An Investigation of Environmental Drivers of Crown of Thorns Starfish Outbreaks on Guam

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

THESIS ADVISOR

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Dr. James Potemra
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To my parents, brother and friends.

Without your endless love and encouragement, I would not be the educated and confident woman I am today. Thank you for always believing in me and reminding me that I am capable of anything.

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ABSTRACT

One of the least understood and prevalent threats to Guam's reefs is *Acanthaster planci*, more commonly known as Crown-of-Thorns Starfish (COTS). COTS are prolific corallivorous asteroid echinoderms. At high population densities, COTS can rapidly decimate coral reef ecosystems in a matter of months. Several devastating COTS outbreaks in Guam dating back to 1967 brought the understanding that COTS outbreaks are a real threat to Guam's coral reefs. Considerable research has been done on COTS biology and several hypotheses have been put forward to explain the occurrence of outbreaks but the cause(s) still remain contentious. This study aims to relate the physical environment to COTS outbreaks in order to find supporting evidence that COTS outbreaks are linked to environmental conditions. We hypothesized that precipitation and low wave events were the two factors that set the stage for the occurrence and proliferation of COTS outbreaks in Guam. To investigate this, we calculated and mapped COTS populations to assess spatio-temporal variability. A seasonal climatology was constructed and surface mapped from regional model data to determine the mean seasonal environmental conditions. An event-based analysis was then performed on two sites, Gun Beach and Uruno Point, to discover any consistencies between the presence of COTS and environmental parameters at the sites. Overall, we were unable to find any consistent or significant spatio-temporal relationships that support our hypothesis. This study highlights the data sparseness of Guam and sets the stage for future research into COTS outbreak ecology in Guam. Further research and long-term fine-scale data will be necessary

to accurately pinpoint the relationship between the physical environment and COTS outbreaks on Guam.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Background

Guam, a U.S. unincorporated territory, is the southernmost and largest island in the Mariana Archipelago. The island is home to approximately 168,000 people and draws in 1.5 million tourists annually (Central Intelligence Agency, 2016; Guam Visitors Bureau, 2018). With a mean annual temperature of 27.8°C and 244 km of shoreline, Guam is a hotspot for marine resources and recreation. Within the 244 km of shoreline, Guam boasts several varieties of reef types including fringing reefs, patch reefs, submerged reefs, offshore banks, and barrier reefs. Reef types are diverse in Guam, and the level of marine biodiversity is unparalleled for any U.S jurisdictions (Vernon, 2000). Over 400 scleractinian and hydrozoan coral species and 5,100 marine species have been identified in Guam's coastal waters (Randall, 2003, Paulay, 2003; Porter et al., 2005).

For Guam, the biodiverse reefs support several economic activities. In 2017, the tourism industry welcomed 1.54 million visitors with 30% of visitors citing the marine environment as a top reason for visiting Guam (Guam Visitors Bureau, 2018). Coral reef-related tourism on Guam contributes $323 million per year to Guam's economy (Spalding et al. 2016). Not only are healthy coral reefs important to Guam's ecotourism activities, but they also are vital for fisheries and the local residents who depend on them. Several studies have shown that when coral reefs are more widespread and healthier, fish abundance and biomass increase as well (Vincent *et al.,* 2011; Friedlander and DeMartini, 2002). Thus, Guam's coral reef health is vital to ecological, commercial and recreational fishing value and harvest. Unfortunately, despite their economic and aesthetic importance, Guam's coral reefs face several threats.

One of the least understood and prevalent threats to Guam's reefs is *Acanthaster planci*, more commonly known as Crown-of-Thorns Starfish (COTS). COTS are prolific corallivorous asteroid echinoderms. COTS populations in low densities are a part of a healthy reef system. However, when COTS populations reach higher than normal densities, they can rapidly decimate coral reef ecosystems in a matter of months. Various thresholds for outbreak densities exist but the most common convention for outbreak densities 0.15 organisms $100m^{-2}$ (Moran & De'Ath, 1992). COTS outbreaks can increase coral reef vulnerability, which is increasing due to climate change and local stressors. Anthropogenic climate change can decrease the ability of reef ecosystems to recover from other impacts such as coral bleaching and when combined synchronously with COTS outbreaks, presents a major issue in coral reef management. While much is known about the COTS lifecycle and biology, little is known about the causes and temporal cycles of outbreak populations.

In 2017, the Guam Bureau of Statistics and Plans published the Guam Crown-of-Thorns Outbreak Response Plan that provides a standardized framework for responding to COTS outbreaks. Within the report, several areas of future research were identified. This study focuses on the research goal of examining outbreak occurrence and detecting potential cycles and trends. No studies have investigated the causes or trends of COTS outbreaks in Guam. This study is specifically focused on investigating the link between the physical environment and COTS outbreaks in Guam.

1.2 Crown of Thorns Starfish

1.2.1 COTS Taxonomy and Morphology

Acanthaster planci, more commonly known as the Crown of Thorns starfish, have been reported on coral reefs across the Indo-Pacific, traversing a wide range of latitudes from 32°S to 34°N but have never been recorded in the Caribbean or Atlantic Ocean (Pratchett et al., 2014). Until recently, researchers regarded *Acanthaster planci* as a single taxonomic entity. A molecular study by Vogler et al. (2008) revealed that *Acanthaster* is in fact a species complex consisting of four strongly differentiated mitochondrial clades that represent distinct regions and species: Red Sea, southern Indian Ocean, northern Indian Ocean, and Pacific. However, no genetic differentiation was found within the Pacific region (Vogler et al., 2013) therefore COTS from the Pacific are explicitly referred to as A. *planci* whereas *Acanthaster* spp. is used to refer to the entire species complex (Pratchett et al., 2014).

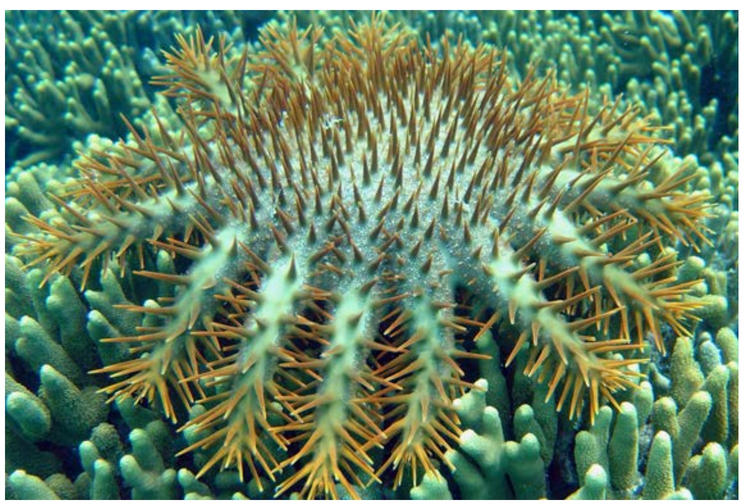

Figure 1.1 Image of a Crown of Thorns Starfish feeding atop coral. Photo credits to David Burdick and the NOAA Photo Library.

COTS are corallivore starfish with unique morphological traits which include being disc-shaped, multiarmed (8-21 arms in adults), pliable, prehensible, having a high stomach surface area to biomass, and having sharp toxic spines (Figure 1.1; Birkeland & Lucas, 1990; Moran, 1986; Cowan et al., 2017). Adult COTS usually are 25 to 35 cm in total diameter and have a lifespan of up to 8 years (Moran 1986; Chester, 1969). The pliability of the COTS body allows them to climb onto corals inaccessible to other species which grants sole access to extensive food supplies relieving them from interspecific competition (Birkeland & Lucas, 1990). The flat and multiarmed morphology also allows COTS to remain attached to large mound-shaped coral colonies (Birkeland & Lucas, 1990).

1.2.2 COTS Reproductive Biology

One of the most interesting biological features of A. *planci* is its enormous reproductive potential (Pratchett et al., 2014). A. *planci* is a gonochoristic broadcast spawning species with a male to female ratio close to 1:1 (Moran, 1986). After reaching sexual maturity after two years, large females (400 mm diameter) are capable of producing 46-65 million eggs per year (Birkeland & Lucas, 1990).

The reproductive success of A. *planci* is dependent on several environmental and biological factors. Pratchett et al. (2014) describes that broadcast spawners such as A. *planci* typically achieve low fertilization unless individuals are highly aggregated, spawning is synchronized and spawning occurs in low to moderate flow conditions. Like several other marine invertebrates, seasonal temperature changes are an important trigger for spawning. In locations such as Guam, there is a tendency for starfish to reach maximum maturity of gonads and begin spawning when the sea surface temperature (SST) rises above 27°C (Figure 1.2; Pratchett et al., 2014).

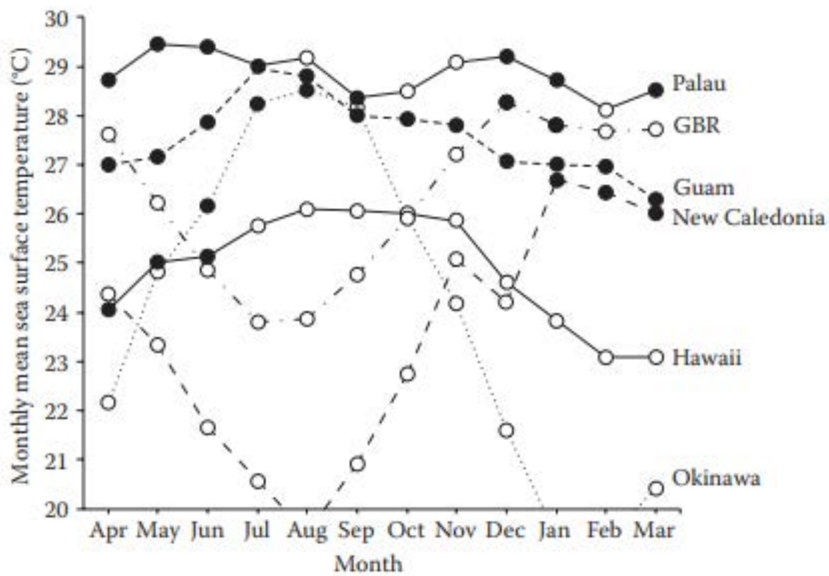

Figure 1.2 Seasonal variations in sea surface temperatures and COTS spawning occurrences (solid circles) (From Pratchett et al., 2014)

At higher latitudes, where temperatures never reach the 27°C threshold, breeding and spawning seasons are constrained to the few months where the SST starts to rise and are typically shorter and more well-defined events than lower latitude spawning events such as those on Guam (Pratchett et al., 2014). Guam is an anomaly as mature gonads have been found year-round whereas most other *Acanthaster planci* spawning occurs during the summer months at most locations (see Table 1.1; Cheney, 1974).

Table 1.1 Peak seasons in the annual reproductive cycle for Acanthaster planci in various locations based on spawning and gonad development. Guam, located at 13°N, is the only studied location where mature gonads and spawning occur year-round (From Pratchett et al., 2014).

		Month (April to March)												
Latitude	Location	04	05	06	07	08	09	10	11	12	01	02	03	Reference
33°N	SW Honshu[a]				●	●								Hayashi 1975
28°N	Amami-Ohshima[b]		○	○	●	○								Yasuda et al. 2010
26.5°N	Okinawa[c,d,e]	○	○	○	●	●	○	◍		○		○	○	Yamazato & Kiyan 1973
	Okinawa[c,d]	○	○	●	●	○	○	○	○	○	○	○	○	Okaji 1989
	Okinawa[b]		○	○	●	○	○							Yasuda et al. 2010
26°N	Kerama Islands[b]		○	●	●		○							Yasuda et al. 2010
25°N	Gulf of California[d]	●												Dana & Wolfson 1970
24.5°N	Miyako Island[b]		○	●	○			○						Yasuda et al. 2010
24°N	Iriomote[c]	○	○	●	○	○	○	○	○	○			○	Yokochi & Ogura 1987
	Iriomote[c]	○	●	●	○	○	○	○	○	○			○	Habe et al. 1989
24°N	Sekisei Lagoon[b]		●	○	○	○								Yasuda et al. 2010
20–21°N	Red Sea[f]					●	●							Crump 1971
	Red Sea[f]					●	●							Moore 1985
21°N	Hawaii[a,b]	●	◍	●		○			○		○			Branham et al. 1971
13°N	Guam[f]								●	●				Chesher 1969
	Guam[b]	◍	◍	◍	◍	◍	●	●	●	◍	◍	◍	◍	Cheney 1974
9°N	Panama[f]										●			Glynn 1974

The main source of food for COTS larvae is phytoplankton. It has been suggested that larval survival rates are limited by phytoplankton availability (see Lucas, 1982 & Fabricus et al. 2010). The foremost abiotic factor affecting larval survivorship and development is temperature with the fitness of larvae being highest within 26-30°C (Pratchett et al., 2017). Salinity has also proven to be a factor in larval development and survivorship. Lucas (1973) suggested that larval survivorship was 3-fold higher at 30 psu salinity when compared with ambient conditions however, Caballes et al. (2017) showed that rates of fertilization declined significantly at salinities <30 psu.

1.2.3 COTS Settlement and Feeding Behavior

Due to the broadcast spawning nature of COTS, larvae are passively transported by ocean currents to settlement sites. Several field and laboratory experiments (see Pratchett et al., 2014) have shown that COTS larvae are particular about the areas they settle in. Preferential settlement sites of larvae include habitats with fine-scale topographic complexity so that larvae can hide within the coral rubble or carbonate matrix of corals (Lucas, 1975). Larval settlement usually occurs within 9-14 days but can be as long as 43 days after fertilization (Pratchett et al., 2017). Most larvae settle within 10-100 km of their native reef (Pratchett et al., 2017).

