CORAL RESILIENCE: THE EFFECT OF SUCCESSIVE BLEACHING ON *ACROPORA PULCHRA*

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Abstract. Anthropogenic induced climate change will lead to future surface ocean temperature rise. This thermal increase will drastically effect the coral reef ecosystem, a highly productive ecosystem that is key for coastal erosion protection, tourism, tropical island economies, and marine organisms' breeding, spawning and feeding. *Acropora pulchra* is a highly susceptible, common, fast-growing, branching, staghorn coral that provides a habitat for many reef organisms. The objective of this study was to assess the susceptibility to thermal stress of *A. pulchra* to determine if a relationship was present between thermal stress history and the susceptibility to bleaching. Coral was treated in 30°C conditions for six hours then allotted a recovery period and treated again. Statistically significant higher mortality rates were observed in the first heat shock than the ambient 27°C control treatment. No mortality was observed in the second heat shock. No statistical significance was observed in growth rate between the different heat treatment rounds and the control treatment. Although a potential resilience during the second successive stress treatment was observed, prolonged exposure at 30°C will likely lead to reduction in population size of *Acropora pulchra* and lead to a severe impact on the entire coral reef ecosystem.

Key words: Acropora pulchra; *climate change; RCP 8.5; surface ocean temperature rise; temperature; coral bleaching; Moorea, French Polynesia*

INTRODUCTION

Anthropogenic effects of human agricultural land use changes and fossil fuel emissions have increased carbon dioxide levels from 280 ppm preindustrial concentration to 406 ppm today (Siegenthaler et al., 1993; NASA, 2017). Due to human activity, greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, have accumulated in the atmosphere at concentrations higher than ever recorded in the last 800,000 years, intensifying the greenhouse gas effect and inducing accelerated warming of earth's surface (Stocker, 2013; Jacobs, 1999). According to the different representative concentration pathways (RCPs) of future greenhouse gas emissions, global surface temperature increase will range from .3°(RCP2.6) to 4.8°C (RCP8.5) by the end of the 21st century (Stocker, 2013).

In addition to increased global temperatures, 30 percent of anthropogenic atmospheric carbon dioxide has dissolved into the ocean, causing reduction of ocean pH and ocean temperature increase (Stocker, 2013; Jacobs, 1999). Of the cumulative anthropogenic carbon dioxide emissions, ~155 Gt carbon have been absorbed by the ocean sink (Stocker, 2013). Surface ocean temperature is expected to increase by 0.2° (RCP2.6) to 2°C (RCP8.5) by the end of the 21st century with corresponding pH decrease of 0.06-.32 (Stocker, 2013). Surface ocean pH has already decreased 0.1 pH units below the pre-industrial levels (Stocker, 2013). Projected ocean acidification will further contribute to the reduction of calcification rates in calcifying organisms, including essential coral reef building hermatypic corals and crustose coralline algae (Shaw et al., 2016, Hoegh-Guldberg et al., 2007). With the current rate of greenhouse gas dependence and evident time needed before a carbon neutral emission status, the need to understand the outcomes of higher concentrations effect on ambient environmental conditions must be acknowledged. With average ocean temperatures increasing, the ambient conditions of the marine environment are changing. It is critical to assess the consequences of these changes of ocean chemistry because it will directly alter the environment of all marine organisms.

Coral is an ecosystem engineer, forming habitat for other biota to reside in. Coral reefs compose less than one percent of the ocean floor, yet support more species per unit area than any other marine ecosystem (Frost, 2016). In general, coral reefs are found in oligotrophic waters with low nutrients and serve as a source of productivity for other organisms (Hatcher,

1988). These areas of high productivity create an environment for breeding, spawning, and feeding (Moberg et al., 1999).

Coral reefs are not only essential for marine organisms, but also physically and economically important to global communities. Coral reef ecosystems provide a source of income for island and coastal communities by supporting reef fish and creating a food source for many commercial fish (Spurgeon, 1992). The complex, aesthetical structures of coral reefs also draw in tourism revenue that supports local communities. Reefs provide support for coastal land as well. Barrier reefs provide a physical defense against coastal erosion by dissipating wave energy (Cesar et al., 2004). Six thousand square kilometers of coral reefs protect coastal shore land along the Pacific, Indian and Atlantic oceans, supporting more than 100 countries' coastal lands (Salvat, 1992). If coral growth diminishes, the defense they provide will be reduced, yielding economic losses for coastal communities (Spurgeon, 1992). Study of coral reef species has opened a door to advances in the pharmaceutical industry. Different species dependent on coral reefs have been used in research for HIV therapy, tumor inhibition, anti-inflammatory agents, and anticoagulating properties (Carte, 1996). Due to the marine organisms that are dependent on the well-being of the coral reef community, and their global impact, the need to understand coral and its resistance to increase in ambient temperatures is the first step to understanding how anthropogenic-induced global warming will alter coral reefs.

