Thermal Stress Monitoring for Coral Reef Conservation: Multivariate Analysis of the Brazilian Coast

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ABSTRACT

Coral reefs, high-biodiversity ecosystems, are critically threatened by rising water temperatures, the main trigger for coral bleaching. This study aimed to assess thermal risk in two Brazilian reef regions, the Baía de Todos-os-Santos (BTS) and the EPA (environmental protection area) Costa dos Corais, using the NOAA-provided Degree Heating Weeks (DHW) metric. The methodology employed thermal stress metrics on remote sensing data and high-resolution in situ buoy measurements, standardizing the DHW calculation to ensure comparability between sources. Results showed that buoy data are crucial, capturing thermal variations and short-duration extreme events often missed by satellite estimates. Interannual analysis for the BTS (2020–2025) identified that 2024 recorded the highest DHW peak (above 12), a maximum alert level consistent with mass mortality observed in the Northeast during the El Niño event. The study concludes that combining satellite monitoring with the local precision of buoys is essential to optimize conservation strategies and bleaching prediction in a changing climate scenario.

KEYWORDS: Coral Bleaching; Degree Heating Weeks; Ocean-Monitoring

RESUMO

Os recifes de coral, ecossistemas de elevada biodiversidade, estão criticamente ameaçados pelo aumento da temperatura da água, principal fator desencadeador do branqueamento de corais. Este estudo teve como objetivo avaliar o risco térmico em duas regiões recifais brasileiras, a Baía de Todos-os-Santos (BTS) e a Área de Proteção Ambiental (APA) Costa dos Corais, utilizando a métrica Degree Heating Weeks (DHW) fornecida pela NOAA. A metodologia empregou métricas de estresse térmico aplicadas a dados de sensoriamento remoto e a medições in situ de alta resolução obtidas por boias, padronizando o cálculo do DHW para garantir a comparabilidade entre as fontes. Os resultados mostraram que os dados das boias são fundamentais, pois permitem captar variações térmicas e eventos extremos de curta duração frequentemente não detectados pelas estimativas de satélite. A análise interanual para a BTS (2020–2025) identificou que 2024 apresentou o maior pico de DHW (acima de 12), correspondente a um nível máximo de alerta, consistente com a mortalidade em massa observada no Nordeste durante o evento El Niño. O estudo conclui que a combinação do monitoramento por satélite com a precisão local das boias é essencial para otimizar as estratégias de conservação e a previsão do branqueamento em um cenário de mudanças climáticas.

PALAVRAS-CHAVE: Branqueamento de corais; Degree Heating Weeks; Monitoramento oceânico.

1 INTRODUCTION

Recognized as one of the most biodiverse ecosystems on the planet, coral reefs are distributed across more than 100 countries and territories. These structures, which occupy less than 1% of the ocean floor, support approximately 25% of all marine species **[1-2]**. This notable concentration of life makes them one of the most valuable and ecologically significant natural environments on Earth. Furthermore, they ensure coastal protection, well-being, food, and economic stability for hundreds of millions of people living in coastal regions, including less-developed countries, economies in transition, and small island states **[1-5]**.

Despite this enormous relevance, reefs are extremely fragile ecosystems, and their vulnerability is directly linked to the biological functioning of the corals themselves **[5]**. The maintenance of the entire system depends on the symbiotic relationship between the coral and its zooxanthellae algae (photosynthetic dinoflagellates), constituting a nutrient exchange system in which each organism offers direct benefits to the other **[6-7]**. The algae, through photosynthesis, provide the coral with essential organic compounds—carbohydrates, proteins, lipids, vitamins, and other particulate and dissolved products—which sustain a large part of the host's nutrition and energy. In turn, the coral provides the algae with a protected environment within its tissues, as well as inorganic nutrients derived from its feeding and metabolism, such as inorganic carbon, nitrogen, and phosphorus in dissolved forms. In this manner, the coral guarantees the algae stability and chemical resources, while the algae supply the coral with most of its metabolic energy, maintaining the symbiosis that allows both to exist **[6]**.

