2021

Impact of geographical variability on the bleaching stresses in the Atlantic, Indian and South Pacific Ocean

Bowdler, N.

Bowdler, N. (2021) 'Impact of geographical variability on the bleaching stresses in the Atlantic, Indian and South Pacific Ocean', The Plymouth Student Scientist, 14(2), pp. 48-66.
http://hdl.handle.net/10026.1/18497

The Plymouth Student Scientist
University of Plymouth

*The Plymouth Student Scientist, 2021, **14** (2), 48-66*

The impacts of geographical variability on bleaching stresses between reefs in the Atlantic, Indian and South Pacific Ocean

Niamh Bowdler

Project Advisor: *Dr Jill Schwarz, School of Biological and Marine Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA*

Abstract

This dissertation examines the relationship between the geographical location and the degree of coral bleaching. Corals within different ocean regions are subjected to fluctuations in temperature causing variations in thermal thresholds which affects how the reef fauna adapts to the changing environment. Quadrats were obtained from XL Catlin Global Reef Record and analysed to determine the state of the coral at three locations: East Bermuda (Atlantic Ocean), Egmont (Indian Ocean) and Agincourt (South Pacific Ocean). The mean monthly and weekly sea surface temperature (SST) data was extracted from Giovanni between 2002-2020 for all three reefs. ANOVA: single factor tests (analysis of variance) were carried out to test for differences between reefs on each of three factors: if there was a difference between bleaching, long term heating and number of degree heating weeks (DHW) between the sites. The analysis of the quadrats showed that the condition of the coral deteriorated with the increase of SST and bleaching was worse at Egmont and Agincourt. The DHW results at the three reef sites were consistent with previous findings that long term heating events above °C lasting for a minimum of two weeks can cause DHW's which push the coral past their thermal threshold causing bleaching. Although there were limitations to the scale of the research results indicated that the geographical location of the reef has an impact on the severity of bleaching. This knowledge is important when deciding mitigation and conservation strategies.

Keywords: Sea surface temperature, coral bleaching, global variation, degree heating week

Introduction

Coral reefs span 300,000km² (Masselink., 2014) across more than 100 countries despite covering less than 1% of the ocean floor (Moberg and Folke., 1999). Although the overall coverage is small, they are known as “the rainforests of the ocean” with a diversity of 9 million species living in and around the reefs (Reaka-Kudla.,1997). They are one of the most important ecosystems providing economical and biological services to marine and human life, whereby 25% of marine life (Masselink., 2014) inhabit coral reefs due to the nursery, spawning and feeding sites provided to both juvenile fish and other organisms. Reefs increase the quality and clarity of the inshore waters by filtering the carbon and nitrogen along with nutrient recycling (Moberg and Folke., 1999). For humans, reefs provide coastal regions with protection from threats posed by hurricanes, storms, and tsunamis by reducing the wave energy (Reaka-Kudla., 1997). Around 8% of the population rely on coral reefs (Reaka-Kudla., 2001) for food, protection and revenue which exceeds $375 billion annually (West and Salm., 2003)

Coral reefs are one of the most vulnerable ecosystems affected by climate change. One of the major threats to coral is the rise in sea surface temperature (SST) caused by the increase of CO_2 which is being emitted into the atmosphere (Baker et al., 2008). This dissertation focuses on the SST change over an 18-year period from 2002-2020 within the Atlantic, Indian and South Pacific Ocean. The Indian Ocean is the warmest ocean with the Pacific being second and Atlantic is third. This provides a comparison for how the rise in SST affects the coral.

Although a lot of studies have been conducted, research into coral bleaching only started in the past four decades, so it is still a new topic. Very little is known about the effect that ocean acidification has on coral reefs as there is no tell-tale sign of damage until there is a mass bleaching event. Many reefs go under researched due to access issues such as geographical locations and politics. Other well-known reefs are highly researched due to high funding and easy access. The full extent of bleaching is not known due to most research providing future estimations. For this reason, it is important to understand how reefs in various oceans are being affected due to the range of thresholds because of varying temperatures within the environments.

This research aims to investigate the relationship between the geographical location of coral reefs and the degree of bleaching. This was achieved by gathering and analysing quadrats along a transect of three reefs within the Atlantic, Indian and South Pacific Ocean, along with gathering the SST data between 2002- 2020 for each reef.

Background

What is coral bleaching?

Coral bleaching is the stress response to changing environments which results in the whitening of coral tissues. Stresses include coral disease, sedimentation, destructive fishing, and global warming. (Abdo et al., 2012). Global warming is currently one of the biggest threats to coral reefs. (Anthony et al., 2011) An increase in the sea surface temperature (SST) triggers a stress response in the coral (McWilliams et al., 2005) which disrupts the symbiotic relationship between the coral and the zooxanthellae causing the bleaching (Hughes et al., 2017).

Coral has a symbiotic relationship with dinoflagellate known as zooxanthellae which photosynthesises to provide the host (coral) with nutrients. This enables the growth and calcification of corals whilst also providing the coral with its colour (Baker et al., 2008). The symbiotic relationship between the coral and the zooxanthellae is sensitive to the environment; physical and chemical changes such as temperature, light or toxins can cause a breakdown within the relationship leading to bleaching (Hoegh-Guldberg et al., 2017). The breakdown causes the coral to either expel the zooxanthellae or the photosynthetic pigments within the zooxanthellae. For this reason, corals that have become bleached are physiologically damaged and prolonged exposure to higher than normal temperatures causes high coral mortality rates within coral colonies. (Lough., 2000).

What are the drivers of bleaching?

Global mass bleaching events are driven by the increase of carbon dioxide being emitted into the atmosphere. The ocean absorbs around 30% of atmospheric carbon dioxide which causes an increase in SST, ocean acidification and UV-B radiation (Gattuso and Hansson., 2011). Local bleaching is driven by coral disease, pollution, sedimentation, and freshwater input (Reaka-Kudla., 2001)

The rise of carbon dioxide has increased the global SST by 1°C over the past four decades (Cantin et al., 2010), resulting in three global mass bleaching events. Temperatures that are above the seasonal mean by 1.0-1.5°C create “hot spots” which push the corals past their thermal thresholds. Hot spots cause prolonged periods of higher than normal temperatures which can last for months (Goreau and Hayes., 1994).

The absorption has caused the PH level of the water to decrease. The ocean previously maintained an average PH level of 8.2, however in recent years it has fallen to 8.1 which is a 25% increase in acidity (Gattuso and Hansson., 2011). This impacts corals due to the decrease of carbonate ions in the water. Corals use carbonate ions to build thick, strong skeletons to withstand the damage from the environment i.e., damage caused by storms. The reduction results in the skeletons being weaker and more prone to damage (Cao., 2007) This also means that corals are unable to recover as quickly due to their skeletons eroding faster than they can build (Anthony et al., 2011).

