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Investigating Sea Surface Temperature and Coral Bleaching in the Coastal Area of Khanh Hoa Province

Tran Thi Van^{1,2*}, Nguyen Trinh Duc Hieu^{1,2,3}, Nguyen Huu Huan^{3,4}, Nguyen Phuong Lien⁵

¹ Department of Environmental and Resources Information System, Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology, (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

² Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam

³ Institute of Oceanography, Vietnam Academy of Science and Technology (VAST)

⁴ Graduate University of Science and Technology, Vietnam Academy of Science and Technology (VAST)

⁵ Coastal Branch, Vietnam – Russia Tropical Centre

* Corresponding author: tranthivankt@hcmut.edu.vn

Abstract. Khanh Hoa Coastal area is considered the area with the most diverse coral reefs in the west of the East Sea. With the trend of increasing global temperature, the coral reefs here are affected, including the phenomenon of bleaching. This paper uses a Multi-scale Ultra-high Resolution Sea Surface Temperature (MUR SST) data source to evaluate the possible relationship between sea surface temperature and coral bleaching in the period 2010-2019 in Khanh Hoa coastal area is based on two parameters: Hot Spot (HS) and Degree Heating Months (DHM). Research results show that in the past 10 years, corals in Khanh Hoa coastal area may experience heat stress in 6 years, including 2010, 2013 and the years from 2016 to 2019. The phenomenon of heat stress starts to occur in May of each year, and the level of heat stress in 2010 was stronger than in other years. Within 6 years, there have been heat stress, coral bleaching events due to temperature only occurred in 2010; while in 2013, 2016, 2017, 2018 and 2019, corals suffered from heat stress in the watch level, meaning an increase in temperature is not yet capable of causing coral bleaching. The cause of coral bleaching in 2010 was the combined effect of the increase in sea surface temperature and the suppression of upwelling during the southwest monsoon.

Keywords: coral bleaching, degree heating months, hot spot, sea surface temperature

1. Introduction

Coral reef ecosystems are characterized by high diversity, biological productivity and are home to many marine species. Thus they are considered the “rainforest” of the sea [1]. Today, coral reefs are considered an essential marine resource and are closely linked to the lives of many communities living in and around the reef. However, recent statistics show that the world coral reefs have lost about 19%. About 15% of reefs are in a state of serious threat, and they disappear within the next 10-20 years. 20% of reefs are threatened and likely disappear within 20-40 years [2]. Since the 1970s, coral bleaching has become



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more severe and frequent with the increase in CO₂ content and sea surface temperature [3]. In the future, the frequency and extent of bleaching are predicted to become more severe as the earth temperature gets hotter and hotter, which become a threat to the world coral reefs; because an increase in sea temperature is considered to be the main cause of mass coral bleaching [4]. Tropical coral reefs live just below their maximum temperature limit, and even slight increases above historical values can cause bleaching [5].

According to the US National Oceanic and Atmospheric Administration (NOAA) statistics, three severe coral bleaching events have been recorded worldwide due to global warming [6]. The first global bleaching event, combined with a strong El Niño, raised ocean temperatures by about 2°C and destroyed about 16% of the world corals in 1997-1998 [7, 8]. The second bleaching event was during a mild El Niño in 2010 that raised sea temperatures and caused mass bleaching of coral reefs in many parts of the world [6]. The third bleaching event was a strong El Niño-induced global warming in 2015-2016, which NOAA announced as the most prolonged and most extensive bleaching event on record [6, 9]. In addition, the bleaching event in 1982-1983 killed 95% of corals in the Galapagos Islands [10], but NOAA did not record this event.

Today, sea surface temperature data collected from satellites are used to monitor coral heat stress [11]. NOAA has developed a reef monitoring program to monitor coral bleaching events caused by increases in global sea surface temperature (<https://coralreefwatch.noaa.gov/>). Through this monitoring program, NOAA has developed a monthly or seasonal coral bleaching warning scheme on a global scale. These schemes are widely used and adapted in all tropical countries to predict and monitor bleaching phenomena. However, these products have a rather large resolution (5 km x 5 km) for a detailed evaluation of bleaching events at islets or reefs [6]. In addition, the NOAA method uses Degree Heating Weeks (DHW) to assess coral bleaching. Meanwhile, the majority of outputs from climate models are average monthly temperatures. Therefore, some recent studies have used Degree Heating Months instead of Degree Heating Weeks [12].