This tight dependence makes the reef highly sensitive to environmental changes: any disturbance that affects the symbiosis, such as increased temperature, pollution, or acidification, can compromise the coral's life and, consequently, the integrity of the entire ecosystem. The increase in water temperature is considered the main trigger for instability in the coral-algae relationship, directly affecting the physiological functioning of this system **[4-7]**. When exposed to thermal stress, Symbiodinium symbionts begin to exhibit metabolic dysfunctions that lead to the release of toxic compounds. In response, the coral expels the algal cells and loses the associated pigments, resulting in the loss of color—a phenomenon known as coral bleaching. This bleaching is a deleterious response, frequently associated with reduced growth and increased mortality. Although other factors may contribute, such as variations in salinity and light [8], elevated temperature remains the central trigger of the process, making it the principal parameter to be monitored in assessing the risk of bleaching **[7-13].**

In this context, this study utilizes the Degree Heating Weeks (DHW) metric **[5]**, provided by the National Oceanic and Atmospheric Administration (NOAA), to estimate the risk of coral bleaching occurrence, following parameters already consolidated in the literature **[5,14]**. These parameters include the Averaged Monthly Mean (AMM), which acts as a safety limit based on historical thermal tolerance, and the HotSpot, which represents thermal anomalies above this limit. The DHW is calculated by accumulating these anomalies over a 12-week period, providing a measure of the intensity and duration of thermal stress.

Therefore, the central objective of this work is to perform a comparative analysis between in situ temperature data collected by oceanographic buoys and remote sensing estimates provided by NOAA satellites. By applying the DHW metric to both datasets for the regions of Baía de Todos-os-Santos and Costa dos Corais, we aim to evaluate the discrepancies between the methods and assess the potential of local monitoring to detect thermal anomalies that global satellite products might underestimate or miss, thus contributing to a more robust early warning system for coral bleaching.

2 METHODOLOGY

The data used in this study were obtained from two main sources: the NOAA Coral Reef Watch (CRW), responsible for global coral reef monitoring, and SimCosta, which provides in situ oceanographic data in CSV format. The NOAA data were extracted from the Coral Reef Watch 5 km Product, an operational product based on a satellite constellation including Suomi-NPP, NOAA-20, the AVHRR series, and MODIS/Aqua, managed by the NOAA STAR (Center for Satellite Applications and Research) system **[14-16].** The buoy data, in turn, were obtained through SimCosta, publicly accessible and provided by Brazilian environmental monitoring institutions **[17].**

The present work employs metrics consolidated in the literature to evaluate the risk of coral bleaching based on thermal changes in the marine environment. Four central metrics were used: SST (Sea Surface Temperature) (1), AMM (Average Monthly Mean) (2), HotSpot (HS), and Degree Heating Weeks (DHW) (3). The SST represents the sea surface temperature and is available for both buoy and satellite data. The AMM corresponds to the maximum monthly average temperature for each locality. To obtain it, the daily average of all days of each month is initially calculated; subsequently, the month with the highest average is identified, thus defining the AMM.

$$\overline{SST}_{month} = \frac{1}{N}\sum_{j=1}^{N} SST_j \quad \textbf{(1)}$$

$$AMM = max(\overline{SST}_{month}) \quad \textbf{(2)}$$

$$DWH(t) = \frac{1}{7}\sum_{i=t-84}^{t} max(HS(i), 0) \quad \textbf{(3)}$$

From the daily SST, the HotSpot is calculated, defined as the difference between the SST and the AMM. When the SST exceeds the AMM, a thermal anomaly (HS) is considered to have occurred.

$$HS(t) = SST(t) - AMM \quad \textbf{(4)}$$

The DHW quantifies the accumulation of these anomalies over a period of approximately three months (84 days): the total sum of positive HotSpots is calculated, and subsequently, the cumulative value is divided by the corresponding number of weeks. The classification of the risk follows the standard NOAA table 1, where values of DHW between 0–1 indicate an observation state; between 1–4, an alert state; between 4–8, the possibility of bleaching; and values greater than 8 suggest severe bleaching.

Table 1 - Illustrating NOAA DHW alert levels

Stress Level	**Definition**
No Stress	HotSpot ≤ 0
Bleaching Watch	0 < HotSpot < 1
Bleaching Warning	1 ≤ HotSpot & 0 < DHW < 4
Bleaching Alert Level 1	1 ≤ HotSpot & 4 ≤ DHW < 8
Bleaching Alert Level 2	1 ≤ HotSpot & 8 ≤ DHW

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To ensure methodological consistency between the different data sources, the same procedure used by NOAA was adopted. In the CRW 5 km Product, the reference climatology is defined from the 90th percentile of the historical SST satellite series, a criterion that also determines the AMM used in the analyses **[18-19]**. Consequently, the 90th percentile was applied to the SST series from the buoys, so that the definition of thermal anomalies and thresholds was equivalent between in situ measurements and remote estimates. This standardization is essential to avoid methodological biases and ensure direct comparability between the two data sources.