COTS in the Pacific are generally nocturnal feeders (Moran, 1986). Adult organisms feed by extruding their stomachs over the surface of corals to consume the soft tissue of the coral (Brauer et al., 1970). Studies done by relocating uniquely tagged individuals at regular intervals show that COTS move <35 m per day and tend to have little motivation to move when they have an abundance of coral pray within their immediate area (Pratchett et al., 2017). COTS also avoid open expanses of sand due to their limited ability to grip in sandy environments and the lack of coral pray (Chesher, 1969). Experiments conducted in the laboratory have shown that COTS preferentially feed on table and branching corals such as *Acropora* spp. and *Montipora* spp. (Moran, 1986; Pratchett et al., 2017). Typically COTS only move considerable distances when they have consumed desirable coral in the vicinity but are able to adapt to feed on other less preferred species of coral and can consume algae, soft corals, and sponges (Chesher, 1969; Birkeland & Lucas, 1990; Pratchett et al., 2017).

1.3 COTS Outbreaks

1.3.1 Primary Versus Secondary Outbreaks

Not all COTS outbreaks are thought to arise in the same way. It is thought that COTS outbreaks can be classified as either primary or secondary outbreaks in which the distinction would be from differences in the population structure (Potts, 1981). Primary outbreaks, also referred to as initial outbreaks, involve abrupt (within the manner of weeks to months) increases in starfish abundances and have not arisen from nearby populations (Potts, 1981; Moran, 1986; Pratchett et al., 2014). These primary outbreaks are thought to consist of similar size starfish from the same cohort or year class, have a unimodal size distribution, and do not build up gradually over years (Birkeland, 1982; Moran, 1986).

Secondary outbreaks are essentially waves of outbreaks spread among well-connected reef systems after one or more primary outbreaks with a multimodal size distribution (Moran, 1986; Pratchett et al., 2014). The leading assumption of secondary outbreaks is that *A. planci* larvae disperse widely *en mass* on oceanic currents (Timmers et al., 2012) and therefore would be able to traverse open ocean expanses. As for outbreaks in isolated regions such as Micronesia, the primary outbreak hypothesis was inferred and outbreaks were assumed to have arisen in response to changes in local environmental conditions, adult migration, or distant larval input (Moran, 1986). To test the secondary outbreak hypothesis for distant regions, a genetic structure and connectivity study was conducted by Timmers et al. (2012) among 23 outbreak populations across the Pacific Ocean. Timmers et al. (2012) found that larval dispersal is highly constrained and that high densities of larvae do not spread across open ocean expanses to initiate secondary outbreaks. Outbreaks on distant reefs were found to have similar genetic makeups as their primary

No evidence was found that supports the notion that outbreaks on distant reefs have a distinct genetic makeup from the greater population (Timmers et al., 2012) which suggests that primary outbreaks have likely gone unnoticed in areas such as Micronesia or that individuals from a variety of cohorts and populations are mixing to form distant outbreaks.

While the distinction between the two types of outbreak populations appears clear cut, it is very difficult to ascertain which outbreaks are considered primary or secondary. It is often not possible to determine if an outbreak is primary or secondary due to the lack of quantitative data available (Moran, 1986) and the identification of primary outbreaks is largely conjectural (Pratchett et al., 2014). Furthermore, cases exist that show so-called primary outbreaks consisting of individuals of great size ranges with individuals from at least five or six different cohorts (Pratchett et al., 2014, and references therein) which further convolutes the validity of primary versus secondary outbreak hypotheses. Therefore, for the purposes of this study, the distinction between primary and secondary outbreaks is not distinguished.

1.3.2 Existing Hypotheses Surrounding Causes of Outbreaks

While much is known about COTS lifecycle and biology, little is known about the causes of outbreak populations. Several hypotheses have been presented to explain the occurrence of population outbreaks, but no single hypothesis has unanimous support. Scientists have long been recording the effects of disturbances on corals reef and have distinguished these disturbances into anthropogenic or natural causes. For most reef disturbances, including COTS outbreaks, this distinction between natural and anthropogenic is not always apparent. For example, severe tropical storms have been considered a recurrent natural disturbance yet research such as that by Webster et al. (2005) has reported that due to anthropogenic climate change the severity, and possibly frequency, of severe tropical storms is increasing. This convolutes the delineation between anthropogenic and natural drivers of disturbances. Many hypotheses surrounding COTS outbreaks have been formulated by combining one or more disturbance drivers. Today, several prominent hypotheses have emerged in an attempt to explain outbreaks (Table 1.2).

Table 1.2 Existing hypotheses surrounding COTS outbreaks

Hypothesis Name	Basis	References
Terrestrial Runoff	Suggests that enhanced nutrient supply from terrestrial run-off is critical for enhanced COTS larval survival. Run-off events provide a pulse of nutrients that stimulate phytoplankton blooms which can supplement otherwise food limited COTS larvae. Phytoplankton blooms sources may include river runoff, upwelling, and resuspension of sediment during storms.	Birkeland (1982), Lucas (1982), Brodie (1992), Furnas (1989), Wooldridge & Brodie (2015)
Enhanced Larval Survivorship	A modification of the terrestrial runoff hypothesis, this suggests that the critical stage of the life cycle at which large changes in the adult population could be initiated in the larval stage. This hypothesis also suggests that low salinities and high temperatures enhance larval survival and growth.	Lucas (1972, 1973, 1975, 1982), Henderson (1969), Pearson (1975), Fabricus et al. (2010)
High Island	Spatial hypothesis based on the observations that COTS outbreaks occur on high islands or continental edges but not off low-lying coral atolls free of rivers and deep soils. Preliminary research suggested that high islands have outbreaks 2-3 years after periods of high rainfall around high islands and continental masses. The delay accounts for the time required for larvae to settle, metamorphose into adults, feed on corals, and attain sufficient size to be recognized during surveys.	Tsuda (1971), Pearson (1975), Birkeland (1981, 1982, 1987
Predator Removal	Based on the assumption that the COTS population is largely controlled by predation (particularly by fish and gastropods), and thus the number of starfish to survive to maturity would increase in response to the commercial exploitation of predatory fish.	Endean (1969),, McCallum et al. (1989), Dulvy et al. (2004), Sweatman 2008)

Common to several COTS outbreak hypotheses is that high rainfall, terrestrial runoff, and elevated nutrients are likely to increase the likelihood that outbreaks will occur. Due to inconsistencies and discrepancies in their spatial and temporal occurrences, these factors cannot account for all recorded COTS outbreaks. For the purposes of this study, some aspects of environmental-related hypotheses will be considered in an attempt to temporally investigate the environmental drivers of COTS outbreaks specifically on Guam.

1.4 Physical Environment of Guam

The island of Guam has its origins rooted in the active arc submarine volcanism that was common in the Western Pacific. Guam currently sits at the edge of the Philippine Plate where the Pacific Plate subducts below and has a total landmass of 560 km^2 (Burdick et al., 2008). Guam can be split into two major distinct areas based on geologic composition: the southern end and the northern end. The northern end of Guam is characterized by being composed of a relatively flat uplifted limestone plateau bordered by steep wave-cut cliffs (Tracey et al., 1964, Ward et al., 1965). The southern half of Guam features rugged dissected upland terrain composed mostly of volcanic rock (Ward et al., 1965). The tallest point stands in the southern volcanic uplands at approximately 405 meters (Burdick et al., 2008).

The island has 244 km of shoreline and possesses a variety of reef types (Burdick et al., 2008). In nearshore waters (0-5.5 m), the combined area of the coral reef and lagoon is approximately 108 km^2 (Hunter, 1995). The most predominant reef type around the island is fringing reefs. The shallow reef platform (0-2 m) around the island varies in width around the island from tens of meters to over 781 m in Pago Bay on the Eastern side of the island (Randall and Eldredge, 1976). Guam established a network 5 marine preserves to preserve, protect, and manage aquatic resources. The five preserves are Sasa Bay, Piti Bomb Holes, Tumon Bay, Achang Reef Flat, and Pati Point. The health of the island's reefs varies significantly over spatial and temporal scales. Overall, Guam's coral reefs are reported to be in fair condition.

Figure 1.3 Map of Guam indicating the locations of rivers, marine protected areas, and coral reefs.

On Guam, more than 40 rivers, streams and creeks are present and are only located in the south due to the low permeable volcanic rocks (Figure 1.3). The highly permeable limestone in the north does not allow for rivers or streams to exist (Ward et al., 1965). Rivers on the western side of the southern mountain ridge have short and steep gradients. The longer streams on the eastern side of the ridge have steep upper region gradients and more gentle gradients that flow into wide valley flats (Ward et al., 1965).

1.5 Project Objectives

The overall objective of this project is to relate the physical environment to COTS outbreaks to find supporting evidence that COTS outbreaks are linked to environmental conditions. Existing research has shown that high rainfall and terrestrial runoff increase the likelihood that COTS outbreaks will occur in some regions, giving some validity to the terrestrial runoff hypothesis. It is also well established that COTS are unable to remain attached to coral heads during high surf events. We believe that high wave events also have the potential to bury or increase sedimentation of corals, therefore decreasing COTS ability to feed on corals. Therefore, we hypothesized that high precipitation events and lack of significant wave events are main factors in the occurrence and proliferation of COTS outbreaks in Guam.

In order to investigate our hypothesis and achieve our main objective, we proposed two questions to address gaps in knowledge: (1) When are where are outbreaks occurring? and (2) What are the average seasonal conditions where outbreaks are found? To investigate the first question, first we had to map the spatial extent and severity of COTS populations using available data from NOAA. Prior to this study no seasonal climatology existed for Guam, so in order to investigate the second proposed question, we had to construct a climatology using several regional models and map the data. By answering the aforementioned questions, we were able to draw primary conclusions regarding the spatial relationship between COTS populations and average environmental conditions. Using these primary conclusions, we investigated our hypothesis further by selecting sites during differing years to do a fine-scale analysis of wave and precipitation data. By doing so, we were able to assess any visible correlations between COTS outbreaks and the physical environment that may be linked to the occurrence and proliferation of outbreaks. This spatio-temporal comparison is important to investigate and potentially validate any trends between COTS outbreaks, waves and precipitation. The conclusions drawn from this study may be further investigated and could potentially serve as the basis of further research into environmental drivers of COTS outbreaks on Guam which will aid in local coral reef management.

2.0 METHODS

2.1 Benthic Towed Diver Surveys

The benthic towed diver surveys are a suitable method of quantifying benthic components and the general distribution and abundance patterns of corals, algae, and macroinvertebrates over a relatively large reef area. The method involves towing two NOAA-certified Coral Reef Ecosystem Division (CRED) divers, one benthic and one fish, 60 m behind a small boat that generally moves at a velocity of 1-2mph. Each diver is equipped with a tow-board that they actively maneuver in an attempt to maintain a constant elevation (1 m) above the reef surface at a ~15 m depth contour. Attached to the tow-board are several instruments including pressure and depth sensors, strobe lights, benthic downward-facing camera, timers, and an observer datasheet (Figure 2.1). A visually estimated 5 m transect on either side of the diver is assumed. A complete towed diver survey is approximately 50 minutes and is divided into 10, 5-minute segments with visual observations recorded per 5-minute segment covering a total of 2-3 km of reef habitat. The towed diver survey data were obtained during the Pacific Reef Assessment and Monitoring Program (RAMP) cruises to the Mariana Archipelago for the years 2003, 2005, 2007, 2009, 2011, 2014 and 2017. COTS densities were calculated and mapped using QGIS to analyze spatiotemporal trends of COTS outbreaks. These data are available online via the NOAA National Centers for Environmental Information (NCEI) Ocean Archive.

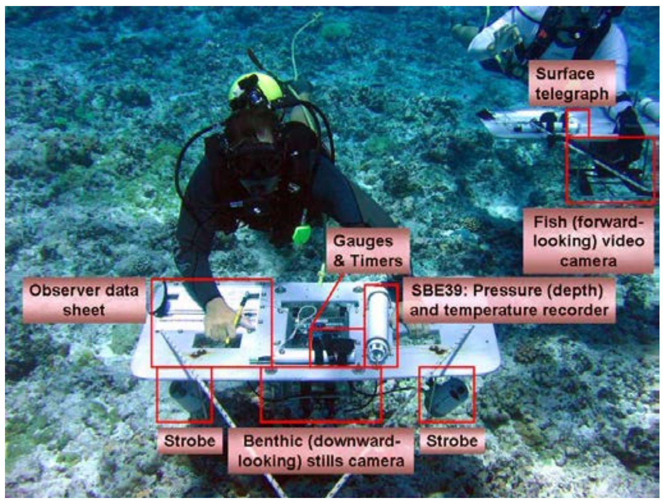

Figure 2.1 An example of a tow-board diver collecting benthic habitat data using a tow board equipped with several instruments. Photo courtesy of NOAA.

2.2 Regional Ocean Modeling System (ROMS)

Model output from the Regional Ocean Modeling System (ROMS) was used to provide current speed, wind direction, wind speed, sea surface temperature, sea surface height, and sea surface salinity. These data were obtained online using the ERDDAP data server published by PacIOOS (PacIOOS; http://pacioos.org/erddap). ROMS output is based on a 6-day, 3-hourly forecast for the region surrounding Guam and parts of the Commonwealth of the Northern Mariana Islands (CNMI) at approximately 2-km resolution and was provided by Dr. Brain Powell of the University of Hawai'I (Powell, 2015). The dataset encompasses the latitude and longitude range of 11.93793 to 15.97538°N and 142.91875 to 146.97229°E.

2.3 Simulating WAves Nearshore (SWAN) Regional Wave Model

Outputs from the University of Hawai'i "Simulating WAves Nearshore (SWAN) Regional Wave Model: Guam" were obtained online using the ERDDAP data server published by PacIOOS (PacIOOS; http://pacioos.org/erddap). Model output is based on a regional model 7-day output with a 5-day hourly forecast for the island of Guam at approximately 500-m resolution provided by Dr. Kwok Fai Cheung (Cheung, 2012). The dataset encompasses the entire island of Guam from 13.15 to 13.75°N and 144.55 to 145.05°E.