In the world, there have been many studies using DHM/DHW to assess coral bleaching levels from SST data collected from satellite devices. In 2009, Donner forecast heat stress on coral reefs worldwide using DHM over four months based on SST data over the period 1985-2000 [13]. The results of their study shows that coral bleaching occurs when the DHM is 1°C greater than the maximum monthly mean (MMM). When DHM is greater than MMM 2°C, bleaching becomes severe and can be fatal to corals. In 2014, the team of authors Yumiko Yara and colleagues evaluated the impact of increased sea surface temperature on coral bleaching caused by global warming. They used 21st century monthly SST data collected from 23 climate models to determine the DHM index to predict coral bleaching [12]. They predicts that corals will be severely bleached or dead in large areas of tropical and subtropical oceans by the middle of this century. In 2016, the author group Sam Wouthuyzen and colleagues compared the increase in SST and its effect on coral bleaching in 2010 and 2016 in Indonesian waters using the temperature parameter such as HS and DHW from the 4-km-resolution SST data source, collected from the MODIS Aqua satellite during the period 2002-2017 [6]. Their study shows that the normal temperature threshold to which corals can adapt is 29.1°C. Heat stress for corals occurred in 2010 and 2016. Both coral bleaching events in these two years started and ended in the same period (starting March and ending June). However, the bleaching intensity of 2016 was stronger than that of 2010, with an average SST of about 0.4°C higher in May - June.

This paper uses the monthly average SST data source to determine HS and the DHM to examine the possible relationship between sea surface temperature and coral bleaching events in Khanh Hoa coastal area in 2010-2019.

2. Data and method

2.1. Study area

The study area is located in the coastal area of Khanh Hoa province, limited to the range of coordinates from 11.80° – 12.84°N and 109.05° – 110.00°E (Figure 1). The study area is dominated by a tropical monsoon climate in winter (northeast monsoon) and summer monsoon (southwest monsoon). The winter

monsoon has the prevailing wind direction from north to northeast. The active period of the winter monsoon coincides with the rainy season in Khanh Hoa province, especially when the northeast monsoon combines with the activity of the equatorial trough. The path, the tropical convergence zone, storms, and tropical depressions cause heavy rain to create floods for Khanh Hoa province. The summer monsoon usually occurs in early summer, with the prevailing wind direction being southwest. This wind brings hot, dry air, high temperature and low humidity, making the weather over the basin during this period the hottest and driest of the year [14].

Khanh Hoa is a coastal province with 385 km of coastline, with a particular position facing the East Sea with favourable natural conditions for high biodiversity [15]. An overview from previous studies has shown that the coastal area of Khanh Hoa has high biodiversity. It is home to many habitats such as coral reefs, mangroves, seagrass beds, islands and beaches with various marine species. Among them, coral reefs are distributed in shallow water, mainly in Nha Trang Bay and Van Phong Bay and outside Cam Ranh Bay, with an area of more than 3,000 hm². Therefore, the coastal waters of Khanh Hoa are considered to be the area with the most diverse coral reefs in the western part of the East Sea [16]. However, marine economic development in Khanh Hoa generates several environmental problems such as overexploitation, loss and degradation of ecosystems, pollution, and landscape degradation [15]. Previous research showed that coral reefs in Khanh Hoa coastal area are being affected by bleaching events related to current climate change [17]. Coral bleaching has been recorded in Khanh Hoa and southern Vietnam in 1998, 2010, 2013 and 2014. Besides, coral reefs in Khanh Hoa have been severely affected by the integrated effects of rising sea surface temperature and other anthropogenic activities [16]. The above data shows that the increase in sea surface temperature may affect the coral reef system in Khanh Hoa coastal area.

