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RESEARCH ARTICLE

Warming Waters, Whitening Reefs: Unveiling the Thermal Thresholds of Coral Survival

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ABSTRACT: Rising sea surface temperatures are widely recognized as the main cause of frequent coral bleaching events worldwide. As ocean temperatures rise, coral reefs experience stress that threatens their survival and benefits, including marine life support and coastal protection. This study examines how different forms of heat stress affect coral bleaching using a dataset with observed bleaching percentages and temperature indicators such as Sea Surface Temperature Anomalies, Thermal Stress Anomalies, and Degree Heating Weeks. Local environmental conditions are also considered. These factors are analyzed using multivariate linear regression to assess their relationship with bleaching intensity. The results show that bleaching is most strongly associated with heat exposure. In contrast, local conditions such as greater reef depth and higher turbidity sometimes show lower bleaching levels, although these effects are inconsistent across sites. Some variation in bleaching remains unexplained due to differences in coral species or data inconsistencies. The findings support the conclusion that prolonged heat stress is the primary driver of coral bleaching, while reef protection depends on reducing greenhouse gas emissions.

KEYWORDS: Earth Science, Marine Science, Coral Bleaching, Thermal Stress, Degree Heating Weeks.

Introduction

Coral reefs are important ecosystems. They support many marine species and also help people. Reefs protect coastlines and support fishing and tourism.[1] Even so, coral reefs are under serious threat today. Climate change is one of the main reasons for this. Rising sea-surface temperatures are especially harmful to corals. Corals do not tolerate heat well. When water temperatures rise above normal levels, corals become stressed. If the stress continues, corals lose the algae that live inside them. These algae are important because they help corals get energy. When corals lose them, the corals turn white. This process is called coral bleaching. Bleached corals are weak, and many die if temperatures stay high for too long.[2,3]

In the past few decades, coral bleaching has happened more often. Some of the largest bleaching events occurred in 1998, 2010, and between 2014 and 2017. These events were linked to unusually warm ocean temperatures and strong El Niño conditions.[4,5] Scientists often use Degree Heating Weeks (DHW) to measure heat stress on reefs. DHW considers both how hot the water becomes and how long the heat lasts. Higher DHW values are usually linked to more severe bleaching.[6] Even when reefs experience similar temperatures, bleaching levels can be very different. Some reefs bleach heavily, while others nearby do not. Local conditions can help explain this. Depth, water clarity, water movement, and storms can all affect how much stress corals experience during heat events. Coral type and past exposure to stress also matter.[7,8]

Many previous studies focus mainly on temperature or mainly on local conditions. Fewer studies look at both together. This can be difficult because temperature variables are often closely related. Bleaching data are also not always measured in the same way, which can affect results. This study uses data from multiple reef sites to examine coral bleaching. The dataset includes bleaching percentages, temperature indicators (SSTA, TSA, and DHW), and local factors such as depth, turbidity, wind speed, cyclone frequency, and distance from shore. Regression analysis is then used to examine how heat stress and local conditions are related to bleaching levels.

Research Question:

This study asks whether short-term temperature changes are linked to higher coral bleaching after accounting for local environmental conditions, and whether factors such as depth and turbidity help explain differences between reef sites.

Literature Review:

Research on coral bleaching has long emphasized the susceptibility of reef-building corals to anomalously high sea surface temperatures, with early foundational studies establishing that bleaching is fundamentally a stress response to the breakdown of the coral–Symbiodiniaceae symbiosis.[9,10] Subsequent empirical work has demonstrated that even modest deviations above mean summer maxima can induce bleaching, particularly when thermal anomalies persist for extended periods.[11] The development of satellite-derived temperature metrics, especially the Degree Heating Week (DHW) index, has markedly advanced understanding of the temporal dynamics of heat stress. Studies using DHW consistently show a strong, near-linear relationship between cumulative heat exposure and bleaching severity across diverse reef systems.[12] Recent global assessments further corroborate this link, indicating that marine heatwaves of increasing frequency and duration are now the dominant driver of mass bleaching events, particularly those recorded in 1998, 2010, and 2014 -2017.[4,5]