2.4 Weather Research and Forecast (WRF) Model

The precipitation and wind direction, and wind speed datasets were obtained from a model developed by the University of Hawai'i entitled "Weather Research and Forecasting (WRF) Regional Atmospheric Model: Guam" (Chen, 2013). Output model runs were produced and made available at the University of Hawaii by Yi-Leng Chen as a 7-day hourly forecast for the region surrounding the island of Guam at approximately 3-km resolution. Data can be found online using the ERDDAP data server published by the Pacific Islands Ocean Observing System (PacIOOS; http://pacioos.org/erddap). The data encompasses Guam and the Northern Mariana Islands and the dataset encompasses the latitude and longitude ranges from 11.93188 to 15.9786°N and 142.9017 to 147.07249°E.

2.5 Spatio-Temporal Comparisons

The approach to executing the spatio-temporal analysis follows four main steps: (1) use the mapped NOAA benthic towed-diver surveys to map spatial distributions of COTS populations, (2) use available PacIOOS regional models for Guam to construct a 5 year climatology in order to assess mean seasonal conditions around the island, (3) assess any relationships between seasonal physical parameters and COTS outbreak populations, and (4) choose suitable sites during differing survey years with available continuous model data to further investigate any site-specific relationships between COTS populations and physical parameters.

A review of available regional model data for Guam revealed that the earliest available data is only available after 2012. NOAA MARAMP benthic towed-diver surveys were completed in 2003, 2005, 2007, 2009, 2011, 2014, and 2017. While all years of NOAA MARAMP benthic surveys were mapped, our study requires regional model data to be available during times when the benthic surveys were done. Thus, our analysis was constrained to 2014 and 2017. For 2014, data were assessed from March 20th to the 27th and for 2017 data were assessed from April 30th to May 7th.

The selection of suitable sites for the 2014 and 2017 survey years was based on the difference in COTS populations between the two survey years. The two sites that were selected to test our hypothesis (see section 1.6) were Gun Beach and Uruno Point (Figure 2.2). Gun Beach was selected due to having a higher abundance of COTS in 2014 and relatively lower COTS abundance in 2017. Uruno Point was also selected as a study site due to difference in COTS densities at the same location between the 2014 and 2017 survey year. Uruno Point had a higher abundance of COTS in 2017 and a relatively lower abundance in 2014.

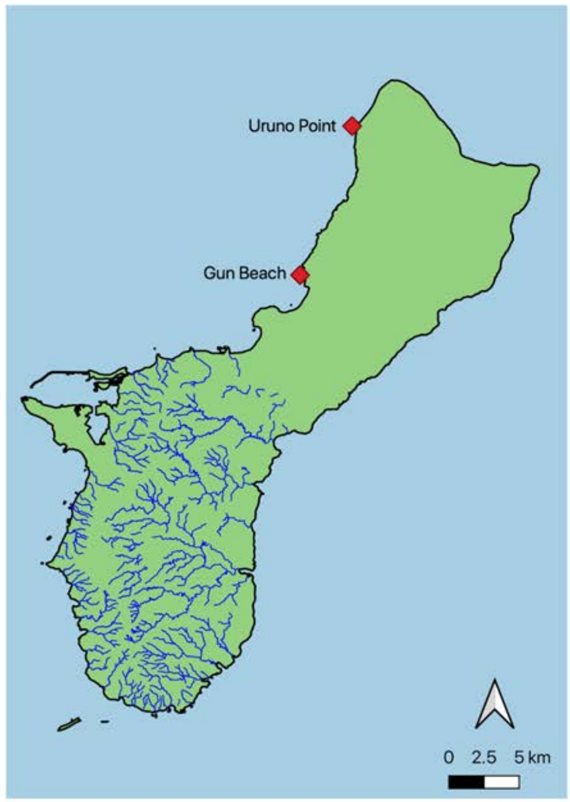

Figure 2.2 The two selected study site locations for further investigation that were both surveyed during MARAMP 2014 and 2017.

We graphed precipitation flux and significant wave heights for Gun Beach and Uruno Point during the aforementioned study period to visual discover any consistencies among the data that could explain the occurrence and proliferation of COTS populations at the chosen sites. We categorize this method as an event-based analysis due to the fact we are not looking into long-term trends or correlations. It is important to note that we addressed all environmental variables that were included in the climatology (see section 3.2) for their potential to be environmental drivers of COTS outbreaks but all besides precipitation flux and significant wave height were excluded based on several factors.

The main factors that contributed to all other variables being excluded in the study were: (1) they were not implicated in previous literature as potential environmental drivers of COTS outbreaks, (2) there was not enough continuous regional model data available, and (3) they exhibited minimal seasonal fluctuations which could not be attributed to the cause of outbreaks due to the lack of extreme seasonal signals. Data limitations only allow for visual correlations between variables rather than statistical correlations.

3.0 RESULTS

3.1 COTS Outbreak Density History on Guam

Guam has a long and continued COTS outbreak history. Due to their ability to decimate coral reefs, understanding when observed populations reach outbreak densities is critical. While several outbreak thresholds exist, for the purposes of this study the observations by Moran and De'Ath (1992) will be used. Moran and De'Ath (1992) defined a potential outbreak as a reef area where the COTS density is ≥ 0.15 organisms 100 m^{-2} due to their observations that significant COTS-related coral mortality was only seen on reefs that density or higher. COTS outbreaks were recorded on Guam's reefs throughout the early 2000s and throughout the 2010s during the Pacific Reef Assessment and Monitoring Program (RAMP) cruises. The MARAMP cruises were conducted biennially from 2003 to 2011 and triennially from 2011 to 2017.

During MARAMP 2003, COTS were recorded during 9 of the 20 towed-diver surveys with an island wide mean density of 0.05 organisms 100 m^{-2} (Figure 3.1). COTS were concentrated on the western side of the island. Out of all surveys, the survey done near Bangi Point had the highest mean density of COTS with 0.03 organisms 100 m^{-2} and segment densities ranging from 0 to 1.94 organisms 100 m^{-2}. The second greatest mean density of 0.23 organisms 100 m^{-2} COTS was recorded on the southern tip of Tumon Bay; segment densities from this survey ranged from 0 to 1.17 organisms 100 m^{-2}.

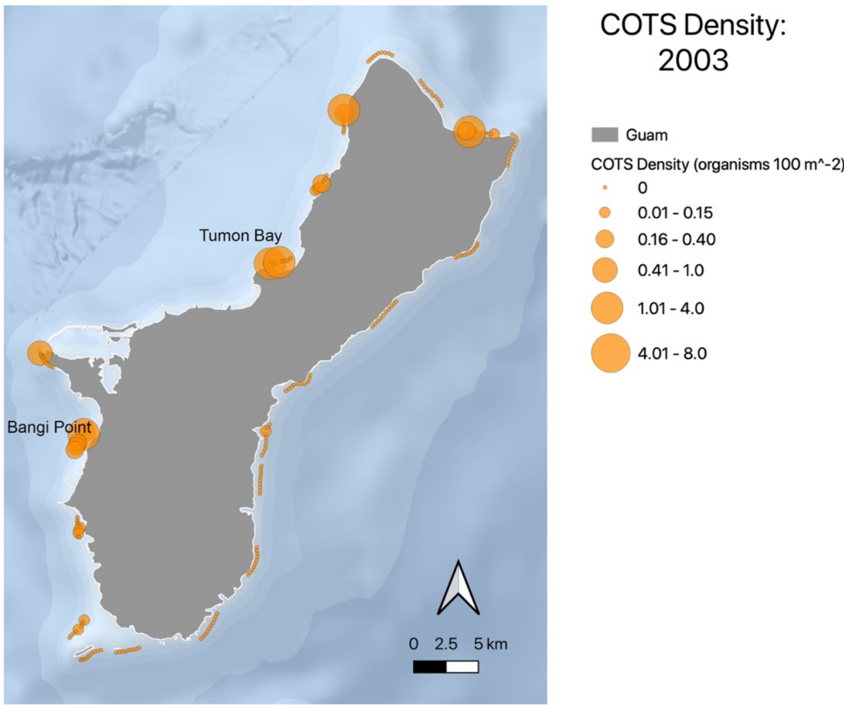

Figure 3.1 Densities (organisms 100 m^{-2}) of COTS from towed diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003 (Sept. 23rd-26th)

During MARAMP 2005, COTS were recorded during 14 of the 23 towed-diver surveys with an island wide mean density of 0.1 organisms 100 m^{-2} (Figure 3.2). COTS appeared more concentrated on the west side and the eastern region between Talofofo and Togcha Bays. The survey with the highest COTS mean density of 0.82 was organisms 100 m^{-2} near Togcha Bay; segment densities from this survey ranged from 0 to 4.79 organisms 100 m^{-2}. The second highest COTS mean survey density was also found near Togcha bay with 0.29 organisms 100 m^{-2}; segment densities ranged from 0 to 1.16 organisms 100 m^{-2}.

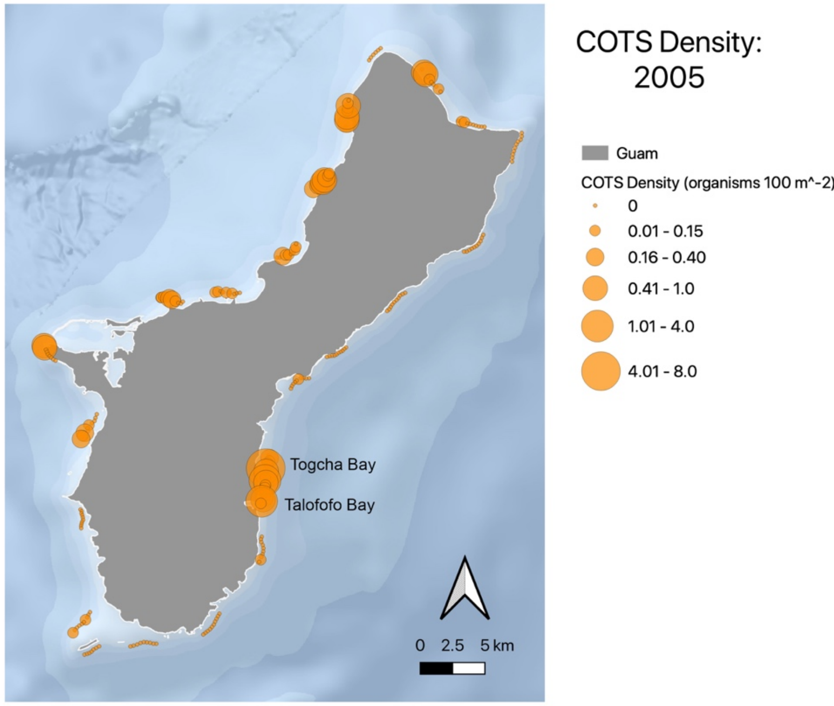

Figure 3.2 Densities (organisms 100 m^{-2}) of COTS from towed diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2005 (Oct. 3rd-5th, Oct. 8th)

During MARAMP 2007 COTS were observed during 18 of the 19 towed-diver surveys with an island wide mean density of 0.154 organisms 100 m^{-2}, the highest island-wide mean density recorded for all seven survey years (Figure 3.3). COTS appeared more concentrated on the east side although COTS were found around the entire island. Among all surveys, the greatest COTS mean density of 0.77 organisms 100 m^{-2} was reported along Fadian point; segment densities from this survey ranged from 0.09 to 3.24 organisms 100 m^{-2}. The second highest survey mean density of 0.55 organisms 100 m^{-2} was also found on the east side of the island near Champanaya Point; segment densities from this survey ranged from 0 to 4 organisms 100 m^{-2}.

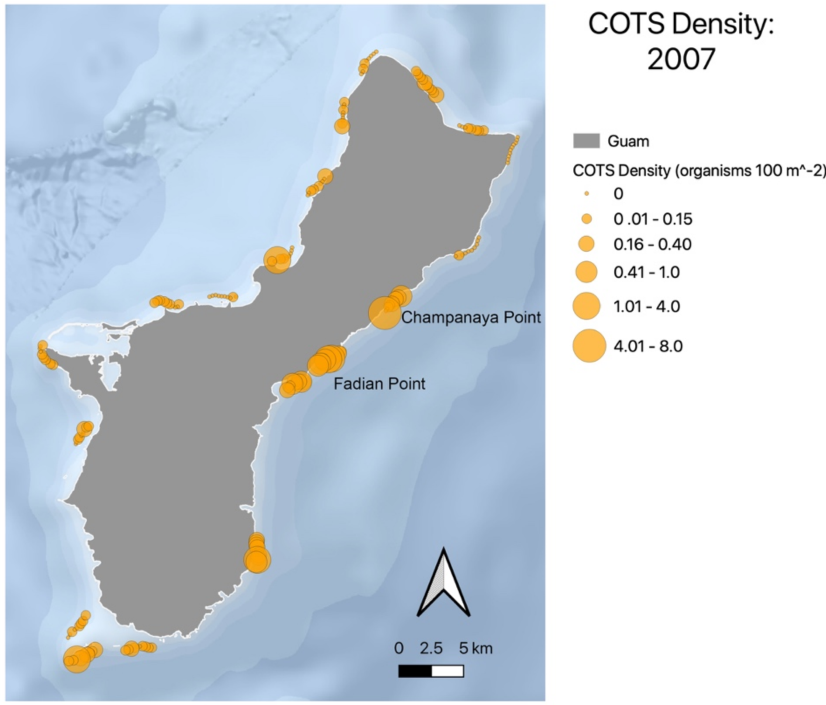

Figure 3.3 Densities (organisms 100 m^{-2}) of COTS from towed diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2007 (May 12th-15th).

During MARAMP 2009 COTS were observed during 21 of the 25 towed-diver surveys with an island wide mean density of 0.126 organisms 100 m^{-2} (Figure 3.4). COTS were found around the entire island but appeared more concentrated on the northeastern and eastern sides of the island. Out of all surveys, the survey done around Mati Point had the highest mean density of COTS with 0.75 organisms 100 m^{-2} and segment densities ranging from 0 to 7.5 organisms 100 m^{-2}. The second greatest mean density of 0.73 organisms 100 m^{-2} COTS was recorded near Haputo Point; segment densities from this survey ranged from 0 to 1.17 organisms 100 m^{-2}.