Before the definitive application of the metrics, it was necessary to validate the implementation of the DHW calculation. For this purpose, the NOAA dataset corresponding to the Baía de Todos-os-Santos (BTS) region was used, comparing the DHW calculated in this study with the official values provided by NOAA for the same area and period. The analysis was performed using historical data from 2020 to 2025. The resulting curves showed excellent agreement, evidenced by a small RMSE and maximum absolute difference between the series (values presented in the Results Section), demonstrating that the method reproduces adequately the official NOAA calculation.

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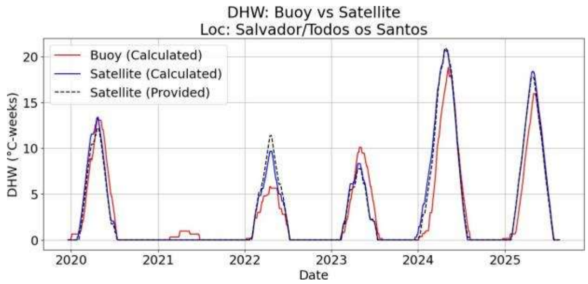
Figure 1 - Graph comparing the DHW calculated in the study versus the official NOAA DHW for the BTS region, 2020-2025.



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After validation, analyses with buoy data were initiated. The two selected regions were the Baía de Todos-os-Santos, monitored by a buoy installed in Salvador (12.98953330º S, 38.5418º W), and the EPA Costa dos Corais, whose in situ data come from the buoy located in Tamandaré, Pernambuco (8.774167º S, 35.083611º W). For the BTS, the available time series spans the period from 2020 to 2025, allowing for robust interannual analyses. For the Costa dos Corais, the availability of buoy data restricted the analysis to the year 2025, which limited long-term comparisons but still allowed for seasonal investigation and contrasted with satellite estimates.

The application of the SST, HotSpot, and DHW metrics to both regions made it possible to investigate the influence of temperature—the main variable associated with the onset of coral bleaching—and directly compare the differences between data acquisition methods. The obtained results, including time series, discrepancies between buoy and satellite, and error metrics (RMSE and maximum absolute difference), are presented in the following section.

3 RESULTS

To ensure the reliability of the monitoring system proposed in this study, a rigorous statistical validation was performed before analyzing the specific regional scenarios. This step is fundamental to confirm that the implementation of the Degree Heating Weeks (DHW) calculation algorithm reproduces the official standards with high fidelity. For this purpose, two main statistical metrics were employed to quantify the discrepancies between the datasets: the Root Mean Square Error (RMSE)(5) and the Maximum Absolute Error (MAE)(6).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(y_{calc,i} - y_{ref,i})^2} \quad \textbf{(5)}$$

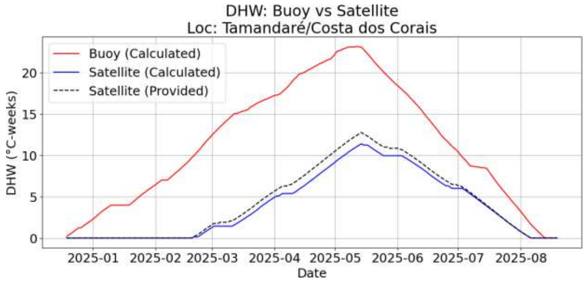
$$MAE = max(|y_{calc,i} - y_{ref,i}|) \quad \textbf{(6)}$$

The RMSE represents the quadratic mean of the differences between the values predicted by the model and the observed reference values. Because it squares the errors before averaging them, the RMSE is a metric particularly sensitive to large deviations, serving as an excellent indicator of the method's average precision over time. In contrast, the MAE measures the absolute magnitude of the largest single discrepancy found in the entire time series, representing the "worst-case scenario" of the model. Analyzing these two metrics in conjunction is essential in this context: a low RMSE combined with a controlled MAE confirms that the calculated curves not only follow the general trend of the official data but also do not present isolated catastrophic errors that could trigger false bleaching alerts.