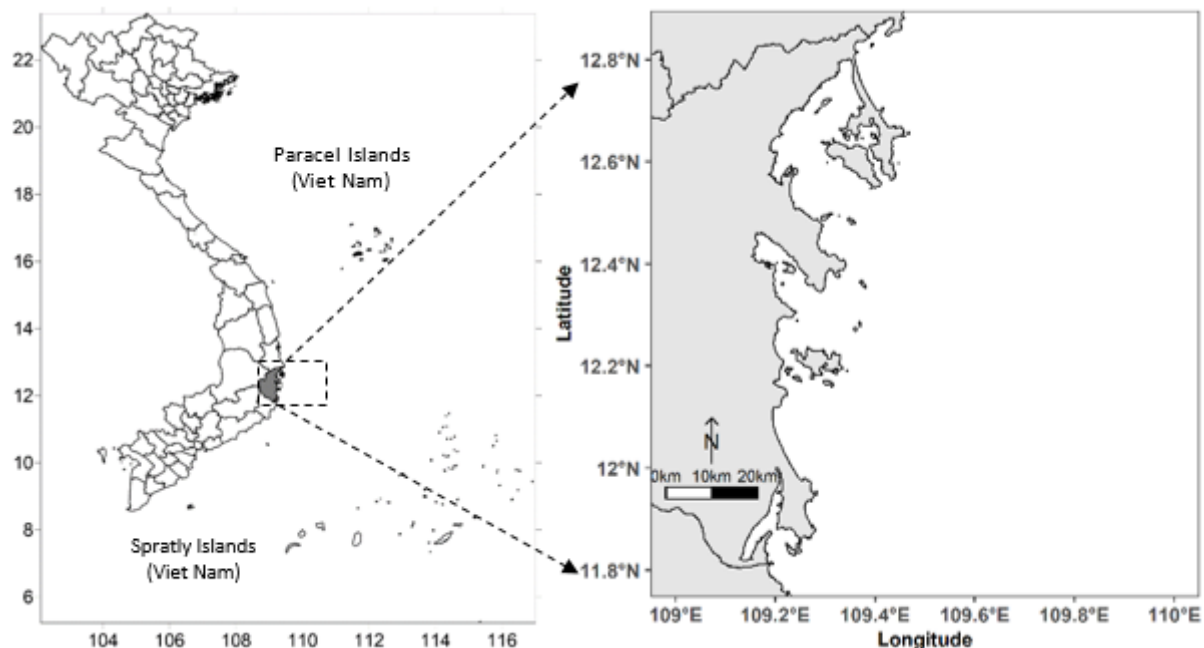


Figure 1. Map of the study area

2.2. Data

This study uses monthly mean data, spatial resolution 0.01 degrees (Latitude) x 0.01 degrees (Longitude) from the dataset MUR SST (Multi-scale Ultra-high Resolution Sea Surface Temperature). The data was mined between January 2010 and December 2019. The MUR SST level 4 dataset is analyzed based on sea surface temperature observations from several satellites of the National Aeronautics and Space Administration (NASA), NOAA, and field SST observations from the NOAA iQuam project. This dataset is sponsored by NASA, provided by the Physical Oceanography Distributed Active Archive

Center (PO.DAAC) of NASA Jet Propulsion Laboratory (JPL). The data is collected free of charge from the website <https://coastwatch.pfeg.noaa.gov/erddap/files/>.

2.3. Method to assess coral bleaching risk using sea surface temperature

Consider the possible relationship between SST and coral bleaching events during the past 10 years in Khanh Hoa coastal area based on two parameters, HS and DHM. These two indices are used to assess the heat stress leading to coral bleaching. The procedure for determining HS and DHM is described in detail in Figure 2 and equations (1) and (2) [18].

From the SST data series, calculate the 10-year MMM for the period 2010-2019. MMM is considered as the value of sea surface temperature under normal conditions, and corals can adapt over a long period of 10 years [6]. After determining the MMM, calculating the difference between the average monthly SST in each year and the MMM, this value is called HS, and is determined by equation (1) [6, 18]:

$$HS = \text{Average monthly SST for each year} - \text{MMM} \quad (1)$$

After calculating the HS, the DHM value was determined based on the monthly HS accumulation $> 0^{\circ}\text{C}$ at any pixel over 3 consecutive months according to Equation (2) [4]:

$$DHM_t = \sum_{i=t}^{t+2} HS_{ij} \quad (2)$$

In which, t is the start month of the forecast.

