Journal of Sustainability Science and Management
Volume 19 Number 12, December 2024: 192-218
eISSN: 2672-7226

CORAL BLEACHING IN PENINSULAR MALAYSIA: A DECADE OF STUDY

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http://doi.org/10.46754/jssm.2024.12.012
Received: 3 May 2024 *Accepted: 27 August 2024* *Published: 15 December 2024*

Abstract: Globally, coral bleaching events are increasing both in frequency and intensity, and are usually associated with Sea Surface Temperature (SST) anomalies. The objective of this paper is to review coral bleaching trends and its consequences in Peninsular Malaysia's waters over the past decade with the help of scarce government and reef monitoring program reports and published journal papers. Malaysia has experienced two Mass Bleaching Events (MBE) in the past decade—in 2010 (2nd global MBE) and between 2014 and 2017 (3rd global MBE)—it was estimated up to 5% to 6% of corals experienced mortality following each MBE. Branch corals (*Acropora* and *Pocillopora*) were susceptible to higher bleaching and mortality while massive corals (*Fungia*) were more resistant to bleaching. Long-term underwater temperature monitoring (2015-2019) with HOBO loggers across Peninsular Malaysia recorded maximum sea water temperatures below the threshold required to initiate coral bleaching. While the bleaching trend in the past decade has shown that corals in Peninsular Malaysia have largely escaped impacts of MBEs with minimal mortality, increasing ocean warming will ultimately lead to catastrophic MBEs across reefs of Peninsular Malaysia. This will lead to coral community compositions shifting towards more thermally tolerant taxa.

Keywords: Mass bleaching events, sea surface temperature, Coral Triangle, NOAA Coral Reef Watch.

Introduction

Coral reef ecosystems are some of the most vital underwater ecosystems, which encompass half of the world's coastlines (Spalding *et al.*, 2001; Awak *et al.*, 2016), host one-third of all marine fish species (Crabbe, 2008), and provide between US$29.8-375 billion a year in economic goods and services to millions of people via the fishing and tourism industries (Cesar *et al.*, 2013).

Coral reefs are amongst the most sensitive coastal ecosystems to Sea Surface Temperatures (SSTs) changes (Anthony, 2016). Coral bleaching occurs when SSTs exceed the long-term Maximum Monthly Mean (MMM) summer sea temperatures by as little as 1°C (Jokiel & Brown, 2004; Harrison *et al.*, 2018) and remain high for more than 28 days (Vivekanandan *et al.*, 2008). Coral Mass Bleaching Events (MBEs) have been firmly linked to elevated SST (Li & Reidenbach, 2014) caused by global warming and climate change and their associated SST thermal anomalies (Eakin *et al.*, 2018a). Although coral reefs can re-establish themselves to prebleaching state following MBEs, this process can take up to one to two decades (Baker *et al.*, 2009). However, coral bleaching events are increasing both in frequency and intensity (Hughes *et al.*, 2003; Veron *et al.*, 2009) and overwhelming the ability of coral reefs to recover between MBEs (Eakin *et al.*, 2019; Skirving *et al.*, 2019; Thinesh *et al.*, 2019). This consequently is leading to shifts in coral reef community structures to being dominated by cyanobacteria and algae (Frieler *et al.*, 2013).

Remote sensing satellite assessment of SST and thermal stress are increasingly being used for coral bleaching due to the practical difficulty of in situ monitoring of coral reef habitats (i.e., resource intrusive field/ground survey) (Liu *et al.*, 2004; Yamano & Tamura, 2004; Skirving *et* *al.*, 2020). SST data from the National Oceanic and Atmospheric Administration (NOAA) Pathfinder satellite is used because of their good agreement with in situ data from ships and buoys, also because of its large-scale adjustment of satellite biases with respect to in situ data (Reynolds *et al.*, 2007).

NOAA's Pathfinder satellite product computes the extent of thermal stress on coral reefs using the bleaching indices: Bleaching Threshold (BT), Positive SST Anomaly (PA), and Degree Heating Weeks (DHW) (Liu *et al.*, 2004; Heron *et al.*, 2016). Definition and formulas of the different bleaching indices used by NOAA's Coral Reef Watch (CRW) program include:

- Positive SST Anomaly (PA): Daily (elevated) SST - Thermal Threshold (MMM)
- Weekly SST Anomaly: Mean of the "Positive Anomaly" for continuous seven days
- Monthly SST Anomaly: WM (Warmest month) - TT (Thermal Threshold)
- Thermal Threshold (TT): Temperature thresholds in which corals can tolerate SST
- Bleaching Threshold (BT): Above these threshold values, corals begin to stress which in-turn triggers bleaching. BT is defined as TT + 1°C
- Degree Heating Week (DHW) Index: Measures the intensity and duration of thermal stress experienced by coral reefs (i.e., cumulative thermal stress)

A schematic representation of the thermal stress analysis on coral reef ecosystems used by NOAA's CRW program is shown in Figure 1.

The Coral Triangle (CT), which includes Malaysia is experiencing an average warming trend of 0.2°C per decade, as per satellite-derived SST data between 1985 to 2006 (Peñaflor *et al.*, 2009) while also experiencing pronounced SST increases during phases of the El Nino-Southern Oscillation (ENSO) phenomenon (Eakin *et al.*, 2018a; Harrison *et al.*, 2018). This has been particularly evident during the 1997 to 1998, 2010, and 2014 to 2017 ENSO events, which led to widespread occurrences of coral bleaching in the Indo-Pacific region (Oliver *et al.*, 2009; Hughes *et al.*, 2019a). In the Caribbean Islands, a 0.1°C increase in regional SST saw a 35% increase in areas that reported bleaching while mass bleaching events were reported in areas with regional SST increases of 0.2°C and above (Baker *et al.*, 2008). The Indo-Pacific region, which encompasses the Coral Triangle and accommodates ~76% of world's coral species and ~37% of world's reef fish species (Veron *et al.*, 2009), reported a coral cover decline of 1% per year with current SST warming (Bruno & Selig, 2007).

Coral species live within relatively narrow temperature margins and anomalous sea temperatures can lead to bleaching (Sammarco *et al.*, 2006). During the bleaching process, high temperature or irradiance leads to overproduction of oxygen radials (which under normal circumstances would have been removed by the coral symbionts), leading to damage to the cellular machinery of the symbionts or their coral hosts (Lesser, 2006). Eventually, the corals expel their dinoflagellate endosymbionts (also known as "zooxanthellae")—leading to their pale white "bleached" colour, as the calcareous skeleton becomes visible through the coral's transparent tissues (Glynn *et al.*, 2001). The loss of these zooxanthellae leads to an energy deficit of the coral's energy budget (as it is their primary energy source for most reef corals), as well as decelerating calcification in some reef-building corals (Al-Hammady, 2013). Post-bleaching can however eventually lead to zooxanthellae recovery and does not necessarily mean coral mortality (Head *et al.*, 2019).

Numerous factors have been attributed to preventing bleaching or promoting thermal resilience of corals. These factors include: Local upwelling (Riegl *et al.*, 2019) leading to vertical mixing and associated surface cooling, or high turbidity (Morgan *et al.*, 2017), regional winds modulating thermal stress and reducing SSTs (Al Senafi *et al.*, 2015), and repeated bleaching

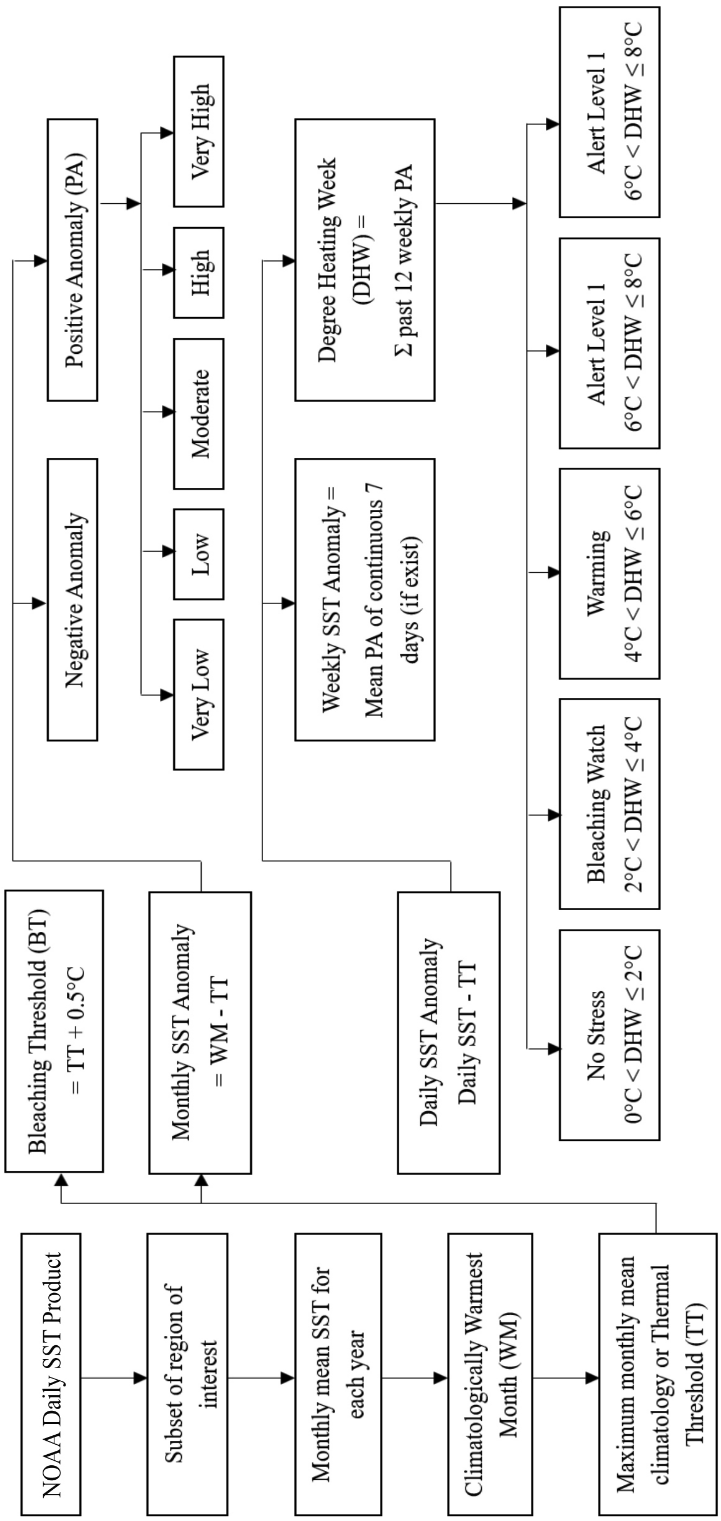

Figure 1: Schematic representation of the thermal stress on the corals used by NOAA's Coral Reef Watch (CRW) program

