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Note

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Impact of Thermal Bleaching Events on the Non-scleractinian Reef Inhabitants of the Lakshadweep Atolls

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Abstract The Lakshadweep Islands, renowned for their highly biodiverse and pristine reef ecosystems, face increasing stress from climate change, notably rising sea surface temperatures (SST), leading to recurrent bleaching events. In 2024, the Lakshadweep Islands experienced mass coral bleaching when the SST peaked to 32.2°C and Degree Heating Weeks (DHW) reached an unprecedented 9.2°C-weeks, the highest ever recorded for the Lakshadweep Islands. Concurrently, several non-scleractinians, such as *Radianthus magnifica* (Ritteri anemone) and *Tridacna maxima* (Small giant clam), experienced complete bleaching, while *Heliopora coerulea* (Blue coral) and *Anemonia* cf. *majano* (Carpet anemone) exhibited 60% and 55% bleaching, respectively. In contrast, during another comparatively less intense bleaching event that occurred in 2025, characterised by SST above the bleaching threshold but DHW <4°C-weeks, bleaching was evident only in *Heliopora coerulea.* This study indicates that DHW >4°C-weeks can induce widespread bleaching in non-scleractinians similar to scleractinians, and the distinct responses and bleaching thresholds of the diverse non-scleractinians to varying bleaching intensities.

Keywords Coral bleaching, Sessile organisms, Lakshadweep, *Heliopora coerulea*

Introduction

The Lakshadweep archipelago represents the only atoll reef ecosystem in Indian waters. These biodiverse reefs are among the least explored regions of the Indian Ocean (Mallik 2017). Being in the tropical ocean, these islands are subjected to elevated sea surface temperatures (SST), resulting in recurrent coral bleaching events (Shenoi et al. 1999). Bleaching events are primarily induced by elevated sea surface temperatures (SST) and further intensified by increased solar irradiance, resulting in physiological stress that causes the expulsion of symbiotic zooxanthellae from host tissues (Brown 1997). Most reef-building corals harbor symbiotic zooxanthellae, however, some hard corals, such as *Tubastraea*, lack these symbionts and are therefore classified as azooxanthellate. Zooxanthellae have also been observed in diverse non-scleractinians, such as sea anemones, corallimorphs, octocorals, and mollusks (McClanahan et al. 2009). Their symbiotic relationship with zooxanthellae raises their vulnerability to a wide range of environmental stressors (Baird et al. 2009). Thus, similar to the scleractinians, these organisms are also prone to bleaching during elevated SST. Most bleaching studies have primarily focused on scleractinian corals (McClanahan et al. 2009), as they are the main reef builders in shallow-water ecosystems and are most severely impacted by bleaching events. The impacts of bleaching on other sessile reef organisms harboring zooxanthellae remain poorly documented to date, despite their ecological importance in water purification and habitat provisioning within reef ecosystems.

The 2023 El Niño triggered severe thermal stress in the Lakshadweep reef ecosystem, leading to a mass bleaching event in 2024. In this study, we assessed the bleaching susceptibility of four non-scleractinian organisms, such as *Radianthus magnifica* (Ritteri anemone), *Tridacna maxima* (Small giant clam), *Heliopora coerulea* (Blue coral), and *Anemonia* cf. *majano* (Carpet anemone) during the two bleaching events, the high-intensity bleaching event in 2024 and the lower-intensity event in 2025, to evaluate the varied responses of the non-scleractinians to bleaching corresponding to the elevated SST.