Based on the calculated HS and DHM values from equations (1) and (2), classify the heat stress of corals according to Table 1 [4, 18]. Combining the calculation results of HS, DHM and published documents on coral bleaching events in Khanh Hoa, we will consider the possible relationship between coral heat stress and SST at the time of the bleaching event.

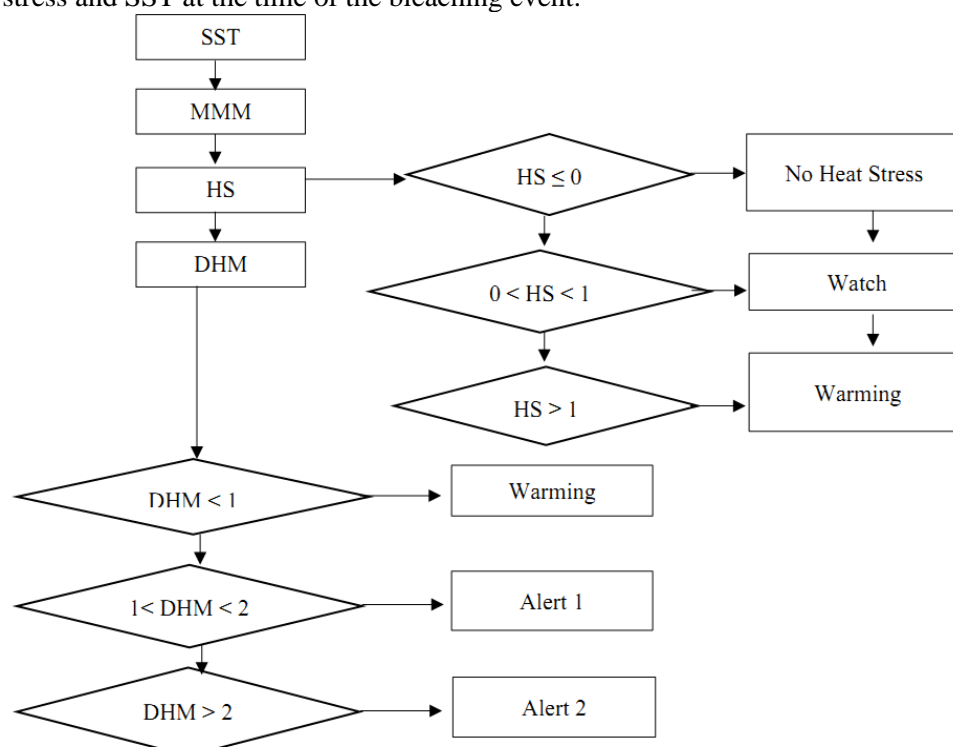







Figure 2. Procedure for determining the heat stress of corals

Table 1. Classification of coral heat stress levels based on HS and DHM

Stress level	Definition	Effect	Color
No	$HS \leq 0$	No heat stress	

Stress level	Definition	Effect	Color
Watch	$0 < HS < 1$	Low level heat stress, no effect on coral yet, observed bleaching	
Warming	$HS \geq 1$ $DHM < 1$	Heat stress at cumulative level, coral bleaching possible	
Alert 1	$HS \geq 1$ $1 \leq DHM < 2$	Strong heat stress, capable of causing partial bleaching of corals	
Alert 2	$HS \geq 1$ $DHM \geq 2$	Heat stress is severe, causing widespread coral bleaching, corals are likely to die	

3. Result

Statistical calculation results show that the SST in the period 2010-2019 in Khanh Hoa coastal area fluctuates in a wide range from 22.5 to 30.8°C, with the average value reaching $27.6 \pm 1.6^\circ\text{C}$ (Figure 3). The difference between the maximum and minimum SST values in Khanh Hoa coastal area is about 8.3°C, two times lower than the fluctuation range in the Vietnam South Central Coast (17.4 - 35.0°C) and nearly 3 times lower than in the East Sea (10.1 - 35.0°C) [19]. The value of the 95% highest density interval (HDI) in the SST data series ranged from 24.3 to 30.5°C. SST values that fall within the 95% HDI range (blue area in Figure 3) have higher probability density and confidence than SST values outside the 95% HDI range (red area in Figure 3). Based on the probability density graph, the SST data series has a right skewed distribution, so the mean value of SST (27.6°C) is smaller than the median value (28.0°C). SST values common in the Khanh Hoa coastal area range from 28.6 to 29.6°C with probability density greater than 40% and accounts for more than 28% in the data set (Figure 3).

