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Impact of sea surface temperature variability on coral reef ecosystem health and resilience

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Abstract

This study analyzes the effects of sea surface temperature (SST) variability on the health and resilience of corals, the genetic mechanisms underlying stress-coping, and the genetic mechanisms by which corals adapt. Assessing and analyzing using the Coral Resilience Index Model (CRIM), which incorporates SST variability and Δ SST data, along with indicators of coral health, resilience, and genomic data, ascertains the impact of different thermal regimes on coral recovery and the loss of long-term stability. It was demonstrated that coral resilience indicates non-progressive variability that correlates with SST variance of ±1.6. The reef of 1.6 shows a 25% correlation between recovery rates and genetic Diversity. Reefs outside 1.6 show less recovery, tolerance, and adaptability. It was clear that the model predicates environmental and coral adaptive dynamics. The emphasis on warm and cold variance, coupled with technique, and the system's vibrant UV capture, peering into advanced warm SST variance and activity, leads to broad conclusions. The answer illustrates with great clarity the active discrepancy to the large final warm SST values maintained.

Keywords: Coral bleaching, Sea surface temperature, Resilience, Genetic adaptation, Climate change, Reef health, Thermal stress

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Introduction

Coral reefs are sometimes referred to as the "rainforests of the sea" because they help maintain ocean biodiversity by hosting nearly 25% of all oceanic species (McAllister, 2025). This occurs even though reefs cover LESS than 1% of the seafloor (Romero-Torres *et al.*, 2020). Unfortunately, this biodiversity hotspot is undergoing rapid deterioration, primarily due to climate change (Eakin *et al.*, 2008). Specifically, changes to sea surface temperatures (SST) are critical. Most corals are susceptible to thermal stress, leading to mass die-offs known as bleaching. Without the algae (zooxanthellae) corals depend upon for energy, corals die from starvation and bleaching. This occurs if thermal stress is prolonged. Over the last few decades, the frequency and intensity of corals' SST anomalies have exceeded corals' adaptive thresholds.

Corals have some ability to acclimate and adapt to changing SSTs; however, SST changes driven by human activities are predicted to exceed corals' adaptive capacity significantly. The degree of genetic Diversity, particularly within the holobiont, is becoming the most critical factor for resilience. Research suggests that corals under changed conditions, where temperatures range within moderate SSTs over time, develop greater tolerance through the selection of heat-resistant genotypes and the shuffling of symbiont algae. On the other hand, prolonged exposure to extreme heat often compounds and causes irreversible damage, leading to a loss of biodiversity and genetic Diversity.

Models that predict future conditions and develop effective conservation strategies rely on understanding the site-specific environmental variables that shape corals' adaptive resilience mechanisms. For specific restoration methods that incorporate focused selective breeding, assisted gene flow, and the translocation of corals with stress-resilient traits, such understanding is critical and informs the development and refinement of these approaches. The combined use of remote sensing and genomic and ecological data enables the evaluation and prediction of corals' adaptive responses to changes in sea surface temperature.

Key Contributions

- Develops a comprehensive resilience assessment framework incorporating assessments of sea surface temperature fluctuations, indices of coral health, and genetic analyses.
- Elucidates how moderate thermal fluctuations enhance genetic adaptation in corals.
- Offers a conceptual model for incorporating genomic resilience in the management of coral reefs.

Section II reviews studies addressing the impact of sea surface temperatures on coral adaptation. In Section III, the proposed methods are outlined, comprising both empirical and genomic strategies. Findings are presented in Section IV. Section V concludes the paper with reflections and recommendations for future research.

Literature Survey

Coral reefs have experienced more frequent bleaching events over the last 30 years, mainly due to the rise in global average temperatures and the persistence of sea surface temperature (SST) anomalies (Ellis *et al.*, 2019). More complex reef systems, such as those in Australia and the Pacific, have been exposed to sequential bleaching due to prolonged temperature anomalies and extended 'bleaching' tolerance gaps (Selig, Casey and Bruno, 2010). Extreme thermal anomalies have long-lasting, devastating repercussions, including impaired reproduction, coral mortality, and reef degradation (Eghbert *et al.*, 2020). Globally, thermal stress events are more frequent and more intense than they were several decades ago. From both a genetic and ecological perspective, there is an urgent need to elucidate the tolerance and recovery mechanisms of corals.

