THE INFLUENCE OF CURRENT ON THE ADHESIVE POTENTIAL, DENSITY AND ABUNDANCE OF THE MAGNIFICENT SEA ANEMONE (*HETERACTIS MAGNIFICA)* IN MO'OREA, FRENCH POLYNESIA

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Abstract. Adhesion is a mechanism utilized by many aquatic organisms as a means of food capture, defense, and locomotion. For the Magnificent Sea Anemone (*Heteractis magnifica*), adhesion is achieved through the use of stinging nematocysts on the tentacles that pierce and paralyze prey or predators. In this study, the effects of current on the adhesive potential were observed, with predictions that stronger water flow would yield greater adhesion of the tentacles and weak flow would result in less hold. It was also expected that current speed would have an effect on anemone number and spatiality, with predictions that low flow would result in large, clustered populations of anemones and high flow would result in small, widely spaced populations. Current was measured at four sites in Mo'orea, French Polynesia, in which tentacle adhesiveness was determined using a spring scale device and fish bait. No significant relationship existed between current speed and tentacle adhesiveness; however, anemone size did prove to be an influential factor in adhesion, where larger anemones exhibited a stronger hold. Furthermore, anemone density and abundance were also independent of flow, implying that they are most likely influenced by other environmental factors. The findings in this study shed light on how animals respond to stressful environmental conditions through biological adaptations, as the morphology of an organism is correlated with its performance.

Key words: anemone; adhesion; Heteractis magnifica*; force; current; abundance; Mo'orea, French Polynesia*

INTRODUCTION

Marine organisms have adapted to their surroundings through various morphological and physiological adjustments. Temperature, salinity conditions, substrate type, and water current are examples of environmental factors that influence adaptive changes. Sessile animals persist over time by reducing the amount of stress due to ocean currents, evolving to maximize or minimize the impacts of the flowing water that surrounds them (Vogel 1984). To withstand the constant pull of currents, many animals change their physical state, hunkering down close to the seafloor bottom when currents are strong and stretching out when the flow is calmer (Koehl 1982). Some colonial marine organisms such as coral have evolved to moderate their own flow environment, protecting individual polyps by arranging their branches in such a way as to alter the speed and direction of water motion through the colony (Koehl 1982). Even the texture of a sessile organism can make a difference in its chance at survival. An animal that has more surface friction will feel more of a drag force and, as a result, is at a greater risk of being dislodged (Koehl 1982).

Numerous species have adapted to current flow by developing specialized mechanisms of adhesion. Adhesion is employed by sedentary organisms such as sea anemones (phylum Cnidaria) for use in locomotion, mating, anchoring to substrate, food capture, and defense (Dodou et al. 2011; Lutz 1986). Found in shallow waters attached to rocks and shells, sea anemones are often exposed to strong currents and depend on water flow to capture food that passes by (Lutz 1986; Koehl 1977). As sessile scavengers, anemones have a diet that relies on whatever material is delivered to their tentacles by tidal movement and currents. Thus, the food items that sea anemones ingest vary across different shore heights and current speeds (Davenport et al. 2011). Through the use of stinging nematocysts, which are contained within specialized cells on the tentacles called cnidocytes, these cnidarians are able to paralyze small prey that are carried by the current. The debilitated prey is then directed toward the mouth by the tentacles (Lutz 1986).