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Complementing these broad temperature-based approaches, finer-scale ecological research highlights the role of local moderators in shaping bleaching outcomes. Factors such as reef depth, hydrodynamic exposure, and water-column turbidity can mediate light stress and thermal accumulation, thereby producing spatial mosaics of bleaching resistance.[13,14] Shaded or turbid reef zones often exhibit reduced bleaching, suggesting that attenuation of irradiance can buffer thermal sensitivity during peak stress periods. Additionally, work in physiological ecology shows that coral species differ in their thermal thresholds due to inherent variations in symbiont types, tissue densities, and metabolic flexibility.[15,16] These biological and environmental contingencies underscore why bleaching severity can vary significantly even under uniform thermal forcing.

Large-scale climate research situates these ecological findings within the broader context of anthropogenic warming. Projections based on coupled Earth system models reveal that continued emissions will drive ocean temperatures beyond the adaptive capacity of most coral species, drastically shortening return intervals between bleaching events.[4,17] Multiple studies warn that without decisive mitigation, many tropical reefs are likely to experience annual severe bleaching by mid- century, a frequency incompatible with long-term recovery and ecological persistence.[4] At the same time, emerging literature exploring resilience and adaptive mechanisms such as symbiont shuffling, heat-hardening, and genetically tolerant coral strains presents a cautiously optimistic view, though these processes appear insufficient to offset the pace of ocean warming.[18,19]

Taken together, the literature portrays coral bleaching as a phenomenon driven primarily by cumulative thermal stress, but modulated by a complex interplay of local environmental conditions and species-specific traits. The convergence of empirical field observations, satellite-based heat stress metrics, and climate model projections provides a coherent and robust framework within which to situate the present study. By examining the combined influence of cumulative heat stress, acute temperature anomalies, and moderating environmental factors, this paper contributes to an established but continually evolving body of research seeking to identify the thresholds beyond which coral reef resilience is compromised.

Methods

Data Description:

This study used data that already existed instead of collecting new samples. The aim was to understand why coral bleaching looks very different from one reef to another, even when those reefs experience similar heat conditions. The dataset includes 41,361 observations from reef sites around.

Each observation represents one survey carried out at a specific reef location. Basic information is included.

The main focus of the study is a variable called Percent Bleaching. This shows how much of the coral at a site appeared bleached during the survey. It is recorded as a percentage. In some cases, bleaching was reported using categories instead of exact percentages, depending on who collected the data. Because of this, bleaching information is not perfectly consistent across all sites. This difference was taken into account when looking at the results.

Heat stress was described using several temperature measures taken from satellite data. Sea Surface Temperature Anomaly was used to show how much temperatures differed from normal conditions over short periods. Thermal Stress Anomaly was used to represent brief spikes in temperature above expected levels. Degree Heating Weeks were used to measure how much heat built up over time by combining both how high the temperature was and how long it stayed high.

Other temperature-related values, such as average background sea surface temperature, were included to give a general idea of the thermal environment at each reef.

Local conditions were also included because they can affect how corals respond to heat. Reef depth was used to reflect differences in light and temperature exposure. Turbidity was included to represent how clear or cloudy the water was. Windspeed and cyclone frequency were used to capture physical processes that can mix water and reduce heat buildup. Distance from shore was included to show whether a reef was closer to land or farther offshore, which can influence water quality and human impact.

Before the analysis, all variables were checked and converted into numerical form where needed. Missing values in important variables were replaced using median values, which helps reduce the effect of extreme numbers. Many of the temperature variables were very similar to each other, which made direct analysis difficult.

Statistical Analysis:

The primary objective of this study is to examine how thermal stress influences coral bleaching while accounting for additional environmental factors that may also affect bleaching outcomes. We focus on commonly used thermal indicators, including climatological sea surface temperature (ClimSST) and sea surface temperature anomalies (SSTA), which capture long-term background thermal conditions and short-term heat stress, respectively. In addition, turbidity and cyclone frequency are included to represent local environmental and physical disturbance processes at each reef site.