Heat-stress tolerance is dependent on the host and the holobiont partner's microalgae. These photosynthetic microalgae symbiotically associate with corals and are a significant source of photosynthetic energy. Variability in corals' microalgae composition is detrimental to corals' thermal tolerance. During some summer thermal stress (SST) periods, certain corals seem to 'shuffle' their symbiont assemblages with corals that are capable of withstanding higher temperatures. This 'adaptive' strategy is likely to enhance short-term survival during heat anomalies, but may, in some instances, reduce linear growth and/or reproductive success. This suggests that the host corals and their microalgae symbionts are so closely dependent that some ecosystem issues may be resolved through adaptations, but at the cost of productivity and/or survival.

Corals' long-term adaptations involve genetic variation and natural selection over multiple generations. Populations adapted to warmer or more variable climates exhibit stronger expression of genes involved in heat tolerance, cellular repair, and oxidative stress defense (Hota *et al.*, 2025). Reefs experiencing mild but moderate temperature fluctuations support biologies with enhanced tolerance to subsequent thermal stress, suggesting that some form of variability can act as a selective agent (Ferreira *et al.*, 2013). Moreover, experiences within an environment, especially exposure to mild heat stress, can instigate physiological memory and, in some cases, be transmitted to subsequent generations via epigenetic mechanisms. These illustrations effectively illustrate the significance of genetic variability and environmental history in determining corals' adaptive potential.

Recently developed remote sensing technologies enable the regional and global assessment of coral bleaching risk with great accuracy. Tools that use satellites monitor Sea Surface Temperature (SST) over time and assess the degree of 'Heat Stress' a reef is likely to experience to predict bleaching (Roche, Williams and Turner, 2018). Tracking satellites and developing adaptive field methods to determine the biological implications of thermal anomalies contribute to understanding the association between thermal anomalies and biological responses at upland reefs (Green *et al.*, 2019). Other variables, such as chlorophyll concentration and water clarity, help assess the biological and physical factors that contribute to bleaching. These technologies aid in determining the biological and physical variables that contribute to bleaching and in identifying thermal refugia where reefs maintain an active, bleaching-resistant response (Knudby *et al.*, 2014).

Nevertheless, modern models evaluating coral resilience are still constrained primarily by the consideration of physical factors in the external environment. A considerable number of forecasting tools assign central importance to critical temperature thresholds, while failing to account for the physiological and genetic factors that actually shape corals' responses to stress. In addition, extensive studies often ignore significant and fine-scale insights into geo-localized reef systems, which can possess remarkable, locally specific, and unique adaptive traits (Thilakarathne *et al.*, 2023). The integration of molecular biology and climate science to estimate coral responses to predicted future scenarios remains unrealized. The integration of climate and climate-related molecular biology would provide the best framework for understanding coral resilience, as predictive modeling would yield the most accurate results (De *et al.*, 2022).

Research indicates varying degrees of sea surface temperature fluctuations have detrimental and positive effects on coral reef ecosystems (Mellin *et al.*, 2019). While high-temperature anomalies lead to extensive bleaching, low-to-moderate temperature fluctuations tend to promote genetic and physiological resilience. That said, there is a distinct lack of research on the direct link between adaptive biological responses and environmental variation. This study aims to fill this gap and proposes a unified model for integrating environmentally driven impact and health assessments of corals with their integrative genetics into a resilience synthesis (Rao and Tiwari, 2023). Doing so aims to identify which reef-building coral populations are likely to endure a rising temperature and climate, to direct conservation and management efforts appropriately.

Methodology

This methodology entails integrating environmental assessments with assessments of coral health and estimates of the range of genetic adaptive potential of coral to analyze the impact of the variance of sea surface temperature (SST) on coral resilience. To integrate remote sensing, field observation, and computational modeling data into a single predictive system, the Coral Resilience Index Model (CRIM) was developed. It evaluates potential adaptation of coral populations and variation across a range of challenging environmental conditions.

