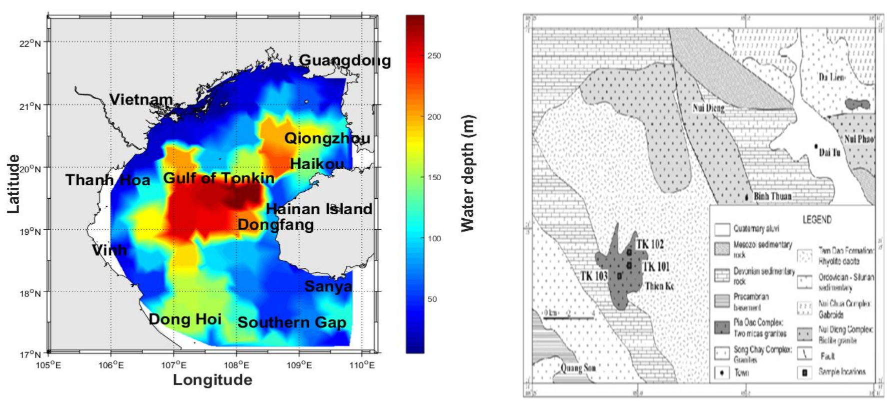
2.1. Description of the Study Area

2.1.1. Geography of the Study Area

The GoT, whose coordinates are 19°45′ N 107°45′ E as shown in **Figure 1a**, is a gulf at the northwestern portion of the South China Sea, located off the coasts of Tonkin (northern Vietnam) and South China. It has a total surface area of 126,250 km^2 (48,750 square miles). It is defined in the west and northwest by the northern coastline of Vietnam down to the Hòn La Island, in the north by China's Guangxi Zhuang Autonomous Region, and to the east by the Leizhou Peninsula and Hainan Island. The GoT is a relatively shallow portion of the Pacific Ocean; the majority of the gulf's ocean floor is less than 75 metres (246 ft) in depth, and no part of the gulf is submerged in more than 100 metres (330 ft) of water[33]. The region is enclosed by North Vietnamese coast in the west, the Chinese coast to the north and Leizhou peninsula and Hainan island in the east. The gulf extends from 106° E to 109° E and from 18° N to 21° N. Tonkin gulf is quite shallow, the water depth ranges mostly from 40–70 m and the deep water locates in the south of the gulf, which also is the main entry for water interactions between Tonkin gulf and the South China Sea[34]. The water temperature around GoT changes dramatically year round. The temperature ranges from 14.5 °C (58.1 °F) in February up to 29.6 °C (85.3 °F) in the month of August, as illustrated below. The average water temperature throughout the year is 25 °C (77 °F) and the best time for water activities is late summer, since GoT is located in the northern hemisphere.

2.1.2. Geology of the Study Area

Figure 1b presents the geological map of the study area. Outcrops of rock types around the GoT range in age from Cambrian to Recent. The basement complex of the GoT consists of Carboniferous carbonates and Lower Paleozoic metamorphic rocks. The GoT and vicinity are comprised of three tectonic units: (1) the Caledonian South China-North Vietnam Foldbelt, (2) the Variscan Southeastern Maritime Foldbelt and (3) the Indosinian Foldbelt of Vietnam. The GoT subsided after the Cretaceous period. Up to 5 km of Tertiary sediments has accumulated in the GoT. A distinct Bouguer gravity anomaly of +10 mgal is present in the middle of the GoT and is also associated with shallow depth to Moho. Recent discovery of natural gas and oil in the GoT may indicate major oil and gas fields[35].



(**a**) (**b**)

Figure 1. Description of the study area. (**a**) Geography and Topography, GoT. (**b**) Simplified geological map; showing the distribution of rock types in the study area. Color version is available online from http://japanlinkcenter.org/DN/JST.JSTAGE/jmps/131203.

3. Results and Discussion

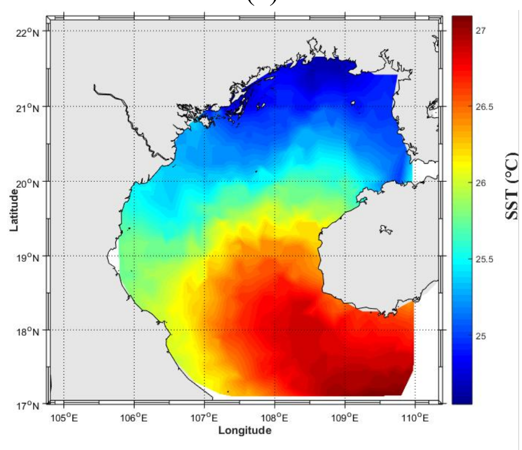
3.1. Spatio-Temporal Characteristics of SST

The regional distribution of annual and seasonal mean SST derived from analysis of the ERA5 Reanalysis SST climatology are presented in **Figure 2a,b**.

Table 1 displays the annual and seasonal average SST in the study area.

The annual and seasonal spatial trends in SST in the study location are shown in **Figure 3**.

(**a**)



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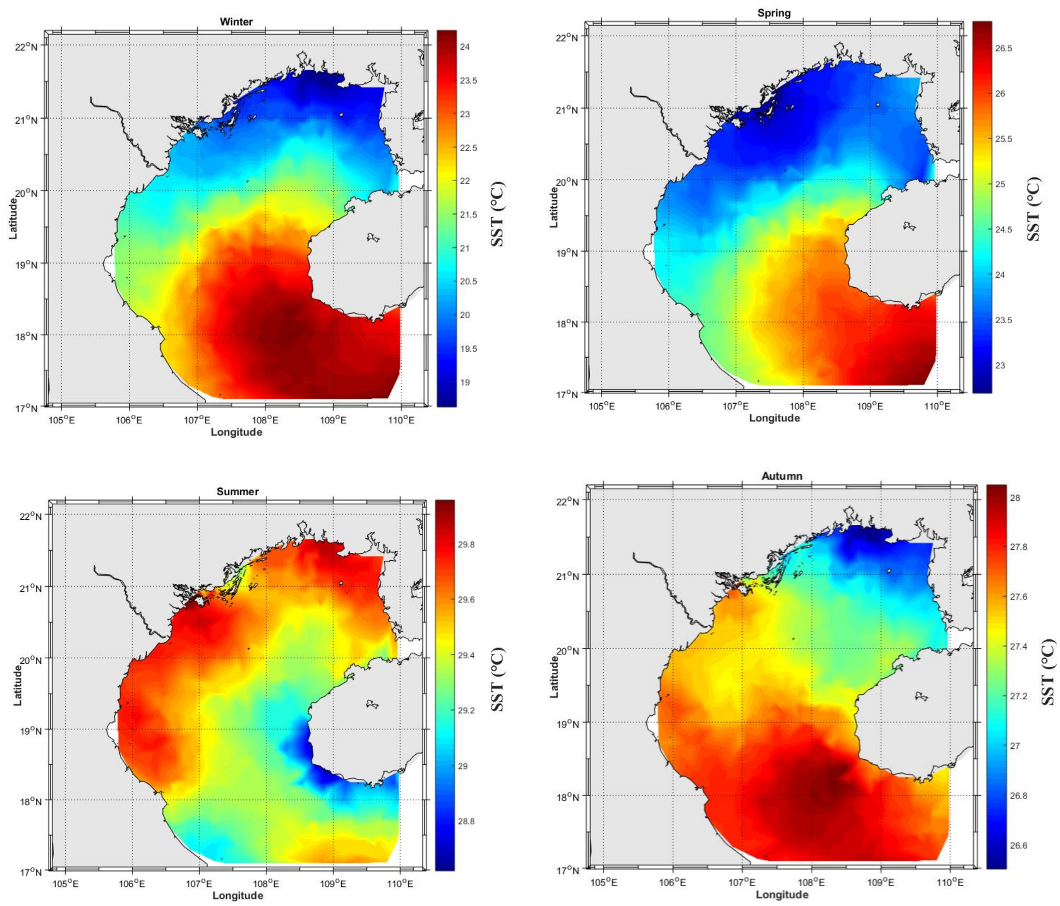
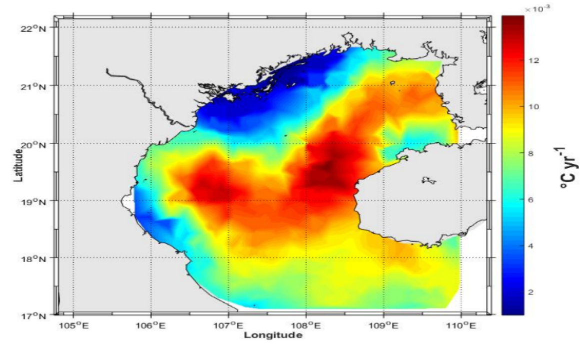


Figure 2. The distribution of (**a**) annual; (**b**) seasonal mean SST in the GoT.

