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Observations of a Red Sea Fringing Coral Reef under Extreme Environmental Conditions

Z. Moustafa[1], P. Hallock[2], M.S. Moustafa[3], M.Z. Moustafa[3]
1) Duke University, P.O. Box 98800, Durham, NC 27708
2) University of South Florida, College of Marine Science, 140 7th Ave. S., St. Petersburg, FL 33701
3) H_2O & Geo, Inc., 70 Whispering Oaks Trail, West Palm Beach, FL 33411

Abstract. A four-year study collected the first comprehensive time-series data from a small Red Sea fringing reef located at the extreme northernmost latitude of tropical coral reefs. Corals here are exposed to 2-6^o C daily water temperature changes with seasonal variations exceeding 14-16^o C, and salinities between 43 and 45 ppt. Annual reef surveys included random photo quadrats, fixed video transects, and environmental measurements. In just four years, this pristine reef ecosystem was subjected to nearby shipping-port construction, rapid coastal urbanization, a bleaching event, and an oil spill. Results indicate that of the approximately 35 coral taxa known to survive here, just six compose 94% of those on this reef. Between 2004 and 2007, statistically significant changes were found in reef health indicators including a 50% increase in dead coral, 58% increase in sea urchins, and decreases in biodiversity and fish abundance. Despite all this, corals here appear to be well adapted to extreme environmental conditions. This ongoing research establishes a reference point for coral reef studies in this region and will be key to future local conservation efforts.

Key words: Red Sea, fringing reef, Gulf of Suez, marginal reefs, oil spill, bleaching, salinity extremes.

Introduction

The impact and rate of change of manmade influences on pristine fringing coral reefs, as well as the organisms that inhabit them, are not well documented. Fringing reefs grow close to shore in relatively shallow water and few fringing reefs remain in good health due to their accessibility and proximity to pollution sources. Although Red Sea reefs are cited among the most diverse in the world (Loya 1972), Red Sea corals are not well studied (Rinkevich 2005). Oceanographic and biologic data and long-term coral reef studies in the Gulf of Suez are nearly non-existent.

The reef investigated (dubbed "Zaki's Reef" after the first author's grandfather) is located in the Red Sea's Gulf of Suez near the most northern latitude for subtropical coral reefs. The very shallow (50 - 80 m deep) Gulf of Suez lies adjacent to an extremely arid desert where rainfall is minimal, evaporation rates are high, and freshwater inputs are non-existent. The persistent trade winds and extreme temperatures result in high salinity (43-45‰) and large daily and seasonal temperature fluctuations. High temperatures and salinity reduce oxygen solubility, which can stress many species of reef-dwelling organisms. The organisms that thrive here must be able to tolerate these environmental extremes. A recent study (Moustafa 2000) estimated that 335 species of corals are found in the Red Sea, yet only 35 species have been identified in the Gulf of Suez.

There are no known long-term studies investigating fringing reefs in the study area prior to the research reported here. Therefore, the main goal for this study was to establish a knowledge base for fringing coral reefs in the Gulf of Suez and provide basic information for future reef management, as reef-related activities generate a significant portion of Egypt's tourism revenue.

The effects of natural and manmade influences on a pristine, isolated fringing coral reef located at an extreme northern latitude were documented annually for four summers. Pollution from shipping and oil spillage pose a significant threat as does rapidly expanding coastal urbanization and other anthropogenic influences new to the region. Specific objectives were to: 1) assess reef condition and identify dominant coral taxa; 2) identify local natural and manmade stressors, 3) assess the reef's resilience to recent natural and manmade influences; 4) document changes in indicators of reef health including incidence of disease; 5) conduct annual fish surveys; 6) evaluate reef sediment components; 7) assess water quality, and 8) share results since data on this region are nearly nonexistent.