events inducing bleaching resistance through natural selection of thermally tolerant coral species (Oppen *et al.*, 2009; Eakin *et al.*, 2010), which may lead to changes in coral community composition. Additionally, corals in shallower depths and near the shore have been found to be more susceptible than their counterparts in cooler offshore habitats and deeper depths (Oliver & Palumbi, 2009). Finally, faster-growing corals (e.g., *Acropora* and *Pocillopora*) were found to be more susceptible to bleaching (Marshal & Baird, 2000) versus slower-growing corals; while reefs with higher structural complexity have been shown to have increased bleaching recovery potential (Graham *et al.*, 2015).

Over the past 30 years, bleaching has been reported in virtually every part of the sea that hosts coral reefs (Baker *et al.*, 2008) with MBEs following El Nino-Southern Oscillation (ENSO) events. The 1st global MBE in 1998 saw the destruction of close to 16% of the world's coral reefs (Wilkinson, 2000), followed by a 2nd MBE just a decade later in 2010 (Heron *et al.*, 2016). Finally, a 3rd MBE, associated with the ENSO cycle, spanned a period of 36 months from June 2014 to May 2017, resulting in bleaching events over successive years (Harrison *et al.*, 2018; Head *et al.*, 2019; Hughes *et al.*, 2019a), and included all three phases— positive (El Nino), negative (La Niña), and neutral—of the ENSO-cycle (Blunden & Arndt, 2018; Eakin *et al.*, 2018a). This 3rd global MBE affected close to 75% of the Indo-Pacific's coral reefs between 2015 and 2016 (Hughes *et al.*, 2018a) and more than 70% of the world's corals succumbed to excessive thermal stress and associated bleaching and/or mortality during these bleaching events spanning three years (Eakin *et al.*, 2016).

Despite the large number of government reports, scientific journal papers and reef monitoring programs covering coral bleaching events in this region and the Coral Triangle at large; most of the knowledge disproportionately covers coral bleaching across the Indo-Pacific region with information about coral bleaching in Malaysian waters being scarce. The aim of this article is to review spatial and temporal SST changes over the past decade across Peninsular Malaysia's waters and "sea-truth" them with corresponding in situ data with the emphasis on coral bleaching; as well as reviewing associated long-term changes in coral cover. Additionally, we will study forecasted coral reef trajectories to understand bleaching susceptibility, possible community shifts, thermal tolerances, adaptation or acclimatisation, and how future Malaysian waters' corals may look like.

Coral Bleaching in Malaysia

2010 Mass Coral Bleaching Event – Satellite SST Data

The 2010 Mass Bleaching Event (MBE), also known as the 2nd Global Mass Bleaching Event, in Malaysia was due to an El-Nino event, which began in early March 2010 and continued until October of that year. NOAA's Pathfinder satellite SST gauges over Terengganu and the Malacca Straits were used as proxies to observe magnitude, intensity, and duration of thermal stress across Peninsular Malaysia between 2009 and 2011.

The NOAA's Pathfinder's satellite gauge over Terengganu provided information on the SST changes in this region between 2009 and 2011. Warmest Month (WM) SST values ranged from 27.09°C to 30.92°C [Figure 2 (a)]. The regional thermal threshold (Maximum Monthly Mean) in Terengganu during this period was 29.80°C while the bleaching threshold was 30.80°C. The WM SST crossed the bleaching threshold in May 2010 (30.92°C). The climatologically mean WM was calculated based on the maximum frequency of the month recording the maximum monthly mean SST for that year, throughout the study period (2009-2011). For Terengganu, the climatologically mean WM was June for the study period. The absolute range of the Positive Anomaly (PA) was between 0.0016°C (25 December 2011) and 1.9743°C (28 September 2010). A high PA was recorded for 15 out of the 36 months while a very high PA was recorded for seven out of the 36 months for the study duration [Figure 2 (b)].

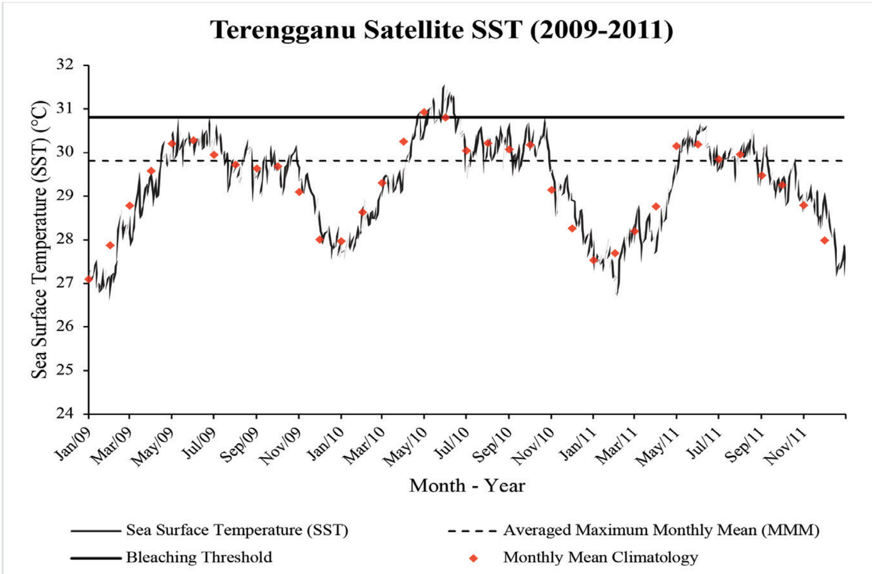

Figure 2 (a): Terengganu satellite Sea Surface Temperatures (SST) (January 2009-December 2011)
Source: NOAA Pathfinder CRW Program

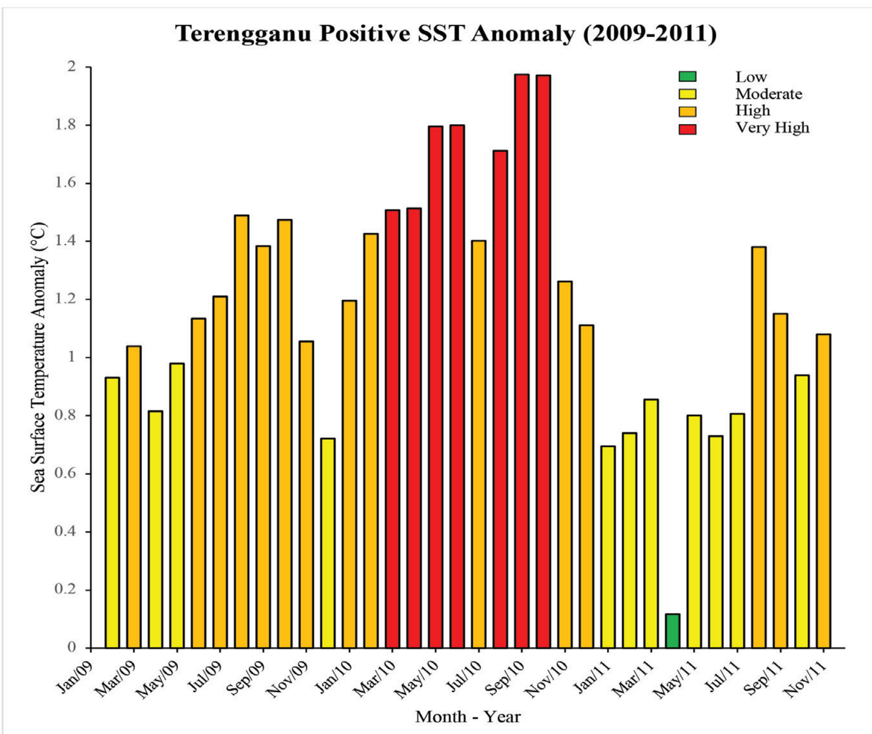

Figure 2 (b): Terengganu satellite Sea Surface Temperatures (SST) anomaly based on their intensity (January 2009-December 2011)
Source: NOAA Pathfinder CRW Program

The NOAA's Pathfinder's satellite gauge over the Malacca Strait provided information on the SST changes in this region between 2009 and 2011 (during the 2nd global mass bleaching event). Warmest Month (WM) SST values ranged from 28.78°C to 31.09°C [Figure 3 (a)]. The regional thermal threshold (Maximum Monthly Mean) in the Malacca Strait during this period was 29.91°C while the bleaching threshold was 30.91°C. The warmest month SST crossed the bleaching threshold in May 2010 (31.09°C) and June 2010 (30.92°C). The climatologically mean warmest month, calculated based on the maximum frequency of the month recording the MMM SST for that year in the study period was June. The absolute range of the Positive Anomaly (PA) was between 0.001°C (13 January 2009) and 1.75°C (15 February 2010). A high PA was recorded for 23 out of the 36 months while a very high PA was recorded for five out of the 36 months for the study duration [Figure 3 (b)].