The rise in atmospheric CO^2 has increased the level of UV-B-radiation that is reaching the ocean’s surface. UV radiation is absorbed by the ozone layer, which is becoming increasingly thinner due to human activities, Exposure to the radiation decreases the growth of the coral. When combined with thermal stress it causes oxidative stress which overwhelms the antioxidant system in the coral, damaging the tissues. UV-B radiation also causes a decrease in the efficiency of the corals photosynthetic abilities which leads to bleaching (Lesser.,1996)

Mitigators of bleaching

Resilience provided by environmental factors aids corals in the recovery and prevention of bleaching. Characteristics of the factors reduce stress caused by temperature and light (Baker et al., 2008).

Areas of local upwelling and mixing can enable the corals to recover over a period of time. Artificial upwelling can be introduced to areas to reduce coral bleaching by pumping large areas of the surface with colder deep water. Reducing the surface temperature makes a small but critical difference by returning the thermal stress to a manageable state (Kirke., 2003)

High water movement provides coral with resilience against SST and UV radiation. It enables the reduction of toxins produced as a result of increased SSTs and radiation. The increase in toxins damages the pigments within the coral, inducing bleaching by deactivating the photosynthesis (Nakamura et al., 2003)

Shade provides coral reefs with the shelter required to provide protection from light and UV radiation exposure. It has been found that corals exposed to sunlight without shade show a reduction in coral colour and have a slower growth rate. Cloud cover provides corals with a natural protection against light stress meaning that if corals were shaded during the summertime then there is a chance for the coral to recover (Coelho et al., 2017)

In 2016 heat stress followed the latitudinal variation pattern in heating of the global mass bleaching event. The geographical pattern however can be affected by local weather such as wind, rain, and cloud cover. These processes can aid in the cooling of the ocean's surface by pushing the heat stress away from the area. (Hughes et al., 2017).

What are the impacts of long and short term bleaching?

The tissue and skeleton of the coral reduces during bleaching. The increased temperatures compromise the growth, regeneration, and calcification through the increase in acidity, and heat stress. The heat stress causes the zooxanthellae to be expelled, leaving the coral with reduced food sources and as a result, reduced energy. The increase in acidity reduces the calcium carbonate ions in the water making it harder for the coral to build adequate shells to survive the damage from the environment. Tissue regeneration is also slower in bleached coral compared to unbleached (Baker et al., 2008).

During DHW's the temperature increase causes the coral to become weak due to the physiological stress caused by heat stress. The stress causes the corals immunity to become impaired leaving it susceptible to disease. Coral disease can also have a significant impact on the ecosystem around it by reducing the population of its inhabitants (Baker et al., 2008).

Studies have shown that mortality rates vary depending on their species and colony size. It has been discovered that larger colonies had a lower mortality rate, due to smaller colonies vulnerability to stress factors and inability to recover fast enough.

Other factors that affect the mortality of coral is the depth of the reef under the surface and whether the area is shaded or not (Baker et al., 2008).

The long term effects of bleaching include the decrease in the reproduction of corals. Bleached colonies have fewer polyps with fewer eggs. Bleaching causes the coral to lose a large amount of their symbiotic algae, reducing the amount of food available to the coral. This causes the coral to have a reduction in energy which could also cause the decrease in reproduction (Ward et al., 2000).

implications for management

Both thermal stress and ocean acidification affect the thermal threshold limit for coral reefs. Corals can be driven past their threshold by temperature increases of 1-2°C above the average summer norms causing bleaching. Thermal thresholds can therefore be used to predict the onset of a bleaching event including potential damage sustained (McWilliams et al., 2005)

Although SST and solar radiation are the main drivers of global mass bleaching events, controlling the increased SST caused by the rise in atmospheric CO^2 is not a quick fix. Given the severity of the rate in ocean surface increase, beaching events would still occur for the next century. However, localised bleaching events caused by coral damage, freshwater input, pollution, and sedimentation can be managed (West and Salm., 2003).

Corals that are situated in areas of cold water upwelling are at an advantage as the upwelling will bring cold water to the surface cooling the reefs. Equally ocean processes and winds can cause an upwelling that produces opposite effects. Corals in upwelling regions may be more sensitive to temperature increases than coral in non-upwelling regions (Kirke., 2003)

It is speculated that previous bleaching events will provide coral with protection from future events. However, there is no definitive evidence of this as a study conducted in 2017 found that coral bleached in 1998 and 2002 still got severely bleached in 2016. (Hughes et al., 2017)

Research was also conducted into the pattern of hotspots. Currently no trends have been found in the latitudinal, seasonal, or regional movements of hotspots. This means that it is exceedingly difficult to predict the occurrence of hotspots due to their movements, size, and duration. (Goreau and Hayes., 1994).

A study found that MPA’s are an effective way to protect coral reefs. Results showed that protected corals were unchanged compared to reefs outside the MPA. There was evidence to suggest that MPA’s need substantial time to provide protection for the corals. This is due to slow growth of reef building coral and recovery rates from previous bleaching. The implementation of MPA’s also benefits the wildlife surrounding the coral which in turn benefits the ecosystem (Selig and Bruno., 2010).

Method

The approach used in this research involved using secondary coral reef transect surveys alongside sea surface temperature. This project aims to investigate the relationship between the geographical location of coral reefs and level of bleaching. This is through the analysis of the sea surface temperature variations and increase due to climate change. This involved extracting coral reef quadrats from XL Catlin Reef Record alongside sea surface temperature data from Giovanni.

Selection of reefs

Reefs were chosen based on their geographical location and variation in sea temperatures. Three reefs in total were selected, East Bermuda reef (32.40”N, 64.79”W) in the Atlantic Ocean, Egmont (6.6699”S, 71.3379”E) in the Indian Ocean, and Agincourt (16.0500”S, 145.8333”E) in the South Pacific Ocean. It was important that the reefs were in oceans of differing temperatures to fully understand the impact of rising SST on coral bleaching.

The maximum mean for the Atlantic Ocean is 29°C, the South Pacific Ocean is 27°C and the Indian ocean is 30°C. This provides an important comparison as each reef has adapted to the different temperatures and therefore may be affected differently by the change in rising sea surface temperatures.

Each reef lay at a max depth of 12m and the transect of each reef were of similar lengths. It was important to get reefs that were at similar depths under the surface to try and reduce differences in light pollution.

Quadrat analysis of XL Catlin Coral Reef Record

XL Catlin Coral Reef Record provided quadrats along a transect for each location. East Bermuda’s transect was 1.45km long however the other two were unknown. 15 quadrats were randomly selected using the random integers coding in MATLAB.

Each quadrat measures 1 X 1 m on the ground. The images were then imported onto separate PowerPoint slides. A 10 x 10 cm grid was created and imported over each image allowing for the percentage analysis of the quadrats. Each square on the grid equates to 1% and a gridline was added over the top to separate each square into four sections that equated to 0.25%. This provided a more accurate analysis.