Materials and methods

The coral monitoring survey was conducted in two major atolls of the Lakshadweep Islands, Kavaratti and Agatti, as part of a continuous monitoring program of the Lakshadweep reef ecosystem (Fig. 1). The survey sites were selected based on the presence of visible coral patches identified through Google Earth imagery and subsequently confirmed by a preliminary in situ survey. These sites were geo-tagged for consistent future samplings. The initial survey for this study was conducted in May 2024, coinciding with a severe coral bleaching event after the 2023 El Niño. The sites were re-surveyed in May 2025, when a minor bleaching event was observed. The coral community monitoring survey was conducted using the line intercept transect (LIT) method and belt transect method, where three 10 m linear transects were laid at each site, 5 meters apart on the shallow lagoon reef, at depths ranging from 1.5 to 5 meters (English et al. 1997). During both surveys, transects were randomly

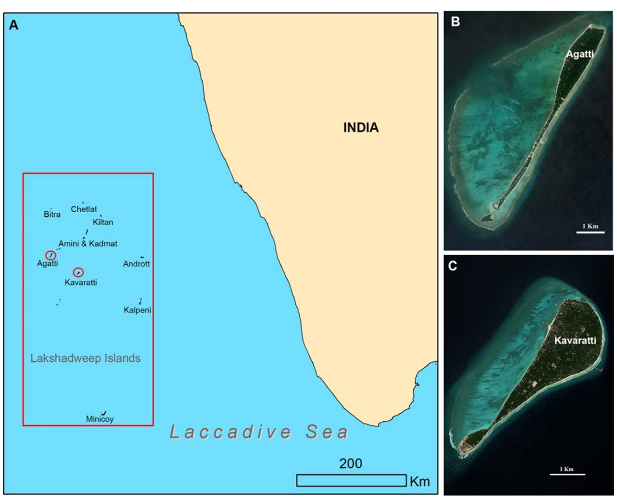

Fig. 1 Map showing the Lakshadweep Islands, with the red circles indicating the study locations (A). Enlarged view of Agatti Island (B) and Kavaratti Island (C).

placed on a fixed coral patch, initially marked with GPS coordinates, to ensure the study was conducted in the same reef patch each time. The individual colonies of *R. magnifica*, *T. maxima*, and *H. coerulea* were counted along the linear transect with a width of 4 m (belt transect of 10 m×4 m). Being a carpet anemone, *A.* cf. *majano* forms a carpet-like assemblage were counting individual colonies of *A.* cf. *majano* becomes difficult; hence, we measured the lengths of *A.* cf. *majano* over the benthic substrate underlying the linear transect (tape). The type of substrate lying directly underneath the tape was recorded. The percent cover of *A.* cf. *majano* along the transect was calculated as the total length occupied by the species divided by the total length of the transect (1000 cm).

Percentage cover = 100 × Total length of transect occupied by *A.* cf. *majano* / Total length of transect.

The prevalence and status of bleaching in non-scleractinian organisms were evaluated and subsequently categorized as healthy with normal pigmentation, partially bleached with visibly lighter pigments than usual, and severely bleached with no pigmentation (Marshall and Baird 2000).

Concurrently with the lagoon sampling, the daily maximum sea surface temperature (SSTmax) and Degree Heating Week (DHW) data for the years 2024 and 2025 were retrieved from the Coral Reef Watch (CRW) website (https://coralreefwatch.noaa.gov/product/vs/gauges/lakshadweep.php). The DWH index measures the intensity and duration of thermal stress experienced by coral reefs (Strong et al. 1997). The SSTmax is the highest SST attained during the specific period. These datasets were compiled and analyzed to generate graphs that demonstrate the temperature trends and DHW variations during the two bleaching years of 2024 and 2025. To assess the significance of variation in the SSTmax distribution between the two survey periods, t-tests were conducted on the SSTmax data from these periods. Before analysis, data normality was evaluated using the D'Agostino and Pearson omnibus normality test (D'Agostino 1986). Based on the results, a Mann-Whitney U test with two-tailed p-values and a 95% confidence level was performed using GraphPad Prism (www.graphpad.com). Furthermore, to examine the variations in the bleaching severity of non-scleractinian organisms between the two sampling periods, a one-way ANOVA was conducted using GraphPad Prism. Before the analysis, D'Agostino and Pearson normality test was done, and based on the results, a non-parametric Kruskal-Wallis test was conducted. However, a homoscedasticity test was not performed, as both *t*-tests and ANOVA are considered relatively robust to modest the differences in variance between groups, particularly when sample sizes are approximately similar, as observed in the present study.