While previous research has documented the effects of flow force on sea

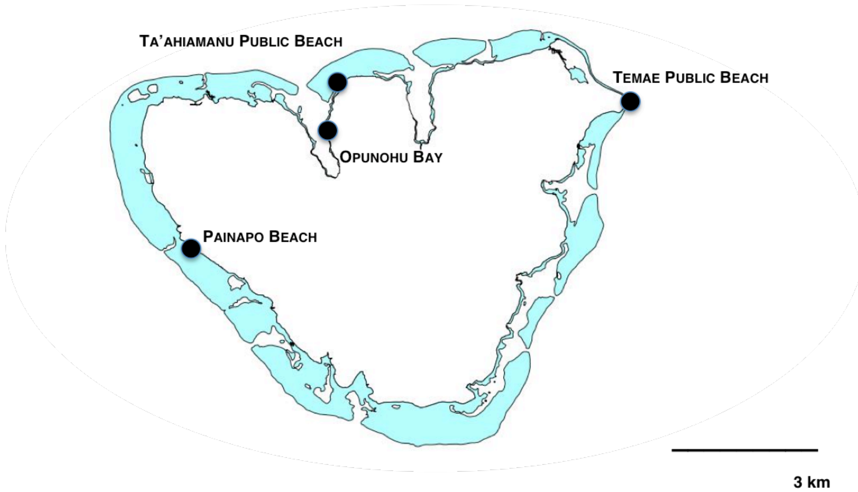


Fig. 1. A map of Mo'orea, French Polynesia. The four sampling locations for *H. magnifica* sp. were (left to right) Painapo Beach, Opunohu Bay, Ta'ahiamanu Public Beach, and Temae Public Beach. *Ta'ahiamanu Public Beach and Painapo Beach will be referred to as the Public Beach and Pineapple Beach, respectively, throughout the paper.

anemone diet, shape, and flexibility (Koehl 1977), no studies have analyzed the effects of water flow on how well anemones are able to hold onto their prey items. One study (Shimeta & Koehl 1997) addressed the effects that varying flow speeds had on the feeding behavior of tentaculate polychaete worms. Their results indicated that under faster flow, the efficiency of the tentacles to hold onto particles decreased. However under low flow, the efficacy of the tentacles was not affected. Similar results were observed with suspension-feeding soft coral. Such studies are an indicator that current can influence the adhesiveness of tentacles in marine organisms.

This study analyzed the impacts of varying water flow on the holding potential of the sea anemone *Heteractis magnifica* in Mo'orea, French Polynesia. It was hypothesized that a faster current would require a stronger holding force by the tentacles on prey items. Furthermore, it was hypothesized that anemone density would be highest under low current conditions.

METHODS

Study organism

Heteractis magnifica, commonly known as the Magnificent Sea Anemone, dwells in shallow tropical Indo-Pacific seas and is an ideal species to test the effects of current on the adhesiveness of sea anemones (Gosliner et al. 1996). Usually located around coral reefs in waters 1 to 20 m deep, *H. magnifica* can be found either solitary or in large clusters (Dunn 1981). Surveying in Mo'orea, French Polynesia revealed that the species was most commonly found at depths that ranged between 1-2 m and resided either on large rocks or on sand. Characterized by its symbiotic relationship with various anemonefish, *H. magnifica* was often found with the two fish species *Amphiprion chrysopterus* (Orange-fin Anemonefish) and *Dascyllus trimaculatus* (Three-Spot Dascyllus) (see Appendix A). The anemones provide shelter for the fish and protection from predators, while the fish defend the anemone in return. Recorded data included water depth of each sea anemone, the oral disc size and the number of anemonefish residents. Observation was performed by snorkeling, and experimentation required some standing and free diving for deeper anemones.

Study sites

Fieldwork for this study was conducted at four sites on the island of Mo'orea, French Polynesia (17° 30' S, 149° 50' W). Sites were based on variations in water current (Fig. 1). Temae Public Beach (17° 29' 50.71" S, 149° 45' 14.66" W), Ta'ahiamanu Public Beach* (17° 29' 23.54" S, 149° 51' 0.14" W), Opunohu Bay (17° 30' 4.62" S, 149° 51' 16. 44" W), and Painapo Beach* (17° 32' 39.22" S, 149° 53' 35.80" W) displayed average flow rates that ranged from high to low, respectively. Sites were also ideal due to the high numbers of the study organism, *Heteractis magnifica.*

Current

In order to measure the average water current at each site, the plaster of Paris clod card technique was used (Jokiel and Morrissey 1993). All molds were made from the same batch of plaster and were allowed to dry in small, plastic cups that were 5 cm in diameter, and 4 cm in height. After 12 hours, molds were removed from containers and attached to 5 cm x 5 cm tiles using chicken wire; the corners of the tiles were marked with numbers for identification. Once set in the field, each plaster was tied to a rock using fishing line, marked with flagging tape, and placed randomly next to anemones where the highest flow was experienced by the organisms. Ten plaster of Paris molds were weighted and deployed at each site, where they remained set for three to five days before being picked up. Once retrieved, the molds were dried in an oven for 24 hours, and then weighted. Relative flow rates were then compared between the sites based on the differences in mold mass.

