THE 4TH GLOBAL CORAL BLEACHING EVENT IN MALAYSIA: INSIGHTS, OUTCOMES, AND PATHS FORWARD

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The 4th global coral bleaching event in Malaysia: insights, outcomes, and paths forward

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Executive summary

- In 2024, a severe coral bleaching event was observed globally, with over 80% of the world's coral reefs exposed to extreme heat stress. This resulted in widespread bleaching and the declaration of the 4th global coral reef bleaching event
- This report synthesizes data collected from four regions across Malaysia, including Peninsular Malaysia and Sabah, to evaluate bleaching incidence and mortality rates
- Following record-breaking heat stress between June and October 2024, 50.7% of corals bleached across survey regions in Peninsular Malaysia and Sabah
- Average coral bleaching mortality was 34.1% but varied considerably across the surveyed regions corresponding to the intensity of heat stress at each survey site
- The northeastern part of Peninsular Malaysia (i.e., Terengganu archipelago) was the most impacted by coral bleaching with average mortality rates of 44.2%, resulting in severe and long-lasting impacts on coral reef health

- Coral taxa with complex growth form exhibited high bleaching mortality, underscoring a critical loss of three-dimensional reef complexity which may jeopardize associated fish habitats and aesthetic reef value relevant for local economies.
- While meaningful action on climate change is necessary to prevent further coral reef loss globally, equally urgent action to eliminate local and regional sources of coral reef degradation is required to facilitate resilience and recovery at island scale
- Research to determine and boost coral resilience will be necessary to restore degraded reef sites
- The ensuing sections detail these findings and propose targeted management and restoration measures.

Coral bleaching in Malaysia

Coral reefs are the most biodiverse marine ecosystems with a global economic value of over a trillion dollars (Roberts et al., 2002; Costanza et al. 2014). Malaysia alone hosts approximately 4,006 km² of coral reef, which supports more than 500 species of hard corals (Huang et al., 2015) and 925 species of reef fish (Chong et al., 2010). These ecosystem support tourism and fisheries industries that contribute billions of Malaysian Ringgit to the national economy (Sukarno et al., 2015). However, Malaysian coral reefs have been facing increasing threats from coastal development, unsustainable fisheries, and tourism (Praveena et al., 2012; Safuan et al., 2022; Bernard et al., 2023). Additionally, the increasing scale and duration of marine heat waves are causing more frequent and intense coral bleaching events across the country (Guest et al., 2012; Szereday et al., 2024).

Coral bleaching is a physiological stress response characterised by the whitening of the corals tissue (Jaap, 1979), which is often triggered by prolonged high heat stress. This whitening results from the breakdown of the symbiotic relationship between the coral host and its symbiotic algae partners (i.e., Symbiodiniaceae), which provides the coral host with most of its energy requirements (Muscatine et al., 1990). This symbiosis is crucial for corals to thrive and co-create the world’s most biodiverse marine ecosystems. Unfortunately, marine heat waves are increasing in intensity, scale, and duration due to man-made warming (Eakin et al., 2019). This warming has resulted in three global coral bleaching events in 1998, 2010, and 2014-2017 (Eakin et al., 2019), and many further regional and localized events have been reported (van Woesik and Kratchowill, 2020). In conjunction with these global events, widespread coral bleaching was reported three times across Malaysia in 1998, 2010, and between 2014 and 2017 (Kushairi, 1999; Guest et al., 2012; Reef Check Malaysia 2014, 2020). However, and importantly, other regional coral bleaching events of high intensity did occur in Malaysia. Between 2019 and 2020, the first consecutive back-to-back bleaching events led to widespread bleaching in northeastern Peninsular Malaysia (Szereday et al., 2024), and substantial bleaching was reported in 2020 in eastern Sabah (Rosedy et al., 2023). Taken together, these isolated regional events that occurred in-between global events reflect a worrisome global pattern of intensive warming and subsequent coral bleaching.

Although the 2010 event was once considered the worst in Malaysia, the 2024 event appears to have set new benchmarks in terms of thermal stress and coral mortality (Tan and Heron, 2011; Guest et al., 2012). However, despite isolated monitoring efforts to detail these bleaching events (Tan and Heron, 2011; Guest et al., 2012), comprehensive data to understand both short- and long-term impacts of widespread coral bleaching are insufficient in Malaysia to understand their ecological outcomes. For example, the extent of coral mortality consequential to the 2010 event is unclear as these data are unavailable for many parts of the country, including northeastern Peninsular Malaysia, Sarawak, and Sabah. As a result, the extent of heat stress resilience across regions and reef environments in Malaysia is significantly understudied and unknown.

Record-breaking heat stress and mass global coral bleaching in 2024

Starting in 2023, sea surface temperatures (SST) in all ocean basins reached unprecedented levels (Cheng et al., 2024). In Malaysia, moderate heat stress and mild coral bleaching were observed in Pulau Tioman and within the Terengganu archipelago by April and May, respectively (Figure 1). Concurrently, record-breaking heat stress and severe mass coral bleaching were unfolding in the Western Atlantic Ocean. For example, the Florida Keys experienced one of the most intense accumulations of heat stress on record (Neely et al., 2024). This extreme warming is a direct result of climate change and was further intensified by the 2023-2024 El Niño Southern Oscillation (ENSO), a natural climate pattern that results in periods of above average ocean temperatures. Previous research linked the combination of ocean warming and ENSO events to the occurrence of mass bleaching events. However, since the 1980s, the geographic scale and intensity of bleaching increased with each major ENSO event (van Hooidonk et al., 2020; Skirving et al., 2019), leading to severe coral mortality and degradation of coral reefs worldwide (Hughes et al., 2018a, 2018b). Therefore, if climate change continues to remain unaddressed, further global coral bleaching events will occur, and the survival of tropical reef ecosystems remains critically endangered.

By April 2024, over 60% of the world's coral reef regions exhibited bleaching, prompting the formal declaration of the fourth global coral bleaching event (Reimer et al., 2024). This global event is continuing as of April 2025. In Malaysia, above normal ocean temperatures persisted throughout the 2023-2024 northeast monsoon season, a period typically marked by colder temperatures and increased storm activity (Moten et al., 2014). As the global marine heatwave further unfolded, temperatures eventually reached record-breaking levels by June 2024 in most regions of the country (Figure 1).