Results and discussion

During the first coral survey conducted in May 2024 in the shallow lagoons of both Kavaratti and Agatti, bleaching was observed in both scleractinian corals and zooxanthellae-bearing non-scleractinians. However, during the re-survey in 2025, only minor bleaching was noticed. Our observations indicate that the SSTmax in the Lakshadweep islands peaked at 32.2°C in early May 2024. The SSTmax continued fluctuating between 32.3 and 30.3°C, often exceeding the bleaching threshold of 31°C during the first week of April to the end of May (Fig. S1). This variation in SSTmax between the two periods was found to be statistically significant ($p = 0.0033$). Moreover, in 2024, it was observed that the DHW values started increasing from the end of April and reached values above 4°C- weeks and continued rising till the end of June with a maximum recorded value of 9.2°C-weeks, the highest DHW ever documented in the region over the last two decades (Fig. S1).

In 2025, though the SSTmax exceeded the bleaching threshold of 31°C (as reported by NOAA Coral Reef Watch) during April and May, reaching a peak of 31.4°C in early May; the DHW values remained below 4°C-weeks. The percentage of fully bleached, partially bleached, and healthy non-scleractinian organisms between the two periods also exhibited significant variation ($p = 0.0137$), indicating the varying impact of the two bleaching events on these organisms. During the bleaching event of 2024, all observed individuals of *R. magnifica* showed 100 % bleaching. Likewise, 84 % of the individuals in *T. maxima* were fully bleached, and 16 % were partially bleached, thus highlighting the severity of the bleaching event. In the case of *H. coerulea*, 65 % of the colonies exhibited complete bleaching, while 30 % remained partially bleached. *A.* cf. *majano* showed the least impact, with 55 % complete bleaching and 33 % partial bleaching (Fig. S2).

All the observed individuals of the sea anemone, *R. magnifica*, exhibited complete bleaching in both the surveyed islands, indicating their high susceptibility to a rise in SST. They appeared completely bright white, unlike their usual tan, brown, or green color. While the tentacles of these species showed complete bleaching, their columns retained their normal magenta color. Though bleached, they showed the inhabitance of the resident anemone fish (Fig. 2A). *R. magnifica* is considered to provide essential habitat for three species of symbiotic fishes, such as *Amphiprion nigripes*, *Amphiprion clarkii*, and *Dascyllus trimaculatus* (Fautin and Allen 1997). Bleaching in these organisms can often lead to a reduction in size and number of anemones, which can have an indirect impact on the reproduction of the anemone fish, thus limiting their abundance (Jones et al. 2008; Saenz-Agudelo et al. 2011). The fish often feel the worst impact, as *A. nigripes* exhibits an evident species specificity with *R. magnifica* (Fautin and Allen 1997). Among the studied non-scleractinians, *R. magnifica* was the most severely impacted during the severe bleaching event in 2024, as all

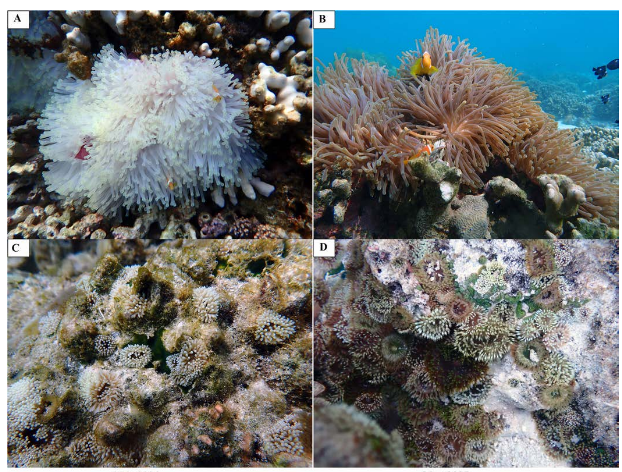

Fig. 2 The bleaching status of non-scleractinian organisms during the two surveys. Bleached *Radianthus magnifica* in May 2024 (A), and healthy *Radianthus magnifica* in May 2025 (B). Bleached and partially bleached *Anemonia* cf. *majano* in May 2024 (C), and healthy *Anemonia* cf. *majano* in May 2025 (D).