(**a**)



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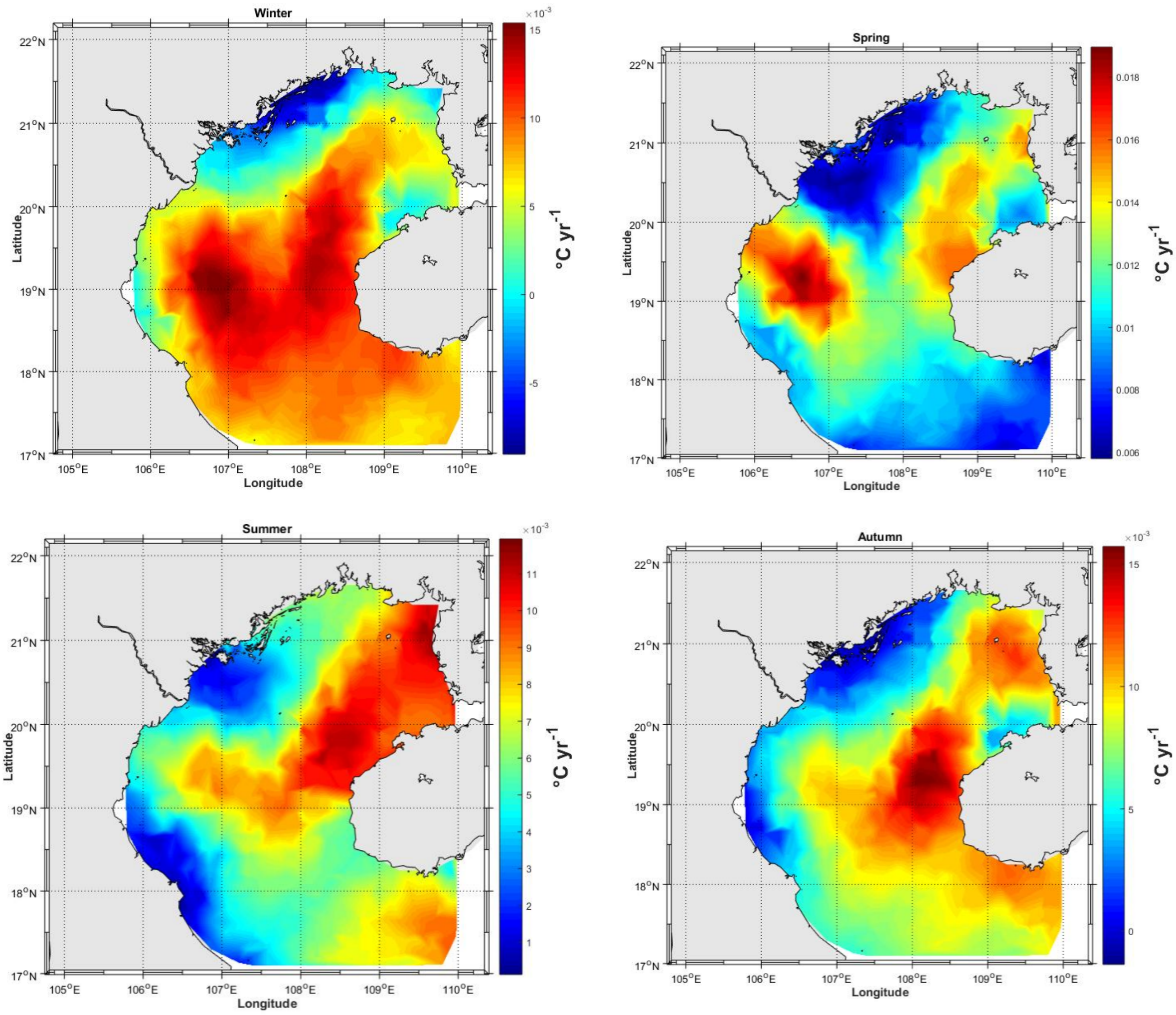


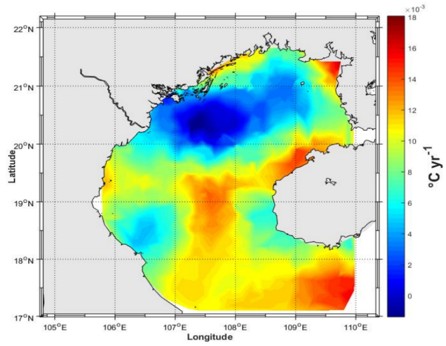
Figure 3. The distribution of the (**a**) annual; (**b**) seasonal spatial trends of SST in the GoT.

Figure 4a presents spatial distribution of trends in the annual 99th percentile SST in the GoT. Moderate warming trends (0.01–0.018 °C yr^{-1}) are found in most waters in the central and southern GoT, and in few locations in the northern GoT. Stronger trends of approximately 0.018 °C yr^{-1} are seen in waters close to Guangdong, Haikou and southern Sanya. Slow warming trends of <0.01 °C yr^{-1} distribute in the rest waters. During winter and autumn, stronger trends (0.01–0.02 °C yr^{-1}) occupied larger waters in GoT. In spring and summer, stronger trends (0.014–0.02 °C yr^{-1}) are found in sporadic waters around Thanh Hoa, Guangdong and Haikou.

Table 1. Annual and Seasonal Mean SST in the GoT.

Location	Annual SST (°C)	Location	Winter SST (°C)	Spring SST (°C)	Summer SST (°C)	Autumn SST (°C)
southern gap of the Gulf	26.3–27	most waters in the southern gap of GoT	22.5–28.1			22.5–28.1
Waters between Vietnam and Guangdong	24.5–25	Southern Sanya		26–26.7		
Dongfang, Thanh Hoa and Vinh	25.5–26.2	most waters of central and northern GoT			29.5–30	
Dong Hoi	26.2	Waters near Hainan Island, Dongfang and Sanya			<29	

(**a**)



(**b**)

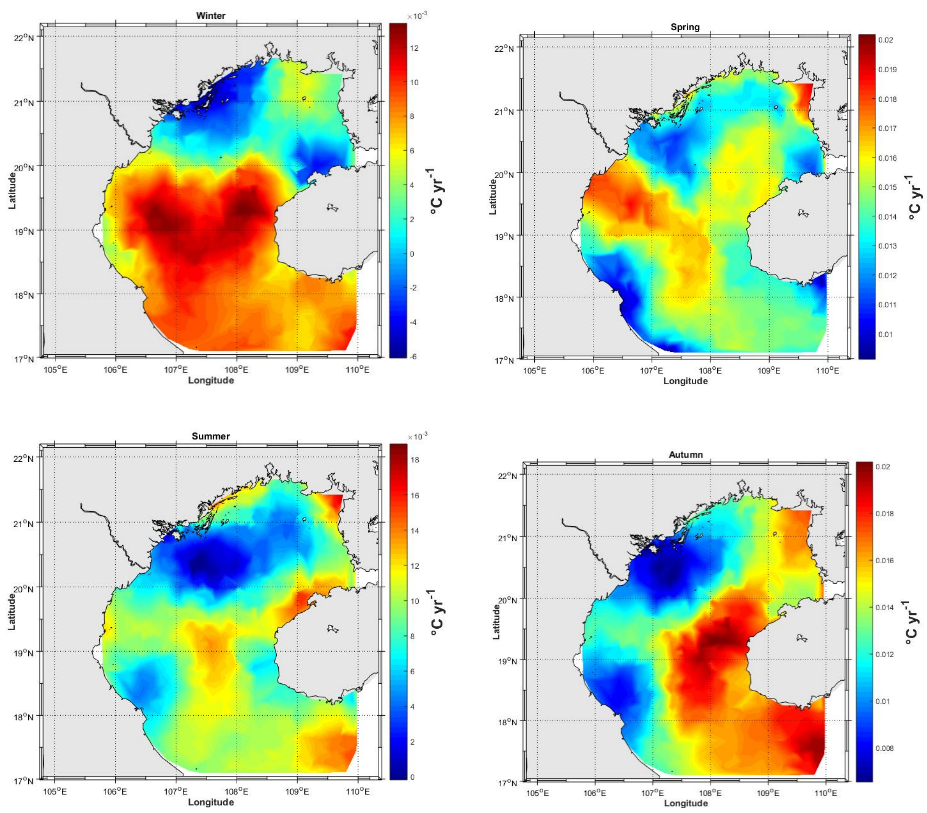


Figure 4. The distribution of the (**a**) annual; (**b**) seasonal spatial trends of 99th Percentile SST in the GoT.

Table 2 shows the annual and seasonal spatial trend in SST in the study area.