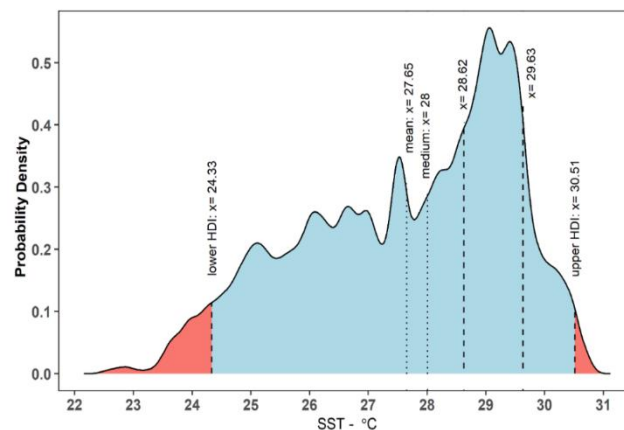


Figure 3. Probability density graph of SST values in Khanh Hoa coastal area

Table 2 and Figure 4 present the monthly average sea surface temperature distribution by year, used to determine the MMM value in Khanh Hoa coastal area in the period 2010-2019. Statistical results show that SST usually peaks in May (or June) each year, then tends to decrease in June, July, and August; continued to increase in September. In Khanh Hoa coastal areas, during the prevailing southwest monsoon (June to August), upwelling usually activates at moderate or weak levels [20, 21]. Therefore, it is possible that due to the influence of upwelling, the SST value does not increase continuously from May to September but tends to decrease in June, or July, or August each year. From the monthly average SST data, the calculation results show that the MMM value reaches 29.6°C, which means that the threshold at which corals can adapt to sea surface temperature is below 29.6°C. Generally, the optimal SST for coral reefs to grow is between 22°C and 28°C [22]. However, the temperature range in which corals can survive is between 18°C and 36°C [23]. Thus, the MMM value in Khanh Hoa coastal area is outside the optimal temperature range for coral growth but still within the allowable range for coral survival. When the SST exceeds the threshold of 29.6°C, coral heat stress occurs with the stress level

depending on the difference between the average monthly SST and the MMM. This difference is defined as the HS heat index and is determined as follows: HS = monthly mean SST (at times of heat stress) – 29.6°C.

The charts in Figure 4 illustrate a comparison of the average monthly SST value for the period 2010-2019 with the MMM value. The results showed that the SST value increased and exceeded the MMM threshold at the following 12 times: from May to July 2010, May and June 2013, May and September 2016, May and September 2017, May 2018, May and June 2019. This result indicates that in the past 10 years, corals in Khanh Hoa coastal area may be subjected to heat stress in 2010, 2013 and the years from 2016 to 2019. In particular, the phenomenon of heat stress begins to occur in May of each year. Previous studies have also recorded coral bleaching in Khanh Hoa coastal area in 2010 and 2015 with different degrees of bleaching [16, 24].

Table 2. Determination of MMM from SST

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	25.5	26.2	26.3	28.8	30.3	30.4	30.1	29.4	29.6	29.2	26.8	26.4
2011	24.6	25.6	25.3	26.5	28.3	28.2	27.5	29.3	29.3	27.1	26.2	24.1
2012	24.0	25.1	26.4	27.7	29.4	28.5	28.6	28.1	29.1	28.2	27.9	26.9
2013	25.2	26.1	27.6	28.9	29.6	29.8	29.4	28.7	28.9	27.5	26.7	24.8
2014	23.5	24.3	26.3	28.6	29.4	28.0	28.5	28.5	29.5	28.5	27.7	25.9
2015	24.5	24.8	26.4	27.5	29.5	29.1	27.6	29.1	29.4	29.1	28.4	26.9
2016	26.2	25.1	25.3	26.8	29.8	28.2	28.6	29.0	29.7	29.2	27.6	26.2
2017	25.2	24.8	25.7	27.1	29.8	29.3	29.4	29.3	29.7	28.8	27.0	25.7
2018	24.6	24.3	26.2	27.7	30.2	28.6	28.6	28.9	29.5	28.5	27.6	27.3
2019	25.7	26.8	27.7	29.5	30.0	30.5	28.7	28.8	29.0	28.8	27.0	25.2
MMM	24.9	25.3	26.3	27.9	29.6	29.1	28.7	28.9	29.4	28.5	27.3	25.9