Corals are a complex, colonial animal that belongs to the phylum Coelenterata. Coral's ability to survive in low-nutrient water is dependent on the endosymbiotic relationship it shares with unicellular dinoflagellates (called "zooxanthellae"), of the genus *Symbiodinium*. The *Symbiodinium* in the coral's tissue are what gives coral its vibrant pigmentation. This relationship with *Symbiodinium* has allowed the ecological success of coral reefs by using photosynthesis to provide coral with metabolic products for $CaCO_3$ for its skeleton. However, this symbiotic relationship also restricts coral to specific thermal and environmental limitations (Gosliner et al., 1996).

As the ocean environment changes, coral's ability to adapt is essential for the survival of many species. Coral reef bleaching and mortality due to alterations of its ambient environment leads to dire consequences for all the organisms dependent on the productivity oasis coral reefs provide. Physical and chemical changes in the marine environment lead to the phenomenon known as coral bleaching in which endosymbiont density decreases enough to cause pigmentation decline, nutrient depletion, and in some cases coral mortality (Fitt et al., 2001). In particular thermal stress of corals has led to notable mass bleaching episodes. When the thermal tolerance of the zooxanthellae is exceeded, it is expelled from the coral or dies, leading to pigmentation loss (Middlebrook et al., 2008). Due to the magnitude of surface ocean temperature anomalies in 1998, 2002, 2016, the Great Barrier Reef, off the northeastern shore of Australia, experienced reef wide mass bleaching events (Hughes et a., 2017). With predicted ocean temperature levels rising, it is essential to quantify the effect of successive thermal stress on coral in order to prevent threats to biodiversity and the global resources that coral reef ecosystems provide.

Some of the known stressors that affect coral are temperature increase, salinity decrease, ocean acidification, and eutrophication (Sakami, 2000). These stressors are all being intensified due to human activity, leading to increased and intensified ocean temperature anomalies. The thermal tolerance of reef building coral is expected to be exceeded on a more regular basis due to global temperature rise (Middlebrook et al., 2008). Increased bleaching events will either lead to coral reef deterioration and the switch to algae dominated reefs or coral will develop thermal resilience. Studies have noted differing bleaching susceptibility among coral taxa (Guest et al., 2012). The understanding of this susceptibility and tolerance will allow the understanding of future coral reef composition.

The two successive bleaching events that occurred in Moorea, French Polynesia in 2002 and 2003 revealed a change in coral susceptibility possibly due to thermal history (Carrol et al., 2017). A change in Acroporid species towards increased durability in the successive bleaching in 2003 was observed (Guest et al., 2012; Middlebrook et al., 2008). This study aimed to analyze the effects that anthropogenic-induced climate change has on *Acropora pulchra* by assessing whether coral resilience to bleaching correlates with its thermal history and if repetitive stress-induced periods affects growth rate and mortality levels.

In this study, collections of a common reef-building sclerictinian coral species, *Acropora pulchra*, were tested to see if a higher thermal

stress history would lead to lower levels of susceptibility to temperature fluctuations expected in Moorea in the near future under RCP 8.5 conditions.

Specimen for this study were collected in the fringing back reef off the eastern shore of the island of Moorea, where average summer sea temperature has been recorded as approximately 27.45°C (Washburn, 2011). Due to their ambient condition and the RCP 8.5 prediction of 2°C from Assessment Report 5, the thermal shock for this experiment was of a 2°C rise. Through repetitive cycles of thermal shocks and recovery periods, this study aimed to assess *Acropora pulchra's* susceptibility to thermal change and determine the relationship between thermal stress history and *A. pulchra's* susceptibility to bleaching. Based on previous studies of *Acropora's* susceptibility, *A. pulchra* was hypothesized to be highly susceptible to thermal change (Carrol et al., 2017, Guest et al., 2012). A negative correlation between increased thermal stress history and *A. pulchra* susceptibility was expected to be observed. Field surveys of *Acropora pulchra* distribution were done at Temae beach off the eastern shore of the island. *Acropora* presence was related to benthic depth, and coral colony peak depth. *Acropora* colonies were predicted to be more prevalent in areas of increased depth due to less direct light exposure. Through this study, the reality of *Acropora pulchra* adaptability to future greenhouse gas concentration scenarios was expected to be understood with intentions to represent coral reef composition shift.

METHODS

Study site

This project was conducted on the volcanic island of Moorea, French Polynesia (S17° 30', W149° 50'; Fig. 1). The island is surrounded by a fringing reef, lagoon and barrier reef. The mean winter ocean temperature is 26°C and the summer maximum is 29°C (Carroll, 2017). The island experienced above average ocean temperatures in 2002, 2003 and 2007 leading to mass bleaching events (Carroll, 2017). These bleaching events are believed to have increased *Acropora pulchra's* resilience against future bleaching. Experimental work was conducted at the Richard B. Gump Research Station's wet lab in Cook's Bay (Fig. 1). Coral collection and survey transects and were done at Temae beach on the Eastern side of the island. The GPS coordinates for the transects are presented in Figure 1.