The empirical analysis is conducted using a multivariate Ordinary Least Squares (OLS) regression framework. To account for potential heteroskedasticity and small-sample bias, HC3 robust standard errors are employed. The regression model is specified as:

$$\boldsymbol{Bleaching_i = \alpha + \beta_1 ClimSST_i + \beta_2\, SSTA_i + \beta_3\, Turbidity_i + \beta_4\, CycloneFrequency_i} + \varepsilon_i$$

where Bleaching_i denotes the observed bleaching intensity at reef site i. ClimSST represents long- term average sea surface temperature, SSTA captures short-term temperature deviations from the climatological mean, turbidity proxies water quality and light conditions, and cyclone frequency reflects exposure to physical disturbance. Each coefficient measures the marginal association between the corresponding predictor and bleaching intensity, holding other variables constant, under the assumption of linear and additive effects. The error term cap-

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tures unobserved influences on bleaching, including biological variation and site-specific factors not explicitly modeled.

We checked the model carefully using residual diagnostics, leverage statistics, and goodness-of-fit measures. We also ran some sensitivity tests, like trying models with the original thermal variables, removing potential outliers, and looking at log-transformed bleaching data.

Results and Discussion

Graphical Analysis:

To start understanding how bleaching varies with different environmental factors, we looked at a set of scatterplots showing bleaching against Depth, Distance to Shore, Sea Surface Temperature Anomaly (SSTA), and Climatological Sea Surface Temperature (ClimSST). Overall, the plots show a lot of scatter, and there aren't any clear trends. This suggests that these variables, by themselves, don't explain much about why some reefs bleach more than others. The relationships between bleaching and environmental variables are illustrated in Figure 1.

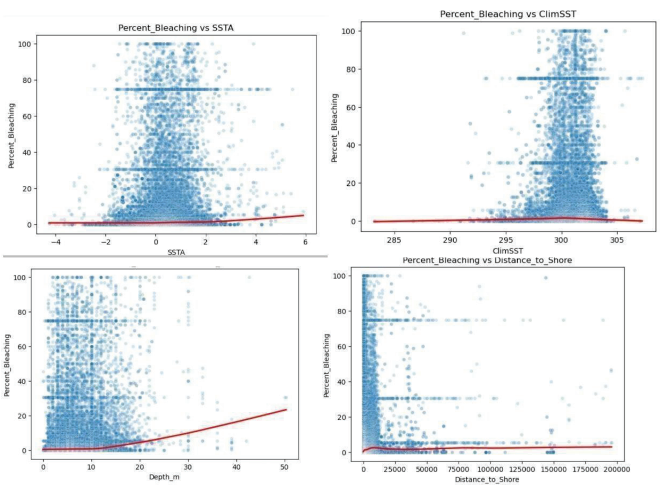

Figure 1: Percent coral bleaching in relation to thermal stress and site characteristics. Panels show coral bleaching versus (a) SSTA, (b) ClimSST, (c) reef depth, and (d) distance to shore. Each point represents a reef observation, and the red lines are LOESS smoothers showing the general trend. Overall, the scatterplots indicate weak relationships between bleaching and individual environmental variables, suggesting that these factors alone do not strongly explain variation in bleaching among reef sites.

One thing that stands out in all the graphs is that many points cluster around 35–40% and 70–75% bleaching. This is likely due to how some monitoring programs record bleaching, using coarse bins and assigning midpoints as values. Because of this, the data has a lot of structured noise, which makes it harder to see real ecological patterns.

In the depth plot, bleaching values are spread across all shallow reef depths, but most observations are from reefs shallower than 20 meters. There's a slight upward bend in the trend line at depths greater than 25 meters, but there are very few data points there, so this is probably just due to sparse data rather than a real biological effect. Similarly, in the distance-to-shore plot, most reefs are close to the coast, and bleaching doesn't show any clear change with distance; the LOESS line is nearly flat.

The SSTA plot shows a little more of a pattern. At higher positive temperature anomalies, the smoothing line curves upward slightly, which fits the expectation that sudden heat spikes can trigger bleaching. Still, bleaching values are very spread out even at low anomalies, so SSTA alone isn't a reliable predictor. The ClimSST plot shows the least structure of all, scattered evenly across all background temperatures, and any slight curvature in the trend is likely just noise.