The first analysis focused on validating the DHW algorithm over an extensive period, ranging from December 19, 2019, to August 19, 2025 by Figure 1. By comparing the calculated DHW (developed in this study) against the official NOAA DHW, an RMSE of 0.46 °C·week was obtained. This value is considered extremely low, especially when analyzed within the scale of bleaching risk, where the first alert level only begins at 4.0 DHW. An average error of less than 0.5 indicates that the calculation method and the definition of the climatological baseline (Average Monthly Mean - AMM) are in good agreement with international standards. Furthermore, the MAE between the calculated DHW and the official NOAA DHW for this period was 1.74 °C·week. This indicates that, even at the point of greatest divergence over nearly six years of data, the difference was less than 2 DHW units, ensuring that the risk category (Table 1 Warning vs. Alert Level 1) would remain consistent in the vast majority of cases.

A similar analysis was also conducted to the data of Costa dos Corais, for the recent period, from December 19, 2024, to August 19, 2025 (Figure 2). The RMSE between the calculated DHW and the official NOAA DHW was found to be 0.69°C·week. This result indicates a high degree of precision in reproducing the official stress metrics, as an average deviation of less than 0.7 DHW units is negligible for risk categorization (where the first alert level begins at 4.0). Reinforcing this consistency, the MAE between the calculated DHW and the official NOAA DHW was 1.37 °C·week, demonstrating that even peak discrepancies were minimal in this window. These results statistically prove that the calculated curves are well-matched to the standard NOAA product, confirming that the proposed method is robust enough to support the subsequent comparative analysis between in situ and remote sensors presented below.

Figure 2 - Graph comparing the DHW calculated in the study versus the official NOAA DHW for the Costa dos Corais region, 2025



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Following this validation, two regions with installed buoys were analyzed: the Baía de Todos-os-Santos (BTS), monitored by a buoy located in Salvador (BA), and the Costa dos Corais, whose reference buoy is located in Tamandaré (PE). Although oceanographic records exist in other parts of the Northeast, the initial efforts were concentrated on these two localities due to the greater availability and continuity of the time series, in addition to the expressive ecological relevance of these areas, which host reefs of great extent and biodiversity.

An essential methodological difference between the regions needed to be considered. The BTS has a relatively smaller and more homogeneous territorial area, which means that the temperature recorded by the buoy represents the thermal conditions of the region as a whole with greater fidelity. In contrast, the Costa dos Corais constitutes one of the largest continuous reef stretches on the planet, extending for over 120 km between Alagoas and Pernambuco **[20]**; thus, the buoy installed in Tamandaré reflects only the local thermal conditions of that specific portion of the system. The satellite, on the other hand, provides spatial estimates that represent the entire extent of the reef area. This difference in spatial scale explains why the discrepancy between the buoy and satellite curves is more pronounced in the Costa dos Corais than in the Baía de Todos-os-Santos.

For each of the regions, time series of daily temperature (Figures 3 and 4) and the DHW metric were generated (Figure 1 and 2), comparing the temperatures obtained by the buoys with those derived from satellite estimates. In both localities, it was observed that buoy data exhibit greater variability, with sharper peaks and drops, as they directly record rapid thermal fluctuations induced by winds, tides, coastal upwelling, or other short-scale phenomena.Satellite estimates undergo stages of filtering and spatial interpolation: atmospheric corrections, removal of cloud-contaminated pixels and radiometric adjustments. These steps make the satellite-derived series more continuous and smoothed.

Figure 3 - Graph comparing the daily temperature given by the buoy in the study versus the official NOAA satellite for the BTS region, 2020-2025.

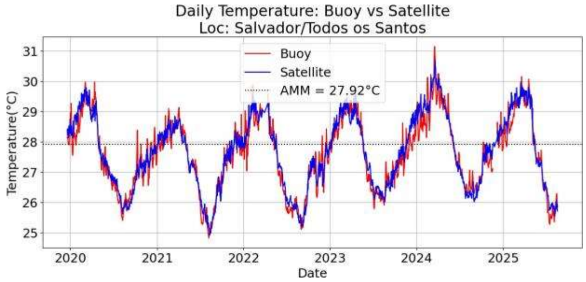

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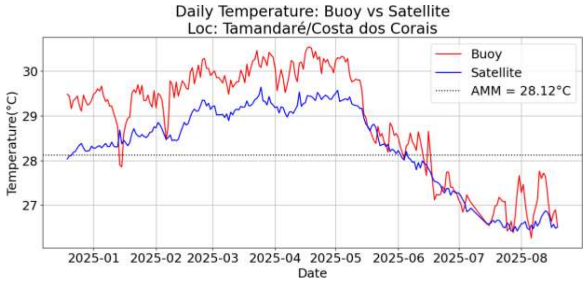
Figure 4 - Graph comparing the daily temperature given by the buoy in the study versus the official NOAA satellite for the Costa dos Corais region, 2025.