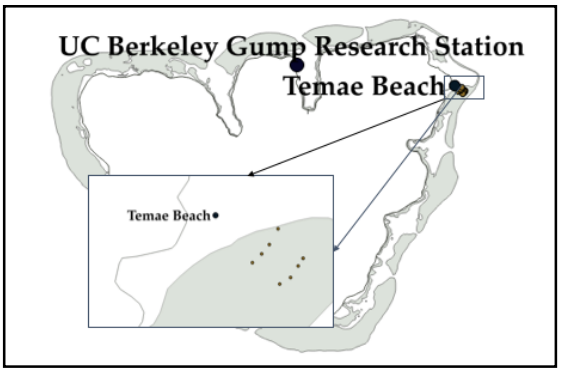

FIG. 1. Map of the island of Moorea, French Polynesia showing the UC Berkeley Gump Research Station, Temae beach and the GPS coordinates of the transects.

Survey design

The outer reef and the lagoon were surveyed for *Acropora* colonies using transects. Two sets of four transects were placed parallel to the back reef at Temae beach, one set in the lagoon and one in close proximity to the back reef. Each of their distances spanned 16 meters. *Acropora* head presence, colony peak height, and maximum length of each colony was recorded. The benthic depth surrounding each colony was also recorded. To maintain depth integrity, all transects were conducted during the same tidal phase.

Species collection and preparation

The specimens were identified and collected exclusively from already broken branches of *Acropora pulchra* at Temae beach (Ditlev, 1980; Appendix A). No intact coral branches were taken or broken in order to perform this experiment. During collection, a total of 24 colonies were collected from in order to allow sufficient replication of each treatment group. Only apex pieces were collected in order for growth rates to be recorded. A minimum of 4 nubbins from each colony were needed in order to allow each colony to receive each treatment (A-D). *Acropora* coral apex pieces were broken into 20-60 mm pieces and mounted to textile squares or chicken wire with super glue and Bison repair aqua epoxy. Each coral's initial length was measured in millimeters and recorded. Each nubbin was given a number identification to indicate which colony it came from (1-24) and a randomly assigned letter value (A-D) to indicate which treatment it would later receive. A minimum of 96 coral nubbins were needed, with excess

prepared to account for potential loss of coral that did not recover from the transportation and introduction to the fresh sea water flow table environment. These excess nubbins were identified with their colony number and assigned with different letter values (E-Z). If mortality of A through D occurred, an excess nubbin from the same colony was substituted into that treatment group.

Each colony experienced varying levels of mortality due to the transition. Due to this, not all colonies went through all four different treatments. After nubbin preparation and a recovery period, colonies 9 and 17 were completely removed from the experiment.

Due to high mortality, colonies 14 and 18 did not receive treatment A, colony 16 did not receive treatment B, colonies 13, 14, 16, and 22 did not receive C, and colony 22 did not receive D. Due to mortality from treatment B heat shock 1, only data collected from colonies 1, 2, 4, 5, 6, 7, 8, 10, 19, 20, 21, 23, and 24 were used to assess the results of heat shock 2. Similarly, for the second control shock of treatment A data was only collected from colonies 1, 2, 3, 4, 5, 6, 8, 10, 11, 12, 15, 16, 22, and 24.

The coral was kept in a fresh seawater flow table in the wet lab at the Gump Station. The tables receive water directly from Cook's Bay and served as a stress-free environment for the species to acclimate in (pH= 8.2, temp= ~27℃).

Monitoring of water chemistry and coral care

In order to assess the seawater carbonate chemistry of the controlled environment, weekly monitoring of salinity, pH and alkalinity were collected, using a LaMotte Water monitoring kit (Lenz & Edmunds, 2017). A HOBOware pendent temperature monitor was placed in the flow table and temperature collected every minute. To remove excessive sedimentation buildup in the fresh flow water table, a siphon was used to clean the nubbin tiles and the bottom of the tank twice a day. If excess sedimentation was present, extra cleaning was done.

Treatments

After the nubbins had been given substantial time (~one week) to recover from collection and cutting, the nubbins from each branch underwent one of the 4 treatment categories shown in Table 1. Each treatment was of six-hour length. Temperature treatments were 27°C (ambient) and 30°C (RCP8.5 surface ocean temperature). The *A. pulchra* nubbins either experienced the treatment once (treatment C and D) or twice (treatment A and B). The ambient treatments A and C served as control groups to quantify the levels of stress the nubbins may have received through the process of being moved from the flow tank to the treatment tanks, where they did not receive flow for six hours. In between each treatment the *A. pulchra* nubbins were placed back into the fresh sea water flow table. During the treatment periods, time of occurrence of initial mucus formation, polyp exposure, and bubble development were recorded. Mucus presence was used as an indicator of stress.

TABLE 1. Temperature shocks received by *A. pulchra* nubbins in treatment categories A-D.

Treatments	No. of Shocks	Temp.	Treatment rounds
A	2	27°C	Control 1 & 2
B	2	30°C	Heat shock 1 & 2
C	1	27°C	Control 1
D	1	30°C	Heat shock 1

Coral resilience treatment procedure

Immediately prior to treatment, post treatment and post recovery, each coral nubbin went through the photograph process described below in the *Coral Health Assessment*. The treatment periods were six hours in length. Each nubbin was placed in its own treatment tank. Each treatment tank was placed within a larger tub, serving as a water bath to reduce the temperatures from fluctuating from its corresponding treatment temperature. Seven separate water baths were used to prevent pseudo replications. Increased temperature treatment water was created by submerging glass jars of boiled water in the heat bath water. Water temperature was constantly monitored throughout the six-hour treatment and when necessary glass jars of boiled water placed in and removed from the heat bath.