Overall, these graphs show that depth, distance to shore, short-term temperature anomalies, and background temperatures have very weak relationships with bleaching. The presence of noise, the effect of categorical reporting, and the lack of clear patterns all suggest that bleaching isn't explained by any single variable on its own. This supports the need for a multivariate approach and emphasizes the role of cumulative thermal stress, which is better aligned with bleaching biology and later confirmed as the main driver in the regression analysis.

Empirical Results:

To examine the factors associated with coral bleaching, we estimated a multivariate linear regression with bleaching intensity as the dependent variable and climatological sea surface temperature (ClimSST), sea surface temperature anomalies (SSTA), reef depth, and distance to shore as predictors. The results indicate that most individual variables have limited explanatory power, consistent with previous findings that coral bleaching is driven by complex and interacting processes rather than any single factor.

The estimated coefficients were −0.06 for ClimSST, 2.02 for SSTA, 0.70 for reef depth, and 0.0000167 for distance to shore, with an intercept of 20.23. The near-zero coefficient on ClimSST suggests that average background temperature alone does not strongly influence bleaching once other factors are accounted for, which aligns with the understanding that bleaching is primarily triggered by thermal anomalies rather than mean conditions. In contrast, SSTA exhibits the largest positive association with bleaching, indicating that short-term temperature spikes contribute to increased bleaching, although substantial variation across reef sites remains unexplained.

The effects of reef depth and distance to shore are small and weak, suggesting that these spatial characteristics do not systematically predict bleaching in this dataset. The overall model fit is modest, with a mean squared error of approximately 312.5, indicating considerable unexplained variability.

This outcome is expected given the influence of cumulative heat exposure, biological adaptation, and local reef-scale conditions that are not fully captured by simple linear predictors. Overall, the results highlight the limitations of single-variable linear models in explaining coral bleaching and underscore the need for more comprehensive measures of thermal stress and local environmental processes.

Discussion:

The results of this study fit well with what is already known about coral bleaching: it's mainly driven by cumulative thermal stress rather than single environmental factors. Even though

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our initial graphs showed weak links between bleaching and things like depth, distance to shore, or long-term background temperature, this doesn't conflict with coral reef ecology. It just shows that these factors matter in context, not as direct drivers. The scatterplots suggest that local environmental conditions can only do so much. Depth and turbidity might reduce sunlight or slightly change temperature exposure, but bleaching still happens across a wide range of habitats. This means local factors can influence how severe bleaching is, but they usually can't stop it, especially when the ocean warms on a large scale. Some of the variation we see in bleaching may also come from differences in how surveys are done and the way bleaching is recorded in bins, which adds extra noise to the data and partly explains the high residuals in our models.

Our results also highlight the bigger picture: global climate pressures are key. Many studies have shown that cumulative heat metrics like Degree Heating Weeks (DHW) and Thermal Stress Anomalies (TSA) are far better predictors of bleaching than static environmental features. Bleaching is really a response to sustained heat over time rather than just background conditions. Overall, the findings make an important point for reef management: local conservation efforts alone aren't enough to offset rising global temperatures. Protecting deeper reefs, improving water quality, or reducing coastal stressors can help, but they don't remove the heat stress thresholds that trigger widespread bleaching. As corals are pushed closer to their physiological limits, reducing global warming is crucial for keeping reef ecosystems alive.

Conclusion

This study confirms that thermal stress is the main driver of coral bleaching, while factors like depth, distance to shore, and background temperature play a secondary, modifying role. The weak correlations in the data show that local conditions can't explain bleaching on their own; it's the cumulative heat exposure over time that really matters. Even where site-specific conditions may reduce bleaching severity, they cannot remove the fundamental vulnerability caused by rising temperatures.

For reef conservation, this has a clear implication: local actions are helpful but not sufficient. Measures like reducing pollution, improving water quality, and protecting deeper habitats can increase resilience, but they can't replace global climate action. The long-term survival of coral reefs depends on controlling greenhouse gas emissions and stabilizing ocean temperatures.

Looking ahead, future research should consider more biological and ecological factors, such as species mix, symbiont diversity, past exposure, and recovery ability. Combining these with detailed thermal stress data could help explain why some reefs survive extreme conditions and guide strategies to protect the remaining coral refuges.

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