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# Testing the relationship between bleaching severity and climate change during the fourth large-scale coral bleaching event

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**Abstract.** The Fourth Global Coral Bleaching Event unfolded amidst the accelerating impacts of climate change, underscoring the urgent need to reassess the relationship between coral bleaching trends and climatic shifts. This study examined the influence of sea surface temperature (SST) anomalies and cumulative thermal stress, quantified by Degree Heating Weeks (DHW), on coral bleaching rates from early 2023 to mid-2024. Satellite-derived coral risk data were analyzed for correlation with field survey data. The results revealed that SST anomalies alone were insufficient to significantly predict coral bleaching events. However, a significant positive correlation was found between DHW and coral bleaching rates, indicating that cumulative thermal stress is a critical predictor of bleaching events. This finding emphasizes the necessity of implementing an effective monitoring and early warning system based on DHW thresholds to mitigate the impacts of coral bleaching, especially given the increasing frequency of such events in the context of climate change.

**Keywords:** Bleaching severity, climate change, fourth large-scale coral bleaching event.

## 1. Introduction

As one of the most important ecosystems in the ocean, coral reefs are known as the rainforest of the sea, providing habitats for countless creatures. And because of the life characteristics of reef-building corals, they grow close to their upper thermal tolerance thresholds [1]. Thus, they are very susceptible to changes in water temperature. Coral bleaching occurs when the symbiotic relationship between reef-building corals and their photosynthetic dinoflagellate algal endosymbionts (Symbiodiniaceae family, hereafter 'symbionts') breaks down, leading to the loss of symbionts, exposing the white calcium carbonate skeleton beneath the translucent tissue devoid of symbionts [2]. These algae perform photosynthesis to provide energy and color to the corals, achieving a balance. Once algae expelled, the corals turn vulnerable, lacking essential nutrients. Prolonged bleaching can lead to coral death, threatening the biodiversity of coral reef ecosystems and impacting marine life and human communities that rely on these habitats. The NOAA Coral Reef Conservation Program recently issued a statement that the world is experiencing the fourth coral bleaching event in recorded history [3]. Due to the impact of climate change, coral bleaching around the world is becoming more frequent and severe [4]. Global warming has caused abnormally high temperatures in seawater for a long time, which is the main cause

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of large-scale coral bleaching [5]. The Fourth Global Coral Bleaching Event began in 2023 and has caused severe damage to coral reefs worldwide, with record heat levels and bleaching alerts at unprecedented levels [6].

There are also studies that have developed DHW calculator and Coral Bleaching HotSpot product based on Sea Surface Temperature (SST) datasets and coral bleaching dataset [7, 8]. However, the program is still under development and needs to be improved. Although considerable attention has been paid to coral bleaching in academic research, the relationship between sea surface temperature and the degree of coral bleaching has yet to be updated since the large-scale coral bleaching in 2023. The risk data from satellite observations need to be correlated with the coral bleaching conditions of the sea surface surveyed by manual observations.

This article focuses on the impact of climate change on coral bleaching. The main topic is the impact of sea surface temperature changes caused by climate change on the extent of coral bleaching, aim to explore the relationship between coral bleaching and sea surface temperature. This study focuses on the time span from the beginning of 2023 to the first half of 2024, conducted the correlation test on Degree Heating Week, SST Anomaly and the degree of coral bleaching to explore the correlation between these variables. The research of the relationship between both each two variables will help us predict the overall trend of coral bleaching in the context of rising global sea surface temperatures, help researchers understand the dynamics of marine ecology and respond to changes in sea ecosystem, and guide us to intervene in threats to species and food chains that depend on corals as possible.

## 2. Method

### *2.1. Dataset*

This research uses sea surface temperature and coral risk data from Coral Reef Watching (CRW) remote sensing products of National Oceanic and Atmospheric Administration (NOAA) and coral inspection data from Reef Check Global Reef Dataset. This study chooses the data of coral reef Check from January 2023 to June 2024, and summarizes the situation of coral bleaching after 2023, and corresponding sea surface temperature data and coral risk data were found in CRW products. Thus, a one-to-one data set corresponding to the actual coral reef bleaching and the corresponding sea surface temperature monitoring is obtained.