Each grid was visually counted and carefully analysed to determine the percentage of healthy, bleached, and dead coral along with coral rubble. Each condition percentage was accumulated using the data from each grid to calculate the total percentage from each quadrat. The data from all three reefs were imported into Excel where ANOVA tests were conducted.

Sea surface temperature

The SST data was extracted from Giovanni (Giovanni, 2021) using the reef coordinates. The data included both monthly and 8 daily time series, area averaged data using MODSI-Aqua at 4km resolution. The csv data files for each reef were downloaded into excel to compare the variation over 18 years. The climatology, anomaly time series and degree heating week (DHW) for each reef was calculated using the weekly data.

The weekly SST climatology was calculated as the average for each week of the year over the 18 year study. The anomaly time series was calculated by subtracting the Giovanni data from the climatology. The maximum temperature was obtained by using the MAX function in excel. The DHW were identified as weeks in which SST exceeded the climatological mean by 1 standard deviation.

The long-term heating events were obtained by accumulating the anomaly time series data and establishing which figures were above 1. DHW were established by figures that were positive.

ANOVA test of Giovanni SST data

Statistical analysis was conducted on the quadrat and SST data. Firstly, a test for normality was conducted using Kruskal- Wallis which was followed by one-way ANOVA tests. ANOVA tests were used to test three hypotheses. The first was conducted to determine if the degree of bleaching varied between sites. This is defined as the percentage of coral that was visibly bleached. The second determined if a difference between long term heating between the sites occurred. This has been standardised by a minimum of two weeks 1°C above the climatology mean. The third determined if there was a difference between the number of degree heating weeks over the past 18 years. This has been standardised by the number of times that the SST has been above the climatological mean for at least one week. Descriptive statistics and ANOVA: single factor tests were conducted in excel using the quadrat percentage and SST data.

Results

Quadrat analysis of XL Catlin Global Reef Record data

Figure 1 shows the effect of SST on the condition of the corals. The graph shows that when there was an increase in SST there was an increase in bleaching. However, quadrat 9, 11, 14 and 15 showed that even though SST and bleaching increased there was still a high percentage of healthy coral. ANOVA analysis showed that there was a significant difference between all the conditions ($p = 2.48x10^{-19}$). Bonferroni comparisons showed that there was a significant difference between healthy and bleached (p =0.00013), healthy vs dead (p = 2.89-11) and bleached vs dead (p = 9.17-09).

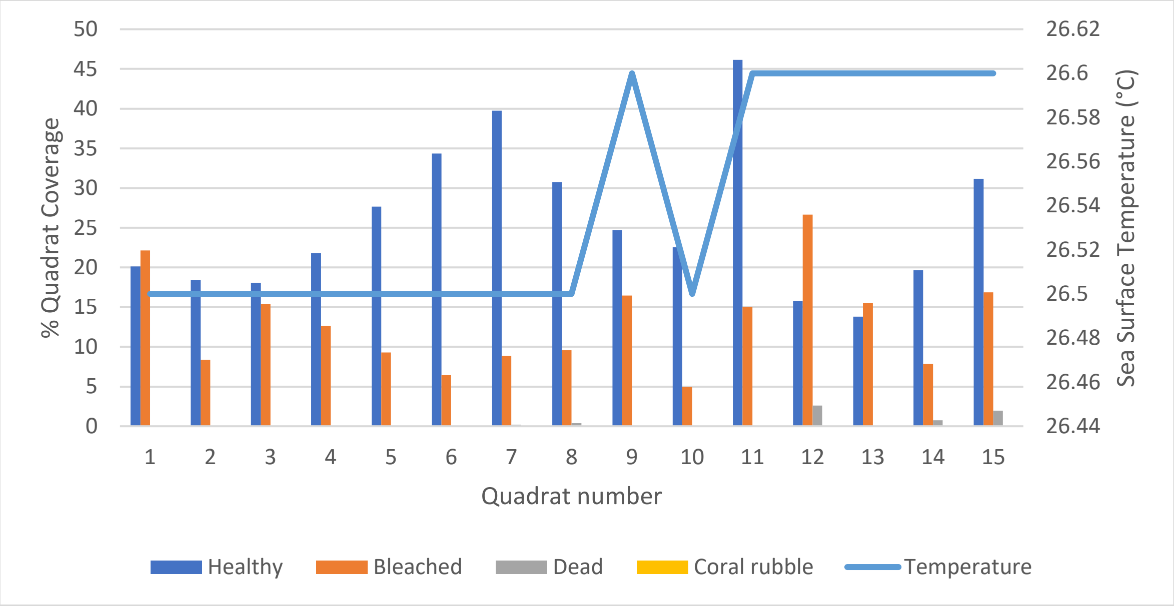

Figure 1: Percent coverage of coral conditions along the East Bermuda transect in relation to the temperature and quadrat.

Figure 2 shows the impact of SST on coral. The graph shows that an increase in SST are consistent with the change in coral condition. There is an increase of bleaching at quadrats 5, 6 and 7 due to the increase from 26.7 to 26.85. There was also bleaching increase at 12, 13, 14 and 15. However, there were cases of dead coral at lower temperatures and during fluctuations between quadrats 9, 10 and 11. There were higher percentages of dead, bleached and coral rubble than healthy even though the temperatures had only increased by 0.1°C. ANOVA analysis showed a significant difference between the state of the coral (p = 2.4-07). Bonferroni comparison showed a significant difference between healthy and dead (3.78-05), healthy and coral rubble (p = 2.36-06), bleached and dead (p = 0.0011) and bleached and coral rubble (p = 0.0001). However, there was a significant difference between healthy and bleached (p = 0.42) and dead and coral rubble (p = 0.29).