Due to manual manipulation of water temperature, the water temperature fluctuated. The aimed for temperature range was 30-31.5℃. If the temperature fluctuated from this range warmer or colder water was immediately added to the water bath. No temperature fluctuations outside this range lasted a substantial amount of time (<5 minutes). The mean temperature, maximum temperature and minimum temperature observed during each

treatment and treatment round is presented below in Table 2.

TABLE 2. The mean, maximum and minimum temperatures the *A. pulchra* nubbins experienced in treatment A, B, C, D.

Treatment	round	Mean	Max	Min
A control	1	27.12	27.6	26.7
A control	2	27.10	27.6	26.6
B heat shock	1	30.71	31.9	30
B heat shock	2	30.61	32.5	29.1
C control	1	27.19	28.4	26
D heat shock	1	30.68	31.9	29.5

Temperature of each tank was recorded every 30 minutes. Throughout the experiment the coral was monitored and the time recorded at which they initially released mucus. Other observations such as timing of polyp exposure and bubble formation were noted. Mucus was assessed visually and by detection of mucus odor. After the six-hour treatment the nubbins were placed back into the fresh sea water flow table and photographed. After an eight-day recovery period photographs were again taken and the entire treatment procedure was repeated for nubbins in treatment groups A and B. At the end of the experimental period all *A. pulchra* nubbins were re-measured and surface area recorded.

Coral health assessment

Immediately before treatment, after and at the end of the eight-day recovery period, each *A. pulchra* nubbin was turned on its side and photographed in the flow table with consistent camera distance and positioning against a color standard. Photographs were taken with an Iphone 7 plus positioned underwater on a tripod on 1.5x zoom. The coral was photographed on the same side for all photos to ensure any pigmentation changes noted were not due to varying pigmentation along the width of the nubbin. Pictures of different severities of bleaching are attached in Appendix B. Before, immediately after and at the end of the recovery period, each coral was visually analyzed for partial mortality as defined as "percentage of dead skeletal areas on each coral colony," with 0% indicating no mortality and 100% indicating complete mortality (Bahr, 2016). Five percent increments were used. Coral declared 100% did not go through a second shock for treatment A and B.

Data analysis

Pearson Correlation tests were run to assess the data from the field survey. Correlations were run using colony length as a proxy for colony size. Correlations were run testing colony peak depth and benthic depth to analyze if either correlated to colony size.

Linear regression models and a chi squared test were run to analyze time of initial mucus excreted. A chi squared test and glmer test from the package "lme4" was used to analyze the difference in mucus present between treatment rounds. A linear model was used to assess growth rates. A glmer test and chi squared test was used to assess mortality rates between treatment groups.

An ANOVA was conducted on Rstudio between the different treatment groups for the comparison of all variables measured.

RESULTS

The peak depth, benthic depth and colony length range can be seen below in Table 3. The correlation between the peak height of the colony and the colony length resulted in a non-significant correlation ($p>.05$; $r=.18$). The correlation between benthic depth of the *A. pulchra* colony yielded a statistically significant correlation ($p<.05$; $r=.64$).

TABLE 3. The mean, maximum and minimum peak depth, benthic depth and colony length in meters of *A. pulchra* colonies surveyed at Temae beach.

Measurements	Mean(m)	Max(m)	Min(m)
Peak depth	0.83	1.59	0.52
Benthic depth	1.7	2.23	1.2
Colony length	3.5	8.72	0.6

The fresh sea water flow tank water temperature was recorded from the HOBOware pendent (Fig. 2). The mean temperature value was 28.05±.175℃. The pH for the flow table was consistently measured at 8.2 and the alkalinity at 2.96meq/L or 8.3 KH ind. Salinity was measured at 34-38 ppm.

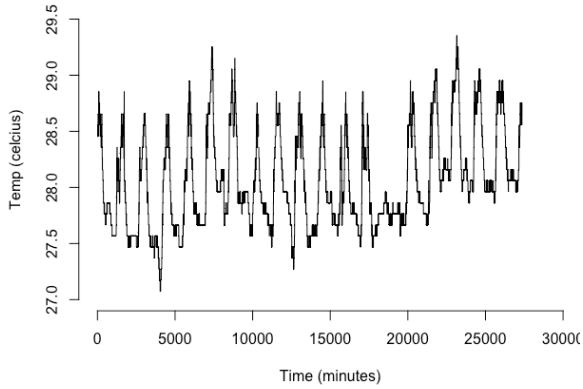

FIG. 2. Fresh sea water flow tank temperature recordings from the HOBOware device pendent in the *A. pulchra's* recovery environment.

All statistical tests were run setting the water baths as a random variable to account for any possible variance due to which water bath the nubbins received the treatment in. The water baths did not prove to have significant variation in results.

Mean time of initial mucus formation and number of nubbins in each treatment round that excreted mucus are presented below in Table 4. No mucus was excreted during heat shock 2 and control 2.

TABLE 4. Mean time of initial mucus formation and number of *A. pulchra* nubbins in each treatment round that excreted mucus.