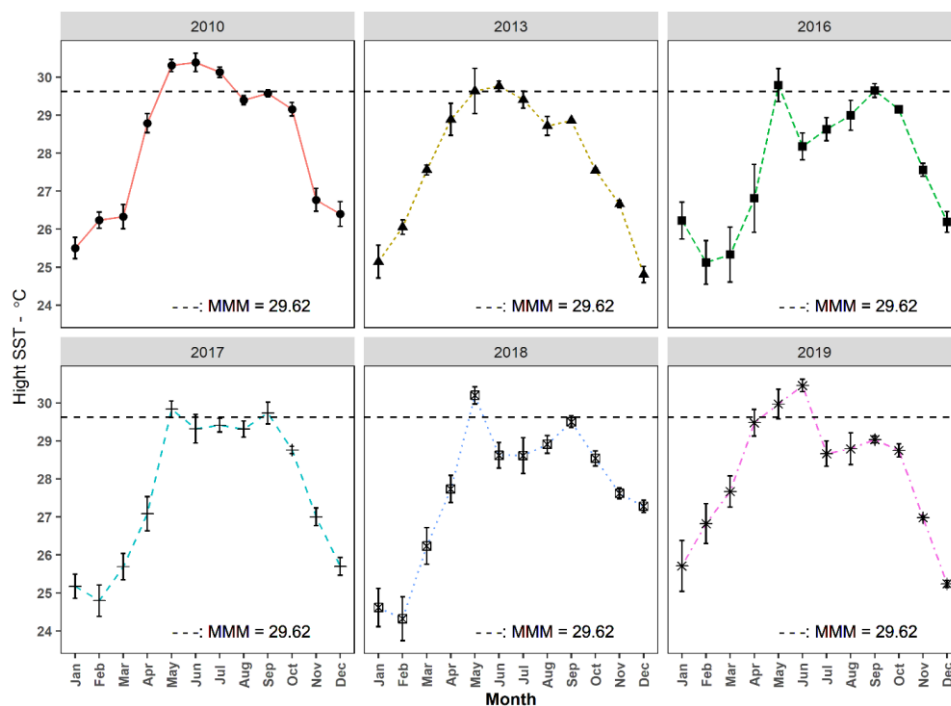


Figure 4. Comparison of average SST per month and MMM

In May 2010, Khanh Hoa coastal area experienced heat stress at three different levels, including alert 2, alert 1 and watch with area ratios of 48%, 51% and 1%, respectively (Table 3). Heat stress in coastal areas (109.4°E back to shore) mainly occurs at alert 1 level – potentially causing partial bleaching of

corals. However, in Van Phong Bay, there is a alert 2 level- coral bleaching and possibly dying (Figure 5). Research on the resilience of coral reefs in the Khanh Hoa coastal area shows that most of the coral reefs in the northern area of Khanh Hoa, especially the coral reefs in the nearshore waters in Van Phong Bay, are more sensitive to rising sea surface temperature. Coral reefs in Nha Trang Bay and the southern region are less vulnerable to heat [16]. In June 2010, heat stress levels also occurred with 3 different levels, including alert 1, warming and watch with area ratios of 4%, 24% and 72%, respectively. However, only heat stress occurred at the watch level in the coastal waters (109.4°E back to shore), i.e. there was heat stress but no effect on coral reefs (Figure 5). Meanwhile, in July 2010, heat stress only occurred at the watch level in Khanh Hoa coastal area (Table 3 and Figure 5).