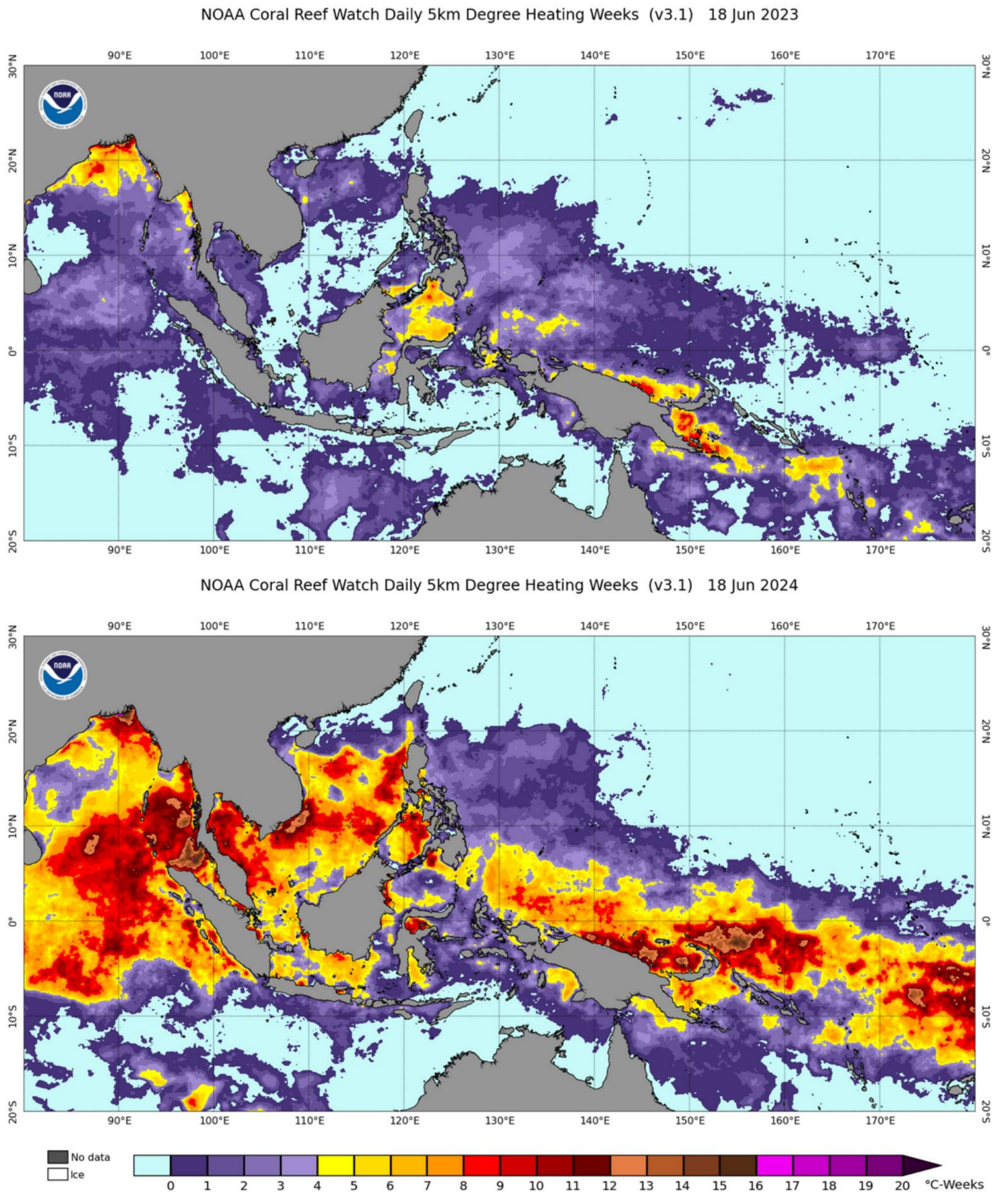

Figure 1. Heat stress across the western Pacific on June 18, 2023 (upper image) and June 18, 2024 (lower image). Both images show the magnitude of heat stress, measured by NOAA Coral Reef Watch in Degree Heating Weeks (°C-weeks).

Mass coral bleaching in 2024 in Malaysia

This report presents the results of individual monitoring efforts carried out by scientists across Malaysia and details the extent of coral bleaching and the short-term outcomes (i.e., 4 months) of the record-breaking 2024 coral bleaching event. Data from belt transects, photo-quadrats, and video transect are analysed to assess bleaching incidence and short-term (i.e., four months) mortality following the peak heat stress period. Monitoring data on coral bleaching incidence and mortality was collected across 24 sites in four Malaysian regions: northeastern Peninsular Malaysia (i.e., the Terengganu Island archipelago), southeastern Peninsular Malaysia (i.e., Pulau Tioman and Pulau Besar), east and west Sabah (Figure 2). In northeastern Peninsular Malaysia and across Sabah, regional heat stress in 2024 was the highest ever recorded (Appendix 1-2), whereas in southeastern Peninsular Malaysia, heat stress reached ecologically significant levels at which mass coral bleaching commonly occurs at severe levels (Appendix 3).

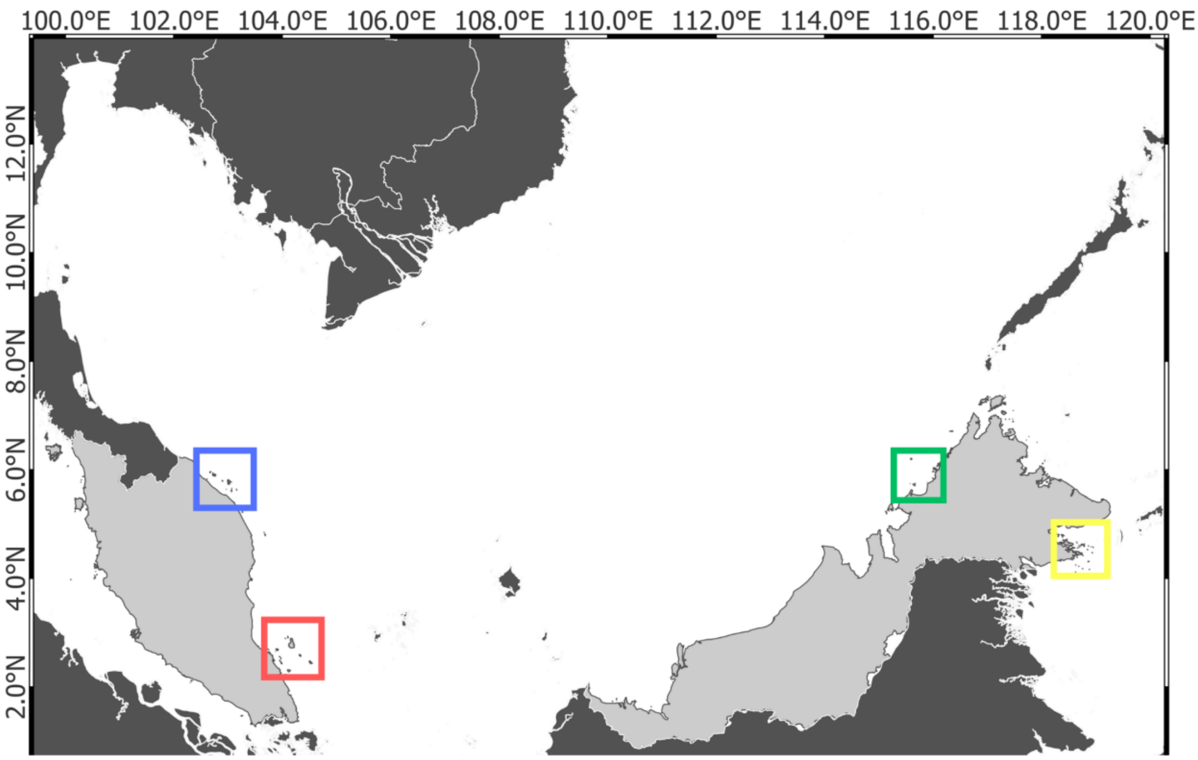

Figure 2. Coral bleaching monitoring locations across Malaysia in 2024. Coral bleaching was monitored within the Terengganu Island archipelago (blue square), in Pulau Tioman and Pulau Besar (red square), in western Sabah near Kota Kinabalu (green square), and eastern Sabah around Pulau Larapan and Pulau Mabul (yellow square).