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This distinction between methods of data acquisition is also reflected in the DHW calculation, which, although a cumulative and relatively robust metric, can still be sensitive to short-duration thermal anomalies when they exceed the minimum limit of 1°C above the AMM. In the Baía de Todos-os-Santos, for example, five events of elevated DHW were identified between 2020 and 2025 (Figure 1) using satellite data. In 2021, however, a peak was recorded only by the buoy, absent in the satellite data, indicating that *in situ*

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measurements are capable of detecting thermal anomalies with greater precision and less variability. This behavior was also observed in the daily temperature, where the buoy series more clearly highlights short anomalies.

Another relevant point is the year 2024, in which the BTS presented the highest DHW value of the entire analyzed series, exceeding 12. This level falls into the maximum alert category and is strongly associated, according to the literature, with events of mass reef mortality. This result is consistent with the report released by the Coral Vivo program **[21]**, which indicated that 2024 presented the highest mortality recorded since 2019, attributed to intense oceanic heatwaves exacerbated by the El Niño event.

In the case of the Costa dos Corais, the analysis was mainly limited by data availability, concentrated in the year 2025 (Figure 2). Still, it was possible to identify that the temperature peak occurs between May and June, a pattern similar to that observed in the Baía de Todos-os-Santos, reinforcing the existence of a characteristic seasonality in the Brazilian Northeast for the occurrence of high DHW values. As previously discussed, the discrepancy between the values calculated by the buoy and the satellite is greater in this region, both due to the more extensive spatial scale and the buoy's sensitivity to local conditions.

5 CONCLUSION

Climate change has significantly affected the survival of coral reefs, primarily due to rising water temperatures, recognized as the main trigger for coral bleaching. This study highlights the relevance of using buoy data in thermal risk analysis. While satellite imagery offers wide spatial coverage, continuity, and standardization, fundamental for mapping global warming trends and providing continuous operational surveillance of reefs worldwide, buoys provide complementary measurements with a more sensitive representation of local environmental conditions.

This allows for the identification of thermal stress episodes and an understanding of the micro-environmental dynamics that directly affect corals. These high-resolution data are particularly valuable for specific actions, such as issuing early warnings, planning emergency responses during bleaching events, evaluating the effectiveness of management interventions (such as coral transplantation or restoration measures), and supporting conservation decisions in priority areas. The combination of these two approaches proves fundamental for improving monitoring accuracy and guiding more effective conservation strategies.

The present work opted to employ DHW as it is the most internationally widespread metric and utilizes the primary parameter associated with coral mortality: the accumulation of stress events associated with elevated temperatures. The application of this metric with buoy data revealed important peaks of thermal stress, including events not detected by satellites, evidencing the potential of these in situ measurements to complement global monitoring.

Furthermore, this study presents a novel analysis for the Brazilian Northeast, highlighting seasonal patterns and the importance of expanding the oceanic monitoring infrastructure in the region. The results reinforce the need to develop more integrated approaches sensitive to environmental particularities, while pointing towards future improvements, such as the incorporation of new parameters and the use of technological tools, including a real-time API-based system, already planned in the development of this work, to assist researchers and conservationists in decision-making.

It is important to note, however, that despite its consolidated international adoption, the DHW metric may not adequately represent all environmental realities, as it uses global parameters for ecosystems that respond differently to thermal stress. The study by Qin et al. (2023)**[5]**, for example, observed bleaching occurrences with DHW values close to 2.5, suggesting that regional thresholds might be more appropriate. Similarly, Panja et al. (2024)**[8]** demonstrated, through machine learning techniques, that other variables, such as salinity, pH, and dissolved CO_2, contribute to bleaching risk, revealing that the coral condition is multifactorial and cannot be reduced exclusively to temperature.

Thus, it is concluded that the integration of buoy and satellite monitoring, combined with the judicious use of consolidated metrics like DHW and the joint analysis of other environmental parameters, constitutes a robust approach for bleaching risk assessment in the current scenario. Thus, the results evidence the urgency of expanding and updating monitoring methodologies to capture with greater precision the magnitude and speed of changes imposed by global warming, strengthening the capacity for response and protection of coral reefs.

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