observed colonies were completely bleached. However, during the 2025 survey, *R. magnifica* exhibited no signs of bleaching (Fig. 2B). When comparing the SST during both years, the SST had surpassed the bleaching thresholds during both periods. However, there was a distinct variation in the DHW values between the two periods. The DHW of 2024 reached a maximum of 9.2°C weeks, surpassing the 8°C-week threshold, which often corresponds to high bleaching intensity. In 2025, it stayed below 4°C-week, showing a less severe bleaching event. The DHW represents one week of sea surface temperatures (SSTs) exceeding the maximum monthly mean (MMM) climatological value, calculated over a rolling 12-week period. The bleaching thresholds of 4°C-weeks and 8°C-weeks correspond approximately to monthly anomalies of 1°C-month and 2°C-month, respectively, above the MMM (Donner et al. 2005). The more intense bleaching observed in *R. magnifica* in 2024 compared to 2025, even though the SSTmax reached the bleaching threshold value in both years, suggests that the species is particularly vulnerable to prolonged exposure to elevated SSTs rather than short-term increases.

A. cf. *majano*, the carpet sea anemone, usually grows on dead corals and in cracks and crevices within the reef. In Lakshadweep, they are considered invasive and are observed more frequently in dead coral reef habitats (Prakash et al. 2022). During the 2024 survey, among *A.* cf. *majano*, bleaching was more pronounced in individuals directly exposed to sunlight (Fig. 2C) than those occupying shaded microhabitats, such as cracks and crevices. These results indicate that combined light exposure and thermal stress increase bleaching susceptibility in exposed carpet anemones, while shaded individuals experience less stress. Observations by Hoegh-Guldberg (1999) indicated reduced bleaching in corals inhabiting shaded environments under elevated ocean temperatures. Similar effects have been reported in sea anemones, where bleaching responses to thermal stress are further exacerbated by increased light intensity (Hill and Scott 2012), corroborating the shading-induced differences in bleaching observed in *A.* cf. *majano* in the present study. During the 2025 survey, most of the observed individuals of *A.* cf. *majano* remained healthy, while a few exhibited partial bleaching (Fig. 2D).

T. maxima, commonly known as the small giant clams, are marine bivalves widely distributed across the Indo-Pacific coral reef ecosystems. By providing food and habitats for diverse fish and invertebrate species, they contribute immensely to the reef biodiversity (Neo et al. 2019). Similar to corals, giant clams harbor symbiotic zooxanthellae across the outer and inner mantle tissues, foot muscle, hepatopancreas, and ctenidium (Poo et al. 2020). The zooxanthellae are primarily concentrated in the brightly colored outer mantle tissues, where they receive sufficient sunlight to support efficient photosynthesis (Poo et al. 2020). Like corals, the extreme heat stress can evoke bleaching and expulsion of zooxanthellae, causing giant clams to turn white. A previous report documented 83% bleaching in giant clams of the Lakshadweep islands during the 2010 mass bleaching event, when the maximum SST reached 31.8 °C and DHW peaked at 6.7 °C-weeks (Vinoth et al. 2012). However, the 2024 mass bleaching event, characterized by a maximum SST of 32.2 °C and DHW of 9.2 °C-weeks, was more severe than the 2010 event, causing higher bleaching intensity in giant clams, with all observed individuals affected (Fig. 3A). Of all observed individuals, 84% were fully bleached, and the remaining 16% exhibited partial bleaching (Fig. S2). However, in 2025, when thermal stress was relatively low, with