NOAA's Coral Reef Watch Degree Heating Week (DHW) SSTs between 2009 and 2011 is illustrated in Figure 4.

2010 Mass Coral Bleaching Event – In Situ Validation

The earliest bleaching was reported in March in Pulau Tioman (GCRMN Report, 2010) with severe bleaching (between 75%-90%) being reported in three islands (Pulau Tioman, Pulau Tinggi, and Pulau Sibu) off the east-coast of Peninsular Malaysia (Department of Marine Parks Malaysia, 2010). By mid-June, up to 50% of hard corals in Pulau Tioman, Pulau Redang, and Pulau Perhentian were bleached (Tan & Heron, 2011). Two-thirds of the coral colonies were recorded to be visibly white and bleaching being observed up to depths of 20 m in Pulau Tioman and Pulau Perhentian, 25 m in Pulau Redang, respectively (Tan & Heron, 2011).

The 2010 MBE saw a lower overall coral mortality, compared to the previous 1998 MBE. It was estimated up to 40% of corals around reefs off Peninsular Malaysia had reportedly died after the 1997-1998 MBE (Reef Check Malaysia, 2011). According to 93 reef surveys carried out by Reef Check Malaysia in 2010, Malaysia's reef health status was categorised as "fair", with an average live coral cover of 44.31% (Figure 5). The three-year (2009-2011) decline

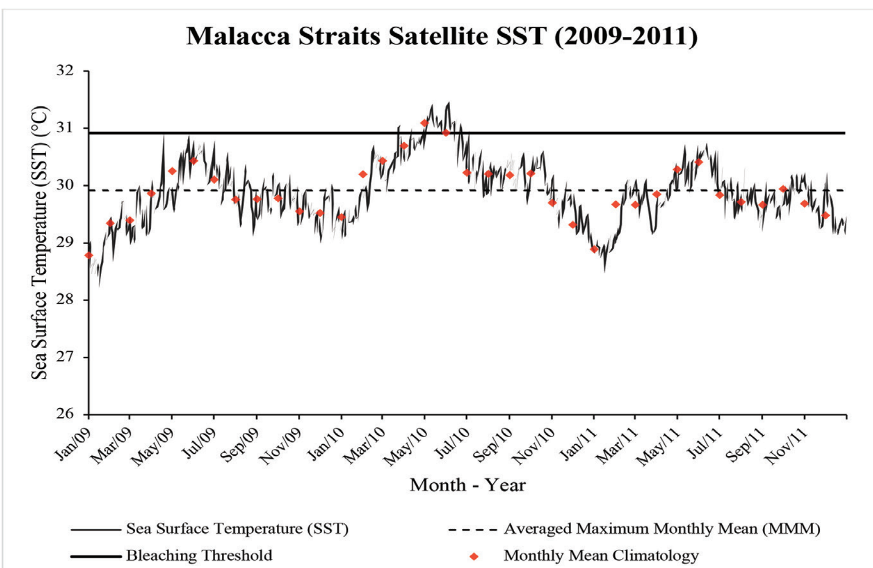

Figure 3 (a): Malacca Strait satellite Sea Surface Temperatures (SST) (January 2009-December 2011)
Source: NOAA Pathfinder CRW Program

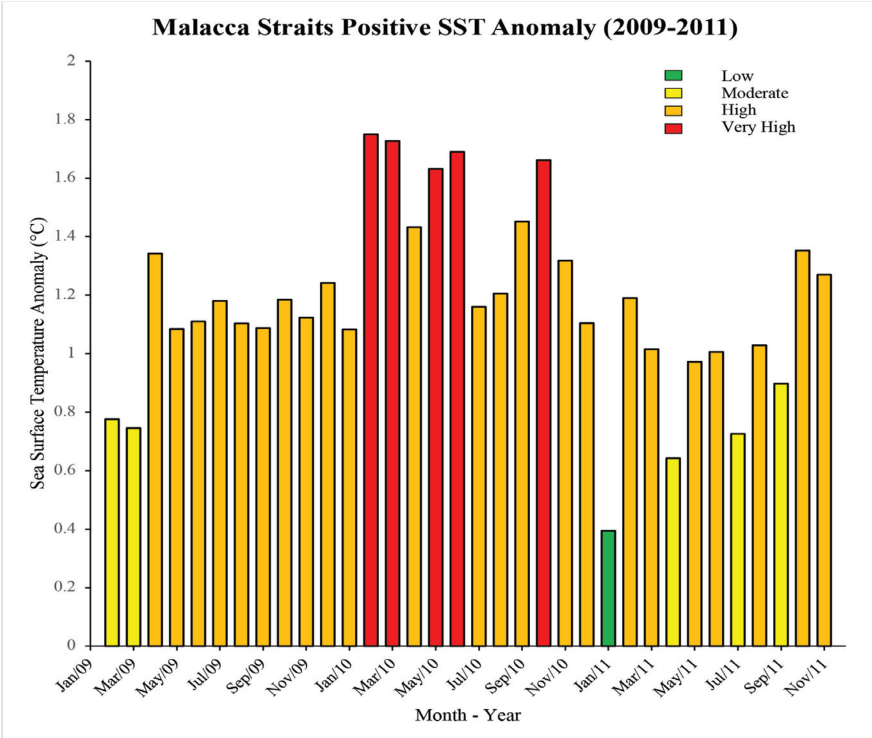

Figure 3 (b): Malacca Strait satellite Sea Surface Temperatures (SST) anomaly based on their intensity (January 2009-December 2011)
Source: NOAA Pathfinder CRW Program

in "Live Coral" cover of 7.39%, from 49.96% in 2009 to 42.57% in 2011 was suggested to be extremely likely due to the 2010 bleaching event (Reef Check Malaysia, 2011). Additionally, an increase in "Recently Killed" corals (RKC) in 2010 of 3.30%, compared to the previous RKC in 2009 of 2.43% and later years RKC in 2011 of 1.77% (Figure 5), supported this theory (Reef Check Malaysia, 2011).

Although there was coral recovery towards the end of 2010, it was estimated that from 5% to 6% of Malaysia's corals may have died due to the 2010 MBE (Reef Check Malaysia, 2011). Overall, in 2010, the bleaching severity was considered medium to high along the coast of Peninsular Malaysia and medium in Eastern Malaysia (GCRMN Report, 2010).

2014-2017 ENSO Induced-global Mass Coral Bleaching Event – Satellite SST Data

From 2014 to 2017, two sequential sets of bleaching events moved from the northern to the southern hemispheres as a result of record-breaking heat stresses lasting for months with sometimes continuous heat stresses observed for the whole year in some regions (Eakin *et al.*, 2017; Hughes *et al.*, 2017). This marked the 3rd global mass bleaching event and it was not only the longest-lasting global MBE ever recorded, but also resulted in severe coral loss globally, albeit distributed unevenly (Eakin *et al.*, 2018a). In particular, all three years (2015, 2016, and 2017) saw the highest annual globally averaged temperatures observed in the last two centuries (Blunden & Arndt, 2018) with the 2016 thermal anomaly surpassing that of the 1998 MBE (Oliver *et al.*, 2018).