To understand the temporal distinction of SST warming, the annual, seasonal and monthly SST trends displayed in **Table 3**, were estimated by linear regression and their statistical significance were tested with a 95% confidence interval. The linear regression equation for annual SST shows a near neutral positive slope value (a = 0.008) for a coefficient of determination R^2 of 0.191. Therefore, the SST exhibits a slow warming trend of 0.008 °C yr^{-1} in the GoT as a whole throughout the 84-year period and that 19% of the variability in the annual SST is explained by this linear regression model. For the seasons, the trend (0.01 °C yr^{-1}) is stronger and moderate during spring and the SST variability stands at 13%. This is attributed to the following: (a) springs marks the transition from the Northeast Monsoon to Southwest Monsoon, thereby leading to changes in wind patterns, ocean currents and SST, (b) spring upwelling brings cooler waters to the surface, but the warming trend dominates and (c) decreased precipitation during spring reduces fresh water input therefore, allowing SST to rise. Slow warming trends of 0.006 °C yr^{-1}, 0.006 °C yr^{-1} and 0.007 °C yr^{-1} exist for winter, summer and autumn respectively. The variability in the seasonal SST ranged between 7% in winter and 13% in summer. For the months, moderate warming trends occurred in February through April, June and September with respective warming rates of approximately 0.01 °C yr^{-1}. The SST variability ranged between 8% in March and 17% in June. Slow warming rates in the range of (0.001–0.008 °C yr^{-1}) occurred for the rest months, with SST variability ranging between 0% in December and 9% in May.

Also shown in **Table 3**, are the temporal trends in the annual, seasonal and monthly mean extreme SST. The annual mean extreme SST exhibits a a slow warming trend of 0.008 °C yr^{-1} in the GoT all through the study period with a 20% variability in the yearly mean 99th percentile SST. Seasonal analysis showed that the trends 0.015 °C yr^{-1} and 0.014 °C yr^{-1} are stronger and moderate during spring and autumn respectively. The SST variability during these seasons are 21% and 24%. Slow warming trends of 0.006 °C yr^{-1} and 0.009 °C yr^{-1} exist for winter and summer respectively. The SST variability are 3% and 20%. For the months, moderate warming trends occurred in February through October, with warming rates of approximately 0.01 °C yr^{-1}, except in February and March that showed stronger warming rates of 0.02 °C yr^{-1}. The SST variability ranged between 8% in March and 17% in June. Slow warming rates of 0.006 °C yr^{-1} and 0.007 °C yr^{-1} occurred for the rest months, with SST variability less than 5%. The ocean ecosystems are affected by these slow warming trends SST. Numerous marine species are vulnerable to even little, insignificant variations in SST. For example, even little temperature increases can cause corals to bleach, and fish migration and bleaching patterns can change. Slow warming trends may precede abrupt changes in ecosystems; for instance, little adjustments might add up to approach ecological tipping points, which can result in significant changes to the productivity of the ocean or the makeup of organisms. Concerning the ocean's heat content, Slow warming trends in SST might not accurately depict the rise in ocean heat content, which encompasses the ocean's deeper layers. As a result, even while surface temperatures seem steady, heat may be building up at deeper levels and impacting marine ecosystems in diverse ways. Slow warming trends in SST often shed light on ecosystem responses, natural variability, and possible early warning signs of major shifts. They highlight the complexity of the ocean-climate system and the necessity for ongoing observation and research to understand long-term effects, even though they might not immediately signal large-scale shifts. Results on SST trends are significant because they emphasize the significance of regional variability and serve to counterbalance our understanding of global warming.

The SST in the GoT coastal area varies seasonally. Monthly averages calculated over 1940–2023 show that SST increases gradually from February to July/August, then decreases steadily to January. The mean monthly SST remains above 27 °C from May (27.39 °C) to October (27.7 °C). In contrast, SST remains in average below 26 °C from November (25.63 °C) to April (24.29 °C), with the lowest value in February (20.92 °C) (**Figure 5**, **Table 3**). To assess the seasonal fluctuations of the SST, months with average temperatures greater than 29.0 °C are regarded as summer months and smaller than 23.3 °C as winter months. The temperature difference between the winter (December through February) and summer months (June through August) is 7.62 °C. Maximum monthly SST ranged from 33.04 °C in June/August and 26.34 °C in February. For May, July, September and October, these maximum values exceed 30 °C. During the

Table 2. Annual and Seasonal Spatial trend in SST in the GoT.

Location	Annual SST Trend (°C yr^{-1})	Location	Winter SST Trend (°C yr^{-1})	Spring SST Trend (°C yr^{-1})	Summer SST Trend (°C yr^{-1})	Autumn SST Trend SST Trend
large portion of the central GoT and in few waters surrounding Qiongzhou, Guangdong and Haikou	0.01–0.014	Most waters in the central and few waters in the northern GoT	0.01–0.015			
Rest waters	0.001–0.01	Small region between Vietnam and Guangdong	−0.001 to −0.01			
		Rest waters	0.001–0.01			
		Waters surrounding Thanh Hoa, Vinh, Qiongzhou and Haikou		0.014–0.019		
		Rest waters		0.006–0.014		
		Southern gap of GoT and in regions betweenVietnam and Guangdong		0.006–0.01		
		Guangdong, Qiongzhou and Haikou			0.009–0.012	
		Vietnam, Vinh and Dong Hoi			<0.003	
		South of Sanya, waters surrounding Dongfang and in regions between Qiongzhou and Guangdong				0.011–0.016
		Some other regions of GoT.				<0.01
		Vinh and in regions between Vietnam and Guangdong				<0.003

winter months, they never exceed 28 °C (**Figure 5**, **Table 3**). The higher Std Dev in spring (from 1.17 to 1.4 °C, with a Coefficient of Variation (CV), ranging from 4.31 to 5.93%) show that the mean SST varies over a wider range in this season. Monthly minimum SST averages ranged from 13.64 °C in February to 26.04 °C in July. In winter, these monthly minima did not exceed 15.24 °C, while in the summer, they were no lower than 23.44 °C (**Figure 5**, **Table 3**).

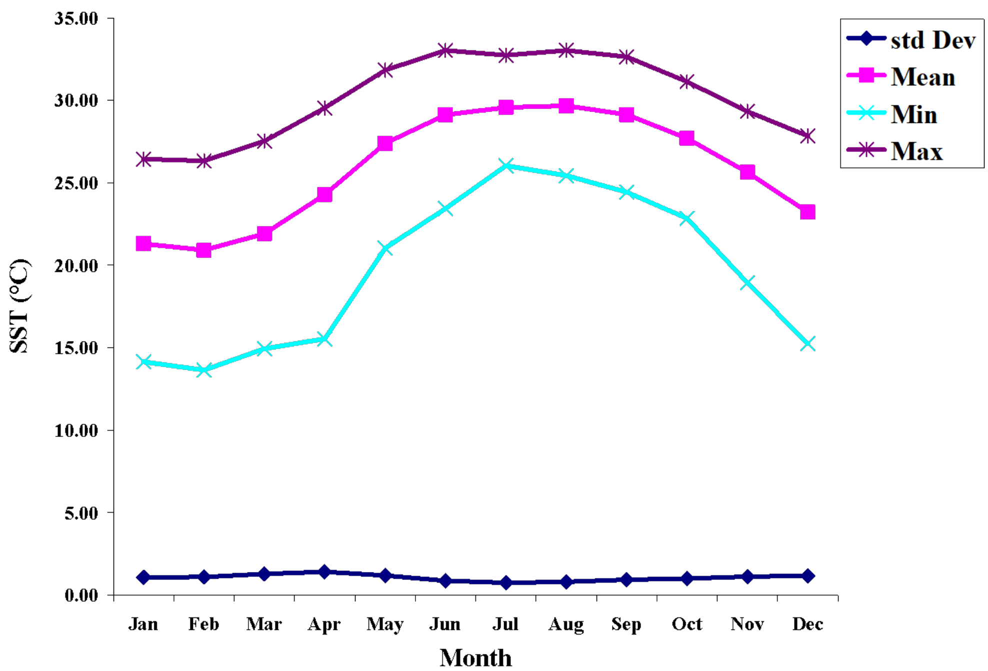


Figure 5. Monthly SST (Mean, Max, Min and Standard Deviation) for the period 1940–2023 in GoT.

Table 3. Statistical Information on SST (°C) for the period 1940–2023 in GoT.