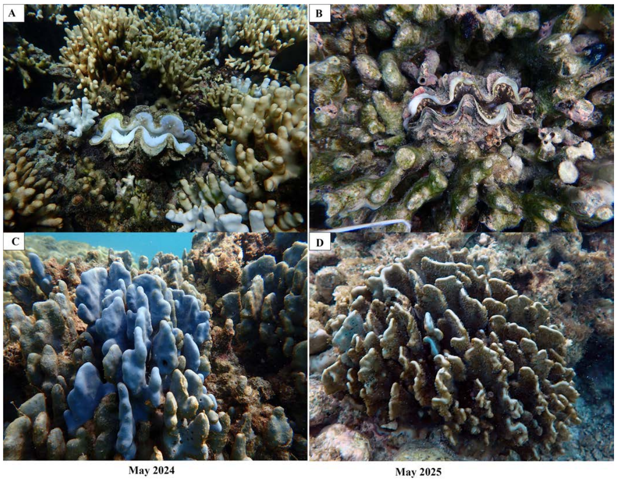

Fig. 3 The bleaching status of non-scleractinian organisms during the two surveys. Bleached *Tridacna maxima* in May 2024 (A), and healthy *Tridacna maxima* in May 2025 (B). Bleached *Heliopora coerulea* in May 2024 (C), and *Heliopora coerulea* with some bleached branches in May 2025 (D).

SSTmax of 31.4°C and DHW values remaining below 4°C-weeks, a marked reduction in bleaching severity was observed. Most giant clams appeared healthy, while a few exhibited partial bleaching (Fig. 3B). These observations indicate that giant clams are particularly vulnerable to severe bleaching events of prolonged duration, especially when DHW values exceed the 4°C-week threshold. In contrast, they can tolerate minor bleaching under less intense thermal stress.

Although not a scleractinian coral, *H. coerulea* plays a vital role as a reef builder in the Indo-Pacific coral reef ecosystems (Colgan 1984). Unlike scleractinian corals, which reveal white skeletons upon bleaching, *H. coerulea* has a naturally blue skeleton that appears bluish rather than white when bleached. An interesting observation of this study was the high bleaching susceptibility of *H. coerulea*. In both surveys, *H. coerulea* showed the highest bleaching severity compared to the other three non-scleractinian taxa. During the more severe bleaching event in 2024, more than 60% of *H. coerulea* colonies showed complete bleaching, whereas a comparatively less intense bleaching event in 2025 caused about 50% bleaching (Fig. S2). This corroborates their higher sensitivity to elevated SST compared to the other three non-scleractinian organisms. Several studies conducted across the Central-Pacific regions, as well as the Indian Ocean, have identified this taxon as bleaching-tolerant (Schuhmacher et al. 2005; Raymundo et al. 2019). Consequently, it has been proposed that *H. coerulea* could replace scleractinian corals as the dominant reef-builders in the future (Courtney et al. 2021). Notably, no previous bleaching studies in Lakshadweep have reported bleaching in the octocoral *H. coerulea*, making this the first documented incidence of bleaching in this species. Several colonies in this region were found to be bleached during both surveys (Fig. 3C, D). A recent study conducted by Szereday et al. (2024) in Peninsular Malaysia also reported severe bleaching susceptibility of *H. coerulea*, further corroborating our finding of their high bleaching susceptibility. However, the specific reason behind their high bleaching vulnerability demands further extensive investigation.

The present study provides a comparative assessment of two successive bleaching events in the Lakshadweep islands, highlighting the responses of zooxanthellate non-scleractinian taxa to thermal stress. The results demonstrate that the intensity and duration of heat exposure, reflected by DHW values, played a decisive role in determining bleaching severity across the studied non-scleractinian species. The 2024 event, characterized by an unprecedented DHW of 9.2°C-weeks, caused extensive bleaching in all the examined non-scleractinians, while the relatively lower thermal stress in 2025, corresponding to DHW $<$4°C-weeks, resulted in comparatively less severe bleaching. The distinct responses of non-scleractinian organisms, particularly *H. coerulea*, to thermal stress during both years indicate a higher thermal susceptibility than previously reported from other regions, contrasting with their known bleaching resistance in many parts of the Indo-Pacific. Further detailed investigations are required to elucidate the factors contributing to the elevated bleaching susceptibility of *H. coerulea* in the Lakshadweep region.

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Compliance/Conflict of interest

The authors have no conflicts of interest to disclose.

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Electronic supplementary material

ESM Figs. S1−S2 can be downloaded from the J-STAGE website: https://doi.org/10.3755/galaxea.G28−1N