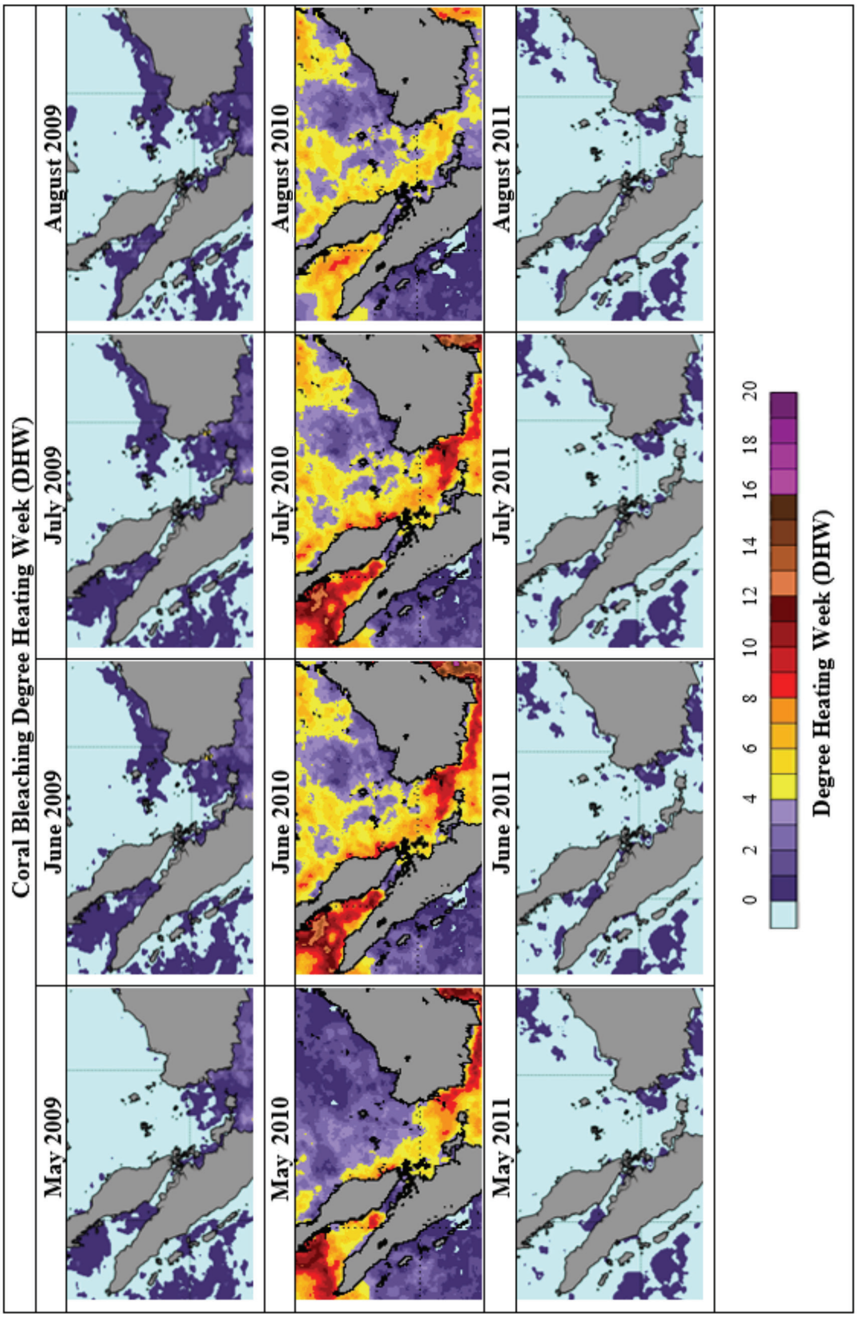

Figure 4: NOAA Coral Reef Watch Degree Heating Week (DHW) sea-surface temperatures during bleaching season for Malaysian waters corresponding with the 2nd global mass bleaching event (May to August, 2009-2011)

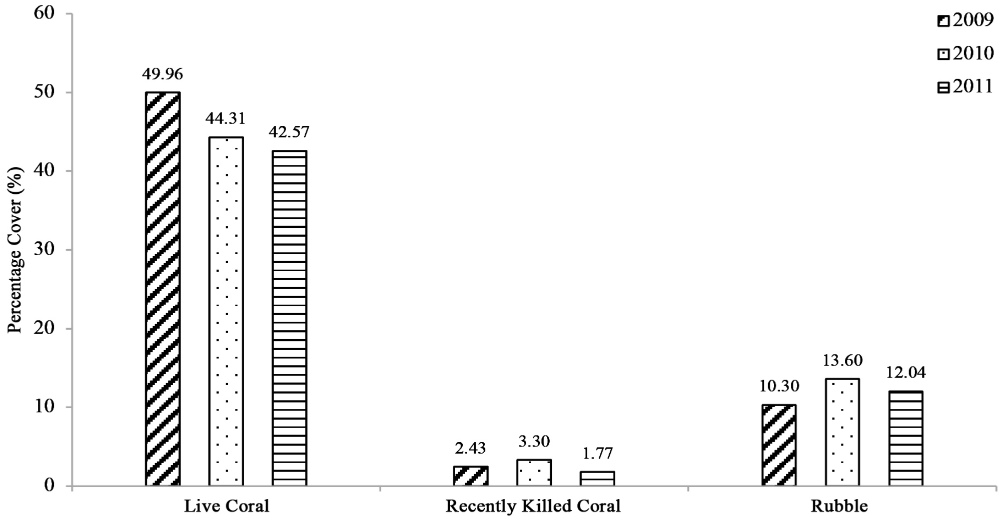

Figure 5: Change in percentage of live coral cover, recently killed corals, and rubble for surveys carried out between 2009 to 2011
Source: Reef Check Malaysia (2011)

The NOAA's Pathfinder's satellite gauge over Terengganu provided information on the SST changes in this region between 2014 and 2017 (during the 3rd global mass bleaching event). Warmest Month (WM) SST values ranged from 26.84°C to 30.83°C [Figure 6 (a)]. The regional thermal threshold (Maximum Monthly Mean) in Terengganu during this period was 29.80°C while the bleaching threshold was 30.80°C. The warmest month SST crossed the bleaching threshold in May 2014 (30.83°C) and May 2016 (30.81°C). The climatologically mean WM, calculated based on the maximum frequency of the month recording the MMM SST for that year, throughout the study period was May. The absolute range of the Positive Anomaly (PA)

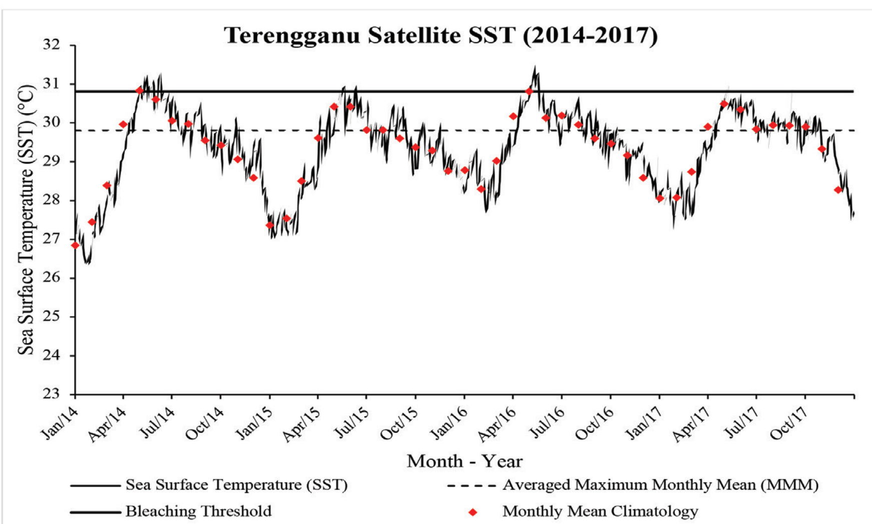

Figure 6 (a): Terengganu satellite Sea Surface Temperatures (SST) (January 2014-December 2017)
Source: NOAA Pathfinder CRW Program

was between 0.0013°C (18 October 2014) and 2.1884°C (18 January 2016). A high PA was recorded for 27 out of the 36 months while a very high PA was recorded for 10 out of the 36 months in the study duration [Figure 6 (b)].

The NOAA's Pathfinder's satellite gauge over the Malacca Strait provided information on the SST changes in this region between 2014 and 2017 (during the 3rd global mass bleaching event). Warmest Month (WM) SST values ranged from 28.79°C to 31.03°C [Figure 7 (a)]. The regional thermal threshold (Maximum Monthly Mean) in the Malacca Strait during this period was 29.91°C, while the bleaching threshold was 30.91°C. The warmest month SST crossed the bleaching threshold in April 2016 (30.92°C) and May 2016 (31.03°C). The climatologically mean WM (maximum frequency of the month recording the maximum monthly mean SST for that year, throughout the study period) was May. The absolute range of the Positive Anomaly (PA) was between 0.0248°C (9 February 2014) and 1.9416°C (21 January 2016). A high PA was recorded for 26 out of the 36 months, while a very high PA was recorded for 10 out of the 36 months in the study duration [Figure 7 (b)].

NOAA's Coral Reef Watch Degree Heating Week (DHW) sea-surface temperatures between 2014 and 2017 is illustrated in Figure 8.

2014 to 2017 ENSO Induced-global Mass Coral

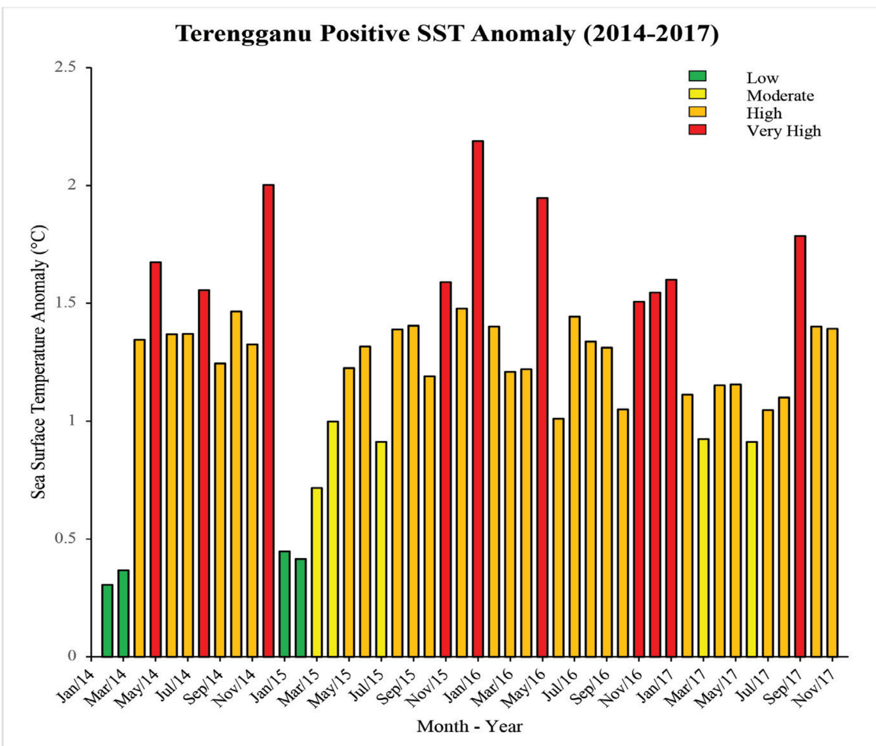

Figure 6 (b): Terengganu satellite Sea Surface Temperatures (SST) anomaly based on their intensity (January 2014-December 2017)
Source: NOAA Pathfinder CRW Program