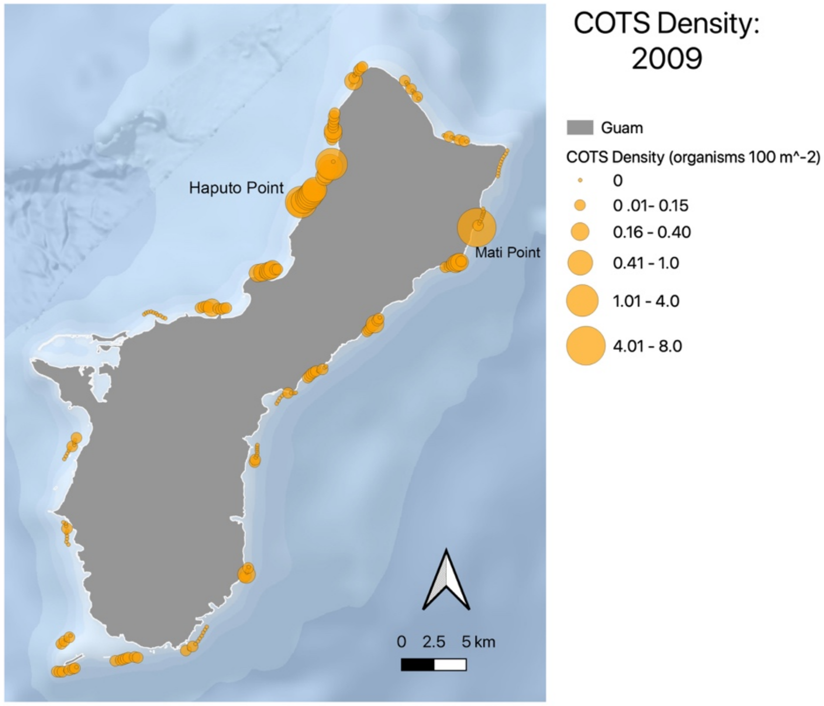

Figure 3.4 Densities (organisms 100 m^{-2}) of COTS from towed diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2009 (April 3rd, 5th, 6th-8th).

During MARAMP 2011, COTS were recorded during 17 of the 23 towed-diver surveys with an island wide mean density of 0.042 organisms 100 m^{-2} (Figure 3.5). COTS were concentrated more on the northeastern tip and northwestern side of the island. Out of all surveys, the survey done off of Ague Point had the highest mean density of COTS with 0.2 organisms 100 m^{-2} and segment densities ranging from 0 to 0.98 organisms 100 m^{-2}. The second greatest mean density of 0.18 organisms 100 m^{-2} COTS was recorded just south of Pati Point; segment densities from this survey ranged from 0 to 1.33 organisms 100 m^{-2}.

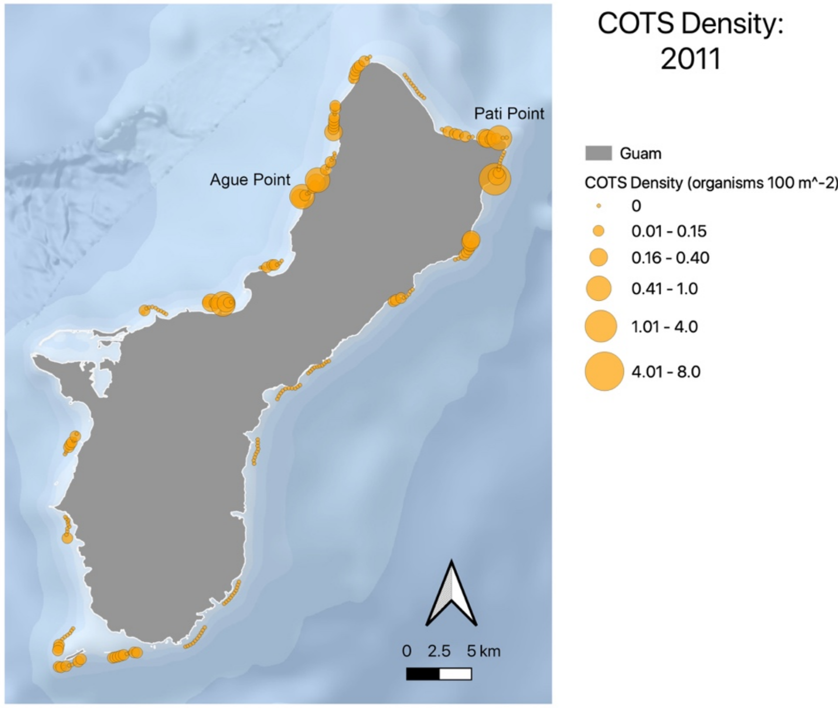

Figure 3.5 Densities (organisms 100 m^{-2}) of COTS from towed diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2011 (May 5^{th}-9^{th}).

During MARAMP 2014, COTS were recorded during 21 of the 31 towed-diver surveys with an island wide mean density of 0.022 organisms 100 m^{-2} (Figure 3.6). COTS were more evenly distributed around the entire island with COTS being more concentrated along the south and northwestern shores. Out of all surveys, the survey done off of Puntan Dos Amantes (Two Lovers Point) had the highest mean density of COTS with 0.19 organisms 100 m^{-2} and segment densities ranging from 0 to 0.55 organisms 100 m^{-2}. The second greatest mean density of 0.067 organisms 100 m^{-2} COTS was recorded near Haputo Point; segment densities from this survey ranged from 0 to 0.2 organisms 100 m^{-2}.

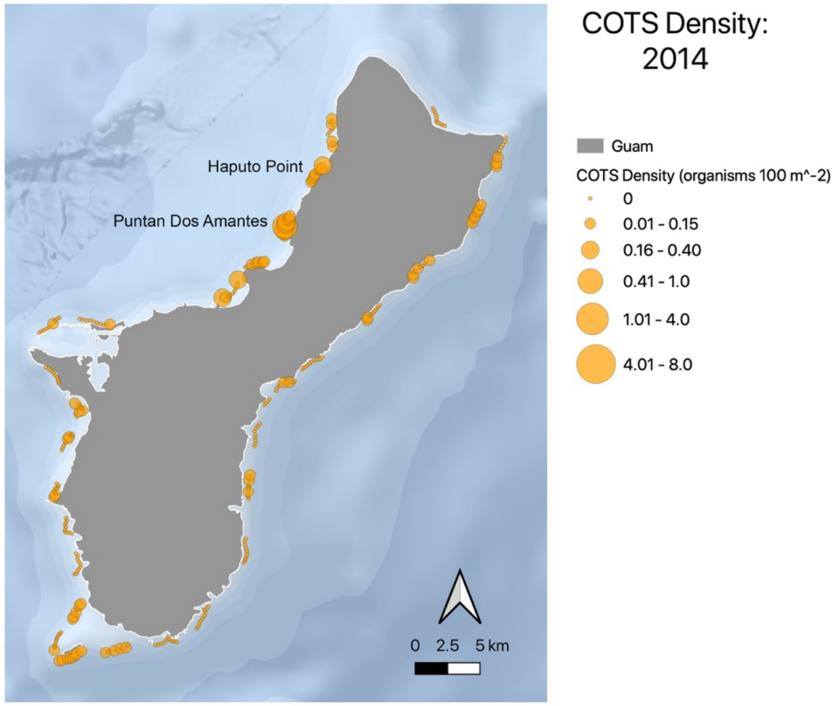

Figure 3.6 Densities (organisms 100 m^{-2}) of COTS from towed diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2014 (Mar. 25th-29th, Apr. 4th).

During MARAMP 2017, COTS were recorded during 11 of the 24 towed-diver surveys with an island wide mean density of 0.008 organisms 100 m^{-2} (Figure 3.7). COTS were concentrated more on the northwest region of the island. Out of all surveys, the survey done near Uruno Point had the highest mean density of COTS with 0.07 organisms 100 m^{-2} and segment densities ranging from 0 to 0.56 organisms 100 m^{-2}. The second greatest mean density of 0.02 organisms 100 m^{-2} COTS was recorded near Gun Beach; segment densities from this survey ranged from 0 to 0.48 organisms 100 m^{-2}.

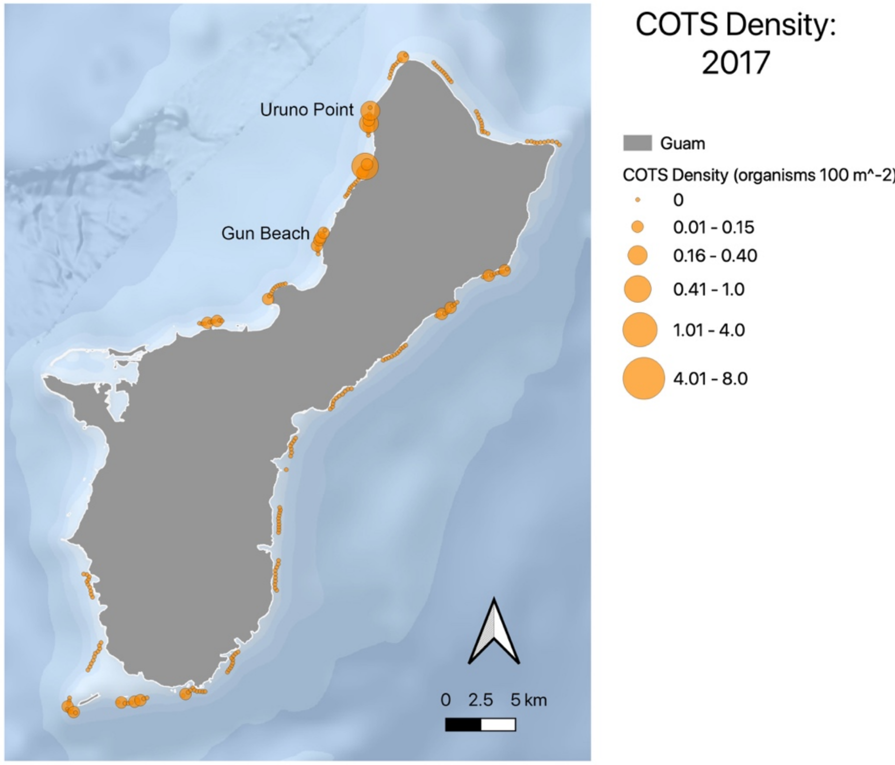

Figure 3.7 Densities (organisms 100 m^{-2}) of COTS from towed diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2017 (May 4^{th}, 6^{th}-8^{th}, 14^{th}).

Figure 3.8 shows the temporal comparison between COTS island-wide mean density for the 7 MARAMP survey years. MARAMP survey results make it evident that COTS populations underwent a linear increase in abundance from 2003 to 2007 and then a linear decrease in abundance from 2007 to 2017. Each survey year displayed varying spatio-temporal trends, validating the conclusions made by Birkeland and Lucas (1990) and Fabricius et al. (2010) that COTS abundance naturally fluctuates based on varied recruitment cycles and food availability. The linear decrease in island-wide density of COTS could potentially be linked to a decrease in preferred prey or environmental phenomenon. It is also possible that due to scattered and inconsistent monitoring that some reefs around Guam have reached the COTS outbreak threshold and have gone undetected.

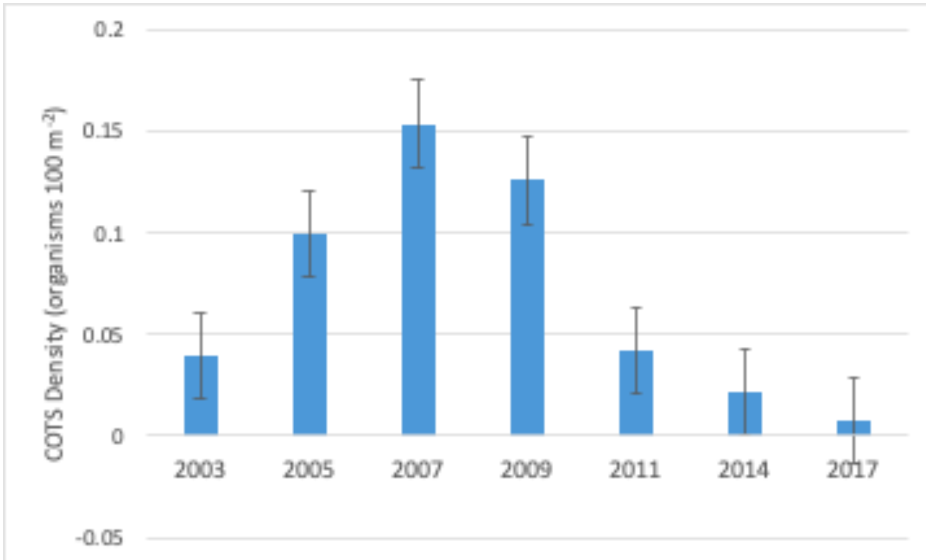

Figure 3.8 Temporal comparison of COTS island wide mean densities (organisms 100 m^{-2}) from NOAA towed diver benthic surveys conducted on fore-reef habitats around Guam during MARAMP 2003, 2005, 2007, 2009, 2011, 2014, and 2017. Error bars indicate standard error (± 1 SE) of the mean.

Despite MARAMP benthic surveys being completed during different seasons, COTS were still found during all survey years. It appears that in Guam, COTS show no seasonality. From the available MARAMP benthic survey data that we examined; COTS populations appear to be patchy in space and vary significantly throughout survey years at the same sites.

3.2 Climatology

No climatology has been previously published for Guam. Creating a climatology is key to understanding the mean seasonal oceanic and atmospheric conditions around Guam. The climatology created for this study uses various regional models to construct a seasonal climatology. To be consistent with available model data, the regional models were run from 2015 to 2019 and were then graphed as surfaces. The mapped seasonal climate data gives new insight into Guam's climate and also allows us to understand the mean climate at specific sites. By comparing the climatology maps to COTS population density maps (see Section 3.1) we are able to relate the mean climate at the specific sites to where COTS outbreaks are known to occur. This information is vital to analyzing the fine-scale data at our two specific sites to see if the data there reflects or diverges from the seasonal mean in the region.