						Mean SST			99th Percentile SST		
	Std Dev	**Mean**	**CV(%)**	**Minimum**	**Maximum**	**Trend (°C/year)**	**R^2**	**Warming Rates**	**Trend (°C/year)**	**R^2**	**Warming Rates**
Annual	3.36	25.85	13.12	13.64	33.04	0.008	0.191	slow	0.008	0.2058	slow
Season											
Winter	1.51	21.84	7.03	13.64	27.84	0.0066	0.0706	slow	0.0059	0.0323	slow
Spring	2.60	24.53	10.69	14.94	31.84	0.0111	0.133	moderate	0.0146	0.2164	moderate
Summer	0.84	29.46	2.86	23.44	33.04	0.0065	0.1394	slow	0.0089	0.2021	slow
Autumn	1.76	27.49	6.42	18.94	32.64	0.0078	0.1136	slow	0.014	0.2432	moderate
Month											
Jan	1.08	21.30	5.20	14.14	26.44	0.007	0.0387	slow	0.0075	0.0475	slow
Feb	1.09	20.92	5.33	13.64	26.34	0.0121	0.1034	moderate	0.0191	0.2265	moderate
Mar	1.28	21.92	5.93	14.94	27.54	0.0121	0.0849	moderate	0.0204	0.2416	moderate
Apr	1.40	24.29	5.84	15.54	29.54	0.0125	0.1146	moderate	0.0131	0.1346	moderate
May	1.17	27.39	4.31	21.04	31.84	0.0089	0.0934	slow	0.0147	0.2165	moderate
Jun	0.86	29.13	2.95	23.44	33.04	0.0112	0.1748	moderate	0.0135	0.3118	moderate
Jul	0.74	29.57	2.51	26.04	32.74	0.0052	0.0544	slow	0.0112	0.2313	moderate
Aug	0.79	29.67	2.67	25.44	33.04	0.0033	0.019	slow	0.0107	0.1888	moderate
Sep	0.93	29.14	3.19	24.44	32.64	0.0116	0.1592	moderate	0.0141	0.237	moderate
Oct	1.00	27.70	3.61	22.84	31.14	0.0064	0.0579	slow	0.013	0.196	moderate
Nov	1.12	25.63	4.39	18.94	29.34	0.0055	0.0302	slow	0.006	0.044	slow
Dec	1.17	23.21	5.11	15.24	27.84	0.0013	0.0018	slow	0.0059	0.0319	slow

3.2. Variability Indexes of SST

Many measures can be conceived to describe the spatio-temporal variability in SST. One simple, straightforward measure is the MVI and SVI. Higher index values indicate larger SST variations and decreased stability and vice-versa for lower index value. The variability indexes of SST are presented in **Figure 6a**, while their temporal variations are displayed in **Figure 6b**. A tabular presentation of this is shown in **Table 4**.

Stable SST regions imply that marine ecosystems there face little to no thermal stress, allowing them to preserve their diversity and balance. These are also the areas where there is less chance of coral bleaching, less influence from sea level rise and coastal erosion, less chance of ocean heat waves, and no increase in ocean acidification or changes in phytoplankton populations.

Table 4. Spatio-temporal SST variability index in the GoT. *a most stable year (value), *b least stable year (value).

Location	Variability	Stability	MVI (Spatial)	SVI (Spatial)	MVI (Temporal)	SVI
Southern GoT and in few waters surrounding Dongfang	least	highest	0.23–0.32	0.19–0.26	*a 1979 (0.283) *b 1945 (0.47)	*a 1969 (0.22) *b 1945 (0.361), 1967 (0.363)
northern GoT, particularly in regions around Guangdong	highest	least	0.5–0.53	0.43–0.45		
regions of low stability in SST			0.42–0.52	0.37–0.46		
regions of high stability in SST			0.23–0.3	0.19–0.25		

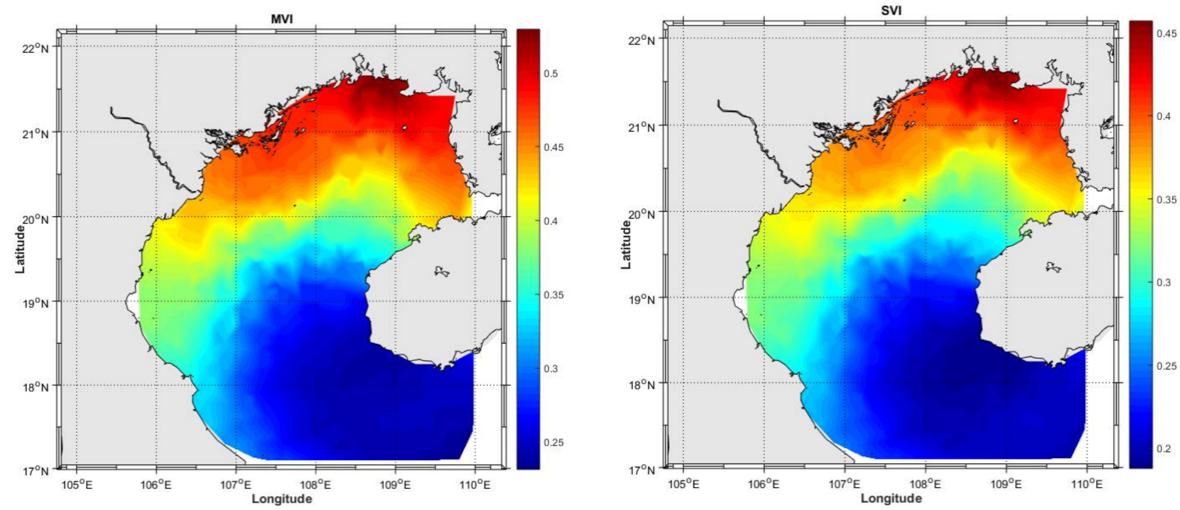
3.3. Decadal Trends in SST in the GoT

The Transboundary Water Assessment Programme [36], often known as the TWAP assessment, specified five distinct warming categories, which were used to illustrate the findings in research region. The categorization was based on the degree of warming that the area underwent during the course of the study period (1940–2023). The warming rates categories are defined in **Table 5**.

Table 5. Category and Warming rate of SST.

Category	Warming Rate (°C/dec)
cooling	<0
slow	0–0.07
moderate	0.07–0.14
fast	0.14–0.21
superfast	>0.21

(**a**)



(**b**)

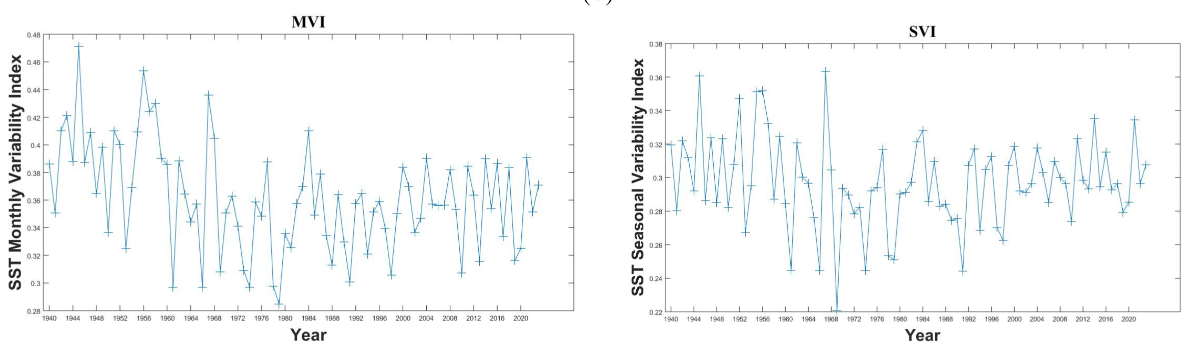


Figure 6. The SST variability index (**a**) Spatial SST variability index and (**b**) temporal SST variability index in the GoT.

3.4. Spatio-Temporal Decadal Trends in SST for Different Return Periods

The return period of extreme SST is a statistical measure that predicts extreme SST events in some years to come. It can be of same or greater magnitudes. Return periods are computed using simulations or historical data, and they are very helpful for research on the effects of climate change. Here, an analysis of the 2, 5, 10, 25, 50, and 100 year return period estimates of the extreme SST values was being done to look for any noteworthy trends. To do this, the annual mean 99th percentile SST is divided into parts of ten years, with an extreme value analysis performed on each portion.