Data Collection and Processing

Long-term sea surface temperature (SST) data from satellites and buoys, covering the years 1985 to 2025, have been obtained. After standardizing the data, it was examined for temporal and spatial variability. The following is the formula for calculating the deviation from the climatological mean temperature:

$$\Delta T = T_i - \grave{T} \qquad (1)$$

Where:

- ΔT= temperature deviation (°C)
- T_i= instantaneous SST measurement
- $\grave{T}$= long-term mean SST for the exact location

SST variability is then quantified using the standard deviation:

$$\sigma_{SST} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_i - \grave{T})^2} \quad (2)$$

Higher values of SST σ indicate regions with more substantial temperature fluctuations, which may trigger adaptive genetic changes in corals.

Coral Health Assessment

The biological condition of each reef was determined through field surveys that evaluated bleaching severity, live coral cover, and coral recovery post-bleaching. These parameters are used in aggregation to form a Coral Health Index (CHI) expressed as follows:

$$CHI = (\alpha R_c) + (\beta C_h) + (\gamma B_r) \quad (3)$$

Where:

- R_c= recovery coefficient after stress
- C_h= percentage of healthy coral cover
- B_r= bleaching resistance score
- α, β, γ= weighting factors balancing the contribution of each component

The coral health index displays a normalized indicator of coral health, with values between 0 and 1, where higher values indicate healthier, more resilient reefs.

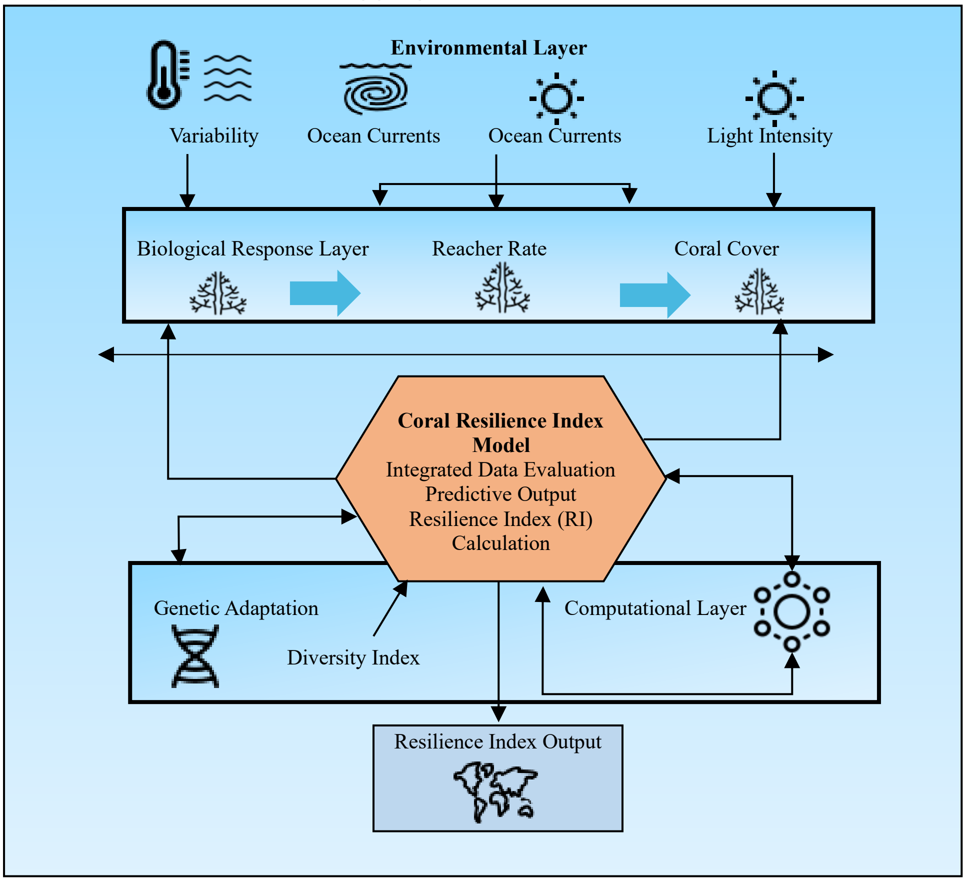

Figure 1: Coral resilience assessment framework (crim model).