At times from 2013, 2016 to 2019, although there was a heat stress phenomenon in Khanh Hoa coastal areas, most of them were only watch level, i.e. an increase in temperature is not likely to affect coral reefs (Table 3). Specifically, in May 2013, the warning status appeared in the offshore area of Cam Ranh Bay with the rate of 2%; the watch and non-heat stressed states accounted for 47% and 51%, respectively. Table 3 also shows that heat stress in the watch state accounted for 83% in June 2013, 66% in May 2016, 59% in September 2016, and 82% in May 2017, 67% in September 2017, 99% in May 2018, 78% in May 2019 and 84% in June 2019. In addition, in June 2019, heat stress at warming level also appeared in the offshore waters (109.6°E and offshore) in Van Phong and Nha Trang Bays, with a rate of 16%.

Table 3. Percentage (%) of areas with heat-stressed corals in Khanh Hoa coastal areas

Classified	May 2010	Jun 2010	Jul 2010	May 2013	Jun 2013	May 2016	Sep 2016	May 2017	Sep 2017	May 2018	May 2019	Jun 2019
Alert 2	48	0	0	0	0	0	0	0	0	0	0	0
Alert 1	51	4	0	0	0	0	0	0	0	0	0	0
Warming	0	24	0	2	0	0	0	0	0	0	0	16
Watch	1	72	100	47	83	66	59	82	67	99	78	84
No	0	0	0	51	17	34	41	18	33	1	22	0

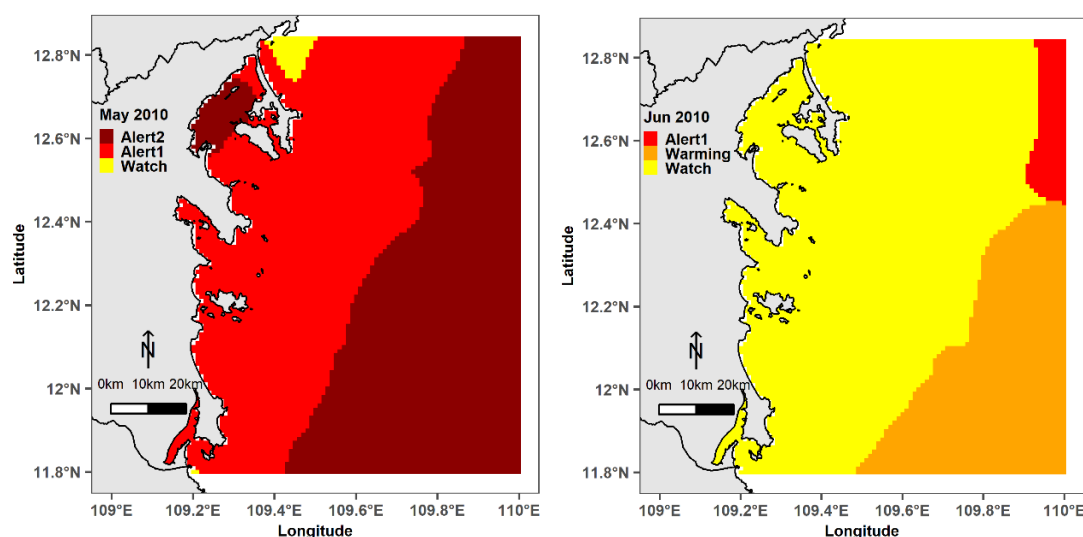


Figure 5. Heat stress on corals in Khanh Hoa coastal area in May and June 2010

4. Discussion

Research results show that, in Khanh Hoa coastal areas, heat stress for corals occurred in 2010. Globally, a mild El Niño in 2010 increased SST and caused mass bleaching of coral reefs in many parts of the

world [6]. In an overview report on coral bleaching in 2010 in Southeast Asia, SST exceeded the bleaching threshold of 2°C from May to July 2010. The increase in SST has caused coral bleaching in some areas of the South Central Coast, such as Van Phong, Nha Trang, Cam Ranh and Ninh Hai [25]. In addition, the field survey results also showed that coral bleaching was recorded in Nha Trang Bay in May 2010 [26].