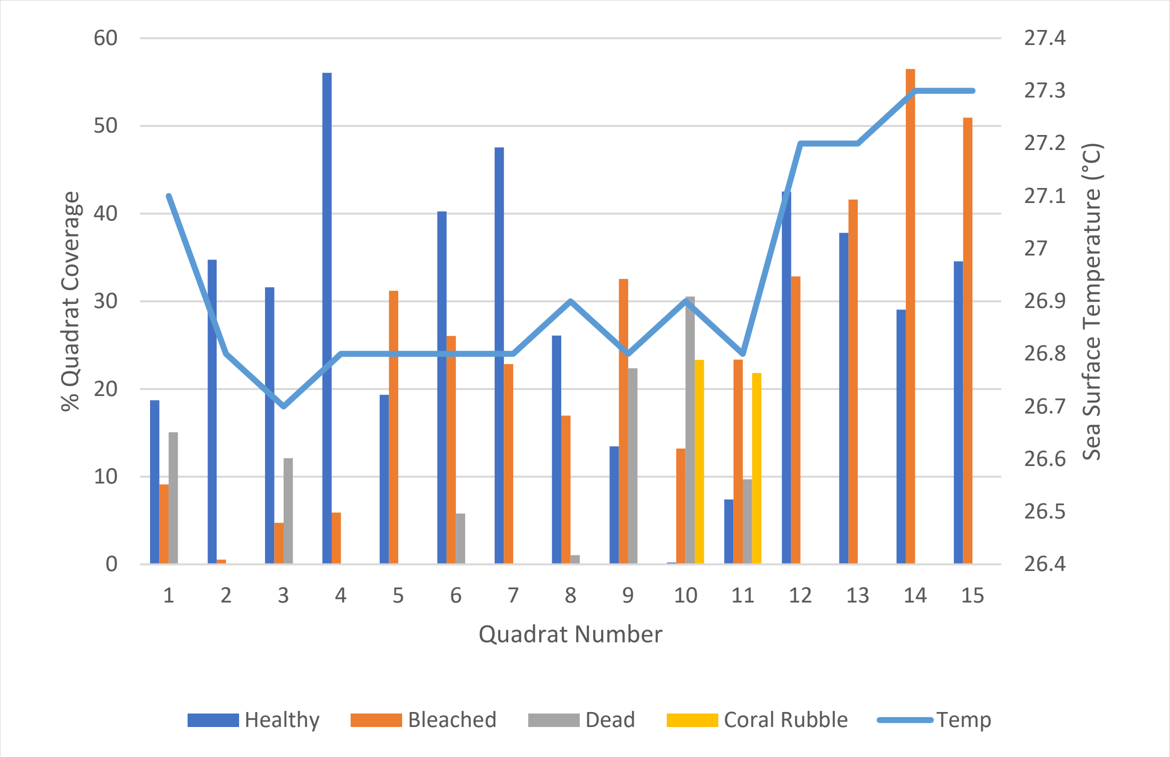

Figure 2: Percent coverage of coral conditions along the Agincourt transect in relation to the temperature and quadrat.

Figure 3 shows the relation between SST and the condition of the coral. This graph shows that with the increase of SST the bleaching of the coral also increases. Just under half of the quadrats have a higher percentage of bleached coral than healthy. However, quadrats 10, 11, 12 and 13 are at the same temperature as 6, 7 and 8 but have a higher percentage of healthy coral than bleached.

There are small percentages of dead coral and coral rubble with the first increase in temperature. ANOVA analysis showed that there was a significant difference between quadrats (p = 9.76-17). Bonferroni comparisons showed there was a significant difference between healthy and dead (p = 5.03-08), healthy and coral rubble (p = 1.44-08), bleached and dead (p = 1.71-12) and bleached and coral rubble (p = 1.36-13). However, there was not a significant difference between healthy and bleached (p = 0.71) and dead and coral rubble (p = 0.10).

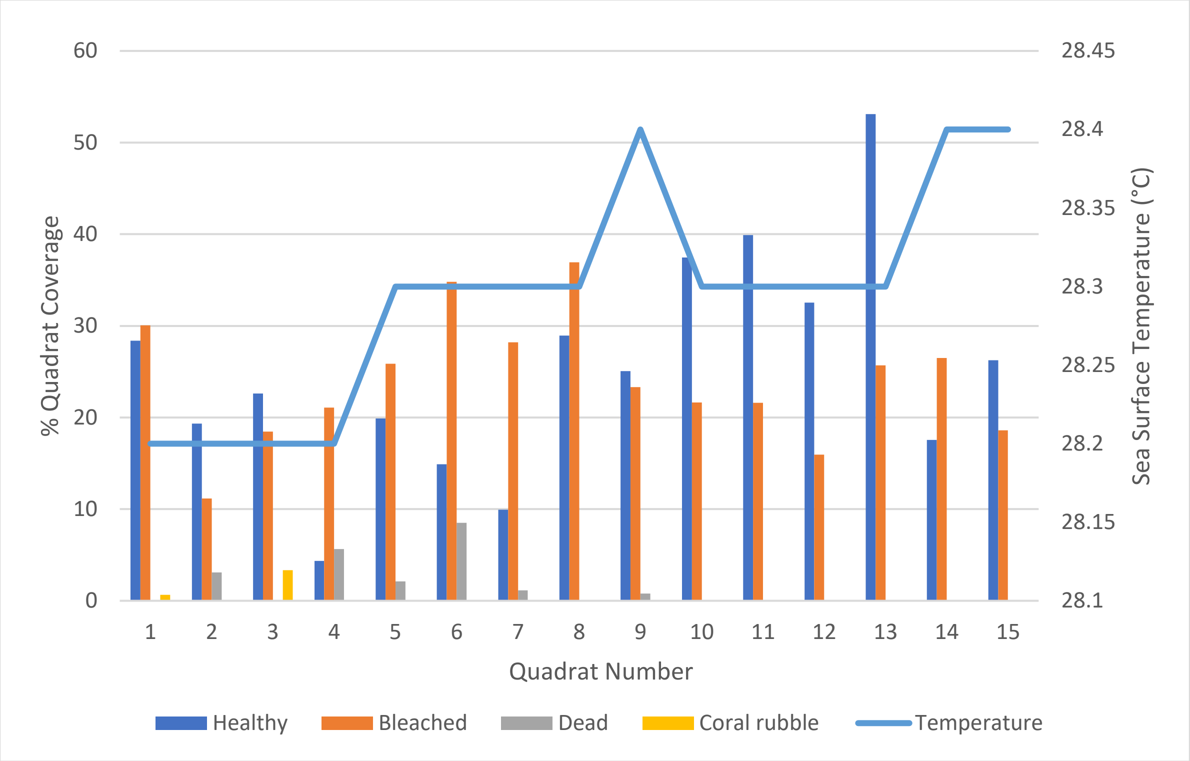

Figure 3: Percent coverage of coral conditions along the Egmont transect in relation to the temperature and quadrats.

Sea Surface Temperature

Figure 4 shows the mean monthly SST data from Giovanni for all three sites between 2002-2020. The graph shows that the temperatures for Agincourt and East Bermuda follow a similar pattern, whereas there were many variations within the Egmont SST. The highest temperatures for East Bermuda were around July of every year indicating the summer season. The highest for Agincourt were around October every year indicating the summer season, Whereas the Egmont reef showed no consistent pattern in the seasonal temperature.

Figure 5 shows the 8 daily SST from Giovanni for all three sites between 2002-2020. The patterns follow the same as Figure 4, however there are fluctuations at both the lower and higher ends of the time series. The arrow for Egmont shows that the SST was on the rise and reaching its highest temperature when the quadrats were taken. Agincourt is the same however it is in between the highest seasonal temperature range found at Bermuda and the smallest at Egmont. East Bermuda however was surveyed when the temperature started to decrease.