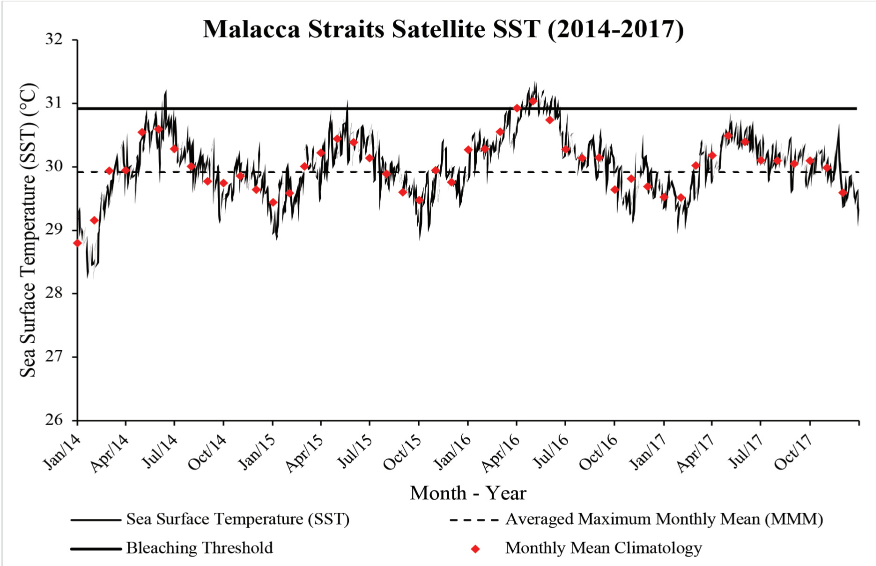

Figure 7 (a): Malacca Strait satellite Sea Surface Temperatures (SST) (January 2014-December 2017)
Source: NOAA Pathfinder CRW Program

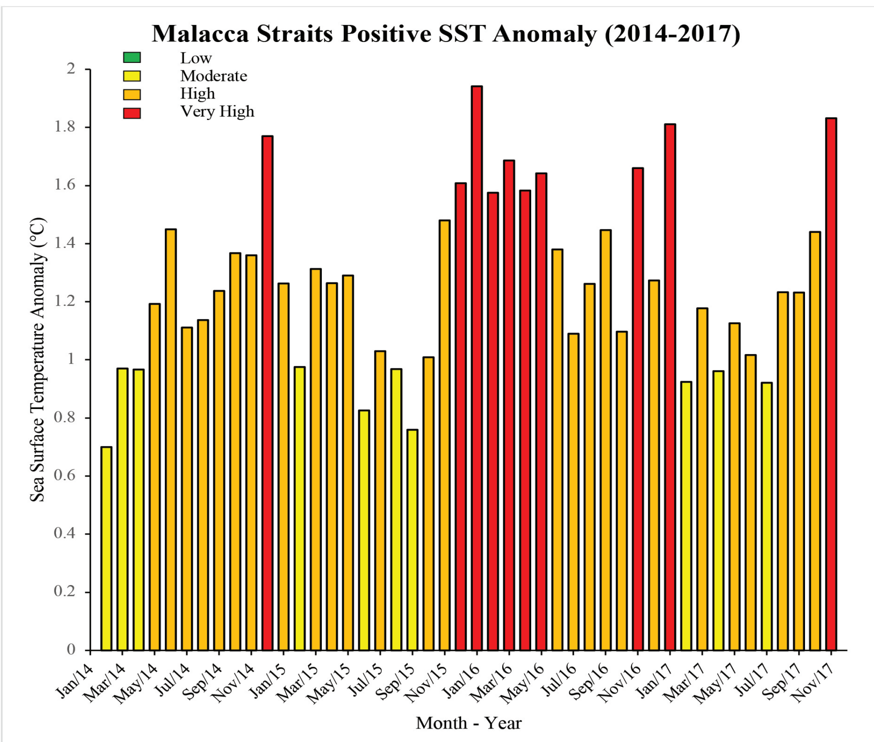

Figure 7 (b): Malacca Strait satellite Sea Surface Temperatures (SST) anomaly based on their intensity (January 2014-December 2017)
Source: NOAA Pathfinder CRW Program

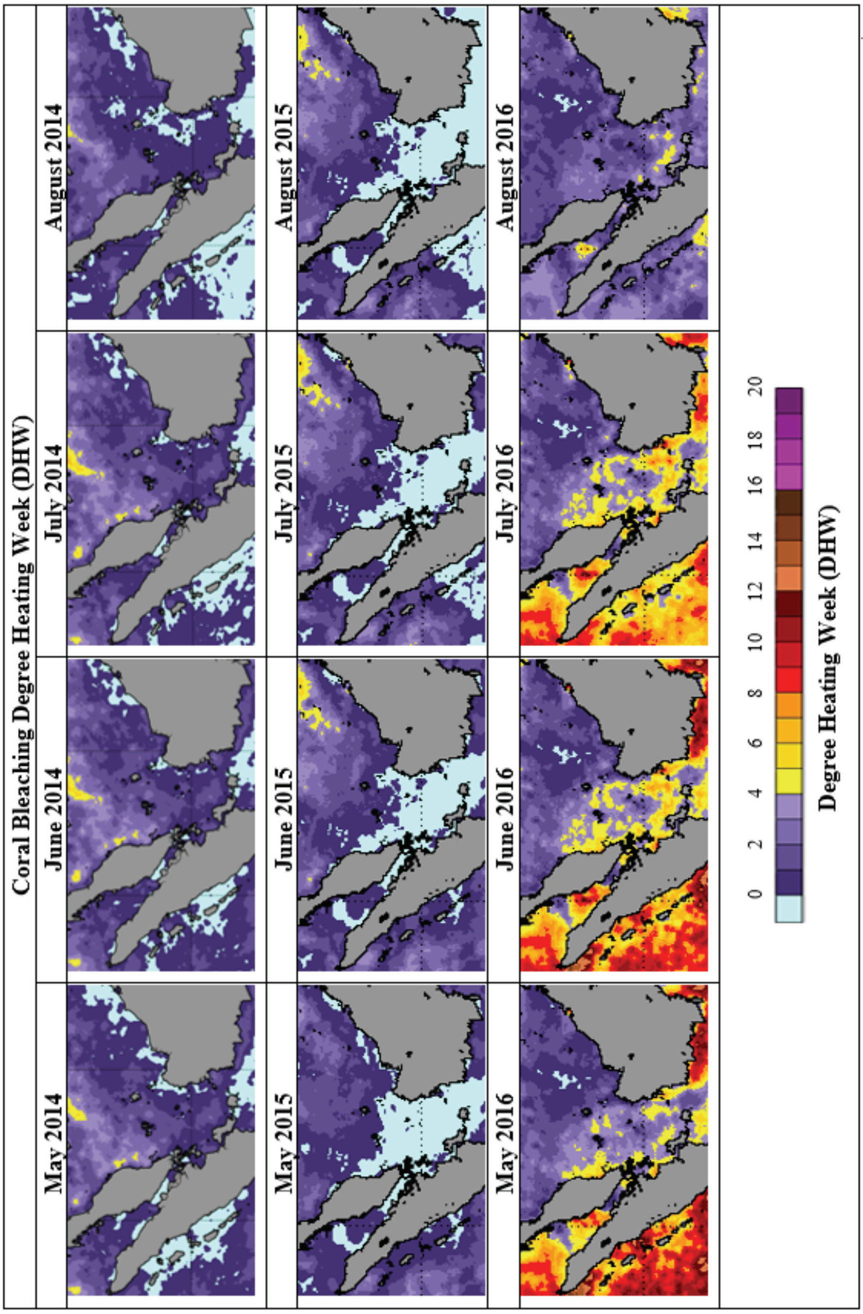

Figure 8: NOAA Coral Reef Watch Degree Heating Week (DHW) sea-surface temperatures during bleaching season for Malaysian waters corresponding with the 3rd global mass bleaching event (May to August, 2014-2017)

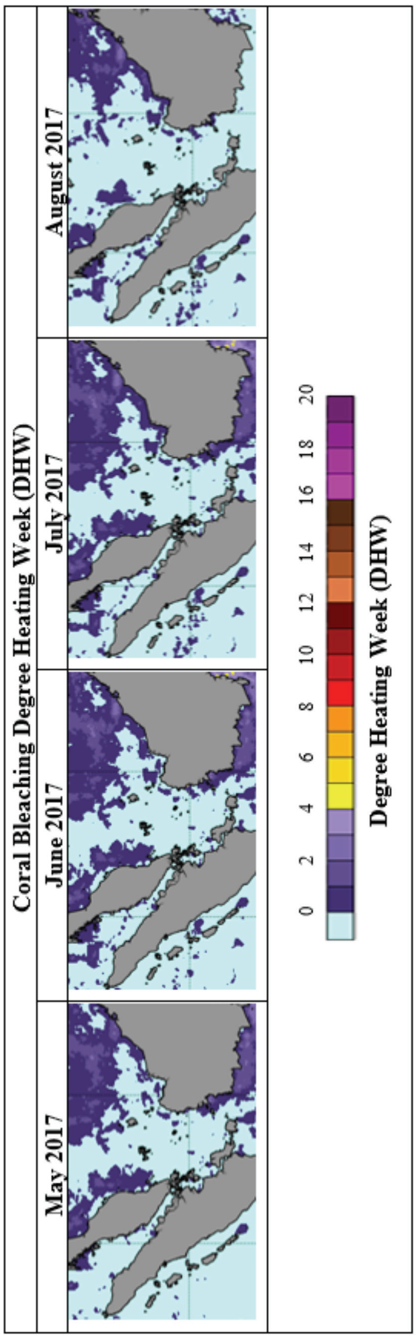

Figure 8 continued: NOAA Coral Reef Watch Degree Heating Week (DHW) sea-surface temperatures during bleaching season for Malaysian waters corresponding with the 3rd global mass bleaching event (May to August, 2014-2017)

Bleaching Event – In Situ Validation

According to Reef Check Malaysia's long-term monitoring (Reef Check Malaysia, 2017; 2018) from 2014 to 2017 there was a clear year-on-year decline in "Live Coral" cover in reefs surrounding Peninsular Malaysia from 48.11% in 2014 to 42.53% in 2017 (Figure 9). This "Live Coral" cover decline may be attributed to the three-year global mass bleaching event sweeping the region. Additionally, elevated "Recently Killed" coral percentages with clear associated increases in "Rubble" composition (from 13.48% in 2014 to 19.42% in 2017) (Figure 9), supported this theory (Reef Check Malaysia, 2015; 2016; 2017; 2018).