Figure 7(a–f) present the distribution of decadal trends for different return periods for the extreme (99th percentile) SST over a 10-year segments (periods) in GoT. For the 2 year return period, slow warming trends (0.01–0.05 °C dec^{-1}) distribute in Vinh and Vietnam, up to Guangdong. Slow to moderate trends (0.05–0.1 °C dec^{-1}) are concentrated around Dong Hai, waters between Dongfang and Sanya, few waters in the central GoT and a large part of the northern GoT. Moderate to fast trends (0.1–0.16 °C dec^{-1}) are seen in most part of the southern GoT and in some few waters in the central and northern GoT. The distribution for the 5 year return period follows closely with the 10 year return period. Moderate warming trends (0.07–0.14 °C dec^{-1}) are found in most waters in the southern GoT, few waters in central GoT and in sporadic regions around Guangdong, Haikou and near Vietnam. Slow warming trends (0.02–0.07 °C dec^{-1}) distribute in waters between Donghai and Vinh, Dongfang and Sanya, and in a large part of the northern GoT. Cooling trends (<0 °C dec^{-1}) are seen in regions extending from Vietnam to Guangdong. For the 25 year return period, slow to moderate warming trends (0.025–0.14 °C dec^{-1}) dominate in most waters in the southern and central GoT and in few waters around Haikou, Guangdong and up the coast of Vietnam. Cooling to slow trends (−0.05 to 0.025 °C dec^{-1}) are observed in few regions in the central and northern GoT. Cooling trends (<−0.05 °C dec^{-1}) exist in waters between Vietnam and Guangdong in the northern GoT. For the 50 year return period, cooling trends (<0 °C dec^{-1}) dominate most waters in the northern GoT and in few waters in the central and southern GoT. Cooling trends of up to −0.15 °C dec^{-1}, especially distributes in a large part of the northern GoT. Slow to moderate trends (0.025–0.14 °C dec^{-1}) are found in most waters in the southern and central GoT and in few waters around Haikou, Guangdong and up the coast of Vietnam. Lastly for the 100 year return period, cooling trends (<0 °C dec^{-1}) dominate most regions in the entire GoT. Slow to moderate trends (0–0.14 °C dec^{-1}) dominate most regions in the southern GoT, Vinh and in few locations in the northern GoT such as Guangdong, Haikou and regions up the coast of Vietnam.

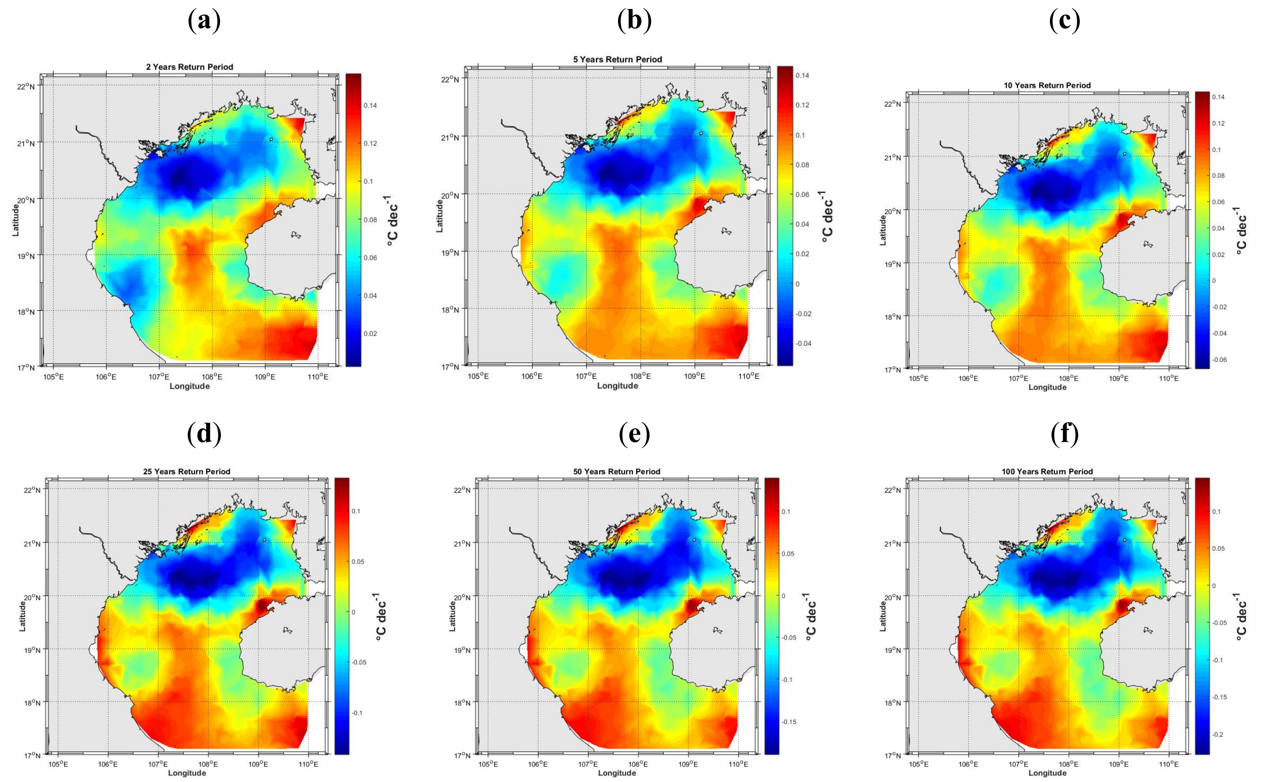


Figure 7. (**a**) Spatial trend in the 2 year return period, (**b**) spatial trend in the 5 year return period, (**c**) spatial trend in the 10 year return period, (**d**) spatial trend in the 25 year return period, (**e**) spatial trend in the 50 year return period and (**f**) spatial trend in the 100 year return period 99th percentile SST calculated using linear regression from the extreme value analysis of the segments (periods) for the GoT.

The temporal trends in the different return periods, 99th percentile SST for each of the 10-year periods, are presented in **Figure 8**(**a–f**). As can be seen, the trends (0.000005–0.00003 °C dec^{-1}) are near neutral and insignificant in all the six cases.

3.5. Decadal Variability in SST

Figure 9a,b, present the annual and seasonal warming rates experienced every 10 years from 1940–2023 in the GoT. From **Figure 9a**, It is observed that cooling trends in SST, occurred from years 1940–1949 (−0.0015 °C dec^{-1}), 1949–1958 (−0.072 °C dec^{-1}), 1976–1985 (−0.068 °C dec^{-1}), 1985–1994 (−0.0001 °C dec^{-1}) and 2003–2012 (−0.0101 °C dec^{-1}). Slow warming trends occurred from 1958–1967 (0.02 °C dec^{-1}), 1967–1976 (0.04 °C dec^{-1}) and 2012–2023 (0.04 °C dec^{-1}). Increased warming (0.07 °C dec^{-1}) only occurred from 1994–2003. For each of the seasons in **Figure 9b**, cooling trends ranging from −0.1419 °C dec^{-1} and −0.0008 °C dec^{-1} occurred from 1949–1958, 1976–1985 and 2003–2012. During the winter and summer of 1940–1949, the cooling trends are respectively −0.0409 °C dec^{-1} and −0.0304 °C dec^{-1}. In the winter and spring of 1958–1967, the cooling trends are respectively −0.0097 °C dec^{-1} and −0.0209 °C dec^{-1}. In the summer and autumn of 1985–1994, the cooling trends are respectively −0.0128 °C dec^{-1} and −0.0248 °C dec^{-1}. During summer, cooling trend of −0.044 °C dec^{-1} occurred from 1967–1976. Slow warming trends of 0.0341 °C dec^{-1} and 0.0297 °C dec^{-1} occurred during spring and autumn of 1940–1949. In the winter and autumn of 1967–1976, slow warming trends of 0.0435 °C dec^{-1} and 0.0002 °C dec^{-1} are observed. During winter and spring of 1985–1994, slow warming trends of 0.0027 °C dec^{-1} and 0.0347 °C dec^{-1} occurred. During winter and summer of 1994–2003, slow warming trends of 0.0059 °C dec^{-1} and 0.0615 °C dec^{-1} occurred. During winter, spring and autumn of 2012–2023, slow warming trends of 0.0556 °C dec^{-1}, 0.016 °C dec^{-1} and 0.0361 °C dec^{-1} occurred. Also, slow warming trend of 0.0262 °C dec^{-1} occurred during summer of 1958–1967. Moderate warming trends of 0.12 °C dec^{-1} and 0.07 °C dec^{-1} occurred in the spring and autumn of 1994–2003. It also occurred in the summer of 2012–2023 and autumn of 1958–1967. The respective trends are 0.07 °C dec^{-1} and 0.08 °C dec^{-1}. The trend (0.17 °C dec^{-1}) is fast and most significant during the spring of 1967–1976.