Treatment	Nubbins that excreted mucus	Time of mucus formation
Heat shock 1	55.56%	4.43 hr
Heat shock 2	0%	NA
Control 1	10.53%	4.43 hr
Control 2	0%	NA

No statistical significance was found in time of initial formation of mucus between heat shock 1 and control 1 ($p<.05$).

The results of mucus presents were run between treatment groups and there was statistically a higher percent of mucus present in heat shock 1 (55.56%) than in control 1 (10.53%; $p<.05$). The percent of nubbins that excreted mucus in each group can be seen graphically in Figure 3.

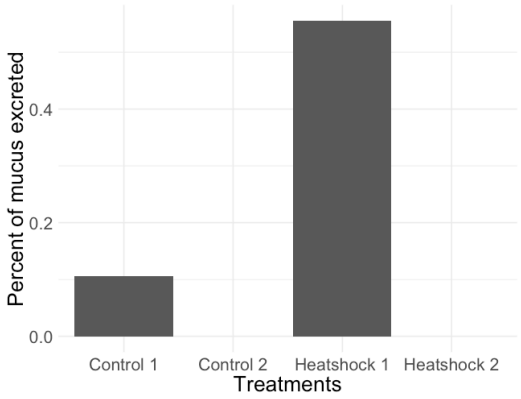

FIG. 3. Percent of *A. pulchra* nubbins that excreted mucus in each treatment round.

In both treatment A and treatment B, a difference in mucus presents was statistically significant, with higher levels present in control 1 and heat shock 1 and no mucus present in control 2 and heat shock 2 ($p<.05$).

Only the survivors of heat shock 1 were able to complete heat shock 2. Of these survivors only 4 had initially excreted mucus during heat shock 1. A chi squared test was run to see if there was significance due to the fact that there was a lack of mucus excreted in the second round from these four individual nubbins and no significance was found ($p>.05$). Similarly, of the survivors of control 1 that experienced control 2, only one initially excreted mucus.

Growth rate was calculated through the measurements taken at the beginning and end of the experiment period. The growth rates for each treatment is presented in Figure 4. No statistical difference in growth rate between treatments was found ($p>.05$).

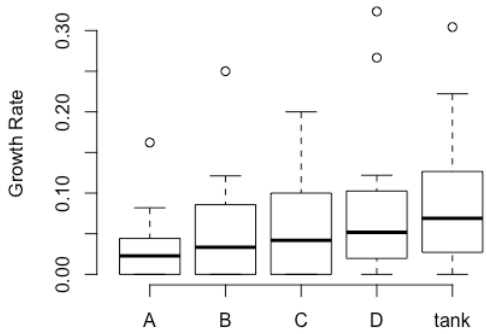

FIG. 4. Growth rate box plots of the *A. pulchra* treatment groups A, B, C, D, and nubbins remaining in tank.

Mortality rate in each treatment group was analyzed and is presented below in Figure 5. A statistical difference was found between treatments ($p < .05$). The highest mortality observed was in heat shock 1 (48.15%), with lower rates of mortality observed in control 2 (33.33%), and control 1 (28.95%). No mortality was observed in heat shock 2 (0%). *A. pulchra* nubbins that did not receive a treatment and remained in the fresh water flow tank for the extent of the experiment were also analyzed for mortality rate (16.67%).

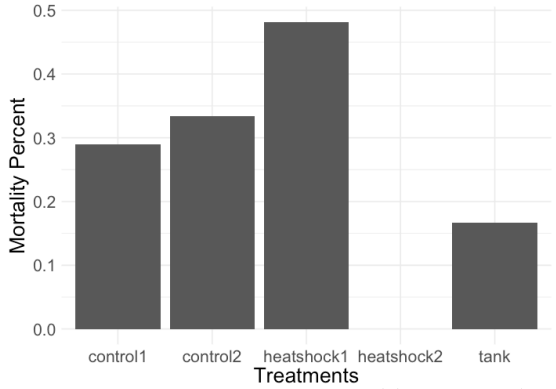

FIG. 5. Rate of *A. pulchra* nubbin mortality observed in the different treatment groups.

DISCUSSION

The field study yielded a significant positive correlation between colony size and benthic depth of the colony. This indicates that in shallow fringing back reefs, *A. pulchra* prefer deeper depths possibly due to less direct light exposure.

During the experimental factor of this research, potential hardening of the *A. pulchra* nubbins that experienced the second heat shock was observed.

The lack of mucus present in both control 2 and heat shock 2 could indicate a resilience to thermal stress observed in the *A. pulchra* nubbins that survived for the second round of treatment. However, mucus proved to be a strong indicator of mortality and of the nubbins that excreted mucus in heat shock 1 only 4 survived. Of the other surviving nubbins that experienced heat shock 2, none had excreted mucus during the first heat shock. Although not proven statistically significant, the fact that the four that initially excreted mucus, did not mucus during heat shock 2, shows a potential hardening due to thermal stress history.

The lack of mucus present in control 2 also could indicate that the nubbins built a tolerance to not being in ideal conditions and not receiving water flow during the six-hour shock. However, statistically fewer nubbins were observed as stressed during the control 1 treatment (10.53%), indicating that the cause of mucus present in heat shock 1 (55.56%) was associated with the temperature rise and not merely due to lack of water flow.