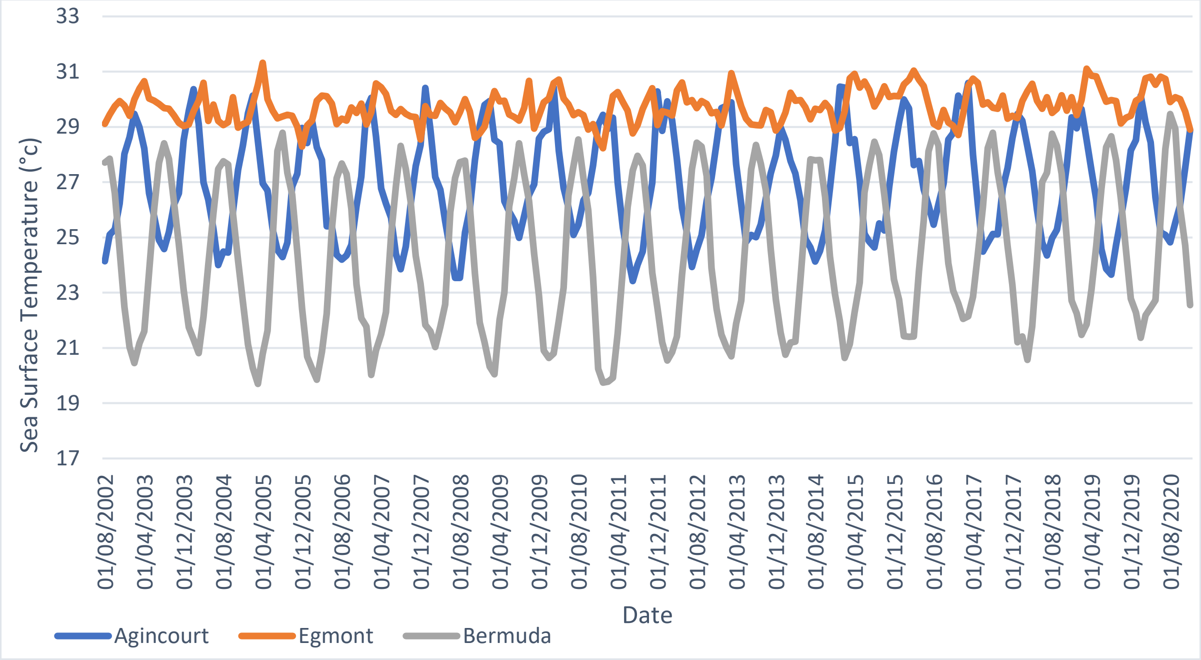

Figure 4: Mean monthly sea surface temperature at all three sites between 2002-2020.

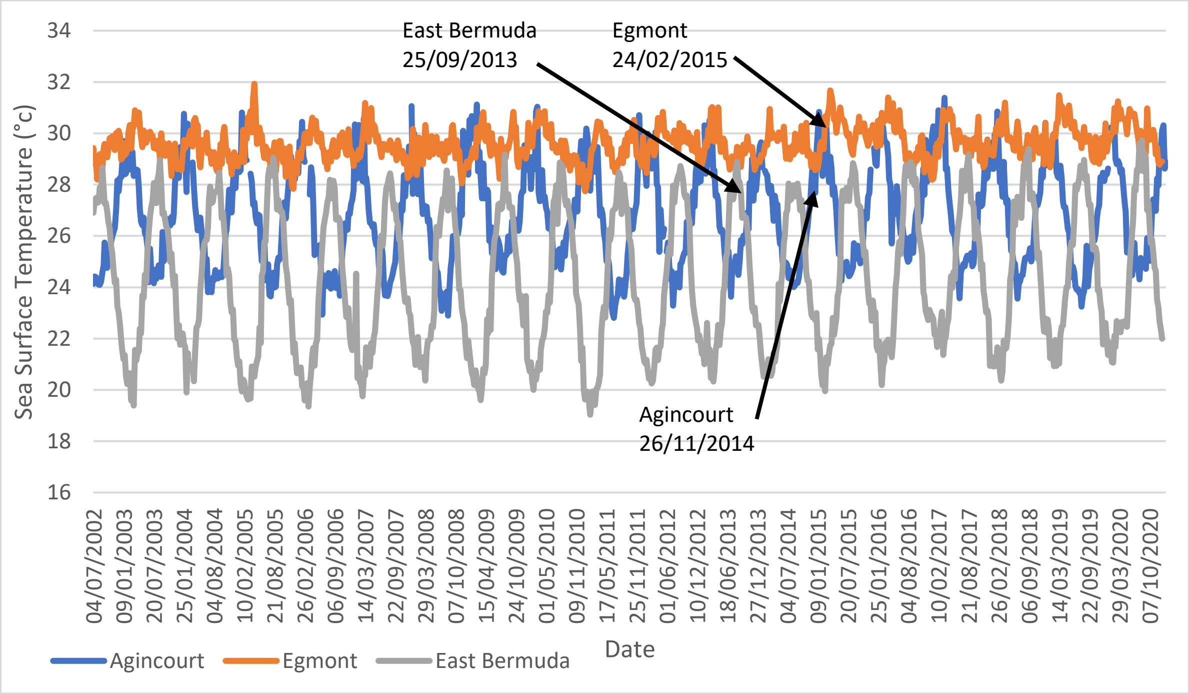

Figure 5: 8 daily sea surface temperature at all three sites between 2002-2020. The annotations show the temperature of the reefs at the time of analysis in comparison to weeks before and after.

ANOVA one way test- hypothesis results

Figure 6 shows the comparison of bleaching between sites using each quadrat. The highest percentages of bleaching occurred at Agincourt with the second highest at Egmont. The percentage of bleaching at East Bermuda was relatively low, apart from quadrats 1 and 12 which had a spike.

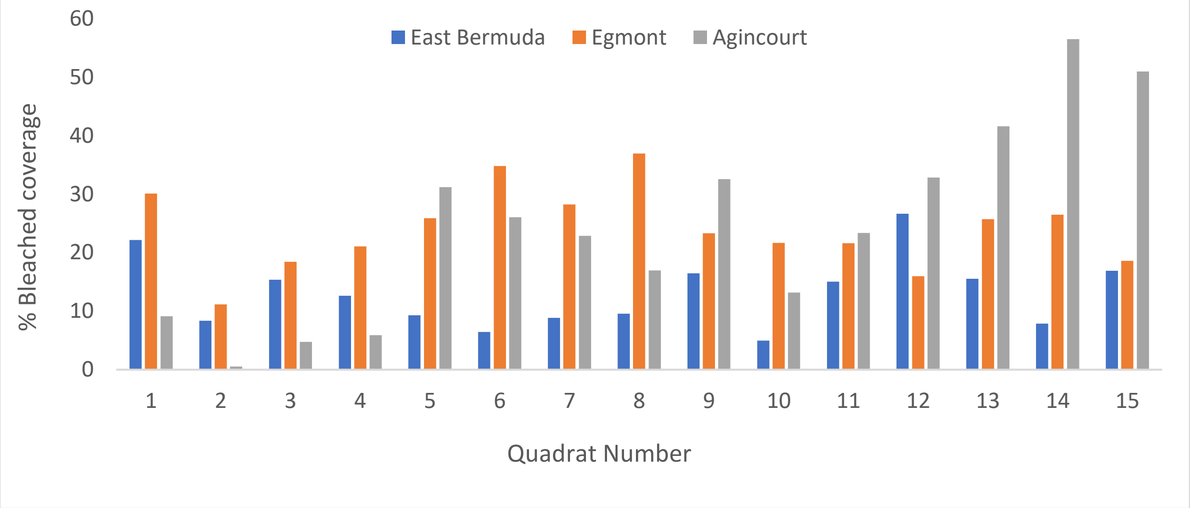

Figure 6: Percent coverage of bleached coral at each quadrat for all three reefs. See (table 1) for ANOVA results.