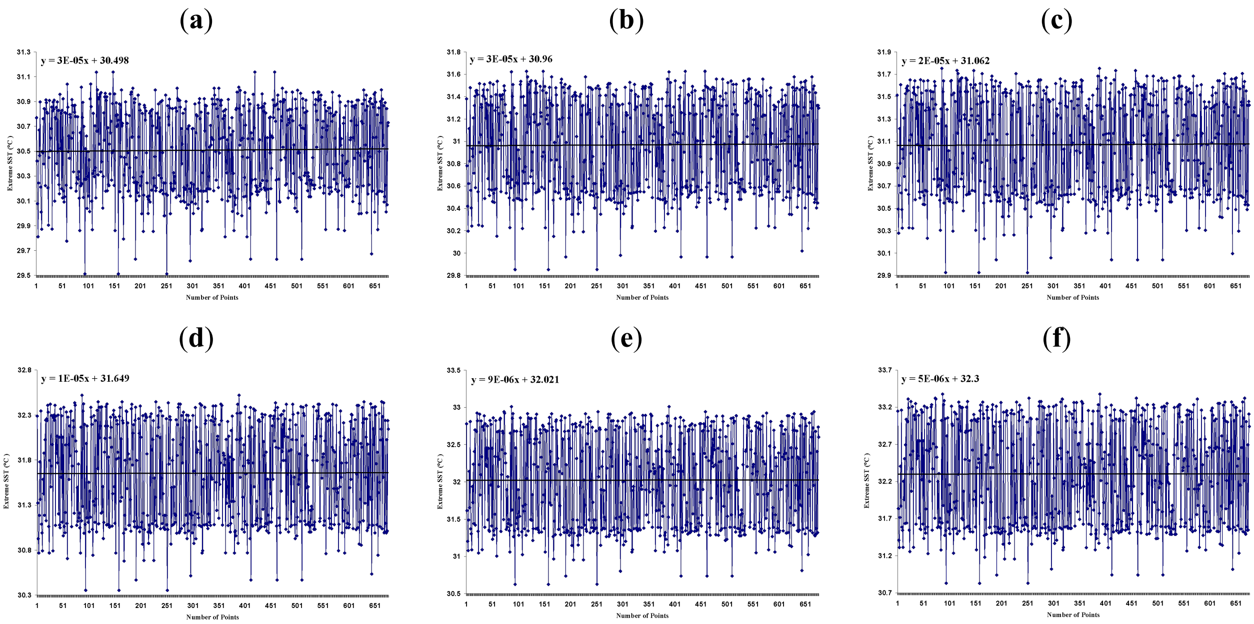
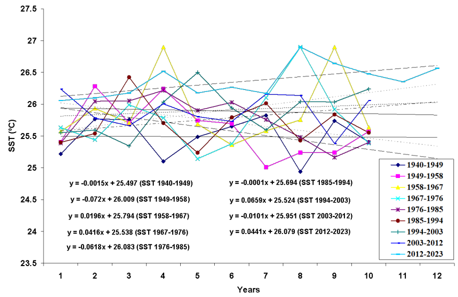


Figure 8. Temporal trends in (**a**) 2, (**b**) 5, (**c**) 10, (**d**) 25, (**e**) 50 and (**f**) 100 year return periods, 99th-percentile SST calculated using linear regression from the extreme value analysis of different segments (periods) for the GoT.
(**a**) 1940–1949; (**b**) 1949–1958; (**c**) 1958–1967; (**d**) 1967–1976; (**e**) 1976–1985; (**f**) 1985–1994; (**g**) 1994–2003; (**h**) 2003–2012; (**i**) 2012–2023.

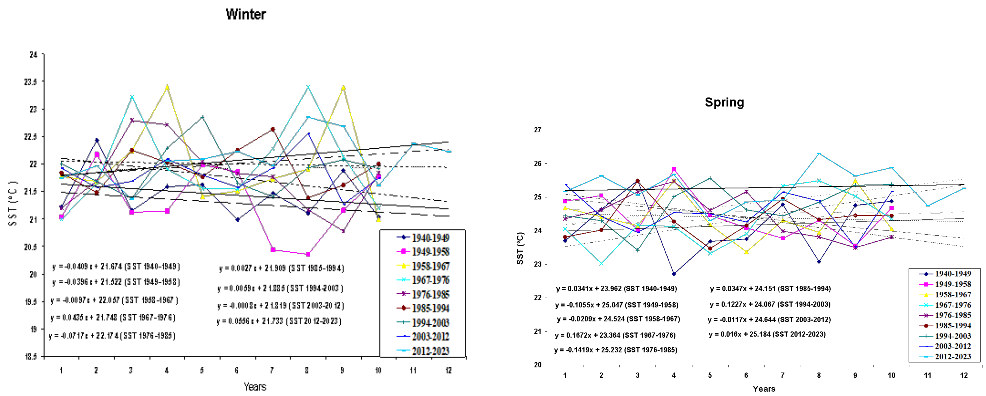
Lastly, **Figure 10a–i** present the spatial decadal variability of SST from 1940–2023 in the GoT. From the figures, it is noticed that moderate warming trends between 0.07 °C/dec and 0.1 °C/dec, are noticed in years 1958–1967, 1967–1976, 1994–2003 and 2012–2023. They are particularly seen around Sanya, Dong hoi and neighbouring waters, few regions in the southern GoT, larger portion of the central and northern GoT, regions between Guangdong and Haikou and in small locations close to Vietnam. Cooling trends occurred in all the decades except in 1967–1976, 1994–2003 and 2012–2023, where the trends (0.02-0.1 °C/dec) vary from slow warming to moderate warming. During 1949–1958 and 1976–1985, cooling trends dominated the entire GoT. Relating the results of the warming rates for 2 different periods, 1940–1980 and 1980–2020 as shown in figure 9c, to the global SST warming of 0.15 ± 0.04 °C/dec for 1980–2020 [37], it can be inferred that the rise in SST between 1980 and 2020 is majorly from these contributing factors, climate change, natural climate cycles such as El Nino, increased tropical storm activity, change in ocean circulation, release of ash and aerosols in large volcanic eruptions and increased anthropogenic activities [37]. It is possible to relate the observed difference between the global and

GoT SST trends between 1980 and 2020 to regional characteristics unique to the GoT, including air circulation, upwelling, freshwater input, and coastal geometry. These variations can be caused by oceanic phenomena within the GoT, such as ocean currents, variations in thermocline depth, and changes in the overall mixed layer depth.

(**a**)



(**b**)



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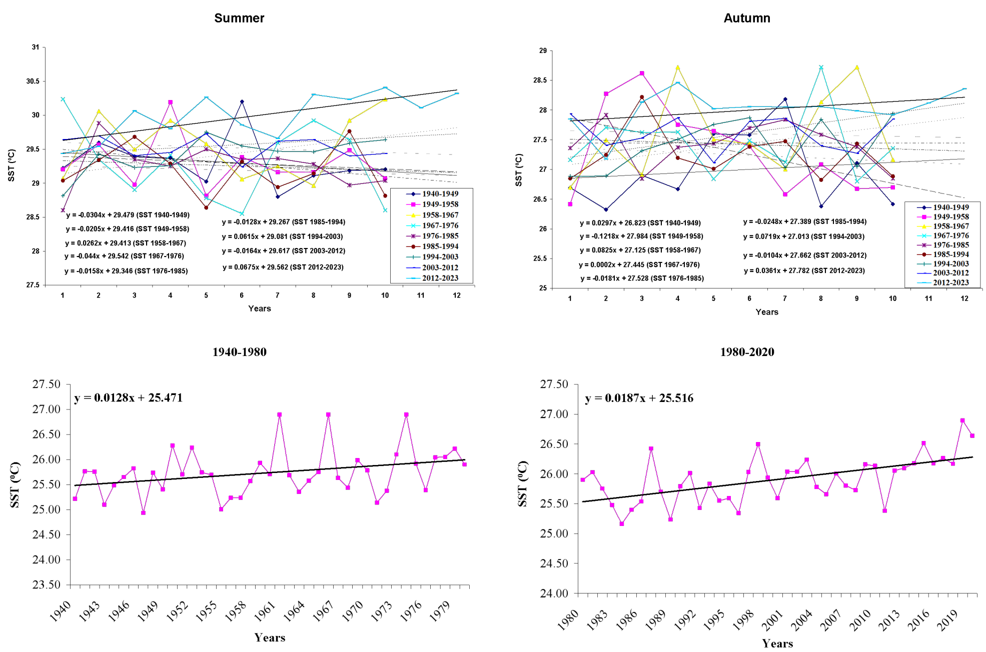

Figure 9. The temporal variation in the (**a**) annual; (**b**) seasonal warming rates experienced every 10 years from 1940–2023 and (**c**) warming rates experienced from 1940–1980 and 1980–2020 in the GoT.