The lack of significant difference in the growth rate observed between the different treatment groups could indicate that the heat shock did not stunt growth. The 0% mortality present in heat shock 2 compared to the 48.15% mortality observed in heat shock 1 also indicates hardening induced by the nubbins' thermal stress history. However, growth and mortality could possibly be factors that needed a longer period of time than the extent of the four-week experimental period for any effects of the heat treatments to be observed.

Altogether my results coincide with other observations of hardening of *Acropora pulchra* due to its thermal stress history (Carroll et al., 2017; Pratchett et al., 2013; Middlebrook et al., 2008). This experiment exposed the nubbins to an acute six-hour stress event rather than a chronic stress event, which would have been more realistic of future RCP 8.5 ocean conditions, but was not possible due to the resources at hand.

For future research on thermal stress history's effect on *Acropora pulchra*, a longer time frame for experimental research would be beneficial. With more time and the proper equipment, the implications of more than two chronic successive thermal stress events could be tested and proper analysis of growth and mortality rate recorded. With the thermal tolerance of *A. pulchra* expected to be exceeded more often under RCP 8.5 conditions, further research should also be done on the timing between successive temperature anomalies and what implications it may lead to. Additionally, research should be done on the pH decrease associated with RCP 8.5 and how that will affect calcifying rates and growth rates.

Although *Acropora* has been observed as having the highest susceptibility among coral genera, it is essential to study other coral genera's resilience to temperature anomalies and assess whether they too form a resilience and harden with an increased thermal stress history (Carroll et al, 2017). Knowing and understanding each coral species' specific response to thermal stress will allow for the understanding of how RCP 8.5 surface ocean temperature rise will affect future coral reef composition. However, past studies on the

mass bleaching of the Great Barrier Reef has shown no lessening of bleaching severity during repeated intense temperature anomalies (Hughes et al., 2017).

This experiment used future ambient conditions of 30°C as the heat shock treatments. Further studies of *A. pulchra*'s ability to survive in a constant ambient environment of 30°C could further clarify the effects of RCP 8.5 temperature rise and if temperature anomalies beyond this point would prove fatal.

In this study, the death toll initially experienced due to 30°C exposures was 48.15%. The RCP 8.5 temperature rise of 30°C will persists longer than the six hours of exposure done in this experiment, with no recovery period, leading to predictions of higher mortality rates, with potential lowering in resilience due to lack of a recovery period in lower temperatures. With the initial mortality rates of *A. pulchra* exposed to 30°C ambient conditions, despite a potential resilience in the survivors, the coral reef community's *A. pulchra* population will be initially drastically reduced.

Understanding the impacts anthropogenic induced climate change will have on coral reefs is vital for understanding the fate of the marine ecosystem under RCP 8.5 ambient conditions. The consequences of coral reef reduction or destruction due to the thermal tolerance of coral species being exceeded beyond recovery is highly likely (Hoegh-Guldberg, 2007). If anthropogenic contributions to climate change continues leading to RCP 8.5 conditions, coral reefs and the dependent organisms, tourism, fisheries and coastal protection will face dire ramifications.

The ambient environment of the future of the coral reef ecosystem is highly dependent on the anthropogenic decisions for future fossil fuel dependence and land use. With the knowledge of the repercussions fossil fuel use has and will continue to have on the coral reef ecosystem, the need to move towards a less carbon dependent future is evident.

ACKNOWLEDGMENTS

I thank Dr. Steve Doo from CSU Northridge for spending his free time mentoring me and helping me with the validity of my research project. I also thank the rest of the CSU Northridge LTER crew, for always being willing to answer my questions and motivating me through their dedication and constant hard work at the station. I thank Sky Poindexter in finding therapeutic value in cleaning my flow tank and Dean Keck, Annie Rosen, Liz Alpine, Madelief Schelvis, Aaron Glover, Charlotte Jamar, and Hannah Lewis for assistance in gluing my plethora of coral nubbins together as well as their fingers. I thank the U.C. Berkeley professors, Jonathan Stillman, Stephanie Carlson, Brent Mishler, and Vince Resh, for their help throughout the challenges of developing this experiment as well as the graduate student instructors, Suzanne Kelson, Audrey Haynes, and Caleb Caswell-levy for teaching me how to run all the needed statistical tests. Lastly, I would like to thank my mom, dad, and grandparents for making this research opportunity possible.

LITERATURE CITED

Alldredge A., C. Carlson. 2016. MCR LTER: Coral Reef: Water Column: Nearshore Water Profiles, CTD, Primary Production, and Chemistry ongoing since 2005. Environmental. Data Initiative. http://dx.doi.org/10.6073/pasta/ba09a6a0b0bd8741f68a0007ac2cafc4. Dataset accessed 10/28/2017.

Bahr, K. D., Jokiel, P. L., & Ku'Ulei, S. R. 2016. Relative sensitivity of five Hawaiian coral species to high temperature under high-pCO2 conditions. Coral Reefs 35(2):729-738.