For Reef Check data, the 100m transect line is divided into four 20m segments (S1 – S4) with a 5 m gap in between them to ensure sample independence. If bleaching appearing, two estimates are made [9, 10]. First, teams estimate the percentage of all corals on the transect that are bleached. Second, they estimate the mean percent of each colony that is bleached. For example, the estimate might be 30 out of 100 corals (30%) along the transect are bleached but of the colonies bleached, the mean level of bleaching per colony is 80%. This study multiplies the first estimated value of the four segments by the second time and then add the product of the four segments as the whitening degree of the region. Because this study focused primarily on the extent of coral impacts, the product of the percentage of bleached individuals and the average bleached percentage of each individual was used as a measure of its.

For sea surface temperature data and coral risk data, this study used UTM 12:00 data uniformly at the time point of data selection. Therefore, in this data study and statistical analysis, the instantaneous sea surface temperature is not of reference value because it is subject to different sunshine conditions at the time. In addition, considering that the variation trend of SST within seven days is related to seasons, and cannot represent the overall global climate change, this study does not analyze this variable. In the dataset, this research selected SST Anomaly and DHW as variables to measure sea surface temperature anomalies under climate change. SST Anomaly refers to the deviation between ocean surface temperatures and long-term averages and is an important indicator in climate change research because it reflects the ocean's impact on the global climate system, as well as the potential impacts of climate change on Marine ecosystems. DHW is used to quantify the cumulative effect of sea surface temperature anomalies, and it represents the total time that sea surface temperature anomalies exceed a specific threshold (usually 20°C). For example, if the sea surface temperature in a region is higher than 20°C for

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a week, the region will be recorded as 1 DHW. DHW is commonly used to assess the intensity and duration of Marine heat waves, which can negatively impact Marine biodiversity, coral reefs, and other Marine ecosystems.

### *2.2. Methodology*

In data analysis, this study performed a scatter plot for initial relationship judgment and then used R, Excel, and SPSS to conduct a correlation test and linear regression analysis of the data. In this study, the Pearson correlation test and linear regression methods were used to analyze the relationship between each two continuous variables. The Pearson correlation test is used to evaluate the linear correlation between variables. It is simple, intuitive, computationally efficient, and can determine significance through the correlation coefficient and p-value. Linear regression can not only quantify and explain the impact of independent variables on dependent variables but can also be used to predict unknown values and provide model diagnostic tools such as residual analysis. Combining these two methods allows for a comprehensive analysis of the relationship between variables, providing a solid statistical foundation for research.

This study screened the data when evaluating the relationship between the degree of coral bleaching and three CRW variables - “Degree Heating Week”, “Coral Bleaching Hotspot” and “Sea Surface Temperature Anomaly”, excluded the data in which the degree of bleaching was all zero, and only explored the relationship between the degree of bleaching and the variables.

Considering that the influence of temperature on coral bleaching is mostly reflected in the influence of heating when exploring the relationship between SST Anomaly and coral bleaching degree, this study excluded the data with negative SST Anomaly.

## 3. Result

### *3.1. SST anomaly with bleaching degree*

This study analyzed the relationship between Sea Surface Temperature (SST) and coral bleaching degree using the Pearson correlation test and linear regression methods.

The scatter plot shows the relationship between SST Anomaly and bleaching degree. The results of the linear regression analyses are as Figure 1. The ordinate represents the average millage ratio of coral bleaching at the site on that date, and the abscissa represents the SST anomaly in degrees Celsius. Each point represents the coral bleaching extent and SST condition at different times in different regions.

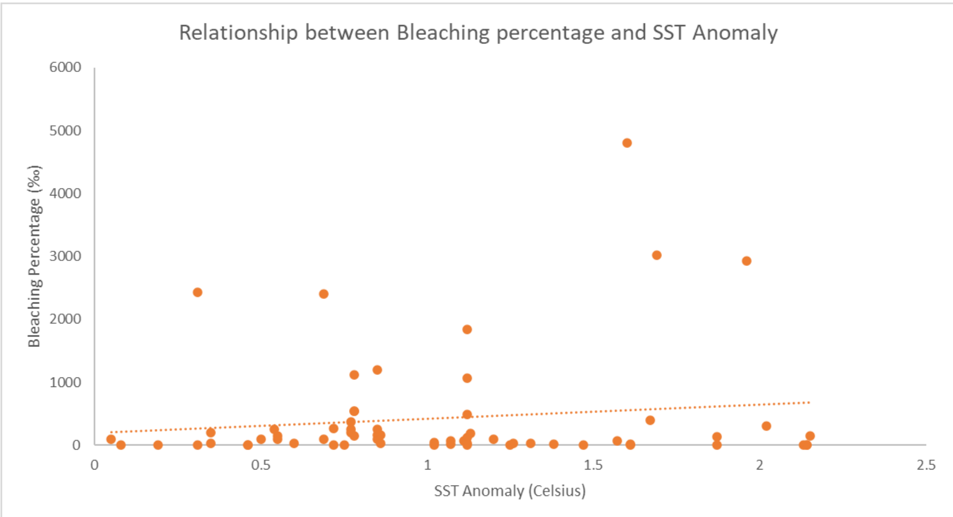


**Figure 1.** Scatter plot and fitted line of the relationship between coral bleaching degree (parts per thousand) and sea temperature anomaly from January 2023 to June 2024 (data from different locations) (Original).