Table 1: Results of the one-way ANOVA analysis of the bleaching between sites

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1257.693	2	628.8466	5.172523	0.009814	3.219942
Within Groups	5106.127	42	121.5745			
Total	6363.82	44				

Agincourt suffered the most bleaching (M = 24.6, SD = 16.8), followed by Egmont (M = 23, SD= 6.9) and East Bermuda (M = 13, SD = 6.4). ANOVA revealed significant differences between groups (*F* = 3.22, *P* = .009). Bonferroni comparisons revealed that significant differences occurred between Bermuda and Egmont (*P* = .00007). There was no significant difference at the 99% confidence level between Egmont and Agincourt (*P* = .0904) and Bermuda and Agincourt (*P* = 0.018).

Figure 7 shows the comparison between the long-term heating events at each site. Agincourt and Bermuda suffered the most heating events with East Bermuda having a few events in 2016 and 2018. The highest temperatures and longest periods occurred between 2015-2017.

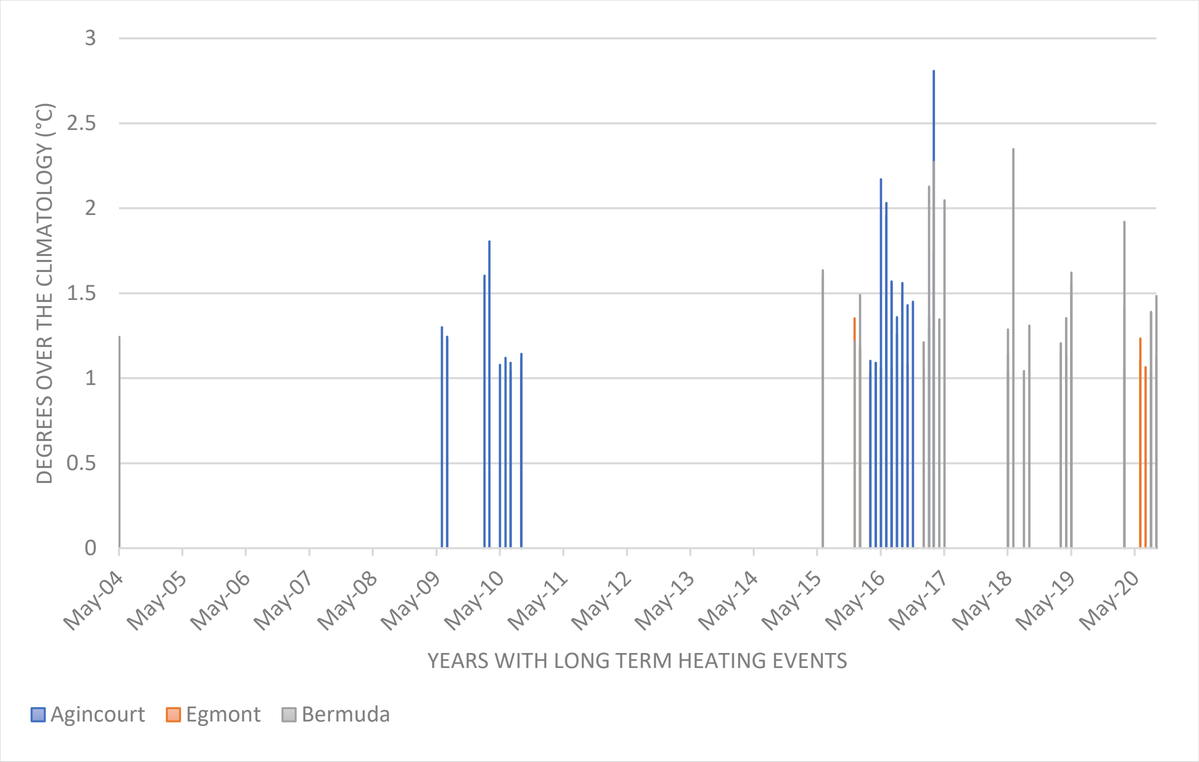

Figure 7: Long-term heating events for all three sites between 2004-2020.

Table 2: Shows the results of the one-way ANOVA analysis of long-term heating between sites.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.193603	2	0.096801	0.737088	0.481939	3.118642
Within Groups	9.849727	75	0.13133			
Total	10.04333	77				

The ANOVA results showed that there was not a significant difference between the long-term heating between sites (F = 3.11, P = 0.48). However, there were slight changes between Agincourt (M = 1.39, SD = 0.38) and East Bermuda (M = 1.38, SD = 0.35) with the most difference from Egmont (M = 1.18, SD = 0.10)

Figure 8 shows that Agincourt suffered the most degree heating weeks over the 18-year period. The main weeks occurred during 2009 and 2015-2017. Egmont suffered two events during 2005 and 2015. With East Bermuda only suffering in 2020.