Tentacle adhesiveness

To estimate the adhesive force of the anemones, a spring scale was used. Frozen shrimp were clamped to the end of the scale and placed onto random areas of the oral disc for five consecutive trials (Fig. 2, see Appendix A). Tested anemones were chosen randomly along a fifty meter transect parallel to the shore at each site. In order to control for food consumption previous to experimentation, each anemone was fed a piece of shrimp and allowed five minutes to settle before testing. Because anemones are not as receptive to food after they have just eaten, feeding removed the potential source of variation. Food was allowed to rest on the tentacles for three seconds before being pulled up. The weight required to pull the food away from the tentacles was then recorded from the spring scale. The number of tentacles that attached to the food was estimated using a digital underwater camera, and the average force per tentacle was then calculated.

In order to measure the force required to pull the shrimp from the tentacles, the following equation was used, which took into account other forces that might have influenced the measurements:

$$F_A \geq F_G - F_B \qquad (Eq.\ 1)$$

where F_A is the adhesive force, F_G is the force due to gravity, and F_B is the force due to the water's buoyancy. Because the gravitational

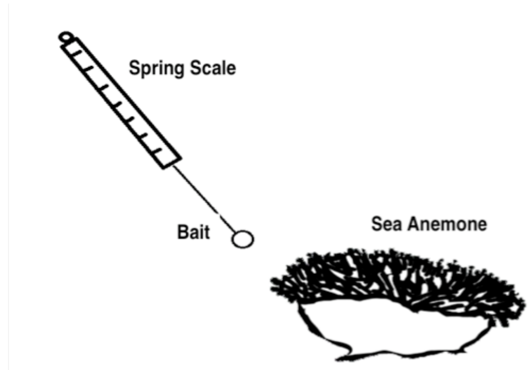


Fig. 2. The measurement of tentacle adhesiveness. Frozen shrimp bait is attached to spring scale and lowered onto the anemone tentacles. Weight required to pull up is the adhesive force. Spring scale approximately 30 cm in length. Illustration by V. Hsieh.

force is mg and the buoyancy force is ρgV the formula is simplified to

$$F_A \geq mg\text{-}\rho gV \qquad (Eq.\ 2)$$

where m is the mass of the shrimp, g is the gravitational acceleration, ρ is the density of the fluid, and V is the volume of fluid displaced by the shrimp. With these calculations, the adhesive force was determined.

Density and abundance

To determine the spatial makeup of *H. magnifica* under different flow conditions, five transects were performed at each site using measuring tape. Transects were set perpendicular to the shore and were ten meters apart with a length of thirty meters. Anemones were counted if they resided within one meter on each side of the transect tape. Measurements began at the shore, and ended when a drop off occurred from the fringing reef to deeper ocean, or if a back reef was present. The distance between each anemone was also recorded during the transects. If anemones resided in a closely-packed cluster, estimation was used in order to count individuals.

Transplant experiment

In order to determine if the adhesiveness would change when anemones were exposed to different current strengths, a transplant experiment was conducted. Five anemones were tested, then moved from the lowest current site (Pineapple Beach), to the highest current site (Temae Public Beach), where they were left there for one week and retested. To control for movement, five anemones were also moved within Pineapple Beach. Anemones chosen for transfer resided on rocks small enough to carry, and were tagged in case movement from rocks occurred. Once tests were over, the anemones were moved back to their original locations.

Statistical analyses

In order to determine if there were significant differences among sites in flow rate and adhesive force, a one-way analysis of variance (ANOVA) test was used. To identify where differences occurred, the Tukey honestly significant differences (HSD) test was performed. Sites that were not connected by the same letter indicated significant differences. Furthermore, a multivariate regression test was run in order to determine if other factors might influence the adhesiveness of the anemone tentacles. Lastly, a discriminant analysis test was run in order to compare how the four sites differed in force, depth, anemone size, and anemonefish number. All statistical analysis and graphs were performed in JMP.10 SAS Institute Inc. 2012.

RESULTS

Current

All ten plaster of Paris clod cards were found at Pineapple Beach, nine were recovered at Temae and the Public Beach, and seven were found at Opunohu Bay. Missing clod cards were most likely swept away or covered by substrate. Temae Beach revealed the highest flow rate, while the Public Beach and Opunohu Bay displayed lower flow rates of similar values, and Pineapple Beach exhibited the lowest rate (Fig. 3).