The intensity of coral bleaching (i.e., the physiological response of corals to heat stress) is not determined by maximum temperatures but rather by the combination of heat stress intensity and duration (Liu et al., 2014). Therefore, heat stress is measured as the accumulation of daily temperatures exceeding the hypothetical long-term temperature threshold (i.e., maximum monthly mean, MMM) by 1 °C and is commonly expressed as Degree Heating Weeks (DHW, °C-weeks) (Wellington et al., 2001). Based on this universal metric, widespread coral bleaching is commonly observed at ≥4 °C-weeks, and ecologically relevant mortality often occurs at ≥8 °C-weeks and above (Eakin et al., 2010; Hughes et al., 2018a). These data were extracted for all survey regions from the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch product (CRW), version 3.1 (Liu et al., 2014), at a 5 km^2 reef scale[1]. These data show that the recorded heat stress in 2024 doubled the previous DHW records in most Malaysian regions (Appendix 1-3). For example, in Pulau Lang Tengah in Terengganu, the previous heat stress record was 5.2 °C-weeks in 2010, compared to 9.9 °C-weeks in 2024. In other words, temperatures were 1 °C above the coral's thresholds for 4.7 weeks longer in 2024 compared to 2010. This increased duration of heat stress represents significant stress for corals and resulted in widespread coral mortality across the surveyed sites in 2024. Importantly, satellite measurements of sea surface temperature have been shown to underestimate actual heat stress levels within Peninsular Malaysia (Guest et al., 2012; Szereday et al., 2024), and experienced heat stress in 2024 was likely even higher than those reported by NOAA CRW (i.e., Figure 1 and 3).

[1] https://coralreefwatch.noaa.gov/satellite/index.php

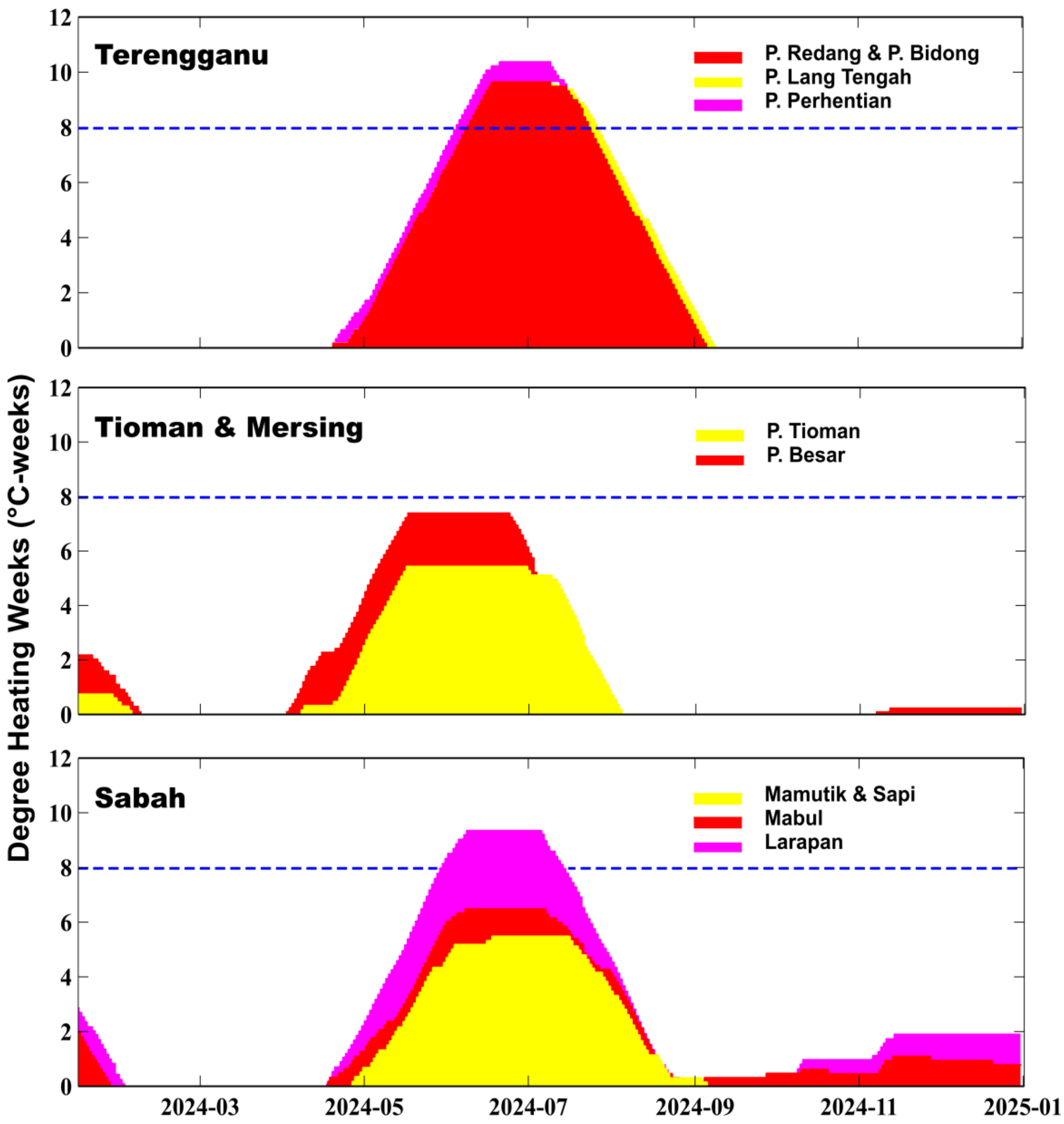

Figure 3. Heat stress across Malaysia in 2024. Accumulated heat stress is expressed in Degree Heating Weeks (°C-weeks, DHW). Data were remotely measured by the National Oceanic and Atmospheric Association (NOAA) Coral Reef Watch (CRW) monitoring program (product version 3.1). Panels are split according to regions: northern Peninsular Malaysia (i.e., Terengganu), southern Peninsular Malaysia (Pulau Tioman and Besar), and east and west Sabah (i.e., Sabah). The blue dotted line shows the putative DHW mortality threshold of 8 °C-weeks at which ecologically relevant mortality occurs.