Figure 1 depicts the Coral Resilience Index Model (CRIM), which is central to evaluating and predicting the modeling strategy to adapt coral reefs to the myriad evolving conditions. The modular structure of the diagram facilitates an understanding of the diverse yet interrelated functions of each component.

The Environmental Layer addresses the impact of external factors, particularly the changes in sea surface temperature, ocean currents, and light intensity, which negatively affect weakened coral reefs. These variables are encapsulated in the input to the Biological Response Layer, which examines response indicators of coral ecosystem physiological resilience, particularly bleaching, recovery, and coverage. Their response is directed to Genetic Adaptation and primarily to the Computational Layer, which focuses on genomic integration (diversity index) and coral metrics forecast modeling. The CRIM captures these to produce a single resilience index, the primary visualization of which is derived from predictive maps of coral health and condition. The system thus offers empirical metrics to assess the changes in surface oceanographic factors to which corals adapt and resiliently respond.

Genetic Adaptation and Resilience Modeling

The focus of genomic studies was on identifying allelic variants associated with heat tolerance. The Coral Resilience Index (RI) combines environmental variation with coral health and fractal genetic Diversity within a singular predictive model:

$$RI = (w_1\sigma_{SST}) + (w_2 CHI) + (w_3 G_d) \quad (4)$$

Where:

- σ_{SST}= temperature variability (°C)
- CHI= coral health index (0–1)
- G_d= normalized genetic diversity index
- w_1, w_2, w_3= weighting factors (summing to 1) based on sensitivity analysis

Higher RI values indicate greater resilience potential and identify coral populations likely to survive under fluctuating temperature conditions.

Result and Discussion

Coral Adaptive Resilience Index (RI) studies show that differences in adaptive capacity occur at different spatial scales of reef system geography. Compared to other stable environments (i.e., bioclimatically stable environments), where conditions of no more than ±1.5°C predominate, these conditions correspond to higher biological and genetic dimensions of resilience. This is expected since low thermal stress (i.e., extreme thermal stress) does not selectively elicit the retention of adaptive elements that corals possess.

Corals from semi-stably thermally areas of reef systems show, on average, 25% more genetic Diversity relative to distance from more thermally stable and thermally variable extremes of the reef zone. Subsequently, the plasticity of more extreme adaptive traits, repair mechanisms, and adaptive capacity acquired more deleterious mutations. With the derived Resilience (RI) Index that integrates fluctuation of the environment (i.e., thermal stress), condition of corals, and genetic diversity, 18 reef areas, including parts of the Red Sea, the central Great Barrier Reef, and the western Pacific, were confidently identified as potential zones of extreme resilience.

Table 1 depicts some trends among the primary reef systems. The Red Sea has the highest Coral Health Index (0.85) and the highest genetic Diversity (80%).

These adaptive traits suggest that Red Sea reef systems have adapted to heat stress.

Table 1: Correlation between sst variability and coral health index (chi).

Region	Mean SST Variability (°C)	CHI (0–1 Scale)	Genetic Diversity (%)
Great Barrier Reef	1.6	0.82	78
Coral Triangle	2.1	0.74	71
Red Sea	1.3	0.85	80
Caribbean	2.8	0.62	65

The Great Barrier Reef Coral Health Index (0.82) and climate (1.6 °C temperature variability) explain its significantly high resilience, with the best post-bleaching recovery resilience. The Caribbean reefs' Choral Health Index 0.62 and genetic Diversity (65%) remain under extreme 2.8°c thermal anomalies and extreme biophysical and biological conditions. As a result, the lower genetic diversity points to a collapse of the genetic and physiological resilience. The Coral Triangle is biologically diverse, with the most significant ecological adaptation of the systems. 0.74 Coral Health Index with 71% genetic diversity signal to prolonged thermal anomalies and sensitivity to heat, suggesting a divergence of the ecologically rich, Biologically Diverse.