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Using SST as the independent variable and coral bleaching degree as the dependent variable:

$$\text{Bleaching Degree} = 193.5 + 224.7 \cdot \text{SST} \quad (1)$$

The regression coefficient for SST Anomaly was estimated at 224.7, with a standard error of 206.9, t-value of 1.086, and p-value of 0.282. This indicates that the effect of SST on coral bleaching degree is not significant. The residual standard error of the model was 887.5, with an R-squared value of 0.01867 and an adjusted R-squared value of 0.00284. The F-statistic was 1.18 (df = 1, 62), with a p-value of 0.2817, indicating that the overall model is not significant.

The Pearson correlation test results indicated that the correlation coefficient between SST Anomaly and coral bleaching degree was 0.1366, with a p-value of 0.2817, suggesting that the correlation is not significant (t = 1.0861, df = 62, 95% CI: -0.11297 to 0.37002).

### *3.2. Degree heating week with bleaching percentage*

The relationship between DHW and the degree of bleaching was analyzed according to the approximate trend obtained from Figure 2. The ordinate is the same as in Figure 1, and the abscess represents the degree heating cycle in degrees Celsius.

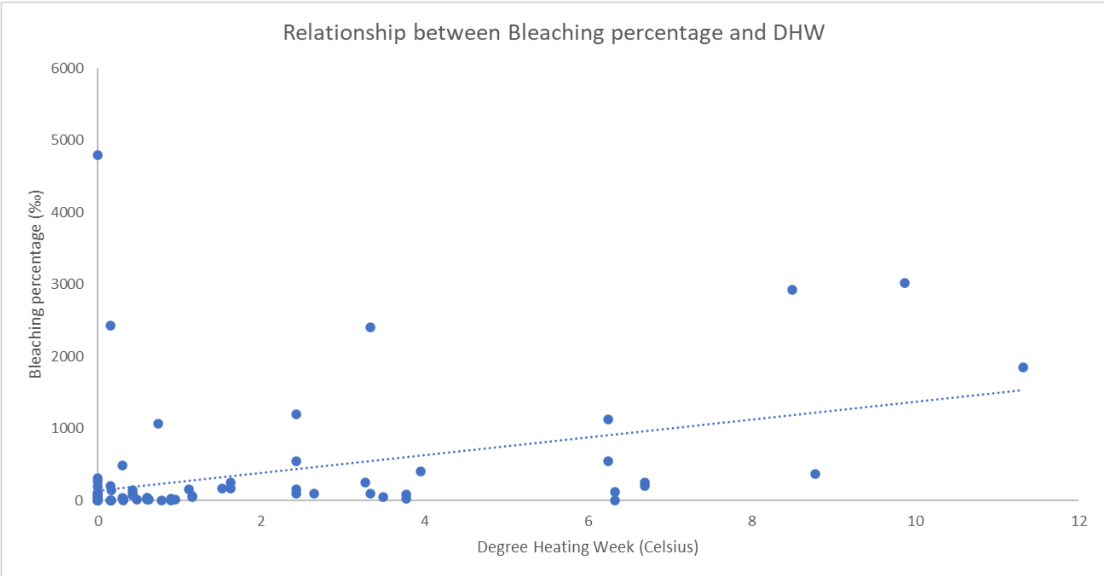


**Figure 2.** Scatter plot and fitted line of the relationship between coral bleaching severity (parts per thousand) and degree heating week from January 2023 to June 2024 (data from different locations) (Original).

Using Degree Heating Weeks (DHW) as the independent variable and coral bleaching degree as the dependent variable:

$$\text{Bleaching Degree} = 142.19 + 122.56 \cdot \text{DHW} \quad (2)$$

The regression coefficient for DHW was estimated at 122.56, with a standard error of 32.04, a t-value of 3.826, and a p-value of 0.000259. This indicates that the effect of DHW on coral bleaching percentage is significantly positive. The residual standard error of the model was 744.2, with an R-squared value of 0.1563 and an adjusted R-squared value of 0.1456. The F-statistic was 14.64 (df = 1, 79), with a p-value of 0.0002593, indicating that the overall model is significant.