Material and Methods

Zaki's Reef is a small fringing reef (approx. 0.8 km x 0.1 km) located in Gulf of Suez (29^o 32' N and 32^o 24' E). The reef averages only one to two meters in depth at mean low tide, and can be accessed by a short swim from the beach (Fig. 1). Methodologies used to sample this reef followed universally accepted protocols (Hill and Wilkinson 2004). Underwater videography was repeated annually (Page et al. 2001) to document changes along five 10m transects located across the reef (Fig. 2). Fish surveys were conducted by visually logging and digitally recording taxa and their abundance during five-minute observation periods at three of the 10m transects.

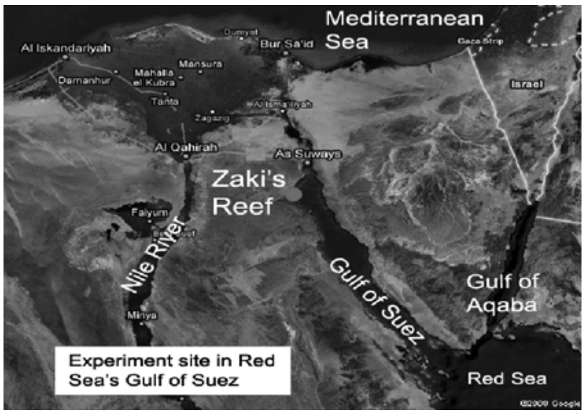

Figure 1: Location of Zaki's Reef in the Red Seas Gulf of Suez, approximate 80 km south of the highly trafficked Suez Canal.

A reef-wide random quadrat (0.5 m^2) photo survey captured bottom substrate from across the reef to establish spatial variation, percent coral cover, diversity, and dominance. Quadrat survey swim direction and distance were randomly determined from the roll of two dice. Each year, statistics for percent bottom coverage by coral taxa were derived from the analysis of approximately 120 randomly collected quadrat photos.

Accessory measurements included salinity and pH measured across the reef annually. Underwater sensors provided temperature readings every 15 minutes at locations across the reef. Air temperature was also obtained during 2006 and 2007. Local tides, wind, weather, dolphin sightings, ship traffic, and oil offloading were regularly logged during fieldwork. Water samples were collected from across the reef and were shipped to Florida International University for water-quality analysis.

Hand grabs of surface-sediment samples were collected from the beach to just offshore of the reef to determine grain-size distributions. Sediment grain-size analysis was performed by manually sieving dried sediment hand grabs into size classes and calculating class weight percentages. The biogenic composition of approximately 100 sand-size grains from each sample was identified under a microscope. The number of coral grains, foraminiferal shells, coralline red algal fragments, gastropods, calcareous algae, echinoid spines, worm tubes, and other skeletal fragments was tabulated and SEDCON Index (SI) was calculated as a measure of reef health (Daniels 2005) where: P_c = number of coral grains, P_f = larger, symbiont-bearing foraminifera, P_{ah} = coralline red algae, gastropods, calcareous algae, echinoid spines, worm tubes, and other skeletal fragments and P_u - unidentifiable grains.

$$SI= (10*P_c) + (8*P_f) + (2*P_{ah}) + (0.1*P_u)$$

Data Analysis: Each year, the sharpest digital images were extracted from all transect and quadrat survey data to identify coral taxa and calculate percent benthic cover. We used a Red Sea comprehensive guidebook (Myers and Lieske 2004) to identify fish and coral taxa. Coral Point Count (CPCe) software (Kohler, 2006) was employed to evaluate coral coverage along each 10m transect by analyzing 25 consecutive frames representing an approximately 0.5 m x 2m wide area of coverage. Percent coral cover was calculated by identifying the bottom type at 60 randomly generated points projected onto each frame. Statistical analysis showed that data from 60 points was statistically identical to identifying the total coverage area from each photo. For each quadrat photo, the total surface area (cm^2) covered by each coral taxon was determined using CPCe software. Coverage analysis included identifying and counting fish, long- and short-spined sea urchins, and sessile organisms.