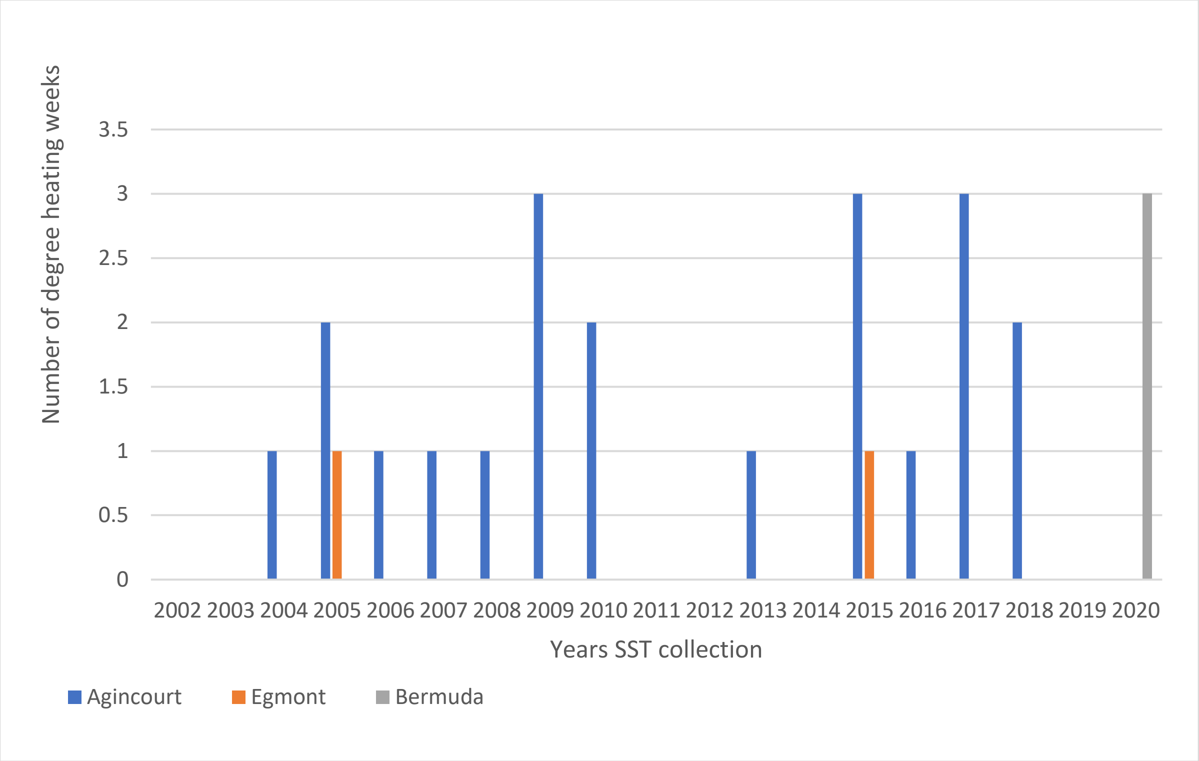

Figure 8: The number of times a degree heating week (DHW) occurred each year between 2002-2020 and each site.

Table 3: Results of the one-way ANOVA analysis of the number of degree heating weeks between sites from 2002-2020.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	12.03509	2	6.017544	10.12131	0.000184924	3.168246
Within Groups	32.10526	54	0.594542			
Total	44.14035	56				

Agincourt suffered a higher number of DHW (M = 1.10, SD = 1.1), followed by East Bermuda (M = 0.15, SD = 0.68) and Egmont (M = 0.10, SD = 0.31). ANOVA revealed significant differences between groups (F = 3.16, P = .00018). Bonferroni comparisons revealed that significant differences occurred between Agincourt and Egmont (P = .00052) and Agincourt and East Bermuda (P = .003). However, there was no significant difference between Egmont and East Bermuda (P = 0.763)

Discussion

Focusing on the SST variations within three different oceans allowed for an insight into how coral thresholds varied depending on their environment and how changing SST affects the condition of the coral. In this study analysis was focused around the Atlantic, Indian and South Pacific Oceans due to the fluctuation and variety of temperatures throughout the year.

Quadrat analysis showed that the temperature increase on the East Bermuda reef (Figure 1) was not sufficient to cause bleaching. This means that the bleaching that was observed along the transect was a result of temperature increase from the weeks/months prior to the survey. There was significant bleaching along the Agincourt transect (Figure 2) from transect 5-15 due to a 0.8°C increase in SST. While there was still a small percentage of bleaching in the first 5 weeks, the temperature was decreasing, reducing the impact. Figure 2 also showed dead coral on quadrats 1-3 suggesting that the temperature of the weeks and days leading up to the survey were prolonged causing coral death by preventing recovery. Quadrats 9, 10 and 11 showed small percentages of healthy (<12%) coral compared to bleaching (<32%) and coral rubble (<23%). Figure 3 showed that the first increase in temperature caused higher percentages of bleached coral compared to healthy coral. However, quadrats that were further down the transect showed higher levels of healthy coral than bleached even though temperatures remained the same level.

The monthly SST time series highlights the patterns and variations between the different sites. Figure 4 East Bermuda shows the largest variation in temperature throughout the 18-year period. These variations are the result of the seasonal cycle, changes in wind and ocean circulation. Warm water is transported from the Indian Ocean and Pacific Ocean into the Atlantic Ocean and cold water is transported back through the Atlantic Ocean once cooled by the Artic Sea (Lozier., 2010). Since the end of 2011, the variation in temperatures has decreased, indicating the potential for increased numbers of bleaching events. The smallest variations can be seen between 01/12/2015 – 01/12/2017 which coincides with the mass bleaching event of 2015-2017. Agincourt showed similar trends with the smallest variation and spikes in temperature between 2014-2016. This coincides with the mass bleaching event of 2016-2017 on the Great Barrier Reef. However, Egmont does not follow the usual trend as the other two reefs. Temperatures spiked in 2005 above 31°C but quickly falls and stays between 29°C and 30°C. However, in 2015 there was a spike in temperature with little cooling which lasted until the end of 2016. There were further spikes in 2018.

The weekly SST time series (Figure 5) highlights the fluctuations that are overlooked by the monthly data. The time series showed that the Agincourt temperature had increased by 3°C by the date of survey and continued to increase in weeks following. This is evidenced in figure 2 by the high percentages of bleached, dead, and coral rubble and the trend in temperature across the transect. The temperature at Egmont had increased by 2°C by the time of the survey. This explains the high percentage of bleached coral on the first quadrat and the increase of temperature throughout the transect as temperature continued to increase two months after the survey date. East Bermuda was surveyed as the temperature started to decrease. The temperature has decreased by 2°C at the time of analysis, which suggests the percentages of bleaching and the decrease of bleaching along the transect except for increase towards the end of the transect with the increase in temperature.

The results from Table 1 proved the hypothesis that there is a difference between the degree of bleaching between the sites. The standard deviation showed that Agincourt suffered the most bleaching, with Egmont second and East Bermuda suffering the least. This could be explained by the increase of 2-3°C in temperature for Agincourt and Egmont causing the coral to be pushed past their thermal threshold resulting in the bleaching. However, at East Bermuda the temperature had decreased by 2°C, returning the coral to their threshold and enabling the coral to start the recovery process.

Results from Table 2 disproved the hypothesis that there was a difference between long term heating events between the sites during 2002-2020. The standard deviation showed there was a slight difference but not enough to be significant. This could be explained by the events occurring during global mass bleaching events. However, Egmont only suffered two long term heating events in the 18-year period. This suggests that the increase in temperature seen in the Atlantic Ocean and South Pacific Ocean was below the climatological temperature of the Indian Ocean, resulting in less heating events.

The results from Table 3 demonstrated the hypothesis that there was a difference between the number of degree heating weeks between the sites during 2002-2020. The standard deviation showed that Agincourt suffered the most DHW with Bermuda in second and Egmont suffering the least. The highest DHW's for Agincourt occurred during 2005, 2009, 2015 and 2017, which coincides with the Great Barrier Reef mass bleaching events. Egmont suffered a bleaching event in 2015-2016 which coincides with the DHW.