Overall, as reefs around the world were experiencing extensive bleaching and mortality; coral reefs in Malaysia experienced minimal to showing no-signs of bleaching. The response of Malaysia's reefs was mild and most survived this 3rd global MBE.

Following a bleaching alert issued for this region in early 2014 by NOAA's Coral Reef Watch (CRW) program, a four-day coral survey study (Tan, 2014) carried around the Pulau Redang archipelago (Figure 10), following the visual analysis of 6,544 hard coral colonies across five islands showed 43.57% of the coral colonies bleaching. The three major genera—*Fungia*, *Acropora*, and *Pocillopora*—accounted for more than 80% of the bleached colonies in this study. Coral colonies of the genera *Leptastrea*, *Lithophyllia*, *Millepora*, and *Stylophora* were all observed to be completely bleached while 13 genera showed 50% bleaching severity and 11 genera showed no visible bleaching (Table 1).

The observations of Tan (2014) on Malaysia's corals have been demonstrated in numerous other studies, where branching (faster-growing) corals were more susceptible to bleach and higher mortality than their massive and encrusting (slower-growing) counterparts (Marshall & Baird, 2000; Wilkinson, 2000; McClanahan & Maina, 2003). Massive encrusting corals demonstrate a higher rate of bleaching survivability, due to the photo-protective capacity of their thick tissues, where retraction of these tissues provide

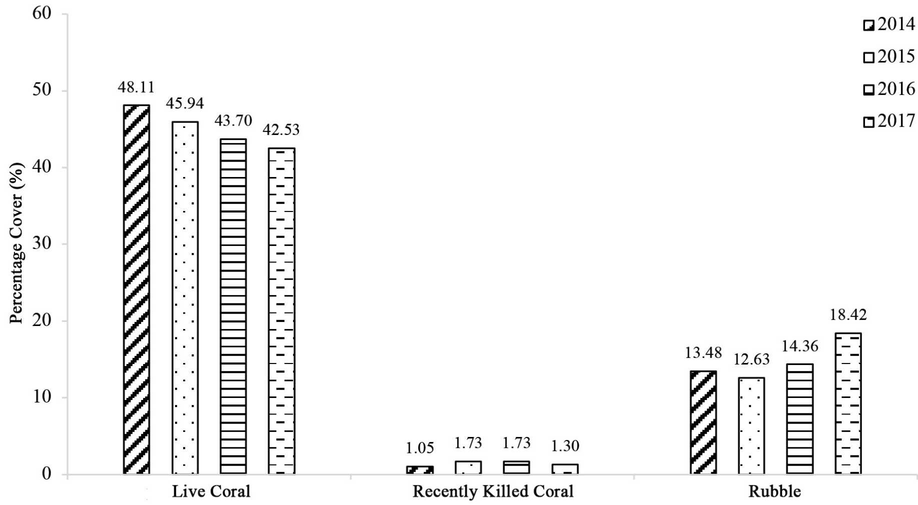

Figure 9: Change in percentage of live coral cover, recently killed corals, and rubble for surveys carried out between 2014 to 2017
Source: Reef Check Malaysia (2018)

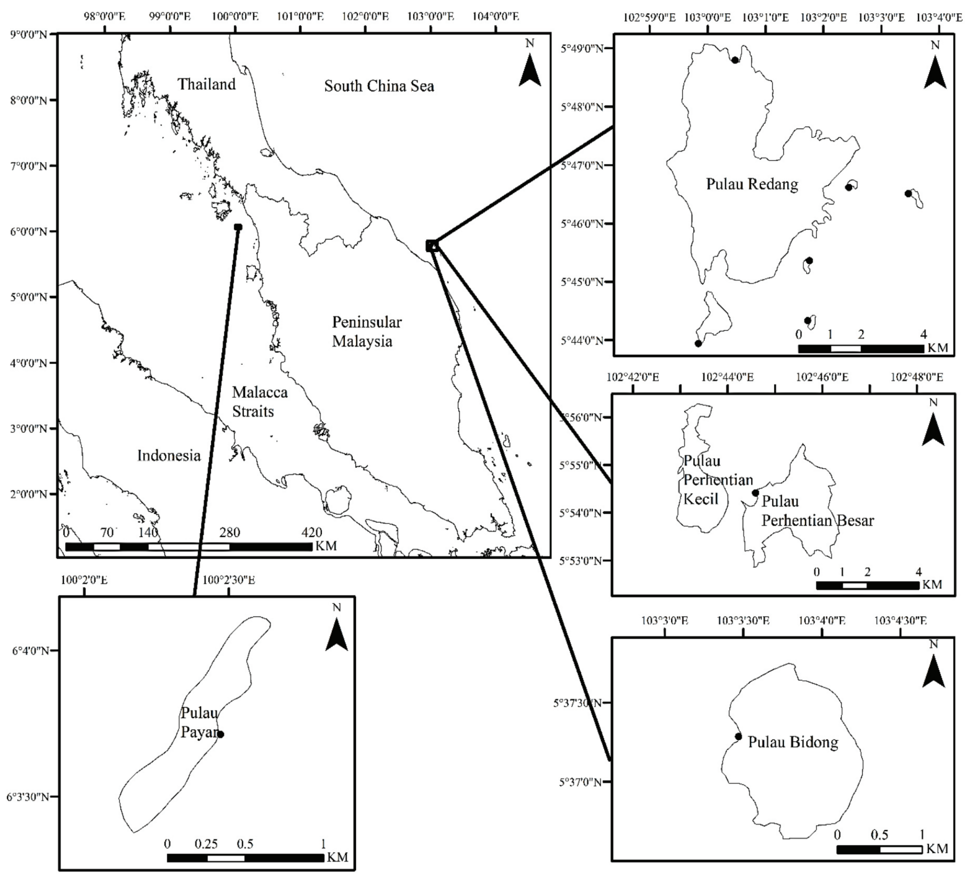

Figure 10: Sites surveyed in the different bleaching surveys or monitoring programs (Tan, 2014; 2018)

Table 1: Coral bleaching percentage ranking for survey carried out in Redang Archipelago, July 2014 (Tan, 2014)

Community Structure				
6,544 hard colonies	45 genera		13 families	
Major Genera				
	Abundance (%)		**Bleaching (%)**	
Fungia	34.90 (2,284 colonies)		42.65	
Acropora	25.14 (1,645 colonies)		27.46	
Pocillopora	16.34 (1,069 colonies)		13.50	
Total	**76.38**		**83.58**	
Bleaching Susceptibility				
No bleaching (0%)	Alveopora Lobophyllia	Cyphastrea Oulophyllia	Cycloseris Scolymia	Goniopora
Moderately bleached (< 50%)	Acropora Diploastrea Favites Herpolitha Montipora Pocillopora Symphyllia	Astreopora Echinopora Favia Hydnophora Pavona Porites	Coeloseris Echinophyllia Galaxea Leptoseris Pachyseris Platygyra	Ctenactis Euphyllia Halomitra Montastrea Pectinia Sandalolitha
Mostly bleached (> 50%)	Fungia	Goniastrea	Leptoria	Psammocora
Completely bleached (100%)	Leptastrea	Lithophyllon	Millepora	Stylophora

a form of self-shading to their zooxanthellae (Glynn, 1993; Hoegh-Guldberg & Salvat, 1995). Additionally, it has been hypothesised that under stressful conditions, the high-mass transfer capacity of these species facilitates the removal of harmful super-oxides and other damaging toxins (Loya *et al.*, 2001).

Similarly, McClanahan and Maina (2003) and Schuhmacher *et al.* (2005) all demonstrated the varied and hierarchical bleaching susceptibility among the different genera with massive species of Porites, Favia, and Goniopora being frequently among the survivors. One particular study of mention (Marshall & Baird, 2000) ranked bleaching according to most susceptible (*Millepora*, *Pocillopora*, and *Acropora*) to most resistant or least susceptible (*Galaxea*, *Cyphastrea*, and *Goniopora*), correlating with the observations in Malaysia's reefs (Tan, 2014).

2018-2020 Long-term Bleaching Monitoring – Satellite SST Data

Following the 3rd global mass bleaching event between 2014 and 2017, long-term bleaching monitoring of Peninsular Malaysia's waters provided insights into the coral reef health status post-third global MBE.

The NOAA's Pathfinder's satellite gauge over Terengganu provided information on the SST changes in this region between 2018 and 2020 (following the 3rd global mass bleaching event). Warmest Month (WM) SST values ranged from 27.64°C to 30.80°C [Figure 11 (a)]. The regional thermal threshold (Maximum Monthly Mean) in Terengganu during this period was 29.80°C while the bleaching threshold was 30.80°C. The warmest months throughout this period did not cross the bleaching threshold. The climatologically mean warmest month, calculated based on the maximum frequency of the month recording the maximum monthly mean SST for that year, throughout the study period (2018-2020) was May. The absolute range of the Positive Anomaly (PA) was between 0.0087°C (27 March 2018) and 1.881°C (7 September 2020). A high PA was recorded for 21 out of the 36 months while a very high PA was recorded for four out of the 36 months for the study duration [Figure 11 (b)].