Additionally, the Pearson correlation test for DHW and coral bleaching degree showed a correlation coefficient of 0.3954, with a p-value of 0.0002593, suggesting a significant positive correlation (t = 3.8256, df = 79, 95% CI: 0.19373 to 0.56493).

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## 4. Discussion

Analysis of the relationship between SST anomalies and coral bleaching rates showed that SST anomalies alone did not significantly predict coral bleaching events. Although the regression coefficient was positive, the high p-value and low R-squared value indicated that only a small part of the variation in bleaching rates could be attributed to SST anomalies. Observing the relationship between the two variables in the scatter plot, it can be found that the correlation between the two is not significant. This suggests that other factors (possibly confounding variables such as water quality, local ocean conditions, or other environmental stressors) may play an important role in coral bleaching events. In addition, the current linear model may not capture the potential complex nonlinear relationship between SST and coral bleaching, indicating that more complex modeling methods are needed.

However, the relationship between the number of warming weeks (DHW) and coral bleaching rates showed a significant positive correlation. The regression analysis showed strong predictive power. The R-squared value (0.1563) indicated that DHW explained about 15.63% of the variance in bleaching degree, indicating that cumulative thermal stress is a key factor in predicting bleaching events. The significant results of DHW after 2023 and early 2024 show that it is still a more reliable indicator for predicting coral bleaching compared with SST anomalies. The robustness of the DHW model is supported by a significant F statistic (14.64) and a low residual standard error (744.2), emphasizing its importance in monitoring and managing coral health. This is consistent with the ecological understanding that prolonged exposure to high temperatures can exacerbate coral bleaching. Compared with the previous statistical analysis results, it shows that only the current SST anomaly may not have a significant correlation with coral bleaching, but the accumulation of thermal stress from an ecological perspective can well predict the risk of coral bleaching.

This study used data from manual field surveys, which may have a certain degree of error from the actual situation. At the same time, it is hoped that the coral bleaching survey technology and survey methods can become more and more rich and accurate. Future research should consider integrating other predictive factors such as seawater acidity, and continue to monitor and collect data after the 2023 coral mass bleaching event, to grasp the laws and influencing factors of coral bleaching more timely and reliably under the general trend of intensified climate change.

In terms of practical application, these findings update the coral bleaching trend status and emphasize the necessity of an effective monitoring and early warning system based on DHW thresholds after 2023 to mitigate coral bleaching. Conservation strategies should prioritize areas with higher DHW for targeted interventions, thereby protecting vulnerable coral reef ecosystems and enhancing their resilience to climate change-induced stressors.

## 5. Conclusion

This study analyzed the effects of sea surface temperature (SST) anomalies and cumulative heat stress (DHW) on coral bleaching rates and reached several important conclusions. The research found that SST anomalies alone cannot significantly predict coral bleaching events, highlighting the complexity of factors influencing coral health. This finding suggests that other factors, such as water quality, local ocean conditions, and additional environmental stressors, may significantly contribute to coral bleaching events. Consequently, relying solely on SST anomalies as a predictor of coral bleaching might overlook these essential factors. In contrast, the study found a significant positive correlation between DHW and coral bleaching rates, demonstrating that DHW has strong explanatory power for predicting bleaching events. This indicates that cumulative heat stress is a critical factor in predicting bleaching events and suggests that prolonged exposure to high temperatures is a key driver of coral bleaching. The results emphasize the importance of implementing effective monitoring and early warning systems based on DHW thresholds to mitigate the impacts of coral bleaching, particularly in light of the Fourth Global Coral Bleaching Event that began in 2023.

The research highlights the need for targeted conservation strategies, prioritizing areas with higher DHW for interventions to protect vulnerable coral reef ecosystems and enhance their resilience to climate change-induced stressors. Future research should consider integrating additional predictive

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factors, such as seawater acidity and nutrient levels, to develop a more comprehensive understanding of coral bleaching dynamics. Furthermore, continued monitoring and data collection following the 2023 mass coral bleaching event is crucial for understanding the patterns and influencing factors of coral bleaching, enabling more effective strategies to safeguard these vital ecosystems against the ongoing challenges posed by climate change.

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