Conclusion

This project aimed to identify the impact that geographical variability has on the bleaching stresses for coral reefs. Based on the quantitative analysis of coral and SST data it can be concluded that the geographical location has key factors for the contribution of stresses causing coral bleaching. The results indicate that the long term heating events contribute to the DHW's which determines the period of time that the coral is subdued to temperatures past their thermal threshold.

The research clearly illustrated the impact that SST has on coral bleaching but it also raised questions relating to how the wind speed, CO_2 levels and ocean circulation impact the corals. Further studies could address how these impact corals.

The findings help address the gap in knowledge as many of the past studies have just focused on singular reefs, so this research provides the comparison between the oceans. The findings confirm and support previous studies stating that the temperature needs to be 1°C above the climatology mean for a minimum of two weeks for bleaching to occur.

Future work

This research posed limitations as only 15 quadrats were selected per transect. A larger number would have provided a more in depth analysis of the impacts. Analysing further reefs within the three oceans could provide more insight into the impacts. This is due to different regions of the oceans having different temperatures and water inputs from warmer and colder regions.

Acknowledgement

I would like to thank my supervisor Dr Jill Schwarz for providing support, guidance, and feedback throughout this project. Through the statistics for marine conservation module Jill also provided me with the tools to successfully complete my dissertation.

I would also like to thank my personal tutor Dr Tim O'Hare for his valuable advice and guidance through my academic career. Tim also advised me in choosing a project advisor and guided me towards Jill.

Thirdly, my lecturers at Plymouth University that have provided me with the knowledge and skills to choose the path of my research and enable the completion of my dissertation.

Lastly, my friends and family that supported me through my research and proofreading my work.

I would also like to thank and acknowledge appropriately Giovanni (2021) for a specific sea surface temperature data set, whereby some 'analyses and visualizations used in this paper were produced with the Giovanni online data system, developed, and maintained by the NASA GES DISC.'

References

Abdo, D. 2012. Turning up the Heat: Increasing Temperature and Coral Bleaching at the High Latitude Coral Reefs of the Houtman Abrolhos Islands. *PLoS ONE*, 7(8), p.e43878.

Anthony et al. 2011. Ocean acidification and warming will lower coral reef resilience. *Global Change Biology*, 17(5), pp.1798-1808.

Baker, et al. 2008. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, [online] 80(4), pp.435-471. Available at: https://doi.org/10.1016/j.ecss.2008.09.003

Cantin et al. 2010. Ocean Warming Slows Coral Growth in the Central Red Sea. *Science*, 329(5989), pp.322-325.

Cao et al. 2007. Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation. *Geophysical Research Letters*, [online] 34(5). Available at: https://doi.org/10.1029/2006GL028605

Coelho et al, 2017. Shading as a mitigation tool for coral bleaching in three common Indo-Pacific species. *Journal of Experimental Marine Biology and Ecology*, [online] 497, pp.152-163. Available at: https://doi.org/10.1016/j.jembe.2017.09.016

Gattuso, J. and Hansson, L. 2011. *Ocean acidification*. United States: Oxford University, pp.41-45.

Giovanni.gsfc.nasa.gov. 2021. *Giovanni*. [online] Available at: <https://giovanni.gsfc.nasa.gov/giovanni/> https://giovanni.gsfc.nasa.gov/giovanni/#service=ArAvTs&starttime=2001-01-01T00:00:00Z&endtime=2020-12-31T23:59:59Z&bbox=73.5938,-4.9219,81.3281,0.3516&data=MODISA_L3m_SST_Monthly_4km_R2019_0_sst&dataKeyword=sst&portal=GIOVANNI&format=json – Agincourt monthly data

Goreau, T. and Hayes, R. 1994. Coral Bleaching and Ocean "Hot Spots." *Ambio*, 23, pp.176-180.

Hoegh-Guldberg et al. 2017. Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science*, [online] 4. Available at: https://doi.org/10.3389/fmars.2017.00158

Hughes et al. 2017. Global warming and recurrent mass bleaching of coral. *nature*, 543, pp.373-379.

Kirke, B. 2003. Enhancing fish stocks with wave-powered artificial upwelling. *Ocean & Coastal Management*, [online] 46(9-10), pp.901-915. Available at: https://doi.org/10.1016/S0964-5691(03)00067-X

Lesser, M. 1996. Elevated temperatures and ultraviolet radiation cause oxidative stress and inhibit photosynthesis in symbiotic dinoflagellates. *Limnology and Oceanography*, 41(2), pp.271-283.

Lough, J. 2000. 1997-98: Unprecedented thermal stress to coral reefs?. *Geophysical Research Letters*, 27(23), pp.3901-3904.

Lozier, M. 2010. Deconstructing the Conveyor Belt. *Science*, [online] 328(5985), pp.1507-1511. Available at: <https://science.sciencemag.org

Masselink, G. 2014. *Coastal environments and global change*. Chichester, West Sussex: Wiley, p.380.

McWilliams. 2005. Accelerating the impacts of temperature-induced coral bleaching in the Caribbean. *Ecology*, 86(8), pp.2055-2060.

Moberg, F. and Folke, C. 1999. Ecological goods and services of coral reef ecosystems. Ecological Economics, [online] 29(2), pp.215-233. Available at: https://doi.org/10.3389/fmars.2017.00158

Nakamura et al. 2003. Water flow facilitates recovery from bleaching in the coral Stylophora pistillata. *Marine Ecology Progress Series*, [online] 256, pp.287-291. Available at: <http://www.int-res.com/articles/meps2003/256/m256p287.pdf>.

Reaka-Kudla M.L. 2001 Known and Unknown Biodiversity, Risk of Extinction and Conservation Strategy in the Sea. In: Bendell-Young L., Gallaugher P. (eds) Waters in Peril. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-1493-0_2

Reaka-Kudla, M.L. 1997. ‘The global biodiversity of coral reefs: A comparison with rain forests’, in *Biodiversity II*: Understanding and protecting our biological resources. Washington, D.C, p.84.

Selig, E. and Bruno, J. 2010. A Global Analysis of the Effectiveness of Marine Protected Areas in Preventing Coral Loss. *PLoS ONE*, [online] 5(2), p.e9278. Available at: https://doi.org/10.1371/journal.pone.0009278

Ward et al. 2002. Coral bleaching reduces reproduction of Scleractinia corals and increases susceptibility to future stress. Pro. 9th Int. Coral Reef Symp.. 2.

West, J. and Salm, R. 2003. Resistance and Resilience to Coral Bleaching: Implications for Coral Reef Conservation and Management. *Conservation Biology*, [online] 17(4), pp.956-967. Available at: **https://doi.org/10.1046/j.1523-1739.2003.02055.x**