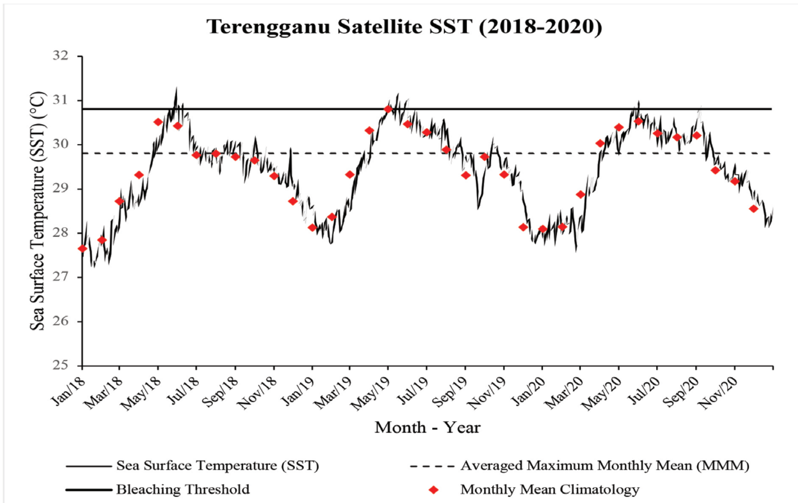

Figure 11 (a): Terengganu satellite Sea Surface Temperatures (SST) (January 2018-December 2020)
Source: NOAA Pathfinder CRW Program

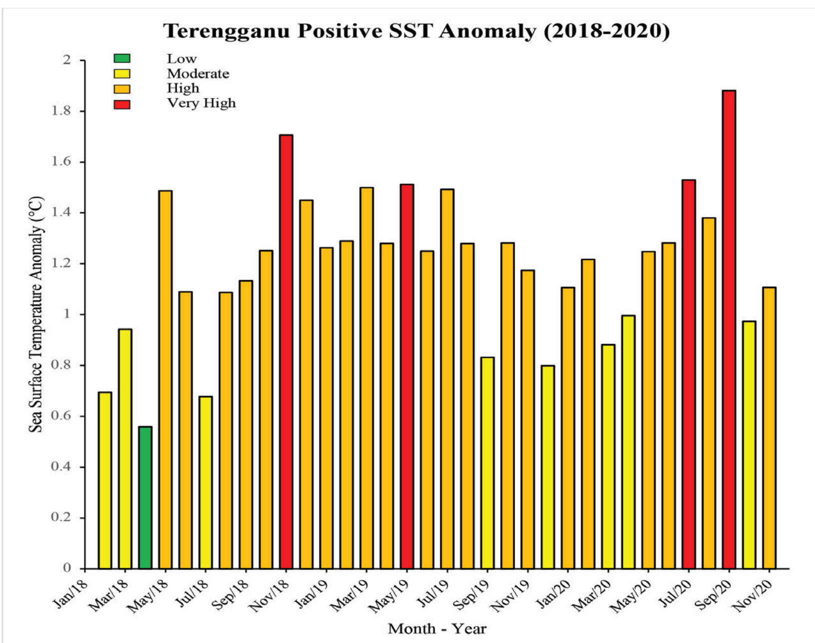

Figure 11 (b): Terengganu satellite Sea Surface Temperatures (SST) anomaly based on their intensity (January 2018-December 2020)
Source: NOAA Pathfinder CRW Program

The NOAA's Pathfinder's satellite gauge over the Malacca Straits provided information on the SST changes in this region between 2018 and 2020 (following the 3rd global mass bleaching event). Warmest Month (WM) SST values ranged from 29.19°C to 30.80°C [Figure 12 (a)]. The regional thermal threshold (Maximum Monthly Mean) in Terengganu during this period was 29.91°C, while the bleaching threshold was 30.91°C. The warmest months throughout this period did not cross the bleaching threshold. The climatologically mean warmest month, calculated based on the maximum frequency of the month recording the maximum monthly mean SST for that year, throughout the study period (2018-2020) was June. The absolute range of the Positive Anomaly (PA) was between 0.038°C (3 July 2018) and 1.7371°C on 27 February 2019 (7 September 2020). A high PA was recorded for 17 out of the 36 months while a very high PA was recorded for eight out of the 36 months in the study duration [Figure 12 (b)].

2018-2020 Long-term Bleaching Monitoring – In Situ Validation

According to Reef Check Malaysia's long-term monitoring (Reef Check Malaysia, 2019; 2020) between 2018 and 2020, "Live Coral" cover on reefs surrounding Peninsular Malaysia was stable (between 40% to 42%) (Figure 13); designating it as in a "Fair Condition" (Chou *et al*., 1994). "Rubble" composition showed a slight increase (from 13.21% in 2018 to 15.24% in 2020) while "Recently Killed" coral percentages were minimal (Figure 13).

A long-term monitoring program (Tan, 2018) was started during the peak of the ENSO Phenomenon in 2016 and continued until the end of 2018 in Malaysia. In this study, underwater temperature loggers were deployed at coral reefs around Pulau Payar, Pulau Perhentian, Pulau Redang, and Pulau Bidong (Figure 14). Also, in situ visual surveys were carried out to monitor and record bleaching.

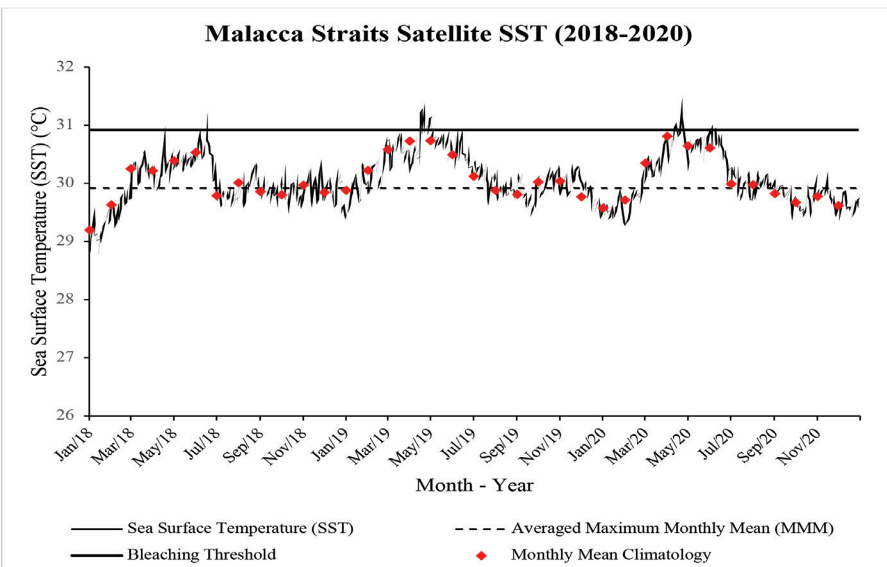

Figure 12 (a): Malacca Strait satellite Sea Surface Temperatures (SST) (January 2018-December 2020)
Source: NOAA Pathfinder CRW Program

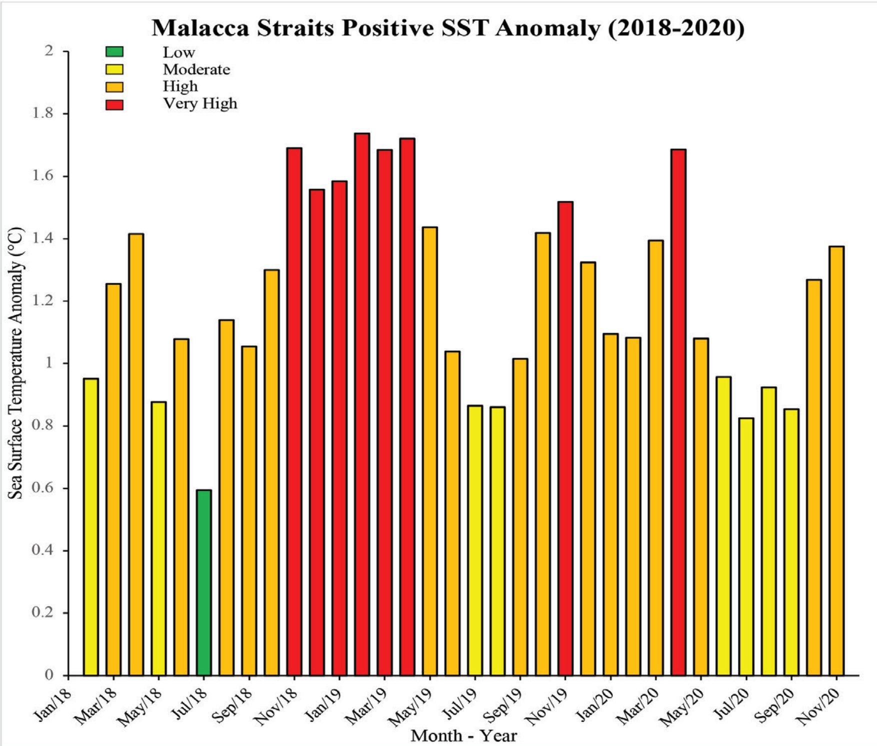

Figure 12 (b): Malacca Strait Satellite Sea Surface Temperatures (SST) anomaly based on their intensity (January 2018-December 2020)
Source: NOAA Pathfinder CRW Program