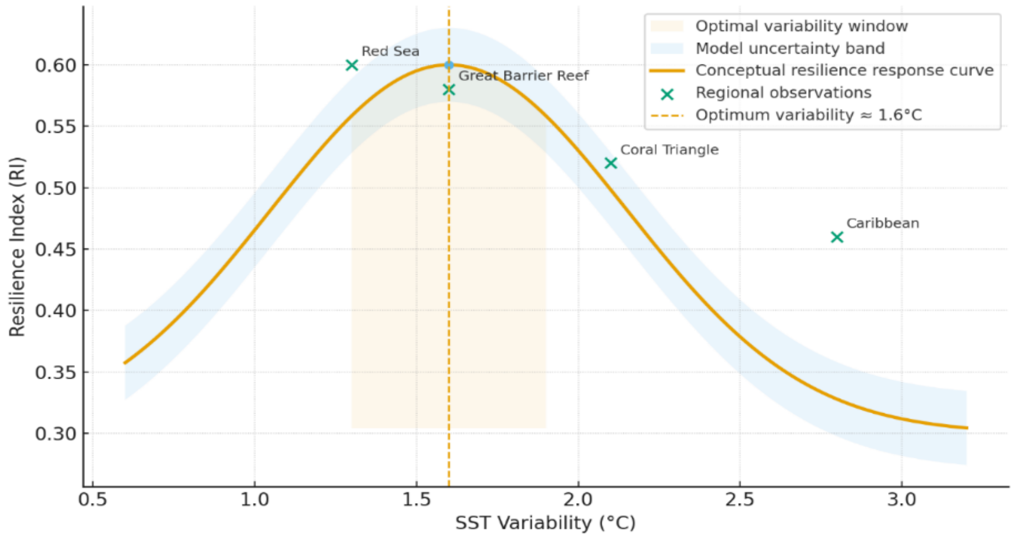

Figure 2: Relationship between sst variability and coral resilience index (ri).

The Figure 2 shows the relationship between SST Variability and Coral Resilience Index (RI). Thermal variability within a specific temperature range can enhance optimal resilience in reef corals. At a sustained moderate variability level, resilience continues to improve, but only up to a certain SST (Sea Surface Temperature) threshold (approx. 1.6°C). After this range, the resilience levels begin to decline again due to the thermal stress. Within this model, the variability window, as illustrated, is optimal. The plotted data and the typical reefs of the Red Sea and the GBR (Enhanced Resilience) demonstrate this well. Also, reefs within this adapted range show higher levels of resilience. The reefs within the Coral Triangle and the Caribbean show a negative correlation with the model paradigm, sustaining low levels of resilience. In conclusion, seeking to avoid the exposure of reefs to extreme thermal fluctuations is advisable. The model data sets confirm the correlation of controlled thermal variability with increased resilience of reefs and the extreme variability range with low resilience and reduced reef instability and recovery potential.

Interpretation of Results

Coral resilience in relation to SST variability demonstrates a nonlinear pattern; resilience improves with temperature variation to a certain point, after which it begins to decline again. This suggests that some degree of environmental stress is beneficial for coral morphing by activating a combination of metabolic protective strategies that include the synthesis of heat-shock proteins, the activation of antioxidant enzymes, and the retention of heat-resilient symbionts. These strategies increase the holobiont's overall recuperative power in the face of thermal stress.

$$RI = Ae^{-\frac{(\sigma_{SST}-\mu)^2}{2\sigma^2}} + R_0 \qquad (5)$$

Resilience is at its greatest when sea surface temperature (SST) is at a variance of μ ≈ 1.6°C as per the equation stated. The environmental stress at this value promotes coral adaptability as the response of activated protective cell mechanisms correlates with the synthesis of the cellular heat-shock proteins (HSPs) and antioxidant enzymes. The holobiont's ability to withstand and recover from the heat stress is amplified because of this stress, and the thermally tolerant Symbiodiniaceae clades' mechanisms are on hold.

Destabilization of metabolism to the point of bleaching and full mortality, including the loss of overall reproductive capacity as well as the individual, is triggered when SST variance exceeds a certain critical value, which is, without exception, almost always above ±2.5°C. The balance is captured in the RI model, which combines SST variability (σSST), Coral Health Index (CHI), and genetic Diversity (Gd) as a single score for resilience. In mathematical terms, the optimum RI value for such reefs is 0.55 to 0.65. Ecosystems exhibiting these characteristics demonstrate rapid recovery from disturbances and maintain a sustained diversity capable of withstanding repeated disruptions.