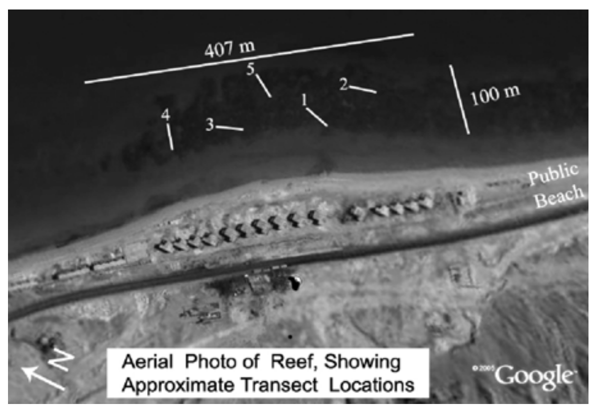

Figure 2: Satellite photo depicting Zaki's reef and the locations of five 10m transects monitored annually since 2004. Newly constructed villas can be seen on the reef's beach.

Results

Coral Taxa and Coverage: Each year percent bottom cover by coral and other parameters were compared to 2004 baseline survey data (Fig. 3). On average, of the 35 coral taxa identified in the Gulf of Suez, only six groups make up 94% of the coral cover on Zaki's Reef, with approximately 80% being hard and 20% soft corals. Dominant hard corals include *Acropora humilis, A. microclados,* and *A. hemprichii* (staghorn), *Litophyton arboretum* (neptheids), *Stylophora pistillata* (finger), as well as *Porites columna* and P. *plantulata* (anemone) corals. On average, 25% of the coral (mainly *Acropora*) were dead in 2004. This value increased to 33% dead by 2007. Spatial patterns of coral cover and fish surveys indicate that offshore regions of the reef, where water is deepest, are typically healthiest and most diverse.

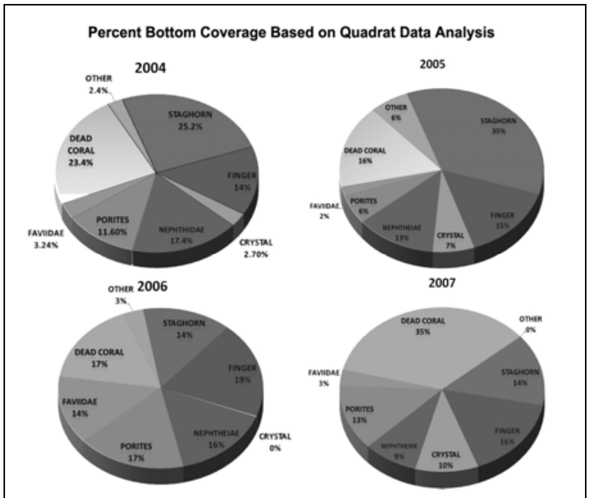

Figure 3: Percent change in coral cover over four years based on the random 0.5 m^2 quadrat survey 2004-2007. Note the increase in dead corals by 2007.

Averaged over four-years, random quadrat survey results indicate that *Acropora* spp. dominate (22.2% ±5.08 SE), followed by *Stylophora pistillata* (16.1% ±1.14 SE, *Litophyton arboreum* (13.5% ±1.92 SE), and *Porites* spp. (11.9% ±2.31SE). Mean dead coral coverage over the four-year study was 22.8% (±4.3SE). The remaining major groups, Faviidae (*Echinopora fructiculosa* and *Platygyra daedalea*, and *Galaxea fascicularis* (crystal coral), were roughly equally common, averaging 5.5% (±2.78SE) and 4.9% (±2.13SE), respectively.

Based on quadrat survey results, *Acropora* spp. were dominant (25%) in 2004 and increased to over 35% coverage in 2005. However, there was a huge decline for both *Acropora* (to 14%) and *Galaxea* (from 7% down to < 0.3%), between 2005 and 2006, yet there was no observed net change in percent dead coral that year (Fig. 3).