Bates, Douglas, Maechler, Martin, Bolker, Ben, Walker, Steve. 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Bower, C. E., and J. P. Bidwell. 1978. Ionization of ammonia in seawater: effects of temperature, pH, and salinity. Journal of the Fisheries Board of Canada 35(7): 1012-1016.

Brown, B. E. 1997. Disturbances to reefs in recent times. Life and death of coral reefs 354-379.

Carbon dioxide concentration | NASA Global Climate Change. (2017, May 17). Retrieved October 06, 2017, from https://climate.nasa.gov/vital-signs/carbon-dioxide/

Carroll, A. G., P. L. Harrison, and M. Adjeroud. 2017. Susceptibility of coral assemblages to successive bleaching events at Moorea, French Polynesia. Marine and Freshwater Research 68(4): 760-771.

Carte, B. K. 1996. Biomedical potential of marine natural products. BioScience 46: 271-286.

Cesar, H. S., and P. Van Beukering. 2004. Economic valuation of the coral reefs of Hawai'i. Pacific Science 58(2): 231-242.

Dai, A., G.A. Meehl, W.M. Washington, T.M. Wigley, and J.M. Arblaster. 2001. Ensemble simulation of twenty–first century climate changes: Business–as–usual versus CO2 stabilization. Bulletin of the American Meteorological Society 82(11):2377-2388.

Ditlev, H., 1980. A field-guide to the reef-building corals of the Indo-Pacific. W. Backhuys.

Dove, S. G., D. I. Kline, O. Pantos, F.E. Angly, G.W. Tyson, and O. Hoegh-Guldberg. 2013. Future reef decalcification under a business-as-usual CO2 emission scenario. Proceedings of the National Academy of Sciences 110(38):15342-15347.

Fitt, W. K., B.E. Brown, M. E. Warner, and R.P Dunne. 2001. Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. Coral reefs 20(1):51-65.

Frost, E. 2016. Coral and Coral Reefs. Retrieved October 06, 2017, from http://ocean.si.edu/corals-and-coral-reefs

Gosliner, T. M., D.W. Behrens, and G.C. Williams. 1996. Coral reef animals of the Indo-Pacific. USA: Sea Challengers.

Guest, J. R., A.H. Baird, J.A. Maynard, E. Muttaqin, A.J. Edwards, S.J. Campbell, S. and L.M. Chou. 2012. Contrasting patterns of coral bleaching susceptibility in 2010 suggest an adaptive response to thermal stress. PloS one 7(3):e33353.

Hatcher, B. G. 1988. Coral reef primary productivity: a beggar's banquet. Trends in Ecology & Evolution 3(5):106-111.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell,P.F. Sale, A.J. Edwards, K. Caldeira, and N. Knowlton. 2007. Coral reefs under rapid climate change and ocean acidification. Science 318(5857):1737-1742.

Hughes, T. P. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science-AAAS-Weekly Paper Edition 265(5178):1547-1551.

Hughes, T. P. 1989. Community structure and diversity of coral reefs: the role of history. Ecology 70(1): 275-279.

Hughes, T.P., J.T. Kerry, M.,Álvarez-Noriega, J.G. Álvarez-Romero, K.D. Anderson, A.H. Baird, R.C. Babcock, M. Beger, D.R. Bellwood, R. Berkelmans, and T.C. Bridge. 2017. Global warming and recurrent mass bleaching of corals. Nature 543(7645):373-377.

Jacob, D. 1999. Introduction to atmospheric chemistry. Princeton University Press.

Lenz, E. A., & P.J. Edmunds. 2017. Branches and plates of the morphologically plastic coral Porites rus are insensitive to ocean acidification and warming. Journal of Experimental Marine Biology and Ecology 486:188-194.

Middlebrook, R., O. Hoegh-Guldberg, and W. Leggat. 2008. The effect of thermal history on the susceptibility of reef-building corals to thermal stress. Journal of Experimental Biology 211(7): 1050-1056.

Moberg, F., and C. Folke. 1999. Ecological goods and services of coral reef ecosystems. Ecological economics 29(2): 215-233.

Pratchett, M.S., D. McCowan, J.A. Maynard, and S.F. Heron. 2013. Changes in bleaching susceptibility among corals subject to ocean warming and recurrent bleaching in Moorea, French Polynesia. *PLoS one 8*(7): p.e70443.

Roff, G., S. Bejarano, Y.M. Bozec, M. Nugues, R.S. Steneck, and P.J. Mumby. 2014. Porites and the Phoenix effect: unprecedented recovery after a mass coral bleaching event at Rangiroa Atoll, French Polynesia. Marine biology 161(6): 1385-1393.

RStudio Team (2016). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/.

Sakami, T. 2000. Effects of temperature, irradiance, salinity and inorganic nitrogen concentration on coral zooxanthellae in culture. Fisheries science 66(6): 1006-1013.

Salvat, B. 1992. Coral reefs—a challenging ecosystem for human societies. Global Environmental Change 2(1):12-18.

Shaw, E.C., S.M. Hamylton, and S.R. Phinn. 2016. Incorporating benthic community changes into hydrochemical-based projections of coral reef calcium carbonate production under ocean acidification. Coral Reefs *35*(2):739-750.