Precipitation patterns around Guam have distinct seasonal cycles, rainy and dry (Figure 3.9). Dry season typically lasts from December to March and the rainy season lasts from July to November. Throughout all seasons, the west side of Guam experiences lower levels of precipitation flux in comparison to the east side. The seasonal climatology does not reflect the large deviations from average precipitation flux caused by the El-Niño Southern Oscillation (ENSO) and tropical cyclones. Changes in precipitation may impact coral reefs due to increased runoff of freshwater, pollutants, and sediments which contribute to algal blooms and shading of reefs.

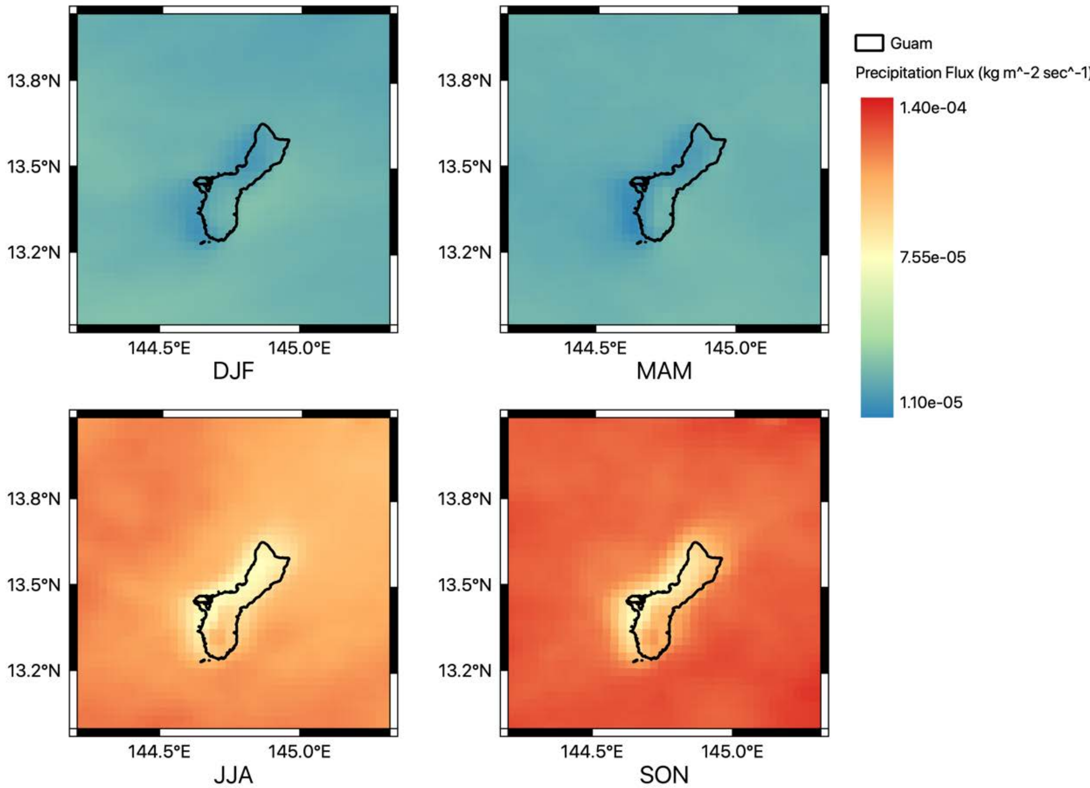

Figure 3.9 Precipitation flux (kg m^{-2} sec^{-1}) around Guam. Data were taken from the WRF model and averaged for each season from 2015-2019.

Wind speeds on Guam have a distinct seasonal cycle with wind speeds ranging from as low as 1.70 m s^{-1} in the spring and summer to as high as 8.50 m s^{-1} in the winter (Figure 3.10). The western side of Guam experiences lower wind speeds each season, with the lowest speeds found in the southwestern side of the island. Winter experiences the highest wind speeds around 8 meters per second.

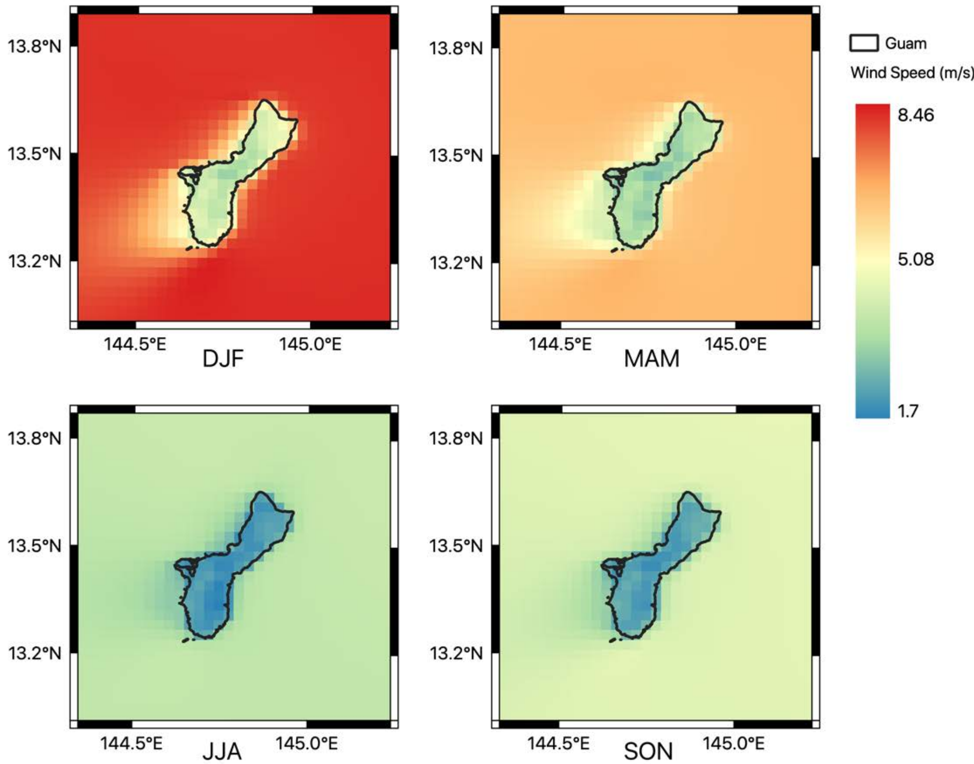

Figure 3.10 Wind speeds (m/s) around Guam. Data from the WRF model with seasonal averages taken from 2015-2019

Sea surface temperatures (SST) around Guam have a very small seasonal cycle, from close to 27.5 C in winter to 29.0 C in summer (Figure 3.11). Nearshore waters typically exhibit higher temperatures than the deeper, offshore waters. The nearshore waters around the island experience approximately 1°C variation in SST throughout all seasons. The eastern coast of Guam exhibits higher temperatures throughout all seasons. The SST of Guam being between 27-30°C during all seasons allows for ideal COTS spawning, gonad maturity and survival of larvae (see section 1.2.2). Therefore, we believe that SST in Guam is not a main factor in the occurrence and proliferation of COTS outbreaks. This small SST range may have an impact on reef ecosystem resilience in the sense that extreme temperature events may have more of an impact on coral reefs.

When extreme temperature events occur and coral reef health is affected, COTS may not be able to access their preferred coral prey and therefore COTS population dynamics could be affected.

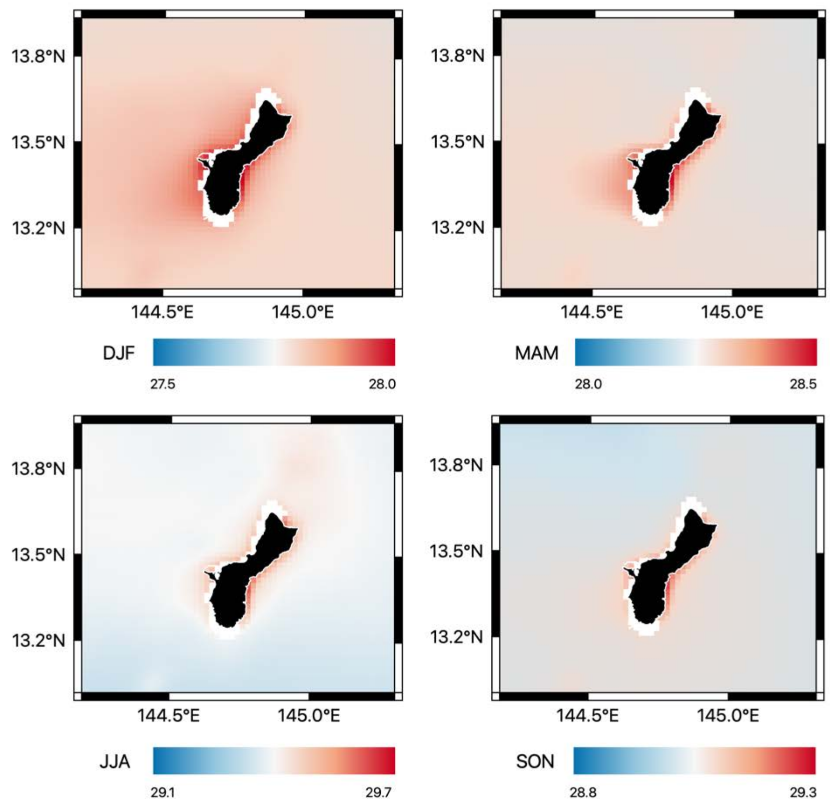

Figure 3.11 Sea surface temperatures around Guam. Data from the ROMS with seasonal averages taken from 2015-2019

Sea surface height around Guam has a varied seasonal cycle from 0.63 m to 0.96 m (Figure 3.12). Nearshore waters of Guam do not appear to experience any significant changes in sea surface height. Summer exhibits the highest seasonal sea surface heights, averaging around 0.8 meters. The lowest sea surface heights appear during winter and fall with sea surface heights averaging around 0.7 meters. No apparent variability in sea surface height exists between the eastern and western shores of Guam.

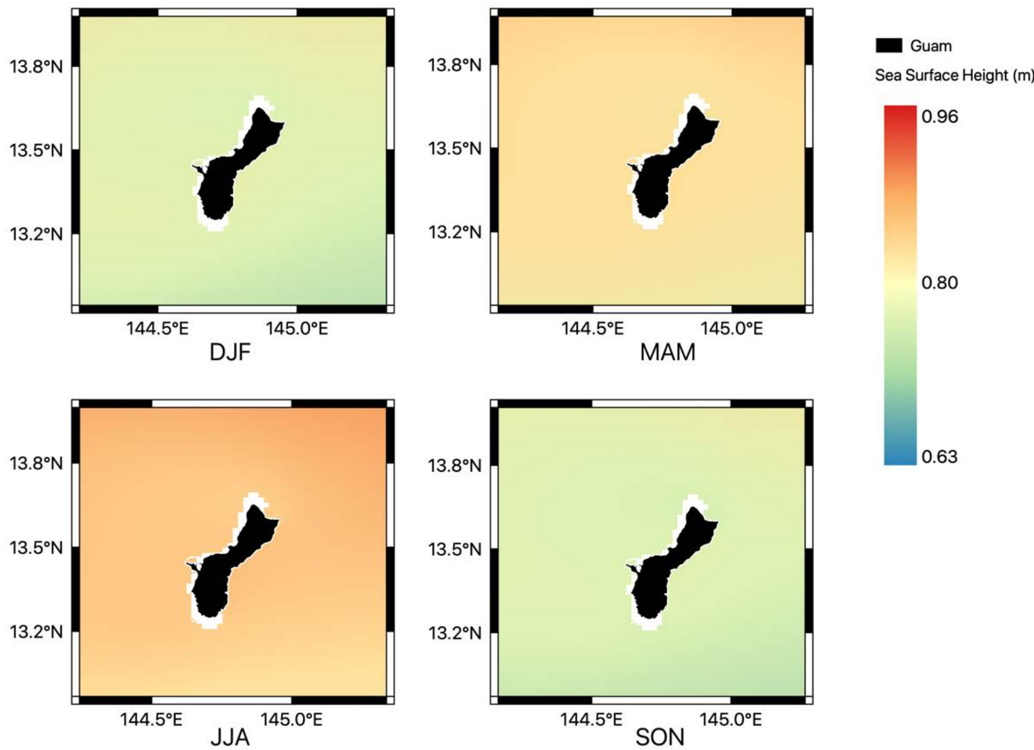

Figure 3.12 Sea Surface Height around Guam. Data from the ROMS with seasonal averages taken from 2015-2019.

Sea surface salinity (SSS) around Guam has a very small season cycle, with a salinity range of only 34.32 to 35 (Figure 3.13). Salinity levels in the nearshore waters stay relatively constant year-round at around 34.50 psu. Eastern nearshore waters have the lowest salinity throughout all seasons, presumably from precipitation runoff and the southward cyclic ocean current. Autumn has the lowest salinity around the island while winter has the highest salinity. Caballes et al. (2017) showed that rates of fertilization declined significantly at salinities less than 30 psu (see section 1.2.2) and with Guam's nearshore waters never being less than 34 psu, we assumed that salinity was not a main factor in COTS fertilization or survival.