The outcome suggested that the average current rate at Temae Beach was significantly different from the other three sites, while the Public Beach and Pineapple Beach also differed from each other. The mean current rate at Opunohu Bay, however, was very similar to both the Public Beach and Pineapple Beach.

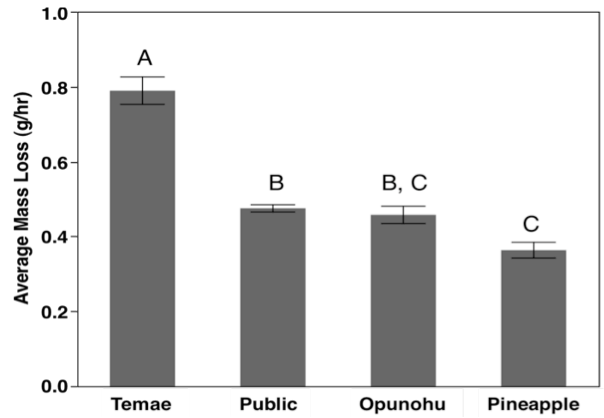


Fig. 3. Relative flow rates among the four sites Temae Beach, Public Beach, Opunohu Bay, and Pineapple Beach. Levels not connected by the same letter imply significant differences (ANOVA, Tukey HSD, SE=0.0145, df=3, F=33.85, $p < 0.0001$, n=10).

Tentacle adhesiveness

A linear regression was run between the adhesive force and flow rate in order to

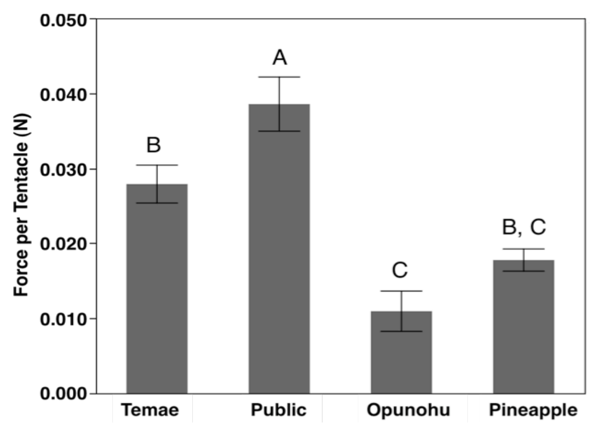
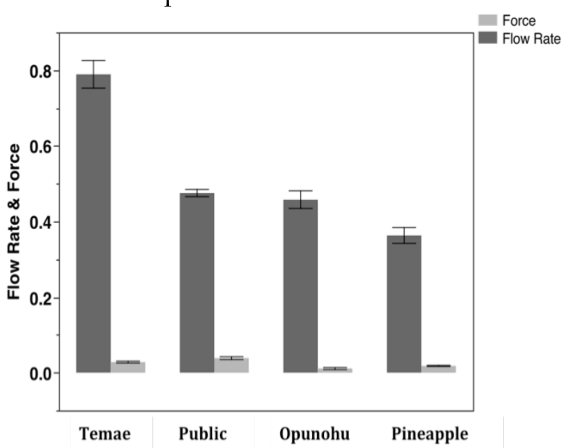


Fig. 4. Adhesive force among the four sites Temae Beach, Public Beach, Opunohu Bay, and Pineapple Beach. Sites in order of highest to lowest flow (left to right). Levels not connected by the same letter imply significant differences (ANOVA, Tukey HSD, SE=0.0013, df=3, F=20.61, $p < 0.0001$, n=10).

determine if a relationship existed between the two factors, however there was no significance (F= 2.729, $p < 0.1068$, R^2=0.067). Much variation was seen among the sites, as the Public Beach had the highest force, Opunohu the lowest, and Temae and Pineapple had middle values (Fig. 4). Oral disc size, depth, and number of anemonefish

Fig. 5. A comparison of the flow rate and adhesive force among the four sites, indicating no relationship.