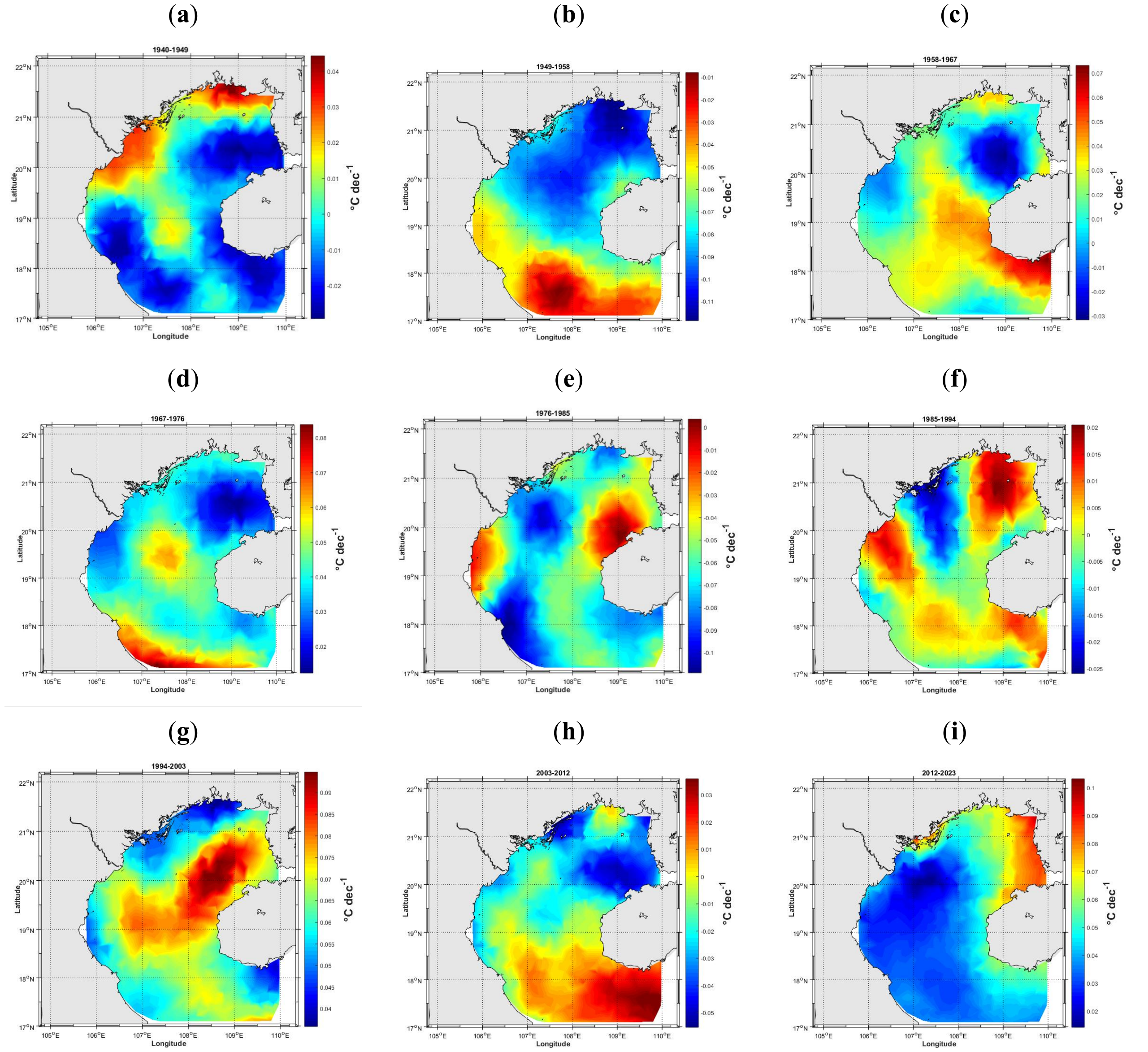

Figure 10. SST trends experienced from different years in the GoT. (**a**) 1940–1949; (**b**) 1949–1958; (**c**) 1958–1967; (**d**) 1967–1976; (**e**) 1976–1985; (**f**) 1985–1994; (**g**) 1994–2003; (**h**) 2003–2012; (**i**) 2012–2023.

4. Conclusions

A 84-year SST data for the GoT based on ERA 5 reanalysis data sets is presented in this study. The long-term spatiotemporal trends in extreme SST in the GoT were investigated. Spatial trend analysis of extreme SST showed that moderate warming trends dominate most waters in the central and southern GoT, and in few locations in the northern GoT. Stronger trends of approximately 0.018 °C yr^{-1} are seen in waters close to Guangdong, Haikou and southern Sanya. Seasonal analysis revealed that the trends are strongest over a large portion of GoT in winter and autumn. The trends are strongest in few regions around Thanh Hoa, Guangdong and Haikou during spring and summer.

Temporal analysis showed that extreme SST exhibited a slow warming trend of 0.008 °C yr^{-1} in the GoT all through the study period. Seasonal analysis showed that the trends are stronger and moderate during spring and autumn. For the months, stronger warming rates of 0.02 °C yr^{-1} existed in February and March.

A spatial analysis of the MVI and SVI showed that SST is most stable in most waters in the southern GoT and in few waters surrounding Dongfang. These are the places where GoT's marine ecosystems are most likely to retain their richness and balance. It is least stable in locations around Guangdong. Temporal variation of both index showed that SST is most stable in the years 1969 and 1979 and least stable in the years 1945 and 1967.

A check was carried out to see if there are significant trends in the 2, 5, 10, 25, 50 and 100 year return period estimate of the extreme values of SST. It was found that the most significant warming trends exist for the 2 year return period. They are the moderate to fast trends (0.1–0.16 °C dec^{-1}) which distribute in most part of the southern GoT and in some few waters in the central and northern GoT. The temporal trends in the 99th percentile SST for the different return periods are near neutral and insignificant for all the decades.

The spatio-temporal warming rates of SST revealed that cooling trends in SST, occurred from 1940–1949, 1949–1958, 1976–1985, 1985–1994 and 2003–2012. It is observed that there was greater coastal upwelling throughout these years. These cooling years may affect the distribution and number of aquatic organisms, upwelling, migration patterns, and the availability of food supplies for human use, among other aspects of aquatic life. As an illustration, certain species might do well in colder climates while others might find it difficult to adjust, which might cause changes in ecosystems and even upheavals in food webs. Coral bleaching and the dwindling of delicate marine life can be caused by prolonged or substantial cold episodes. Furthermore, these are the years when the ocean's capacity to absorb carbon dioxide is impacted and certain aquatic species may be more susceptible to illnesses and parasites in milder climates, thus altering the process of ocean acidification, which may have an effect on marine life, particularly on species that have calcium carbonate shells. Slow warming trends occurred from 1958–1967, 1967–1976 and 2012–2023. Increased warming up to 0.07 °C dec^{-1} only occurred from 1994–2003. A comparison in the warming rates for the seasons showed that GoT appeared warmer during spring. Fisheries and local livelihoods may be impacted by declining fish populations brought on by warmer waters. The foundation of marine food webs may be impacted by this disturbance of phytoplankton dynamics. The societal and economic effects of these temperature shifts include diminished food security, financial losses, migration and displacement, and heightened susceptibility. Fish population decreases, for instance, may have an effect on the cost and accessibility of food. Extreme effects on means of subsistence could drive local populations to relocate, and variations in SST could make pre-existing social and economic vulnerabilities worse. SST variations may have detrimental effects on customary fishing methods, cultural heritage, and ocean health. The following are only a few of the suggested major adaptation and mitigation strategies: (i) Climate-resilient fisheries management (ii) practice sustainable fishing; (iii) early warning systems for ocean heat waves and coral bleaching; and (iv) integrated coastal zone management. In order to lessen the effects of SST changes in the GoT and prepare for them, it is critical to take these possible outcomes into account and create proactive plans. Results of the spatial decadal variability of SST revealed that moderate warming trends occurred in years 1958–1967, 1967–1976, 1994–2003 and 2012–2023. They are especially noticed around Sanya, Dong hoi and neighbouring waters, few regions in the southern GoT, larger portion of the central and northern GoT, regions between Guangdong and Haikou and in small locations close to Vietnam. Cooling trends dominated the entire GoT during 1949–1958 and 1976–1985. Climatic change, natural climatic cycles like El Nino, increased tropical cyclone activity, altered ocean circulation, the release of ash and aerosols during massive volcanic eruptions, and an increase in anthropogenic activities are all contributing factors to the rise in SST in GoT between 1980 and 2020.

Author Contributions

The Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—review and editing, visualization, supervision and project administration for this work were all jointly provided by Y.L. and O.A. to this paper. The funding was sponsored by the Y.L.

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Institutional Review Board Statement

Not applicable for studies not involving humans or animals.

Informed Consent Statement

Not applicable.

Data Availability Statement

The reanalysis data used for this work were sourced from https://cds.climate.copernicus.eu/user.

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Conflict of Interest

The author declares no conflict of interest.

References

[1] Groves, C.R., Game, E.T., Anderson M.G., et al., 2012. Incorporating Climate Change into Systematic Conservation Planning. Biodiversity and. Conservation. 21, 1651–1671. DOI: https://doi.org/10.1007/s10531-012-0269-3

[2] Watson, J.E., Rao, M., Ai-Li K., et al., 2012. Climate Change Adaptation Planning for Biodiversity conservation: A Review. Advances in Climate Change Research. 3, 1–11.

[3] Levitus, S., Antonov, J., Boyer, T., 2005. Warming of the World Ocean, 1955–2003. Geophysical Research Letters. 32(2), L02604.