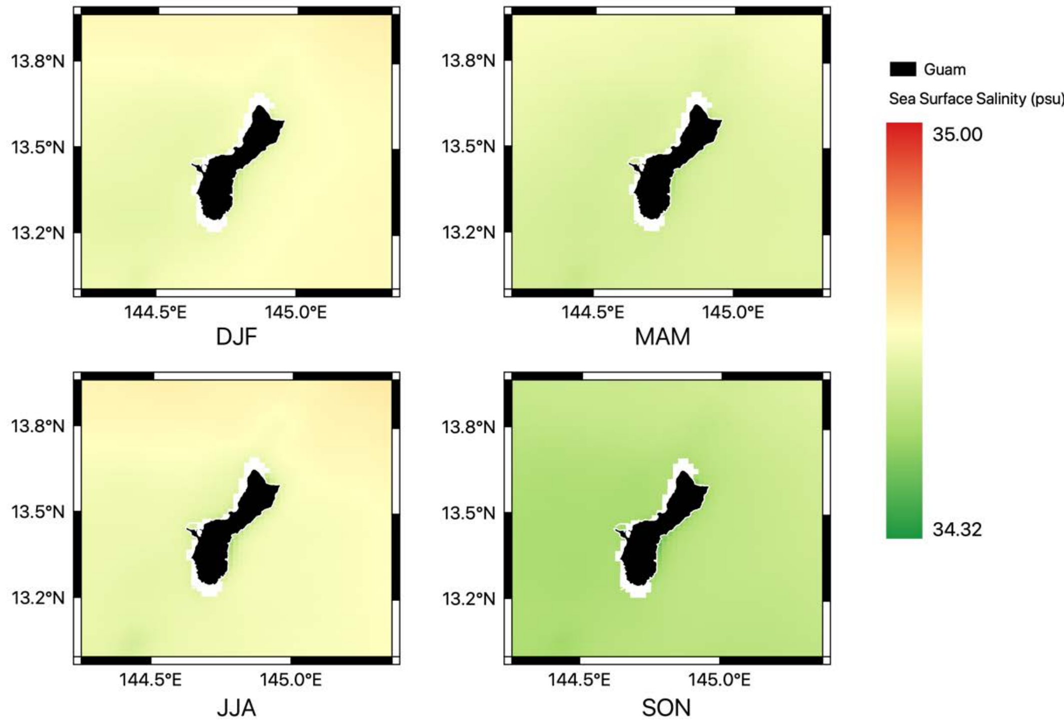

Figure 3.13 Sea surface salinity (psu) around Guam. Data from ROMS with seasonal averages taken from 2015-2019.

Current speeds on Guam have a seasonal cycle with speeds generally being higher in the winter and spring months particularly on the northern and southern ends of the island (Figure 3.14). The west side of Guam shows very little seasonal variation and the slowest seasonal current speeds. The east side has a southward cyclic current for all seasons. Southward currents wrap around the southern tip of Guam with little seasonal variation.

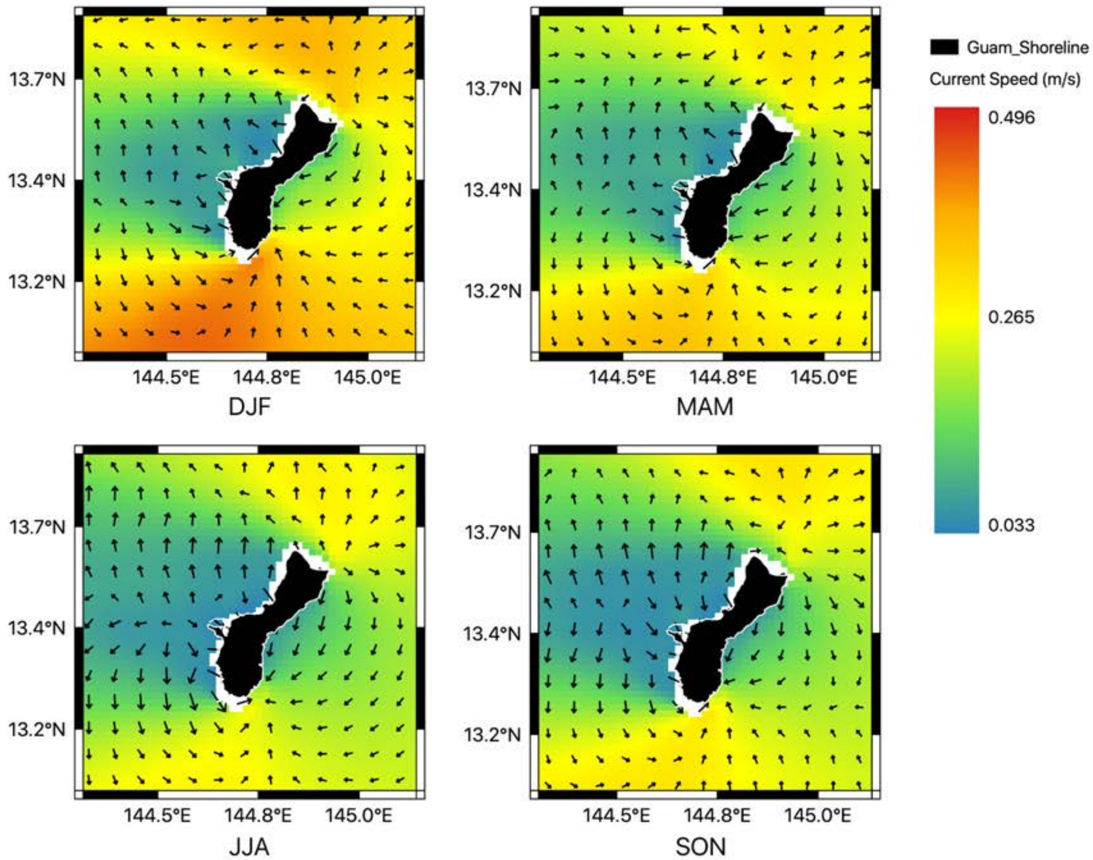

Figure 3.14 Current speed (m/s) and direction around Guam taken from the ROMS model and averaged for each season from 2015-2019. Ocean current speed is shown in color (scale at right) and direction with arrows.

The predominant wave direction for all seasons in Guam is approximately from the North (20°) (Figure 3.15). The southwestern shores as well as the northwestern shores of Guam experience waves from the northwest (315°) for all seasons. The summer experiences the most variable change in wave direction compared to other seasons; the west is dominated by waves coming mainly from the South (180°) and the east is dominated by waves mainly from the East (90°).

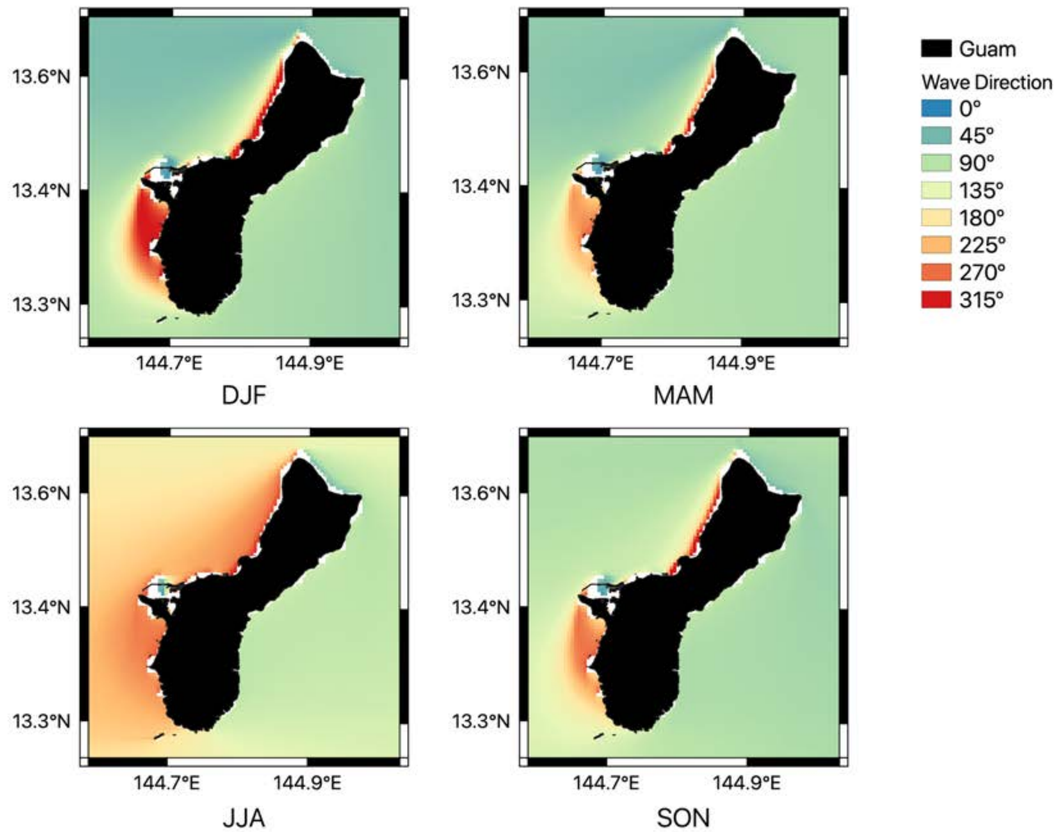

Figure 3.15 Wave direction (°) around Guam taken from the ROMS model and averaged for each season from 2015-2019. Note that the wave direction is the direction waves are traveling from.

Significant wave height around the island of Guam varies both seasonally and for the East and West coasts (Figure 3.16). Autumn and winter experience the highest significant wave heights up to 2.27 meters on the eastern coast of the island and as low as 0.04 meters on the west coast. The east coast of Guam during the spring and summer typically experience significant wave heights of 1.5 meters. During the summer, significant wave height is consistent along all shores of the island averaging about 1.5 meters with the lowest significant wave heights of 0.04 meters observed near Apra Harbor.

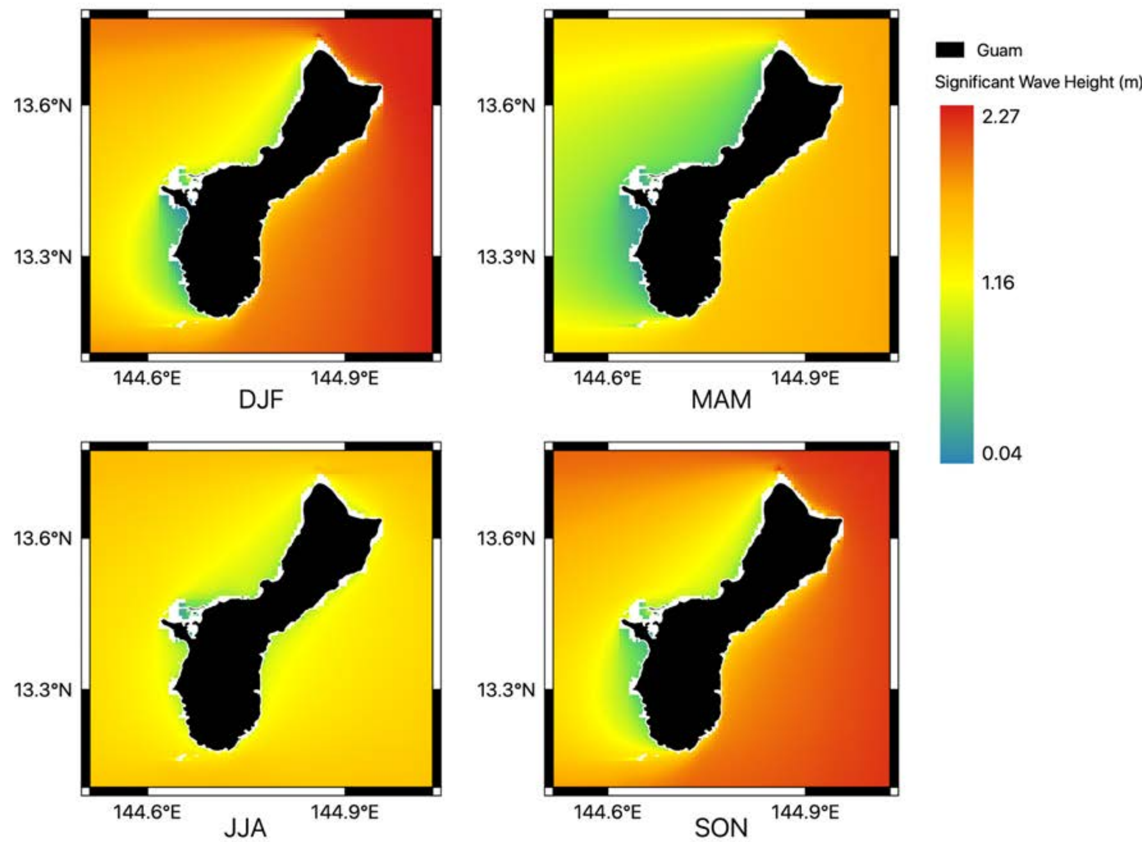

Figure 3.16 Significant wave height (m) around Guam. Data taken from the SWAN model and averaged for each season from 2015-2019.

Mean wave period around Guam has a small seasonal cycle with wave periods typically remaining around 7 seconds around most of the island (Figure 3.17). The winter, spring and autumn exhibit the lowest mean wave periods of approximately 4 seconds on the southwestern shoreline. The summer has the most consistent mean wave period around the entire island compared to other seasons with the mean wave period averaging around 7 seconds. The lowest mean wave periods of 0.83 seconds are observed near Apra Harbor which is sheltered from most wave activity.