An overview report on the status of coral reefs in the East Asian Sea in the years 2015-2017 shows that, in 2015, coral bleaching phenomenon with a mild degree was detected in shallow water (2-7m deep) in Van Phong Bay, Nha Trang Bay and Cam Ranh Bay. However, there was no record of bleaching in these three Bays in 2016 and 2017 [24]. This study also shows that in 2016 and 2017, only the watch state - temperature increase was not likely to affect the reef and the absence of heat stress. Thus, it can be seen that, although a strong El Niño wave occurred in 2016, which increased SST and caused coral bleaching on a global scale [6], it did not affect coral reefs in Khanh Hoa coastal area. Recent research shows that 2016 is a year where two phases co-occur: the end of El Niño, the preparation for the La Niña period; and 2016 is considered the time to bleach corals like 1998 and 2010. However, in July 2016, the upwelling phenomenon appeared with the centre moving closer to the shore than in normal years. The offshore area of Ninh Thuan - Khanh Hoa was strongly affected by upwelling [27]. When upwelling water is active, cold deep water layers move vertically to the surface, reducing sea surface temperature. This can help reduce heat stress for corals in Khanh Hoa coastal area in 2016. Previous studies also showed that the occurrence of upwelling during the southwest monsoon season helped reduce heat stress and coral bleaching in Khanh Hoa coastal area [28, 29].

The above analysis indicates that the occurrence of upwelling during the southwest monsoon helps to reduce the heat stress for corals, however in 2010, coral bleaching was recorded in Khanh Hoa. Research on the upwelling water system in the South Central Coast shows that in June-July 2010, there was a decrease in long-shore currents in the north-northwest direction from the north of Ninh Thuan to the sea of Binh Dinh. This current system eliminated the anti-cyclonic vortex off the coast of Ninh Thuan - Binh Thuan, causing the upwelling phenomenon to be eliminated in 2010 [27]. Thus, due to the combined effect of the increase in SST (above 30°C) and the suppression of the upwelling phenomenon, coral bleaching in Khanh Hoa coastal area in 2010.

Although the results from this study suggest no heat stress on corals in 2015, coral bleaching has been recorded in Khanh Hoa as presented in the overview report on the status of coral reefs in the East Asian Sea. Reviewing previous studies, it can be seen that, in addition to being affected by the increase in SST, coral reefs in Khanh Hoa coastal area are also degraded by other causes such as increased sediment content, outbreaks of starfish and local tourism activities [29, 30]. Some recent studies have shown that, in Nha Trang Bay, coral degradation is not due to an increase in sea surface temperature. Instead, corals were affected mainly by outbreaks of thorns starfish, with average densities increasing from 1.7 to 4.2 individuals per 100m² between 2013-2019 [28, 31].

The analysis results on the distribution over time of SST and the effect of SST on corals show that, in summer, Van Phong Bay (north of Khanh Hoa) has a higher sea surface temperature; and corals are subjected to a higher degree of heat stress than in the southern part of Khanh Hoa. Meanwhile, in the Van Phong Bay area, a thermal power plant with a capacity of 1,320 MW has been started [32]. A recent heat spread calculation study shows that if this thermal power project is operated at total capacity as planned, about 15,000,000 m³ of water (sea) has a higher temperature than water every day. The sea in the receiving area, about 7°C, is discharged into the northwest of the My Giang - Hon Do - Bo Co sea area [33]. The area of reefs from My Giang extending through Hon Theo to Bo Co is home to many coral reefs. Therefore, the most concerned pollutant in Van Phong Bay in the future will be the heat from the cooling water of thermal power projects, and management agencies should have harmonized solutions for the goals of economic development and environmental protection in the locality.

5. Conclusion

Research results show that in the past 10 years, corals in Khanh Hoa coastal area can be subjected to heat stress in 6 years, including 2010, 2013 and the years from 2016 to 2019. Heat stress events all start

to occur in May of each year, and the level of heat stress in 2010 was stronger than in other years. Of the six years of heat stress, the temperature-induced coral bleaching event occurred only in 2010. Meanwhile, in 2013, 2016, 2017, 2018 and 2019, corals suffered from heat stress in the watch state, which means an increase in temperature is not yet capable of causing coral bleaching.

In summer, the Van Phong Bay area (north of Khanh Hoa) has higher sea surface temperatures and higher heat stress corals than the southern part of Khanh Hoa. The cause of coral bleaching in 2010 was the combined effect of the increase in sea surface temperature and the suppression of upwelling during the southwest monsoon.

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