Coral bleaching in northeastern Peninsular Malaysia

Across the Terengganu archipelago, monitoring efforts were carried out around Pulau Perhentian (four sites), Pulau Rhu (one site), Pulau Lang Tengah (three sites), Pulau Redang (two sites), Pulau Bidong, Pulau Geluk, and Pulau Kapas (one site, respectively). These surveys were more detailed in terms of the number of corals and taxa recorded in comparison to the other three regions (Table 1). A total of 4,890 corals from at least 34 taxa were surveyed across the archipelago. Heat stress in this region was very severe and exceeded the universal threshold at which widespread mortality routinely occurs (Figure 3). The recorded level of heat stress in 2024 was 5 °C-weeks higher than during the previous record year in 2010 (Appendix 1), resulting in bleaching of 25.8-100% of the surveyed population (68.8% on average). Overall, these data demonstrate regional variability in bleaching severity, which is likely the outcome of species-specific bleaching response and micro-environmental factors that alleviate or magnify bleaching at a fine scale (Loya et al., 2001; Oliver and Palumbi, 2011; Fordyce et al., 2019). However, and importantly, methodological differences in survey time and monitoring effort existed, impacting bleaching assessments. For example, to accurately measure mortality rates during a bleaching event, these must be assessed multiple times throughout the bleaching event (Claar and Baum, 2019). Across the northeastern region, this was done only around Pulau Lang Tengah and Pulau Redang. At these locations, permanent belt survey transects and location-marked photographic surveys were repeated multiple times between May and October 2024. Surveys were conducted at shallow (i.e., <6 m depth) and intermediate (<15m) water depths (Table 1). Mortality rates measured in October 2024 ranged between 29.9% and 63.6%, resulting in severe mortality of ecological relevance at both sites (Table 1). In comparison, mortality rates following a mass bleaching event in 2019 in Pulau Lang Tengah were only 2.9% across 46 surveyed coral taxa (1826 colonies) (Szereday et al., 2024). This evident difference in mortality is readily explained by the difference in experienced heat stress during these events (i.e., 1.05 °C-weeks in 2019 vs 9.9 °C-weeks in 2024).

Further north near Pulau Rhu, 57.6% of surveyed colonies (151 colonies, 12 taxa) were recently deceased at the end of July 2024, which is attributed to the magnitude of heat stress in the months prior (Table 1). Photo-transect surveys in August and September at four sites around Pulau Perhentian found 42.4-51.0% recently deceased corals (1095 colonies of 28 taxa surveyed, Table 1), indicative of significant coral bleaching mortality. Moreover, 411 colonies from 18 taxa were surveyed near Pulau Seringgih, and moderate mortality was found regardless of depth (i.e., 26.7% at shallow and 24.9% at deeper reef sections, respectively). Around Pulau

Bidong, where coral bleaching was surveyed using video transects, 22.7% of 353 colonies surveyed (16 taxa total) were found dead, but these corals were surveyed in May, approximately three weeks before the local heat stress peak. Thus, these surveys do not capture the full mortality extent as mortality rates of corals increase as heat stress persists (Hughes et al., 2018a). Mortality rates around Pulau Kapas and Pulau Geluk were not recorded, but bleaching rates (i.e., number of colonies observed bleached) at these locations ranged between 57.8% to 84.7% in May, corresponding to the average bleaching rates observed across Terengganu. Therefore, moderate to severe mortality likely occurred at these sites.

Heat stress induced mortality specifically impacted branching and laminar coral taxa (Table 2), which are important for the structural complexity of coral reefs. This complexity is specifically important for habitat formation to support the abundance of reef fauna and to generate aesthetic value for local tourism economies. For instance, in Pulau Lang Tengah, 79.8% of structurally complex coral taxa suffered mortality (Table 2). In Pulau Redang, 42.5% of branching corals (except table corals) died from heat stress (Table 2). Consequently, the structural complexity of these reefs has degraded and disintegrating dead coral biomass has trickle-down consequences on reef regeneration (Kopecky et al., 2024) by increasing the amount of mobile coral rubble and reducing coral recruitment survival (Viehman et al., 2018). The presence of high coral rubble has been correlated with low live hard coral cover and low diversity on reefs around Pulau Lang Tengah (Bernard et al., 2023). This suggests that the negative long-term impacts of the bleaching event will increase as dead coral biomass breaks down into coral rubble.

Table 1. Percentage of bleached and dead corals following severe heat stress (DHW, °C-weeks) across Malaysia. For each survey location, site names, survey depth ranges, number of taxa and colonies surveyed are shown. PM - Peninsular Malaysia. The locations are ranked by mortality percentage.

Region	Location	Site	Depth (m)	DHW	Mortality (%)	Bleaching (%)	Colonies (n)	Taxa (n)
North PM	P. Redang	Pulau Pinang	3-7	9.6	63.6	100.0	11	3
North PM	P. Rhu	Rhu	2-4	7.5	57.6	-	151	12
North PM	P. Lang Tengah	Pasir Besar	5-12	9.7	56.8	88.7	1126	24
North PM	P. Perhentian	Batu Nisan	4-11	11.0	51.0	12.6	292	16
North PM	P. Perhentian	D.Lagoon	4-10	11.0	49.1	15.4	462	28
North PM	P. Perhentian	Batu Layar	15-16	11.0	46.6	32	103	15
North PM	P. Perhentian	Batu Nisan	8-10	11.0	42.4	10.6	238	16
North PM	P. Lang Tengah	Batu Bulan	5-13	9.7	41.4	87.3	573	31
North PM	P. Redang	Kerengga Besar	3-8	9.6	40.0	90.0	10	7
South PM	P. Tioman	Renggis	5-9	5.4	37.5	37.5	8	4
North PM	P. Lang Tengah	Tanjung Telunjuk	5-13	9.7	29.9	80.7	622	34
West Sabah	Kota Kinabalu	Sapi	5-7	5.5	28.6	64.3	28	9
North PM	P. Perhentian	Seringgih	10-15	11.1	26.7	52.5	202	18
West Sabah	Kota Kinabalu	Mamutik	5-7	5.5	25.9	77.8	27	11
North PM	P. Perhentian	Seringgih	3-4	11.1	24.9	54.9	209	14
North PM	P. Bidong	Pasir Cina	8-9	9.5	22.7	52.7	353	16
East Sabah	Larapan	Point 3	9-12	9.4	15.4	69.2	13	8
East Sabah	P. Mabul	Panglima	9-10	6.5	15.4	26.9	26	11
South PM	P. Tioman	Tekek House Reef	5-7	5.4	11.1	44.4	9	5
East Sabah	Larapan	SMEE 2	8-13	9.4	8.7	4.4	23	12
East Sabah	P. Mabul	Eel Garden	8-10	6.5	4.6	27.3	44	10
South PM	P. Besar	Teluk Buluh	4-6	7.5	0.0	69.2	13	9
South PM	P. Besar	Teluk Kalih	2-5	7.5	0.0	26.3	19	3
North PM	P. Geluk	Beach Front	5-7	9.5	-	83.9	-	20
North PM	P. Kapas	Coral Garden	7-10	7.7	-	57.8	211	18
North PM	P. Kapas	Coral Garden	2-3	7.7	-	84.7	327	15