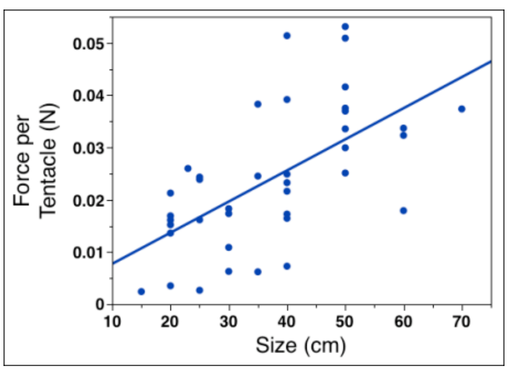


Fig. 6. Oral disc size as a factor in adhesive force. Displays the tendency for larger anemones to have a stronger force (ANOVA, linear regression, SE=0.00487, df=1, F= 23.20, $p < 0.0001$, R^2=0.379, n=10).

present were all tested, however only size proved to be a significant factor (Fig. 6). Larger anemones tended to have a stronger hold than smaller-sized anemones.

Density and abundance

Pineapple Beach displayed both the highest density and abundance of the four sites (Fig. 7). Anemone density was significantly different at Pineapple Beach, while the Public Beach, Opunohu Bay, and Temae Beach exhibited densities that were very similar to each other. Thus, no relationship exists between the current and the abundance of *H. magnifica*.

Transplant experiment

After one week, the anemones were retested for adhesion and then moved back to Pineapple Beach. Results showed no significant changes in adhesion.

Comparison among sites

A discriminant analysis test displays how each of the four sites differs in force per tentacle, oral disc size, anemonefish number, and water depth (Fig. 8). The diagram shows that Pineapple Beach and Opunohu Bay are the most similar to each other, as they overlap, whereas Temae and Public Beach show more differences. Water depth appears to be the most variable factor among the sites, as suggested by the length of the line. Because force per tentacle, size, and anemonefish number are so close together, it is suggested that that they are closely related to each other.

DISCUSSION

The topography of coastlines, such as the amount of exposure, is an important factor in water movement. Land that is sheltered by mountains or rocks tends to have a relatively slower water flow than areas that are highly exposed (Lewis 1968). Because coastal currents are primarily driven by winds, areas of more exposure tend to have increased winds, which exert stress on the water's surface and produce a faster current (Gross 1987; Sverdrup 1947).

Therefore, it is likely that the highest relative water flow was observed at the Temae Public Beach due to the site's high amount of exposure on a curve. The Ta'ahiamanu Public Beach also resides on an open area of land that eventually curves into Opunohu Bay, which may explain its slightly higher current than the other two sites. The Opunohu site is less exposed as it is protected by the walls of the bay, and Pineapple Beach resides in an area that is slightly bordered by land, possibly reducing the amount of wind that the sites are exposed to, and as an effect minimizing the current speed.

Although the plaster of Paris clod card technique has proven to be a very effective method in assessing the relative water motion index at each of the sites, there are other factors that could've contributed to the mass loss of the plaster, such as water depth, temperature and salinity (Jokiel and

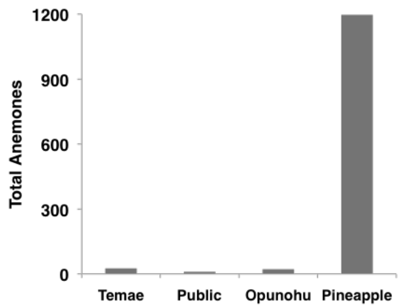


Fig. 7. Total number of anemones counted during the five transects in Temae Beach (n=26), Public Beach (n=10), Opunohu Bay (n=22), and Pineapple Beach (n=1197).

Morrissey 1993). Because measurements were taken at four separate sites, variations in such factors did exist. Moreover, disturbances by fish and other marine organisms might have caused error in the measurements, as it has been suggested that the bright white color of the plaster can attract certain organisms (Jokiel and Morrissey 1993).

While a linear trend was not observed between the relative current rate and the tentacle force, the fact that Ta'ahiamanu Public Beach and Temae Public Beach had the strongest tentacle adhesion suggests that a threshold may exist between the two factors. Perhaps above a certain water flow, generally stronger adhesiveness is required to capture prey, but below this flow rate, a weaker adhesiveness will suffice for survival.