[4] Trenberth, K.E., Jones, P.D., Ambenje, P., et al., 2007. Observations: Surface and Atmospheric Climate Change. In: Solomon, S., Qin, D., Manning, M., et al. (Eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK; New York, NY, USA. pp. 235–336.

[5] Fyfe, J.C., Gillett, N.P., Zwiers, F, 2013. Overestimated Global Warming over the Past 20 years. Nature Climate Change. 3(9), 767–769. DOI: https://doi.org/10.1038/nclimate1972

[6] Schmidt, G.A., Shindell, D.T., Tsigaridis, K., 2014. Reconciling Warming Trends. Nature Geoscience. 7(3), 158–160. DOI: https://doi.org/10.1038/ngeo2105

[7] Knight, J., Kennedy, J.J., Folland, C., et al., 2009. Do Global Temperature Trends over the Last Decade Falsify Climate Predictions? In State of the Climate in 2008. Bulletin of the American Meteorological Society. 90(8), 22–23.

[8] Meehl, G.A., Arblaster, J.M., Fasullo, J.T., et al., 2011. Model-based Evidence of Deep-ocean Heat Uptake during Surface-temperature Hiatus Periods. Nature Climate Change. 1(7), 360–364. DOI: https://doi.org/10.1038/nclimate1229

[9] Blunden, J., Arndt, D.S., 2015. State of the Climate in 2014. Bulletin of the American Meteorological Society. 96(7), ES1–ES32. DOI: https://doi.org/10.1175/2015BAMSStateoftheClimate.1

[10] Blunden, J., Arndt, D.S., 2016. State of the Climate in 2015. Bulletin of the American Meteorological Society. 97(8), Si–S275. DOI: https://doi.org/10.1175/2016BAMSStateoftheClimate.1

[11] Blunden, J., Arndt, D.S., 2017. State of the Climate in 2016. Bulletin of the American Meteorological Society. 98(8), Si–S280. DOI: https://doi.org/10.1175/2017BAMSStateoftheClimate.1

[12] Blunden, J., Arndt, D.S., Hartfield, G., 2018. State of the Climate in 2017. Bulletin of the American Meteorological Society. 99(8), S1–S310. DOI: https://doi.org/10.1175/2018BAMSStateoftheClimate.1

[13] Cheng, L., Zhu, J., 2018. 2017 Was the Warmest Year on Record for the Global Ocean. Advances in Atmospheric Sciences. 35, 3261–3263.

[14] Falvey, M., Garreaud, R.D., 2009. Regional Cooling in A Warming World: Recent Temperature Trends in the Southeast Pacific and along the West Coast of Subtropical South America (1979–2006). Journal of Geophysical Research: Atmospheres. 114(D4), D04102.

[15] Lluch-Cota, S.E., Tripp-Valdéz, M., Lluch-Cota, D.B., et al. 2013. Recent Trends in Sea Surface Temperature off Mexico. Atmósfera. 26(4), 537–546. DOI: https://doi.org/10.1016/S0187-6236(13)71094-4

[16] Pinaud, D., Weimerskirch, H., 2002. Ultimate and Proximate Factors Affecting the Breeding Performance of A Marine Top-predator. Oikos. 99, 141–150. DOI: https://doi.org/10.1034/j.1600-0706.2002.990114.x

[17] Rolland, V., Barbraud, C., Weimerskirch, H., 2008. Combined Effects of Fisheries and Climate on A Migratory Long-lived Marine Predator. Journal of Applied Ecology. 45, 4–13. DOI: https://doi.org/10.1111/j.13652664.2007.01360.x

[18] Nevoux, M., Forcada, J., Barbraud, C., et al., 2010. Bet-hedging Response to Environmental Variability, an Intraspecific Comparison. Ecology. 91, 2416–2427. DOI: https://doi.org/10.1890/09-0143.1

[19] Brown, B.E., Dunne, R.P., Goodson, M.S., et al., 2002. Experience Shapes the Susceptibility of A Reef Coral to Bleaching. Coral Reefs. 21, 119–126.

[20] Fitt, W.K., Brown, B.E., Warner, M.E., et al., 2001. Coral Bleaching: Interpretation of Thermal Tolerance Limits and Thermal Thresholds in Tropical Corals. Coral Reefs. 20(1), 51–65.

[21] Vaughan, G.O., Al-Mansoori, N., Burt, J.A., 2019. The Arabian Gulf. In: World Seas: An Environmental Evaluation. Academic Press: New York, NY, USA. pp. 1–23. DOI: https://doi.org/10.1016/B978-0-08-100853-9.00001-4

[22] Riegl, B., Purkis, S., 2015. Coral Population Dynamics across Consecutive Mass Mortality Events. Global Change Biology. 21(11), 3995–4005

[23] Vu Duy, V., Ouillon, S., Nguyen Minh, H., 2022. Sea Surface Temperature Trend Analysis by Mann-Kendall Test and Sen's Slope Estimator: A Study of the Hai Phong Coastal Area (Vietnam) for the period 1995-2020. Vietnam Journal of Earth Sciences. 44(1), 73–91. DOI: https://doi.org/10.15625/2615-9783/16874

[24] Tac, V.V., Huan, N.H., Son, T.P.H., et al., 2020. Sea Surface Temperature Anomaly in the Coastal Waters of Vietnam Related to ENSO Phenomenon. Vietnam Journal of Marine Science and Technology. 20(1), 1–11. DOI: https://doi.org/10.15625/1859-3097/20/1/15038

[25] Alosairi, Y., Alsulaiman, N., Rashed, A., 2020. World Record Extreme Sea Surface Temperatures in the Northwestern Arabian/Persian Gulf Verified by In Situ, Measurements. Marine Pollution Bulletin. 161(Part B), 111766. DOI: https://doi.org/10.1016/j.marpolbul.2020.111766

[26] Yi, Y., Zhang, H.-R., Jin, J., 2019. Trends of Sea Surface Temperature and Sea Surface Temperature Fronts in the South China Sea during 2003–2017. Acta Oceanologica Sinica. 38(4), 106–115. DOI: https://doi.org/10.1007/s13131-019-1416-4

[27] Kyung-Ae, P., Eun-Young, L., Chang, E., et al., 2014. Spatial and Temporal Variability of Sea Surface Temperature and Warming Trends in the Yellow Sea. Journal of Marine Systems. 143, 24–38. DOI: https://doi.org/10.1016/j.jmarsys.2014.10.013

[28] Sherwood, S.C., Huber, M., 2010. An Adaptability Limit to Climate Change due to Heat Stress. Proceedings of the National Academy of Sciences of the United States of America. 107(21), 9552–9555.

[29] Feingold, J.S., 2011. El Niño, La Niña, and ENSO. In: Hopley, D. (Eds.). Encyclopedia of Modern Coral Reefs. Encyclopedia of Earth Sciences Series. Springer: Dordrecht, The Netherlands. DOI: https://doi.org/10.1007/978-90-481-2639-2_74

[30] Hirahara, S., Ishii, M., Fukuda, Y., 2014. Centennial-scale Sea Surface Temperature Analysis and Its Uncertainty. Journal of Climate. 27, 57–75.

[31] Kurihara, Y., Sakurai, T., Kuragano, T., 2006. Global Daily Sea Surface Temperature Analysis Using Data from Satellite Microwave Radiometer, Satellite Infrared Radiometer and In-situ Observations. Weather Service Bulletin. 73, s1–s18.

[32] Osinowo, A.A., 2019. Combined Exploitation of Onshore Wind-Wave Energy in the Niger Delta Coasts Based on a 37-year Hindcast Information. Energy Management Research Journal. 2(1), 1–20.

[33] Sterling, E., Hurley, M., 2005. Conserving Biodiversity in Vietnam: Applying Biogeography to Conservation Research. In Proceedings of the California Academy of Sciences; San Francisco State University, San Francisco, CA, USA, 17–18 June 2003; Volume 56, Supplement I(1), pp. 9–11.

[34] Minh, N.N., Patrick, M., Florent, L., et al., 2014. Tidal characteristics of the gulf of Tonkin, Continental Shelf Research. 91, 37–56. DOI: https://doi.org/10.1016/j.csr.2014.08.003

[35] Fan, P.-F., 1981. Geology and Bouguer Gravity Anomalies of the Gulf of Tonkin and Vicinity. The South China Sea. 6(11), 1099–1111. DOI: https://doi.org/10.1016/0360-5442(81)90028-1

[36] IOC-UNESCO UNEP, 2016. Large Marine Ecosystems: Status and Trends. United Nations Environment Programme (UNEP), Nairobi. TWAP Volume 4 Technical report 6. 1 January 2016.

[37] Fox-Kemper, B., Hewitt, H.T., Xiao, C., et al., 2021. Ocean, Cryosphere and Sea Level Change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., et al., (Eds.). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK; New York, NY, USA. pp. 1211–1362. DOI: https://doi.org/10.1017/9781009157896.011