Coral bleaching in southeastern Peninsular Malaysia

During the past decade, a noticeable difference in heat stress and bleaching severity between the northern and southern parts of the east coast of Peninsular Malaysia started to emerge. In 2010, while reefs in Terengganu experienced only moderate heat stress below the mortality threshold (i.e., DHW ~5 °C-weeks, Appendix 1), reefs in Pulau Tioman experienced heat stress that exceeded the putative mortality threshold of 8 °C-weeks (Appendix 3). Both regions experienced widespread bleaching that year (Tan and Heron, 2011; Guest et al., 2012), but mortality rates were insufficiently recorded. Based on surveys by Reef Check Malaysia, 50% of surveyed hard corals were bleached in 2010, of which ~66% bleached fully. Furthermore, while severe bleaching was reported in the north in Terengganu in 2019 (Szereday et al., 2024), very low or no bleaching was reported in the south around Pulau Tioman and within the Johor archipelago (Reef Check Malaysia, 2019). These observations resulted in speculations that coral reefs in the south are possibly more resilient as in the north (Figure 4). Indeed, during peak heat stress in 2024, bleaching rates in southeastern Peninsular Malaysia were comparatively lower. In Pulau Tioman and Pulau Besar. Here, bleaching rates ranged between 37.5-44.4% and 26.3-69.2%, respectively, while mortality ranged between 11.1% and 37.5% at Pulau Tioman (Table 1), and no mortality occurred around Pulau Besar. Therefore, bleaching and mortality rates were markedly lower compared to the Terengganu archipelago (Table 1). There are several reasons to explain these differences. Firstly, experienced heat stress was substantially lower in the south compared to the north in 2024 (Figure 3), resulting in less and shorter heat stress periods, which did not exceed the putative mortality threshold of 8 °C-weeks (Eakin et al., 2010; Hughes et al., 2018a). It is not uncommon for corals to recover from such heat stress levels (Hughes et al., 2018b; McClanahan et al., 2020), and swift recovery could be further explained by prevailing environmental conditions (e.g., rainfall, cloud cover, currents). Secondly, past heat stress exposure in 2010 may have elevated the heat stress resilience of corals in the southeast to some degree (Thompson and van Woesik, 2009). The high heat stress exposure in 2010 (i.e., 8.4 °C-weeks in 2010 in Pulau Tioman, data based on NOAA CRW) may have pre-acclimated corals to the lower heat stress levels in 2024 (i.e., 5.4 °C-weeks), enabling corals to survive and recover. Heat stress acclimatization has been noted across geographical scales and taxa (Sully et al., 2019). Nonetheless, such theoretical explanation requires scientific validation, and specific heat stress experiments could facilitate the identification of 'hope spots' of high climate resilience within Malaysia (Cinner et al., 2016). Finally, monitoring efforts in the southern part of Peninsular Malaysia documented a much lower number of corals (Table 1), and more locations were surveyed in the north, resulting in less resolute data. Therefore, whether coral reefs in southern Peninsular Malaysia are more resilient than their northern counterparts cannot be concluded based on the 2024 bleaching event or other historical data, as it is unknown whether corals in the south would currently survive the heat stress levels that occurred in the north in 2024. Standardized surveys at equal levels of heat stress would be needed to validate assumptions of higher resilience, whereby standardized ex situ heat stress assays could help resolve differences in thermal tolerance across these regions (Evensen et al., 2022).