Video Transects. At all five transects, *Platygyra*, *Echinopora*, *Porites*, *Stylophora*, *Litophyton*, and *Acropora* corals were the dominant groups (Table 1). When 2007 coral coverage was compared to previous years, a net loss in coral was observed at Transects 2 and 4, while overall net increase was observed at the remaining three transects. The Kruskal-Wallis statistical test for population equality (Conover 1999) validated the null hypothesis that there was no significant difference in coral coverage at all transects over four years ($\alpha = 0.05$). Therefore, despite noted differences in species coverage between years (Table 1), differences remain statistically insignificant ($\alpha = 0.05$), indicating that as some species declined, others increased. Change in coral cover along Transect 3 over four years (Table 1) illustrate a shifting of corals as seen by a dramatic decline in *Platygyra* between 2004 and 2007. This was balanced by increase in *Porites*, *Stylophora*, and *Acropora*, while the overall amount of bottom substrate (dead coral and rubble) changed very little.

Table 1. Changes in percent coral cover at each 10 m- transect since 2004.

Percent (%) Change in Coral Coverage by Species at Each Transect					
	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5
Location on Reef	Nearshore S.	Mid-depth S.	Nearshore N.	Mid-reef N.	Offshore Mid-reef
	2005-07	2004-2007	2004-2007	2005-2007	2005-2007
Faviidae		3.87	-19.80	1.53	0.33
Porites	9.71	0.47	10.73	11.13	3.61
Finger Coral	1.98	-12.93	9.87	18.45	-1.19
Mushroom			0.27	0.80	
Crystal Coral				-32.34	5.27
Neptheidae	-0.08	0.13	-4.93	-15.30	-8.66
Staghorn	-1.64	-9.93	8.80	7.81	2.41
Leaf Coral		0.00			6.74
Diseased Coral		2.87	0.47	2.20	0.33
Total Change	**9.96**	**-15.53**	**5.40**	**-5.73**	**8.83**
Percent (%) Change in Bottom Substrate					
Rubble	-34.56	18.73	-11.73	-8.27	-9.10
Sand	21.33	-3.20	6.33	3.27	0.27
Ten meter transects surveys take across the reef each year indicate that Transects 1, 3, and 5 show an overall net gain in coral since the initial baseline survey in 2004 or -05, while Transects 2 and 4 reflect an overall decrease in coral and a greater increase in coral disease.					

Coral Diversity: The Shannon Weaver biodiversity index (Shannon, 1948) is an indicator of number of taxa and their evenness. Comparison over time from each transect and among transects indicated that biodiversity varied significantly between years in every instance ($\alpha = 0.05$) (Fig. 4).

Trends in this index varied depending on transect location and water depth, with the most marked increase in the index occurring at Transect 1 that lies furthest offshore. The greatest decreases in the biodiversity index occurred in 2006, one year after the oil-spill and the worldwide bleaching event.

Sediments: Sediment samples from across the reef indicate that grain-size distributions remained fairly consistent over time. In general, the finest sands are found in the reef trough and grade to coarsest offshore on the outer reef edge. Biogenic analysis of the sand fraction of each sample showed a change in the biogenic composition. Beginning with the 2005 data, the SI sediment index showed a statistically significant increase in coral fragments and fewer foraminiferal fragments.

Sea Urchins: Each year, long- and short-spine urchins were counted in quadrat photos with short-spine urchins being noticeably more abundant than long-spined taxa. While sea urchin population counts

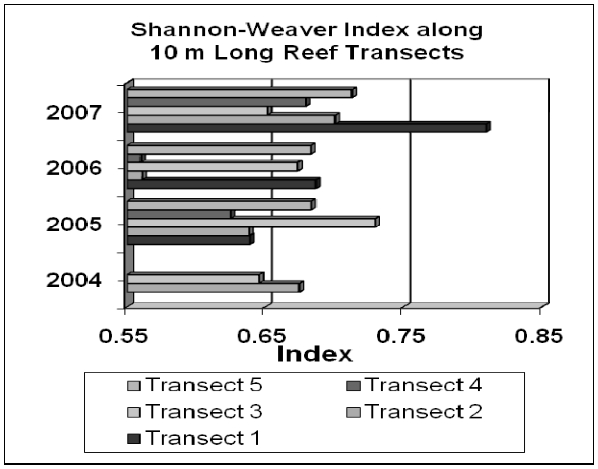

Figure 4: Calculated biodiversity index (Shannon Weaver) based on taxa present along five transects that range between 0.3 m and 3.0 m in depth.

were similar in 2004 and 2005, a notable, 42% increase in short-spine urchin was observed between 2005 and 2006, and a statistically significant increase of 58% between 2006 and 2007. No significant change was detected in the long-spined urchin population over the four years.