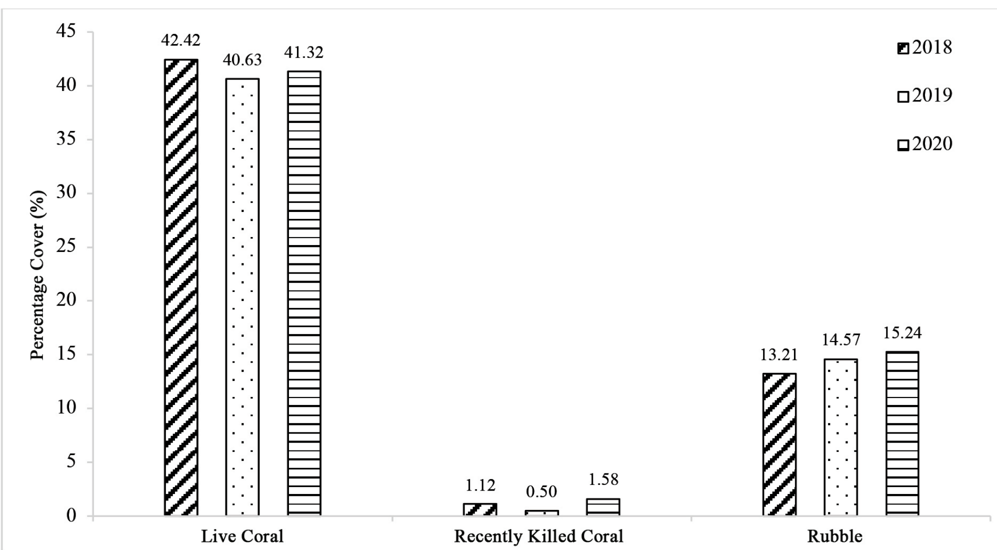

Figure 13: Change in percentage of live coral cover, recently killed corals, and rubble for surveys carried out between 2018 to 2020
Source: Reef Check Malaysia (2018-2020)

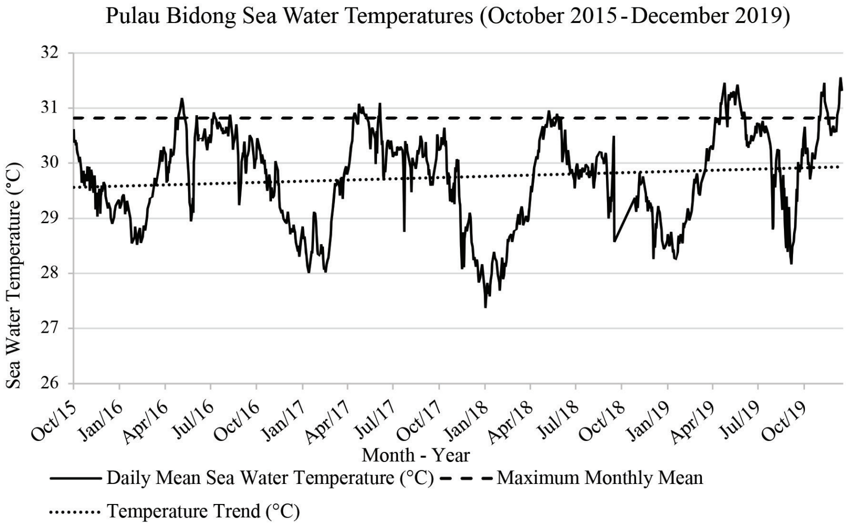

Figure 14: Pulau Bidong Sea Water Temperatures (October 2015-December 2019)
Source: Pulau Bidong in-situ HOBO Logger, Universiti Malaysia Terengganu

Although there were observable increases in sea water temperature during this study period: The maximum sea water temperature was within 2°C of the study period's recorded averages; and sea water temperatures were mostly well below the Maximum Monthly Mean (MMM) of 30.82°C during the four-year study period (Figure 14). Breaks in the MMM, as per the underwater sea water temperature loggers (i.e., Pulau Bidong underwater temperature logger) were of relatively less degree (only during the peak summer months) and of short duration to cause any significant bleaching effect.

The only outlier in the above study (Tan, 2018) was a survey carried out in June 2018 in Pulau Redang when a minimally high short-lived underwater sea water temperature anomaly (Figure 14) caused localised bleaching with up to 20% of the colonies of *Acropora digitefera* recorded as bleached. These corals may have bleached due to their relatively shallow depth (< 2 m), as their counterparts in deeper depths (> 3 m) did not show any signs of bleaching. In fact, shallow reefs are known to have a higher prevalence of bleaching due to the surface waters receiving higher UV-irradiance and solar heat while deeper reefs can have their underwater sea water temperatures reduced due to heat dissipation and cooler water upwelling inputs (van Woesik *et al.*, 2004; Furby *et al.*, 2012).

Validation of SST Data with In Situ Bleaching Observation and Surveys

With the increasing frequency and intensity of SST thermal anomalies, coral reefs globally are increasingly being pushed beyond their photo-inhibitory thresholds (Burt *et al.*, 2019). This leads to associated mass bleaching events (Baker *et al.*, 2008).

In Malaysia, following the 2010 (2nd global) mass bleaching event, there was significant mass bleaching during the peak summer months and detectable mortality associated with the bleaching. The corals did; however, recover towards the end of that year, both NOAA's CRW satellite SST and Reef Check Malaysia's ground "truthing" surveys corroborated satellite SSTs with reef situations on the ground. Similarly, during the 3rd global MBE when the rest of the globe's corals were extensively bleached, Malaysian corals were relatively unscathed (Tan, 2018). While the bleaching trend in the past decade has shown Malaysia's corals to have largely escaped the full brunt of both the 2nd and 3rd global MBEs; nonetheless, both satellite SST data and in situ underwater sea water temperature loggers (i.e., Pulau Bidong underwater temperature logger) recorded an increasing trend in sea water temperatures over the last decade. Furthermore, future warming projections for the Coral Triangle and the South China Sea are large, at 0.04°C per year, over the next 90 years, indicating a rapid warming rate (Khalil *et al.*, 2015) that puts corals in this region on track towards current global bleaching impact trends. In other words, the bleaching consequences we are currently observing in different coral reefs around the world can be expected to be observed in Malaysian reefs in future.

Satellite derived SST data used for long-term monitoring of regional thermal stress combined with in situ ground "truthing" surveys, showed regional differences in the Thermal Threshold (TT) and Bleaching Threshold (BT) in both the Malacca Strait and Terengganu, and that coral thermal stress was not spatially uniform across the Peninsular Malaysian coast.

With numerous factors influencing bleaching susceptibility: Host symbiont (Rowan, 2004), site or location (van Woesik *et al.*, 2004), depth (Oliver & Palumbi, 2009), colony size (Gates, 1990), or structural complexity (Loya *et al.*, 2001) to name a few; these differential bleaching responses are influencing corals assemblages through "adaptation" and "acclimation" processes and leading to coral community-shifts in some instances (van Woesik *et al.*, 2011; Burt *et al.*, 2019). Numerous studies (Marshall & Baird, 2000; McClanahan *et al.*, 2007; Heron *et al.*, 2016a) have demonstrated that with recurrent bleaching events, corals have obtained an increased resistance to bleach through sustained differential declines in the proportion of taxa and colonies that bleach in successive events (Head *et al.*, 2019). These sustained bleaching declines have been attributed to acclimatory and adaptive responses of the surviving coral assemblages, through the selective removal of susceptible genotypes and shifts towards thermally tolerant taxa (Prachett *et al.*, 2013). This form of highly selective mortality is likely to create selective pressures on coral communities and lead to marked changes in community composition towards thermally tolerant locally persistent colonies (i.e., slower-growing massive—encrusting corals and corals hosting clade D symbionts) and post-bleaching survivors that are able to rapidly grow and quickly colonise (Burt *et al.*, 2008; Sheppard *et al.*, 2008). While coral assemblages in one location in Malaysia may shift towards a more thermally resilient community structure through the gradual removal of thermally susceptible genera (van Woesik *et al.*, 2011), corals in another site may exhibit no observable change with increases in SSTs, due to colonies hosting the Clade D *Symbiodinium* (Stat & Gates, 2011).

Conclusions

With unprecedented global ocean warming and the increasing frequency and intensity of associated mass bleaching events, coral bleaching can now be considered a chronic disturbance globally. While Malaysia's corals at the moment are able to handle current bleaching stresses relatively well; nonetheless, we can expect future Malaysian coral communities to be disproportionately affected by climate change. Coral reefs play a vital role as home and nurseries for many commercially valuable fish while simultaneously attracting millions of tourists to Malaysia. Not only does this generate significant revenue for coastal communities, it also injects billions of dollars into Malaysia's economy. Rising ocean temperatures and consequently irreversible collapse of coral reef communities due to extreme mass bleaching events will not only mean decline in fish stock for the fishing industry, but also billions of dollars in lost revenue for Malaysia's tourism industry.

The scarcity of scientific papers and reports on coral bleaching events in Peninsular Malaysia demonstrated significant shortcomings in Malaysia's response to coral bleaching events.

Future research gaps that need to be addressed include deployment of permanent underwater seawater temperature monitoring systems (HOBO loggers) across Peninsular Malaysia with monitoring being done constantly at a national level and any bleaching alert issued by NOAA's Coral Reef Watch satellite monitoring for this region can be followed-up by physical on-site surveying of bleaching alert areas.

Therefore, it is vitally important that governments and policymakers come together to control climate change and limit global warming to 1.5°C to 2.0°C within this century, as runaway ocean warming will lead to catastrophic collapses of reefs worldwide without the possibility of recovery.

Acknowledgements

The authors would like to thank the following organisations:

(1) Bahagian Taman Laut dan Pengurusan Sumber, Department of Fisheries Malaysia in providing funding (UMT Research Vot: 53232) and permit (Reference No.: JTLM 630-1/1/3 Jld. 2(43)) for the studies.

(2) Centre of Research and Field Service (CRAFS), UMT for providing research facilities at Pulau Bidong Marine Research Station.

(3) Laguna Redang Island Resort for providing support in accommodation, food, and SCUBA gears for sampling at Pulau Redang and Pulau Perhentian.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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