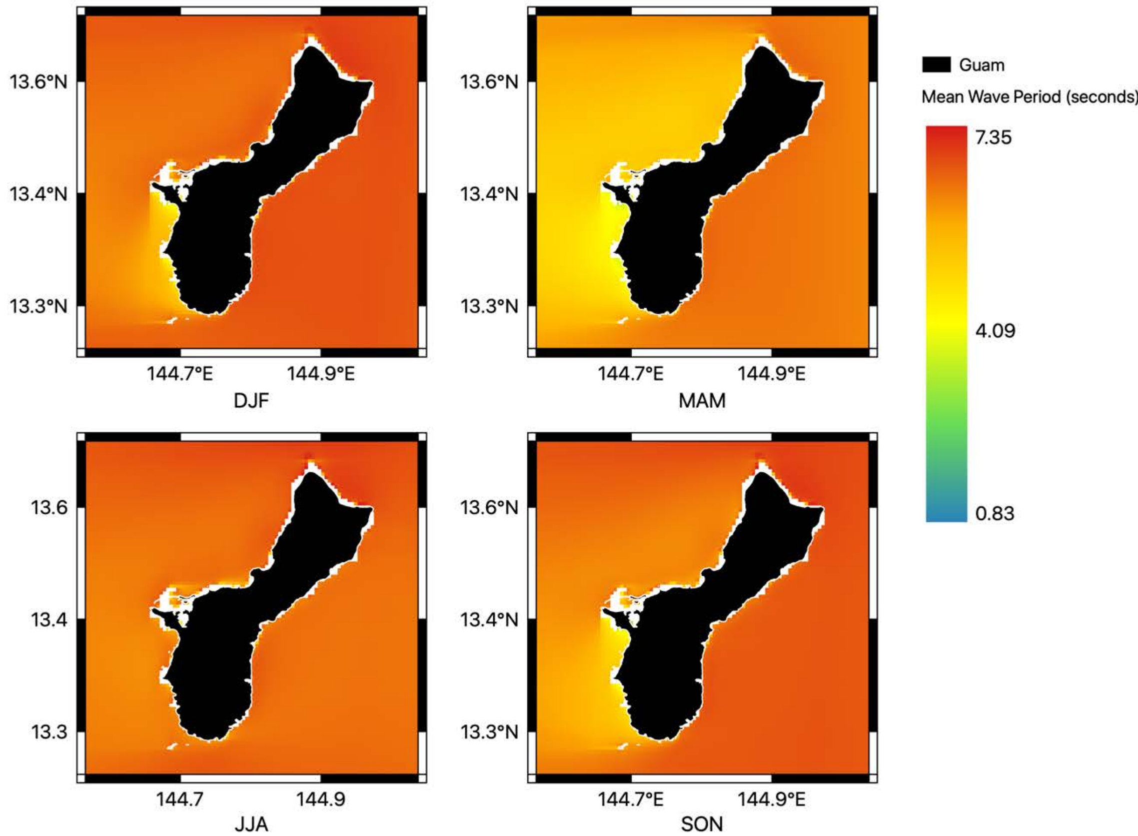

Figure 3.17 Mean wave period (s) around Guam. Data were taken from the SWAN model and averaged for each season from 2015-2019.

3.3 Site Specific Comparisons

3.3.1 Gun Beach

Gun Beach is located on the northwestern coast of Guam and experienced significant COTS density fluctuation between 2014 and 2017. In 2014 COTS densities were much higher than in 2017. Therefore, according to our original hypothesis that the two factors for the occurrence and proliferation of COTS outbreaks are waves and precipitation, we expected that 2014 would have higher precipitation and minimal significant wave events when compared to the 2017 data. Figure 3.18 displays the precipitation and significant wave height data for Gun Beach for 2014 and 2017.

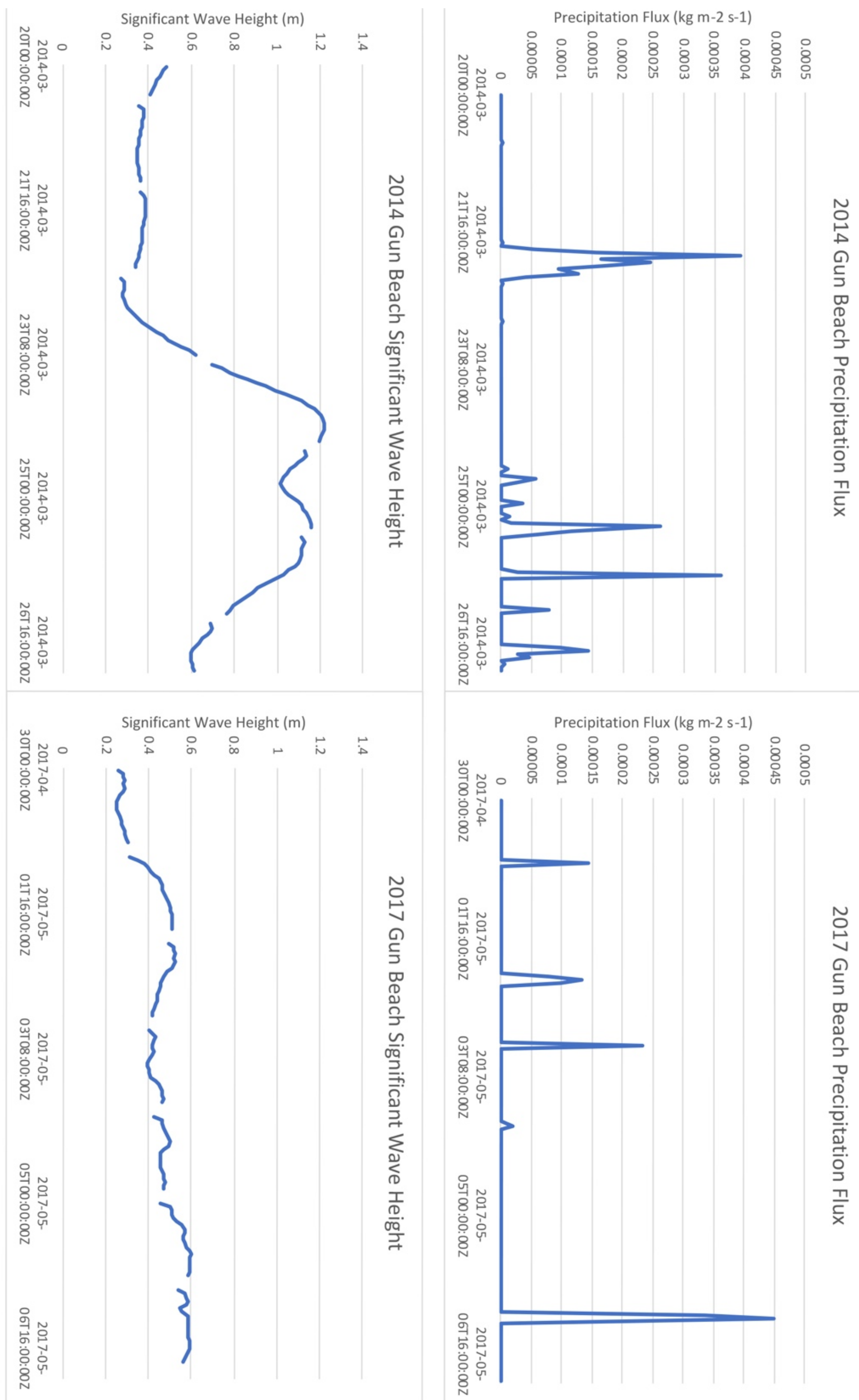

Figure 3.18 Precipitation flux and significant wave height data from SWAN and WRF for Gun Beach during the 2014 and 2017 study periods. Note the gaps for wave data are due to SWAN model data shocks.

Inconsistent with our hypothesis, in 2014 Gun Beach experienced higher significant wave heights than seen in the 2017 data. The significant wave heights observed in 2014 are above average the seasonal average for the region. Our climatology shows that the mean spring seasonal average for Gun Beach is approximately 0.8 m. The 2014 wave heights shown in Figure 3.18 exceed the seasonal average with significant wave heights being over 1.2 m. We originally believed that high significant wave heights would be a barrier to the occurrence of COTS in outbreak populations. The wave data showed that for the study period evaluated, high significant wave events may not be a barrier to the occurrence of COTS outbreaks.

The precipitation data revealed that during the 2014 study period, there was more precipitation flux than seen in the 2017 data. This is consistent with our original hypothesis that 2014 would have more precipitation compared to 2017 data since more COTS were found by the MARAMP benthic towed-diver surveys in 2014. While the precipitation data is consistent with our hypothesis, the wave data is not. Therefore, no definitive conclusions could be made.

3.3.2 Uruno Point

Uruno Point is located on the northwestern coast of Guam, approximately 11 kilometers north of Gun Beach. Similar to Gun Beach, Uruno Point experienced significant COTS density fluctuation between 2014 and 2017. Unlike Gun Beach, Uruno Point experienced higher COTS densities in 2017 when compared to 2014. Therefore, according to our hypothesis, we expected minimal significant wave heights and higher precipitation fluxes in 2017 when compared to the 2014 data. Figure 3.19 displays the precipitation flux and significant wave height data for Uruno Point for 2014 and 2017.

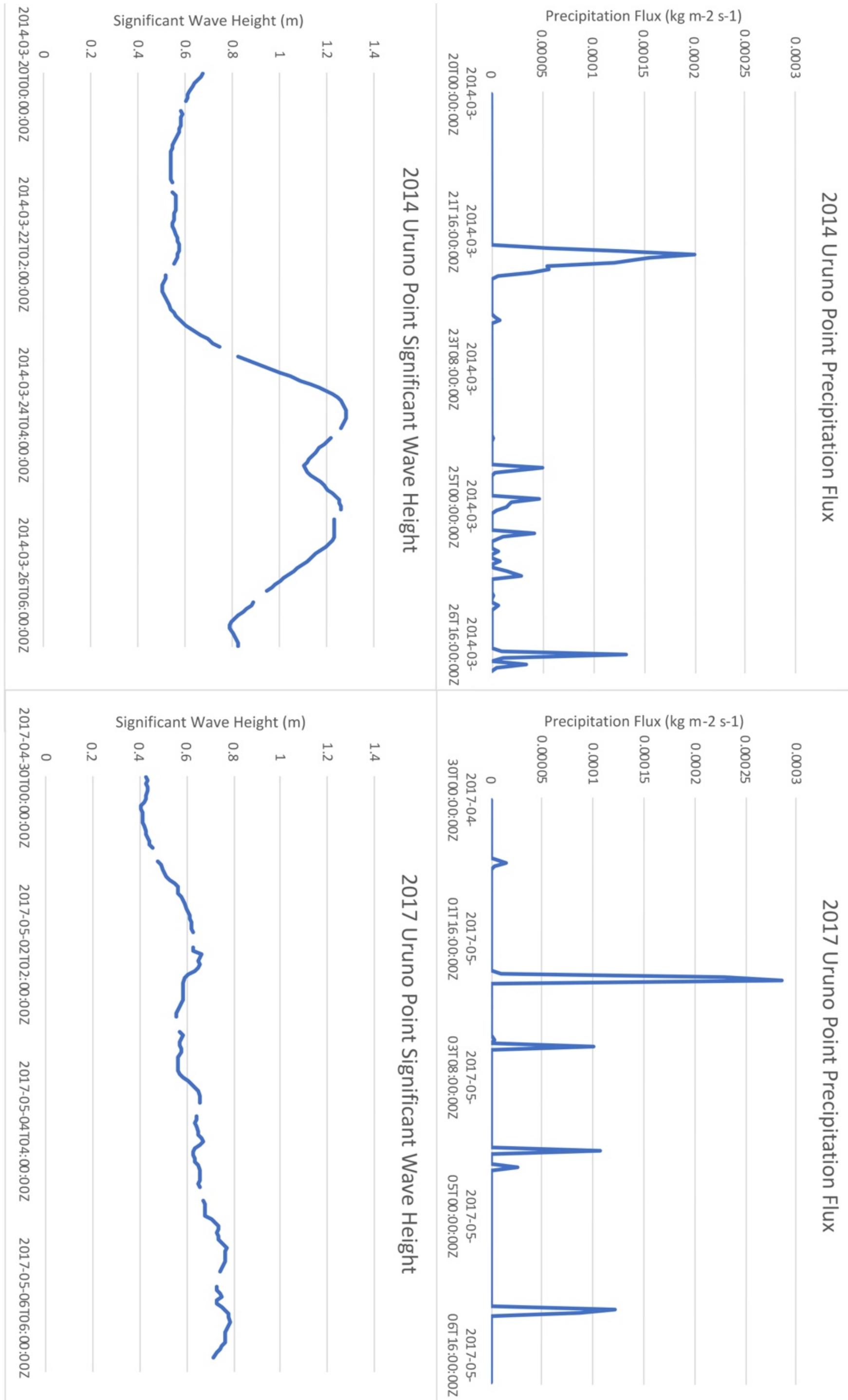

Figure 3.19 Precipitation flux and significant wave height data from SWAN and WRF for Uruno Point during the 2014 and 2017 study periods. Note the gaps for wave data are due to SWAN model data shocks.

During the study period, 2014 experienced more consistent precipitation fluxes when compared to the 2017 data. The 2017 data exhibits the highest precipitation flux seen during the study period with a flux of almost 0.003 kg m^{-2} s^{-1}. Overall, 2014 experienced more precipitation flux over the study period. Both 2014 and 2017 data shows precipitation fluxes higher than the mean spring seasonal average for the region seen in the climatology. This result is inconsistent with our hypothesis since we originally believed that 2017 data would overall show a higher precipitation flux when compared to 2014 data. This is inconsistent with our hypothesis.

The significant wave height data was consistent with our hypothesis. In 2017 Uruno Point experienced lower significant wave heights than observed in the 2014 data. The significant wave height data in 2017 is consistent with the spring seasonal average for Uruno Point. While the significant wave height data was consistent with our hypothesis, the precipitation data was not. Therefore, no definitive conclusions could be made.

4.0 DISCUSSION

An analysis of the two sites during the study periods do not validate our hypothesis that precipitation and low significant wave events are the two factors that set the stage for the occurrence and proliferation of COTS outbreaks in Guam. No consistent or significant relationships between wave heights and precipitation fluxes were found. It is likely that the studied variables do play a role in the proliferation and maintenance of COTS outbreaks to a certain extent. Regardless of the natural occurrences of COTS populations, there must be other driving forces to explain the matinence of COTS populations and their shift from natural populations to outbreak populations. Guam is a data sparse region that particularly lacks long-term and fine-scale environmental data that covers the entirety of the island. The results of this study present many gaps regarding the proper data needed to investigate the environmental variables that are potential drivers of COTS outbreak populations.