It was expected that a stronger correlation would be prevalent between the current speed and the adhesive force of the tentacles, as previous studies indicate that significant relationships do exist between the appendages of aquatic organisms and water flow conditions. Calanoid copepods, for instance, use hair-like appendages to capture food in the surrounding water. The amount of fluid that interacts with the bristles on the appendages determines what mechanism of food capture this planktonic animal will use—under low flow a sieve mechanism is used, however under high flow a paddle mechanism is utilized (Cheer and Koehl 1987). Another study analyzed how the feeding behavior of tentaculate polychaete worms was influenced by water flow, and found that its efficiency in retaining particles was inversely related to current velocity (Shimeta and Koehl 1997). Such research implies that flow speed should in fact be a significant factor in the adhesiveness of the tentacles of the sea anemone species *Heteractis magnifica*. Because an insignificant correlation occurred between the current rate and adhesive force, it is possible that other components might have altered the ability of the anemones to adhere onto the bait, such as its size, texture, and shape. The frozen shrimp used in the study as bait was approximately the size of a quarter, and for some of the anemones, this may have been considered a larger than usual prey, negatively affecting its adhesive force.

Although one piece of shrimp was fed to the anemones approximately five minutes before being tested, their food intake was by no means controlled. Previous studies indicate that food consumption significantly affects the nematocyst discharge in the tentacles (Greenwood et al. 2003; Thorington et al. 2010). Satiation in two species of anemones resulted in an estimated 50% decrease in nematocysts that were discharged compared

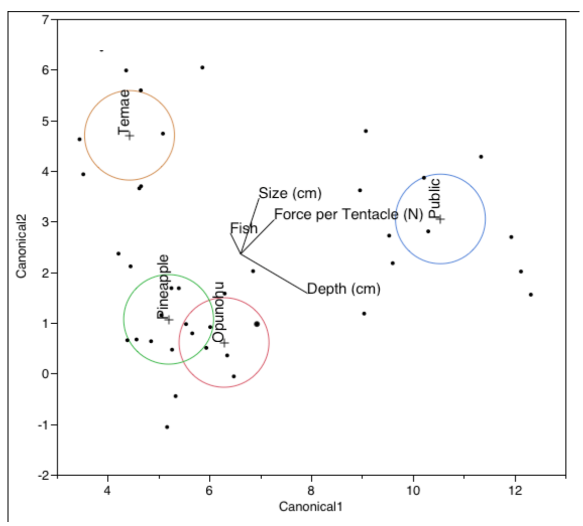


Fig. 8. A discriminant test to show where differences among sites occurred.

to when the organisms were starved. A dramatic decrease in prey killing and ingestion was also observed with satiation (Thorington et al. 2010). Such research indicates the importance of controlling the food intake of the tested anemones in order to attain the most accurate measurements of the adhesive force.

The size of the anemones proved to be one of the more influential factors in determining the tentacle adhesiveness, while water depth, and anemonefish number were not. As indicated by the very small p-value, a significant relationship was present between tentacle force and anemone size; however, because the R^2 value was also low, only a small degree of the adhesiveness is explained by the disc size. Such results imply that larger anemones may require a higher caloric intake, and thus have a stronger need for prey that is carried by the current, while for smaller-sized anemones that don't require as much caloric intake, the energetic cost of holding onto a larger prey is not worth the expense. This indicates that adhesion could potentially be biased toward prey size.

In addition to prey size, tentacle length may also explain why size played a role in adhesive force. Through personal observation, it appeared that larger anemones often had longer tentacles than smaller-sized anemones, which would imply that longer tentacles give a stronger adhesive force. While no research has studied how tentacle length correlates to nematocyst number, it can be assumed that the two are positively related. If longer tentacles do contain a higher number of nematocysts, greater adhesiveness should be observed.

The flow rate did not appear to be a determining factor in the density or abundance of *Heteractis magnifica*. Pineapple Beach was the lowest current site and had the greatest number of anemones all in close proximity of each other, while the other three sites of variable current has almost identical distribution patterns and very few anemones. If a relationship did exist between anemone density and current, it would be expected that the lowest current sites would have the highest compactness in anemones, while the higher current sites would display greater spatiality or vice versa; however these observations did not occur. Most likely other environmental factors are responsible for the density and abundance of the anemones.