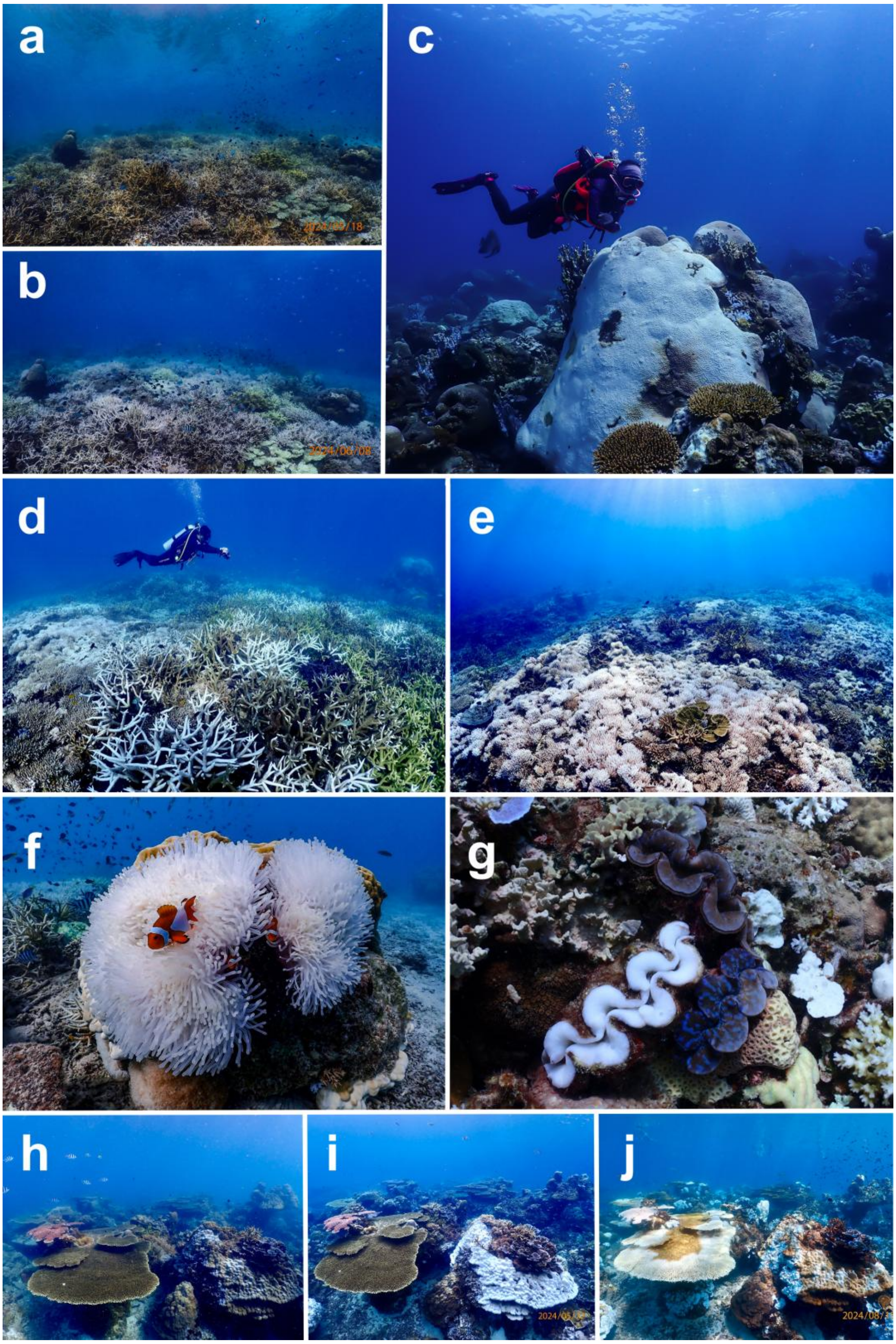

Figure 4. Example images of coral bleaching. Shallow coral reef before bleaching in May 2024 (a) and during peak heat stress in June 2024 (b). SCUBA divers surveying coral bleaching sites in Pulau Lang Tengah, Terengganu (c), and Pulau Pemanggil in Johor (d) early during the bleaching event. Image (d) emphasizes the variability of coral bleaching during moderate heat stress. Images (e-g) show examples of tropical reef taxa that commonly experience bleaching (other than hard corals). Progression of bleaching in Batu Kucing, Pulau Lang Tengah, between

May (h), June (i), and (j) August when widespread mortality started to occur. Photograph credits: a, b, h-j – K.L. Chew; c, f, g – Sebastian Szereday; d-e – Alvin Chelliah.

Coral bleaching in western Sabah

In western Sabah, the 2024 bleaching event was documented along permanent photo-quadrant, repeated at multiple time points during the heat stress event. Two shallow sites (average depth ≤6 m) were surveyed around Pulau Sapi and Pulau Mamutik, respectively, to document the bleaching trajectory of 55 colonies from 11 taxa (Table 1). Despite severe bleaching (i.e., 64.3% and 77.8% in Pulau Sapi and Mamutik, respectively), mortality was moderate. Around Pulau Sapi, 28.6% of surveyed colonies (n=28) died, whereby 70% of branching taxa and 25% of submassive taxa died off following heat stress exposure and bleaching (Table 2). Similarly, branching and digitate taxa were most affected by heat stress induced mortality around Pulau Mamutik (31.3% and 100%, respectively), with 25% of massive taxa dying off due to heat stress (Table 1-2). These bleaching and mortality rates reflect experienced heat stress and correspond with the universal DHW concept. Compared to northeastern Peninsular Malaysia, heat stress was considerably less intense in western Sabah. Taken together, the data suggest that these reefs and coral taxa are highly vulnerable to more intensive heat stress exposure, and the data should not be misinterpreted as signs of heat stress resilience.

Coral bleaching in eastern Sabah

Coral bleaching intensity and outcomes were monitored across two locations in eastern Sabah (Pulau Mabul and Larapan), replicating the survey methods applied in Pulau Redang, Tioman, Besar, Sapi and Mamutik. Survey depth at these sites was kept constant at intermediate depths between 8 to 13 m. Very severe heat stress was recorded around Pulau Larapan at 9.4 °C-weeks, while intensive heat stress of 6.5 °C-weeks below the putative mortality threshold occurred near Pulau Mabul. The low average mortality of 10.0% at Pulau Mabul corresponds well with the observed heat stress magnitude (Table 1), and branching taxa were most impacted (i.e., 40% mortality, Table 2). Similar bleaching outcomes around Pulau Larapan were recorded. Whereas 69.2% of corals bleached, high recovery and moderate mortality of 15.4% were recorded at Point 3, and only 8.7% mortality occurred at the second site (i.e., SMEE 2, Table 1).

Although bleaching rates aligns with heat stress intensity, the low mortality rates are positive outcomes at these heat stress levels. Potential explanations for the low mortality include species-specific heat stress tolerance, absence of tourism at these sites, as well as high turbidity that may reduce compounding environmental stress that magnifies bleaching severity. (i.e., light plus heat stress).

Table 2. Percentage of dead corals following severe heat stress in 2024 categorized by morphology. Relative mortality of corals summarized by colony morphology is shown for survey data recorded in October 2024 at the end of the 2024 heat stress event. Data do not include all coral morphologies.

		Complex morphology				Simple morphology		
Area	**Site name**	**Branching**	**Tabular**	**Digitate**	**Laminar**	**Submassive**	**Massive**	**Encrusting**
Lang Tengah	all sites	80.4	83.3	83.8	36.6	34.8	11.6	20.5
Redang	Kerengga Besar	0.0	0.0	100.0	0.0	0.0	50.0	0.0
Redang	P. Pinang	70.0	0.0	0.0	0.0	0.0	0.0	0.0
Tioman	Renggis	20.0	0.0	0.0	66.7	0.0	0.0	0.0
Tioman	Kg. Tekek	33.3	0.0	0.0	0.0	0.0	0.0	0.0
Mersing	Teluk Buluh	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mersing	Teluk Kalih	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mabul	Panglima Reef	40.0	0.0	0.0	0.0	18.2	0.0	0.0
Mabul	Eel Garden	0.0	0.0	0.0	0.0	9.5	0.0	0.0
Larapan	SMEE 2	0.0	100.0	0.0	20.0	0.0	0.0	0.0
Larapan	Point 3	0.0	0.0	0.0	33.3	0.0	0.0	0.0
K. Kinabalu	Mamutik	31.3	0.0	100.0	0.0	0.0	25.0	0.0
K. Kinabalu	Sapi	70.0	0.0	0.0	0.0	25.0	0.0	0.0

Conclusion and recommendations

The 2024 global coral bleaching event has provided insights into the vulnerability of Malaysian coral reefs to thermal stress and climate change. Concurrent with global coral bleaching, widespread bleaching and corresponding mortality were observed across all regions surveyed in Malaysia. The observed mortality closely mirrored the magnitude and duration of heat stress. Therefore, the combination of extreme and prolonged heat stress led to severe and, in some cases, irreversible loss of corals. The cascading effects on reef structural integrity raise substantial concerns regarding the long-term resilience of these ecosystems, particularly given their critical roles in supporting marine biodiversity and sustaining local economies. Due to the warming that has already occurred, further bleaching events of similar or higher magnitude will impact Malaysian coral reefs. If the current warming trajectory is not halted, 90% of corals reefs will disappear within the coming decades. Beyond severe ecological consequences, several key ecosystems services are at risk if heat stress and bleaching events further escalate, thereby endangering the livelihoods of local communities and reef-based industries. Although climate change cannot be stopped at a regional or local scale, urgent action is required to give Malaysian coral reefs the best possible chance. The following recommendations are put forth to mitigate these outcomes and guide both immediate management actions and long-term research priorities:

1. Eliminate land-based pollution sources such as sewage discharge, waste (domestic and industrial), and agricultural runoff to reduce cumulative stress on coral reef
2. Eliminate sedimentation, siltation, and physical damage due to coastal development projects
3. Improve and increase sustainable tourism practices to avoid direct physical damage to coral reefs
4. Further and more strict enforcement of existing no-take fishing policies to minimise overexploitation and physical damage to coral reef