Siebeck, U.E., N.J. Marshall, A. Klüter, and O. Hoegh-Guldberg. 2006. Monitoring coral bleaching using a colour reference card. Coral Reefs 25(3):453-460.

Siegenthaler, U., and J.L. Sarmiento. 1993. Atmospheric carbon dioxide and the ocean. Nature, 365(6442):119-125.

Spurgeon, J. P. 1992. The economic valuation of coral reefs. Marine Pollution Bulletin 24(11):529-536.

Stocker, T. ed., 2014. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Washburn L. 2011. MCR LTER: Coral Reef: Water Column: Offshore Water Profiles: CTD Transects. Environmental Data Initiative.http://dx.doi.org/10.6073/pasta/489766b5dfa4c233ab284fdac387a708.Dataset accessed 10/28/2017

APPENDIX A

Image 1-6 show different *A. pulchra* colonies at Temae beach. These photos were taken in the same region as that specimen collection.

IMAGE. 1.

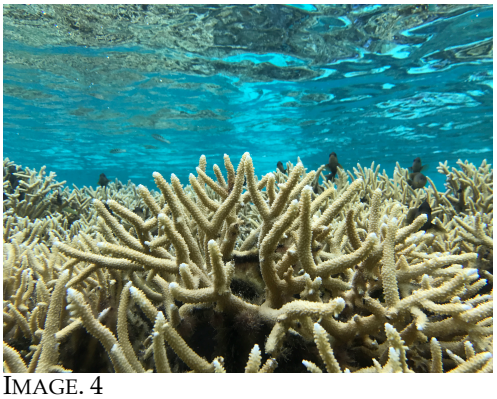

IMAGE. 4

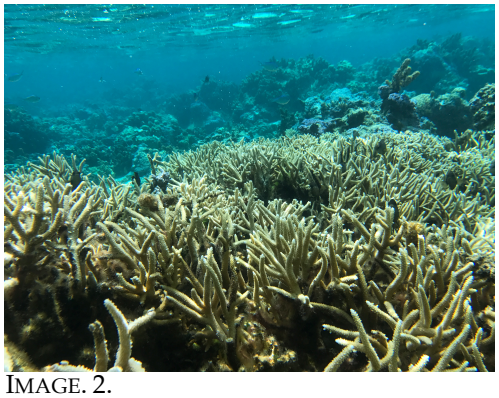

IMAGE. 2.

IMAGE. 5.

IMAGE. 3.

IMAGE. 6

APPENDIX B

Image 7 through 10 show different severities of bleaching observed in this experiment.

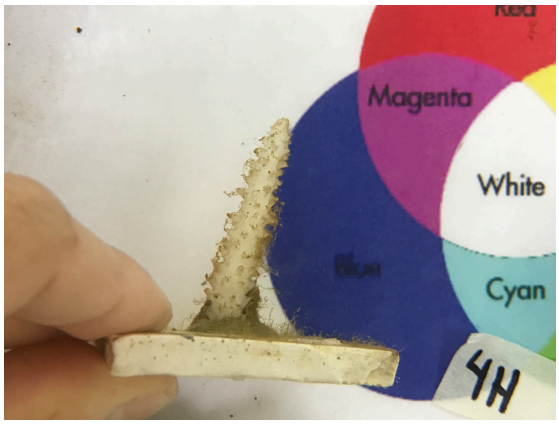

IMAGE. 7. Image of completely bleached coral nubbin (100%).

IMAGE. 8. Image of partially bleached coral nubbin (25%)

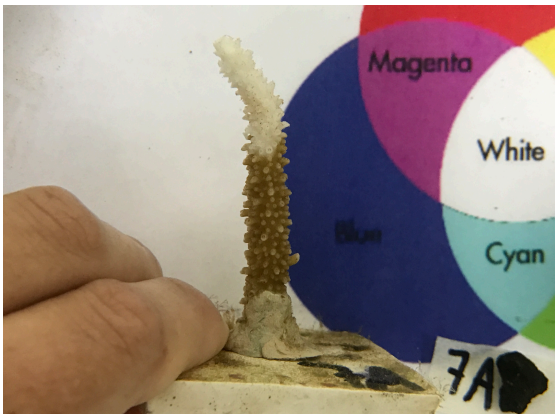

IMAGE. 9. Image of partially bleached coral nubbin (45%)

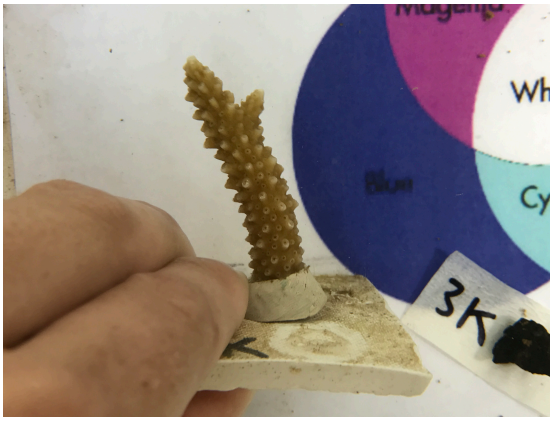

IMAGE. 10. Image of completely healthy unbleached coral nubbin (0%).