Previous research suggests that food availability, water depth, and temperature are influential factors in the reproductive mechanism of certain species of anemones. In one species, longitudinal fission occurs during times of starvation, when water temperatures increase, or when the intertidal height is high (Sebens 1980). Such asexual reproduction would result in a population that is more compact, producing a higher density of anemones.

It is also possible that different forms of reproduction were utilized by the populations among the four sites. It is theorized that under stable environmental conditions, asexual reproduction is used by heterogamous organisms, while under unfavorable conditions sexual reproduction is used (Ayre 1984). Perhaps the environmental conditions at Pineapple Beach were ideal for *H. magnifica*, encouraging longitudinal fission to occur and thus leading to the clumped formation of the species in that area. This would also imply that the anemones at the other three sites utilized sexual reproduction, as they were much fewer in number, and more dispersed. Lastly, the transplant experiment was not successful most likely because a longer amount of time was needed in order to see if any significant changes in adhesion would occur.

CONCLUSIONS

In this study, the effects of current on the tentacle adhesiveness and abundance of the Magnificent Sea Anemone (*Heteractis magnifica*) were measured. Findings showed that while flow rate did not have significant influence on the adhesive force of the anemones, a relationship was present between force and disc size. Furthermore, it was found that the density and abundance of the anemones was not determined by current speed, but most likely by other environmental factors. Although the proposed hypotheses were not supported by the results, the findings from this study will contribute to the knowledge of the sea anemone species *H. magnifica* and how the tentacle adhesiveness of sea anemones is affected by environmental factors, as well as what components may influence their natural history.

Less diversity is often seen in high flow areas such as shorelines because many organisms are swept away, unable to maintain a steady hold to the substrate (Lewis 1968). Adhesion is what allows plants and animals like the sea anemone to thrive, filling in the empty niches caused by the physical disturbances of the crashing waves and wind-driven current. Filling such a niche in coral reef ecosystems, allows sea anemones to function as the protective home for susceptible anemonefish, and contribute to the health of the reef. The biomechanics of marine organisms continues to grow in importance, displaying how environmental conditions alter the physical performance of aquatic life, and even humans.

Further research could delve deeper into the biomechanics of the actual nematocysts, since they play such a vital role in the survival of sea anemones, as well as many other marine invertebrates. For instance, what conditions might inhibit their discharge? What might enhance it? Perhaps there are certain textures that nematocysts are not able to penetrate, which would directly affect the adhesive potential of the tentacles. There is also the question of how long does it take for nematocysts to replenish themselves after being fired? The rate at which replacement occurs may influence what prey the anemones go after, as the energetic cost of replenishment should not be higher than the benefit of a meal.

ACKNOWLEDGMENTS

I would like to thank the "magnificent" professors Brent Mishler, George Roderick, Vince Resh, Jonathon Stillman, and Stephanie Carlson for your enlightenment and support. I would also like to thank the Graduate Student Instructors (GSIs) Darcy Ernst, Rosemary Romero, and Matthew Luskin for your enthusiasm and getting me through any "sticky" situations throughout the nine weeks in Mo'orea. Also, much appreciation to the Gump Station staff , the instructors at the Atitia Center, and the researchers from CRIOBE. Lastly, I want to thank my classmates for being a "force" of motivation and providing an "abundance" of laughter. This research benefited from the support and services of UC Berkeley's Geospatial Innovation Facility (GIF), gif.berkeley.edu.

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APPENDIX A

Fig. 9. Close-up of the study species, *Heteractis magnifica,* portraying its tentacles, which are utilized for food capture and defense. Picture by N. Iyer.

Fig. 10. The measurement of tentacle adhesiveness. A spring scale was used to calculate the force, frozen shrimp was used as bait for attachment. Picture by C. Lewis.

Fig. 11. A family of Three-Spot Dascyllus (*Dascyllus trimaculatus*) that use the anemone for shelter and protection. Usually smaller in size and often found in large groups (personal observation). Picture by C. Lewis.

Fig. 12. A pair of Orange-fin Anemonefish (*Amphiprion chrysopterus*) that also live in H. magnifica. Usually slightly larger in size and found either solitary or in a pair (personal observation). Picture by C. Lewis.