To improve the management and restoration of coral reefs under climate change, the following research is urgently required:

1. Upscale and improve existing standardized coral bleaching monitoring protocols across all regions to delineate and identify reef sites, species, and colonies more resilient to heat stress
2. Identify mechanisms and drivers of coral resilience to inform coral restoration efforts at the local reef scale.
3. Novel techniques to boost coral resilience must be trialled and implemented to prepare corals for future heat stress above the 2024 levels

To support the managerial and research measures, it is critical to:

1. Revise and update national coral reef action plan (established after the 2010 mass bleaching event) to account for the current state of reef health, the global climate trajectory, and advancements in research to coordinate meaningful action across the country.
2. Increase public and private investment in coral reef management, restoration, and research
3. Increase investment in capacity building to provide opportunities for local researchers
4. Increase funding and resources for co-management of protected areas to further empower local communities

5. Foster collaborations between academic institutions, governmental agencies, NGOs, and local communities to promote an integrated, multisectoral approach to coral reef conservation.

Author contributions

SS, CSY, and AC conceived the study and synthesized the data. SS wrote the original draft. All authors were involved in data collection and management, manuscript editing and review.

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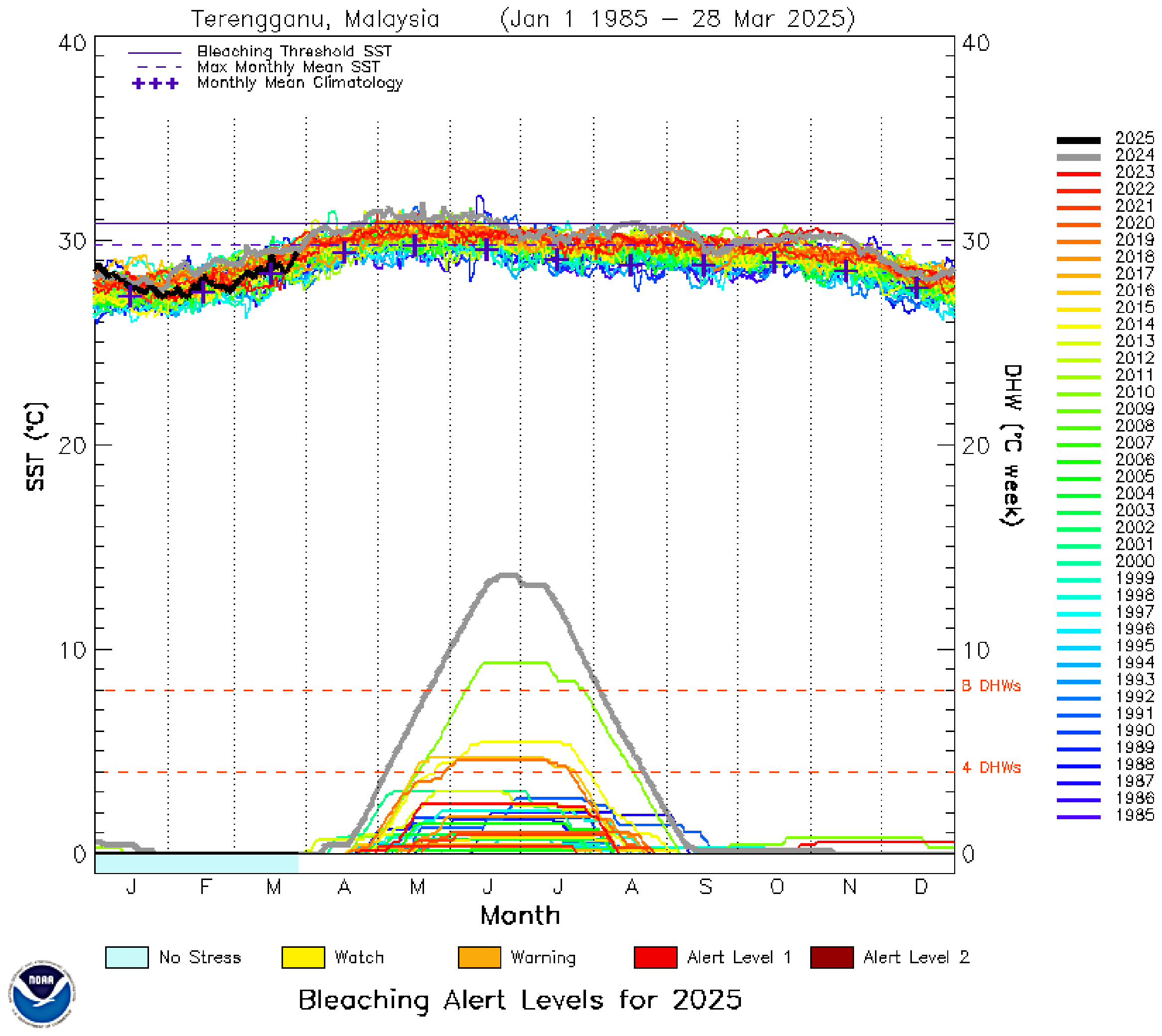
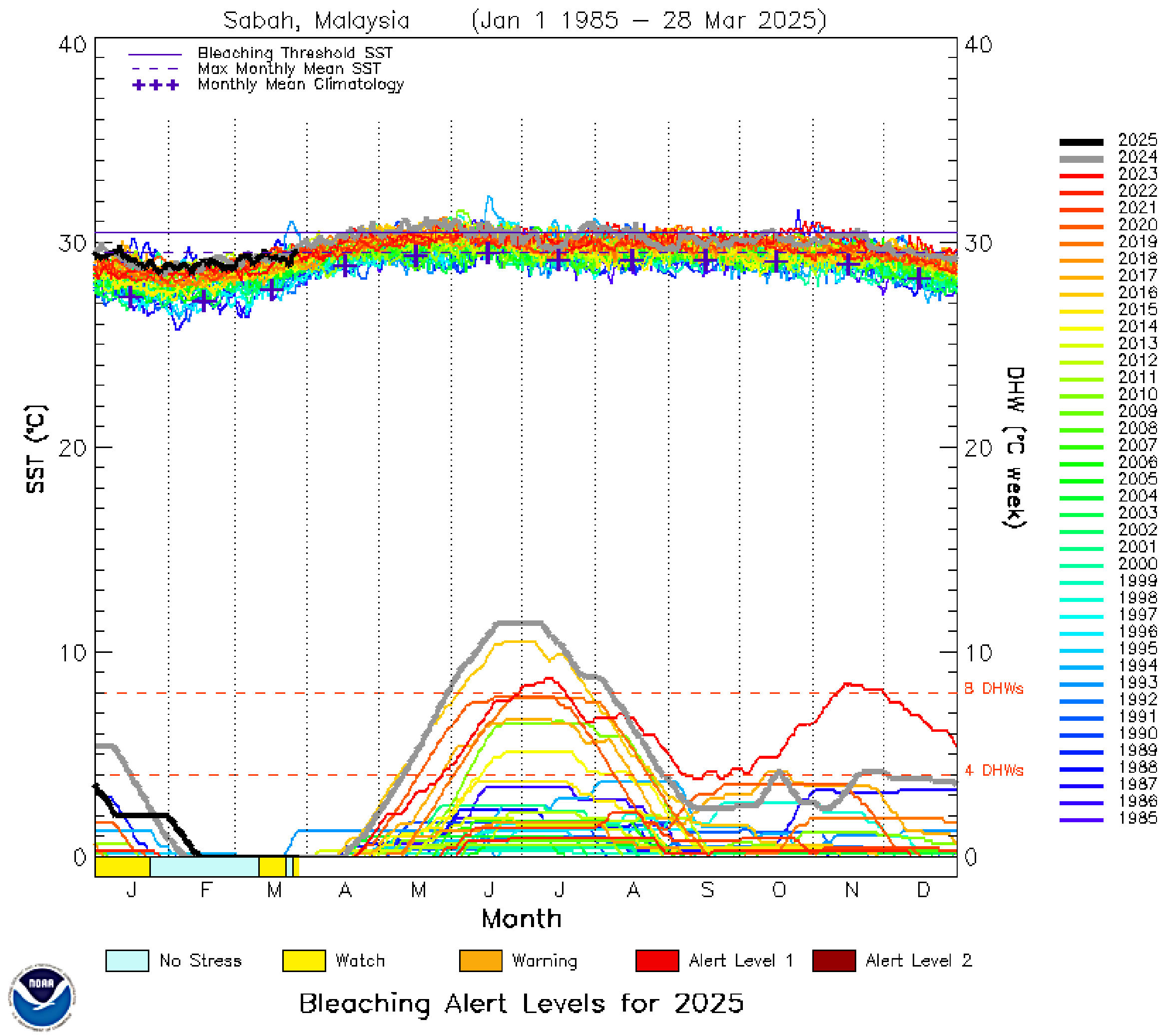
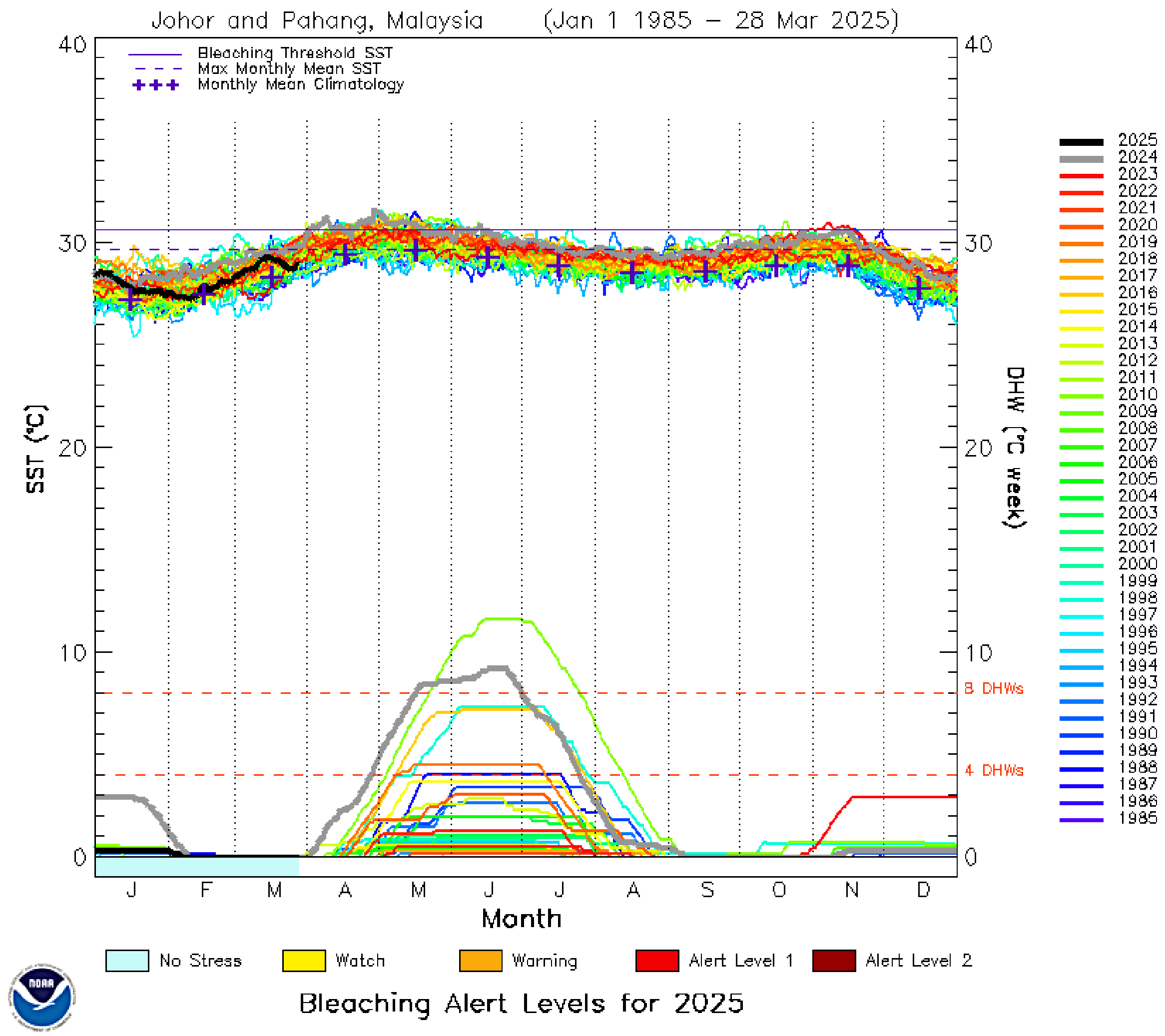
Appendix



Appendix 1. Sea surface temperatures (top) and cumulative heat stress degree heating weeks (bottom) data for Terengganu, collected by NOAA Coral Reef Watch since 1985. Grey lines show the values through the 2024 heat stress events; colored lines show each year's data from 1985-2023. Figure from NOAA Coral Reef Watch.



Appendix 2. Sea surface temperatures (top) and cumulative heat stress degree heating weeks (bottom) data for Sabah, collected by NOAA Coral Reef Watch since 1985. Grey lines show the values through the 2024 heat stress events; coloured lines show each year's data from 1985-2023. Figure from NOAA Coral Reef Watch.



Appendix 3. Sea surface temperatures (top) and cumulative heat stress degree heating weeks (bottom) data for Johor and Pahang, collected by NOAA Coral Reef Watch since 1985. Grey lines show the values through the 2024 heat stress events; coloured lines show each year's data from 1985-2023. Figure from NOAA Coral Reef Watch.