The earliest availability of regional model data for Guam is in July of 2012, long after the extreme island-wide outbreak observed in 2007 (see Figure 22). While other environmental data exists for pre-2012 dates, it is often satellite data in which the resolution of those datasets is too low to capture fine-scale differences in the nearshore waters of Guam. It is also possible that the resolution of regional model data sets used were too low to properly observe the conditions of nearshore fore reef habitats. Higher-resolution datasets may have been able to provide more insights into the dynamic environmental conditions during outbreak periods. While chlorophyll and other nutrients have been shown to have possible effects on COTS populations by previous studies, Guam lacks chlorophyll data for most of the island. Only one nearshore sensor is implemented on Guam and it is located in Pago Bay which was not useful in assessing the chlorophyll concentrations at the two study sites. Satellite chlorophyll data had too low of a resolution to be used to assess temporal trends in chlorophyll as well, further limiting the extent of this study.

Since there are many lengths of shorelines that are not consistently monitored for COTS, outbreaks on Guam are not easy to manage or control. This study only used COTS data taken from MARAMP, which does not focus on only reporting COTS data, MARAMP benthic towed-diver surveys were only conducted around Guam biennially from 2003 to 2011 and triennially from 2011 to 2014. The surveyed sites and dates of the surveys shifted throughout each surveyed year, making it difficult to understand the population dynamics in the same locations. The MARAMP surveys were also completed in the daytime while COTS are nocturnal feeders which could have led to the underreporting of COTS as they would not be as active during the time when divers surveyed. However proper monitoring of COTS including consistent monitoring at the same sites multiple times a year and nighttime surveys, can provide Guam better insight into the COTS population dynamics to better protect its reefs from damaging outbreaks

This research sets a baseline for future investigations into the environmental drivers of COTS outbreaks in Guam. While this study investigated our hypothesis, calculated and mapped available COTS population data and created Guam's first seasonal climatology, much more research is required to address the environmental drivers and issues of COTS outbreaks in Guam.

5.0 CONCLUSION

Overall, we were unable to find any consistent or significant spatio-temporal relationships that support our hypothesis that COTS outbreaks are driven by precipitation fluxes and waves in this study. Based on the limited data available and previously published knowledge regarding COTS, we were able to exclude several environmental variables as being potential environmental drivers of COTS outbreaks. We came to the conclusion that COTS outbreaks are not too dependent on ocean currents, sea surface salinity, or sea surface temperatures as they varied very little throughout all seasons. Unfortunately, overall this leads us to believe that the exact drivers of outbreaks, and their relative influence, are still unknown.

We were able to discover that COTS populations in Guam do not exhibit seasonality and are found year-round around the island. From the available MARAMP benthic survey data that we examined; COTS populations appear to be patchy in space and vary significantly throughout survey years at the same sites. We were also able to create the first seasonal climatology for Guam using available regional model data.

Reef managers and scientists on Guam should commit to monitoring potentially vulnerable reef sites and track potential environmental drivers such as nutrients and flooding events. Moving forward, it is imperative that Guam maintains records of environmental events and data that could cause future outbreaks which would allow scientists to trace the stimulus and over time identify trends in outbreaks specifically for Guam. COTS are a real threat to the future health of Guam's reefs, and it is vital that researchers and Guam reef managers further investigate the spatiotemporal trends in COTS populations.

REFERENCES

Birkeland, C. (1982). Terrestrial runoff as a cause of outbreaks of *Acanthaster planci* (Echinodermata: Asteroidea). *Marine Biology*, *69*(2), 175-185.

Birkeland, C., & Lucas, J. (1990). *Acanthaster planci: major management problem of coral reefs*. CRC press.

Birkeland, C. (1981). Acantlzaster in the cultures of High Islands. *Atoll Research Bulletin*.

Birkeland, C. (1987). Partial correlations of island size, human-population size, and *Acanthaster planci* abundance. In *Bulletin of Marine Science* (Vol. 41, No. 2, pp. 633-633). 4600 Rickenbacker Causeway, Miami, FL 33149: Rosenstiel Sch Mar Atmos Sci.

Brauer RW, MJ Jordan, and DJ Barnes. (1970). Triggering the stomach eversion reflex of *Acanthaster planci* by coral extracts. *Nature*, 228: 344-346.

Brodie, J. E. (1992). Enhancement of larval and juvenile survival and recruitment in Acanthatser planci from the effects of terrestrial runoff: a review. Marine and Freshwater Research, 43(3), 539-553.

Burdick D, V Brown, J Asher, C Caballes, M Gawel, L Goldman, A Hall, J Kenyon, T Leberer, E Lundblad, J McIlwain, J Miller, D Minton, M Nadon, N Pioppi, L Raymundo, B Richards, R Schroder, P Schupp, E Smith, and B Zgliczynski. (2008). *Status of the coral reef ecosystems of Guam*. Guam Coastal Management Program, Bureau of Statistics and Plans. 76 pp.

Caballes, C. F., Pratchett, M. S., Raymundo, M. L., & Rivera-Posada, J. A. (2017). Environmental tipping points for sperm motility, fertilization, and embryonic development in the crown-of-thorns starfish. *Diversity*, *9*(1), 10.

Chen, Y.L. (2013). Weather Research and Forecasting (WRF) Regional Atmospheric Model: Guam. Retrieved from https://pae-paha.pacioos.hawaii.edu/erddap/griddap/wrf_guam.html

Cheney, D.P. (1974). Spawning and aggregation of Acanthaster planci in Micronesia. *Proceedings of the Second International Coral Reef Symposium* 1, 591–594

Chesher, R. H. (1969). Destruction of Pacific corals by the sea star Acanthaster planci. *Science*, *165*(3890), 280-283.

Cheung, K.F. (2012). Simulating WAves Nearshore (**SWAN**) Model: Guam. Retrieved from https://pae-paha.pacioos.hawaii.edu/erddap/griddap/swan_guam.html

Colgan, M. W. (1987). Coral reef recovery on Guam (Micronesia) after catastrophic predation by *Acanthaster planci*. *Ecology*, *68*(6), 1592-1605.

Cowan, Z. L., Pratchett, M., Messmer, V., & Ling, S. (2017). Known predators of crown-of-thorns starfish (Acanthaster spp.) and their role in mitigating, if not preventing, population outbreaks. *Diversity*, *9*(1), 7.

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Dulvy, N. K., Freckleton, R. P., & Polunin, N. V. (2004). Coral reef cascades and the indirect effects of predator removal by exploitation. *Ecology letters*, *7*(5), 410-416.

Ecosystem Sciences Division; Pacific Islands Fisheries Science Center (2017). Gridded multibeam bathymetry of Guam Island, Guam U.S. Territory. https://inport.nmfs.noaa.gov/inport/item/47577

Endean, R. (1969). Report on investigations made into aspects of the current *Acanthaster planci* (crown of thorns) infestations of certain reefs of the Great Barrier Reef. Brisbane, Australia: Queensland Department of Primary Industries (Fisheries Branch).

Fabricius, K. E., Okaji, K., & De'Ath, G. (2010). Three lines of evidence to link outbreaks of the crown-of-thorns seastar Acanthaster planci to the release of larval food limitation. *Coral Reefs*, *29*(3), 593-605.

Fischer, J. L. (1969). Starfish infestation: hypothesis. *Science*, *165*(3894), 645-645.

Fletcher, C. & Pacific Islands Climate Education Partnership (PCEP). (2015). *Climate Change in the Territory of Guam*. Pacific Resources for Education and Learning.

http://pcep.prel.org/resources/%ef%bf%bcclimate-change-in-the-territory-of-guam/

Friedlander, A. M., & DeMartini, E. E. (2002). Contrasts in density, size, and biomass of reef fishes between the northwestern and the main Hawaiian islands: the effects of fishing down apex predators. *Marine Ecology Progress Series*, *230*, 253-264.

Furnas, M. J. (1989). Cyclonic disturbance and a phytoplankton bloom in a tropical shelf ecosystem. *Red Tides: Biology, Environmental Science and Toxicology*, 273-276.

Guam Visitors Bureau. (2018). 2017 Annual Report. Tumon, Guam.

Henderson, J. A. (1969). Preliminary observations on the rearing and development of Acanthaster planci (L.) (Asteroidea) larvae. *Fisheries notes*, *3*, 69-75.

Hunter, C. L. (1995). Review of coral reefs around American flag Pacific islands and assessment of need, value, and feasibility of establishing a coral reef fishery management plan for the western Pacific region. *Final Report. Western Pacific Regional Fishery Management Council. Honolulu, HI*.

Lucas, J. S. (1972). Acanthaster planci: before it eats coral polyps. In Proceedings Crown-of-Thorns starfish seminar, University of Queensland August 25 1972; Brisbane (pp. 25-36). *AGPS Canberra.*

Lucas, J.S. (1973). Reproductive and larval biology of *Acanthaster planci* (L.) in Great Barrier Reef waters. *Micronesica* 9, 197–203

Lucas, J.S. (1975). Environmental influences on the early development of Acanthaster planci (L.). In *Crown-of Thorns Starfish Seminar Proceedings, Brisbane*. Canberra, Australia: Australian Government Publishing Service, 109–121.

Lucas, J.S. (1982). Quantitative studies of feeding and nutrition during larval development of the coral reef asteroid Acanthaster planci (L.). *Journal of Experimental Marine Biology and Ecology* 65, 173–193.

McCallum, H. I., Endean, R., & Cameron, A. M. (1989). Sublethal damage to Acanthaster planci as an index of predation pressure. *Marine ecology progress series. Oldendorf,* 56(1), 29-36.

Moran, P. J. (1986). The acanthaster phenomenon. *Oceanography and Marine Biology*, *24*, 379-480.

Moran, P. J., & De'Ath, G. (1992). Estimates of the abundance of the crown-of-throns starfish Acanthaster planci in outbreaking and non-outbreaking populations on reefs within the Great Barrier Reef. *Marine Biology*, *113*(3), 509-515.

Paulay, G. (2003). Marine biodiversity of Guam and the Marianas: overview. *Micronesica*, *35*(36), 3-25.

Pearson, R. G. (1975). Coral reefs, unpredictable climatic factors and Acanthaster. In *Crown-of-thorns starfish Seminar Proceedings* (pp. 131-134). AGPS Canberra.

Porter, V., Leberer, T., Gawel, M., Gutierrez, J., Burdick, D., Torres, V., & Lujan, E. (2005). Status of the coral reef ecosystems of Guam. *University of Guam Marine Laboratory Technical Report*, *113*.

Potts, D. C. (1981). Crown-of-thorns starfish—man-induced pest or natural phenomenon. *The ecology of pests: some Australian case histories. CSIRO, Melbourne*, 24-86.

Powell, B. (2015). Regional Ocean Modeling System (ROMS): Guam 3-D Variables. Retrieved from https://pae-paha.pacioos.hawaii.edu/erddap/griddap/roms_marig.html

Pratchett M., Caballes C., Rivera-Posada, J., & Sweatman, H. (2014). Limits to understanding and managing outbreaks of crown-of-thorns starfish (Acanthaster spp.). *Oceanography and Marine Biology: An Annual Review*, 52, 133-200.

Pratchett, M. S., Caballes, C. F., Wilmes, J. C., Matthews, S., Mellin, C., Sweatman, H., ... & Bos, A. R. (2017). Thirty years of research on crown-of-thorns starfish (1986–2016): scientific advances and emerging opportunities. *Diversity*, *9*(4), 41.

Randall, R. H., & Eldredge, L. G. (1976). *Atlas of the reefs and beaches of Guam. Bureau of Planning. 191 pp*. MARC/SOPAC/USP/BP.

Randall, R. H. (2003). An annotated checklist of hydrozoan and scleractinian corals collected from Guam and other Mariana Islands. *Micronesica*, *35*(36), 121-137.

Spalding, M. D., Brumbaugh, R. D., & Landis, E. (2016). *Atlas of ocean wealth*. Nature Conservancy.

Sweatman, H. (2008). No-take reserves protect coral reefs from predatory starfish. *Current Biology*, *18*(14), R598-R599.

Timmers, M. A., Bird, C. E., Skillings, D. J., Smouse, P. E., & Toonen, R. J. (2012). There's no place like home: crown-of-thorns outbreaks in the Central Pacific are regionally derived and independent events. *PLoS One*, *7*(2).

Tsuda, R.T. (1971). *Status of Acanthaster Planci and Coral Reefs in the Mariana and Caroline Islands: June 1970 to May 1971*. University of Guam Marine Laboratory, Technical Report 2, Agana, 127p.

Tracey, J., Schlanger, S., Stark, J., Doan, D., & May, H. (1964). General geology of Guam. *Professional Paper,* 1-111. doi:10.3133/pp403a

United States Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Coastal Services Center (CSC). (2002). Pacific Islands Data Portal: Guam CMSP Data Portal. Coastal and Marine Spatial Planning. Retrieved from https://www.oc.nps.edu/CMSP/Guam/index.html

Veron, J.E.N. (2000). Corals of the world, Vol. 3. Australian Institute of Marine Science. Townsville, Australia. 490 pp.

Vincent, I. V., Hincksman, C. M., Tibbetts, I. R., & Harris, A. (2011). Biomass and abundance of herbivorous fishes on coral reefs off Andavadoaka, Western Madagascar. *Western Indian Ocean Journal of Marine Science*, *10*(1), 83-99.

Vogler, C., Benzie, J., Lessios, H., Barber, P., & Wörheide, G. (2008). A threat to coral reefs multiplied? Four species of crown-of-thorns starfish. *Biology letters*, *4*(6), 696-699.

Vogler, C., Benzie, J. A. H., Tenggardjaja, K., Barber, P. H., & Wörheide, G. (2013). Phylogeography of the crown-of-thorns starfish: genetic structure within the Pacific species. *Coral Reefs*, *32*(2), 515-525.

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, *309*(5742), 1844-1846.

Wooldridge, S. A., & Brodie, J. E. (2015). Environmental triggers for primary outbreaks of crown-of-thorns starfish on the Great Barrier Reef, Australia. *Marine pollution bulletin*, *101*(2), 805-815.