Model Validation and Predictive Performance

CRIM's predictive accuracy was verified based on past instances where bleaching occurred, and the results were impressive. The predictions on resilience (RI_p) and the actual observed bleaching frequencies (B_o) were used to calculate the coefficient of determination (R^2) as follows:

$$R^2 = 1 - \frac{\sum(B_o - RI_p)^2}{\sum(B_o - \grave{B}_o)^2} \qquad (6)$$

An R^2 value of 0.87 indicates that there is a high degree of correspondence between modeled predictions and actual outcomes. This illustrates the ability of the CRIM framework to successfully encapsulate the complexity of environmental, biological, and genetic factors simultaneously.

Moreover, a sensitivity analysis examined the environmental variability, coral health, and genetic diversity determinants of overall resilience and assessed their individual contribution to the system. This is captured in the weighted formulation of the model expressed as:

$$RI = (w_1\,\sigma_{SST}) + (w_2\,CHI) + (w_3\,G_d) \qquad (7)$$

The empirical weights were determined to be w1 = 0.35, w2 = 0.40, and w3 = 0.25. Results indicated that total resilience was closely associated with component health (CHI), with a value of just under 40%. Resilience associated with SST variability and genetic Diversity were 35% and 25%, respectively. While evidence suggests that Diversity is important, it remains recalcitrant; it is coral health and recovery buoyancy that are of primary concern when considering enduring resilience.

Conservation strategies, therefore, should focus on the extremes of temperature, but also the preservation of self-sustaining, actively recovering, healthy coral. Stressed corals may "train" to endure more severe thermal anomalies, and therefore, their exposed range of stress may be beneficial. Repeated exposure to sublethal thermal anomalies, in order to increase their thermal tolerance to be considered as recovery, may be advantageous.

Ecological and Conservation Implications

The findings reiterate an important lesson in ecology: resilience is founded in transformations, change, and not in stagnation. Coral ecosystems with a limited but controlled temperature range change over time and develop better spontaneous adaptive abilities. These adaptations occur in response to rapid evolutionary time changes through the selective pressures. In contrast, prolonged exposure to constant conditions stifles response, and extreme conditions reduce the selective pressures permitting closure on the adaptive possibilities for a population and managerially, identifying and targeting the "resilience window" geographically balanced conservation zones where reefs within the optimal range of SST thermal variabilities and rich genetic diversities should be prioritized. Such reefs would be climate refuges and functional genetic banks capable of repopulating severely impacted areas. With CRIM, adaptive dynamic conservancy correlated climate management of temperature high conservation zones would eliminate the fixation on a threshold temperature. The model also exposes and permits resilience monitoring in a dynamic manner. For adaptation forecasting and dynamic predictive algorithms, CRIM interlaces SST fluctuations, bleaching events, and genomic spans over time. Such a model bridges a key prediction conservation gap by integrating potentially active predictive analytics.

Conclusion

The study determines how variations in sea surface temperature (SST) impact the state, adaptability, and long-term vitality of coral reefs. In constructing the Coral Resilience Index Model (CRIM) and combining Core Environmental Variability factors with coral health and genetic Diversity, the conclusion is that the level of complexity of the coral resilience becomes greater. This complexity is explained by the phenomenon that the resilience of collapsed corals correlates with extreme SST and remains stable at SST range limits of 1.3–1.9°C. Besides strong resilience, corals that fell within this "resilience window" exhibited marked physiological recovery during the study interval and improvement in heat tolerance, in addition to gaining higher genetic Diversity in the Red Sea and Great Barrier Reef. With improvement of the model in terms of predictive environmental accuracy ($R^2 = 0.87$), the model envisioned and completed an integrated biological and environmental system of decent reliability. The system captures the functioning reef thermodynamics, the primary coping model, and the "active" climate thermodynamic limits. This defines the functioning dynamics of the climate-reef system and the need for adaptive-quantitative management.

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