2005 Oil Spill: Immediate effects to the area in the days following the spill included increased turbidity, a clumping of oil in sediment and on rock faces, as well as a gummy residue on urchin spines. More than three years later, the effects of the 2005 oil spill were still widespread. Thick oil remained caked on rocks and the upper beach face, and was a few centimeters below the surface sediment on the reef and lower beach.

Temperature: Minimum and maximum daily air-temperature were 21ºC and 39ºC, respectively; an 18ºC difference. Daily underwater temperature range fluctuated between 0.3ºC and 4.5ºC. Seasonal water temperatures on the reef fluctuated widely between a low of 14ºC in February to a maximum of 34ºC in September. Shallower regions of the reef are markedly warmer and displayed greater daily variability than those in deeper water that experience stronger currents that allow for greater mixing.

Fish Bites, Coral Disease and Algae: Since 2004, annual digital photos documented a marked increase in fish bites, coral diseases, algae cover, and sedimentation on the reef. After 2006, an increase in parrotfish bites were observed on *Porites* corals, either territorial in nature, or possibly from remnant hydrocarbons in coral tissue attracting feeding (T. Goreau, pers. comm. 2008). Coral diseases were documented using photography beginning in 2006 and include *Porites* Ulcerative White Spot Disease and Pink and White Line Disease.

Water Quality: Average pH was 8.13 and average salinity was 44 ppt. Other analyses included total phosphorus (TP), soluble reactive phosphorus (SRP), total organic carbon (TOC), and dissolved inorganic nitrogen (DIN).

Discussion

At the outset of this research (2004), the reef was extraordinarily healthy and could be characterized as pristine. In 2005 a major oil spill occurred just three kilometers offshore of the reef during our field sampling. Although environmentally disastrous, it provided an opportunity to document reef conditions before and after an oil spill. This 2005 spill coincided with a widespread bleaching event (Lesser, 2007). Since 2005, new anthropogenic influences to this developing region of the Red Sea coastline included construction of a major shipping port, Port Soukna, less than 5 km north of the reef; a boom in seaside vacation homes within a few km of the reef; and the construction of villas on the reef's beach. In 2006, local fishermen staked claim on the beach at the southern portion of the reef for use as their port.

Table 2 summarizes known man-made and natural influences thought to be affecting this reef. The response of the reef community to recent stresses is mixed. In 2007, some positive signs of reef health were evident as three of the five monitored transects indicated an overall net increase in coral cover since 2004. On the other hand, since 2004, statistically significant differences were found in the amount of dead coral, urchin abundance, and biogenic components in the sediments. An increase in coral disease, fish bites, water turbidity, and sedimentation on corals, indicates a decrease in reef health.

Table 2. A subjective ranking of local influences affecting the reef.

Ranking of Current Stressors Affecting Zaki's Reef											
Stressor Scale		Minor			Intermed.			Major			
	0	1	2	3	4	5	6	7	8	9	10
Oil											X
Fishing/Fishermen				X							
Sedimentation								X			
Temperature				X							
Divers/Ecotourism		X									
Sewage/Pollution						X					
Swimmers		X									
Sea Level Rise	X										
Industrialization/Shipping									X		
Urbanization/Construction										X	
Low Tide Episodes		X									

Despite evidence that the reef continues to thrive, overall reef health deteriorated. Quadrat surveys showed a 50% increase in dead coral across the reef between 2006 and 2007. After the reef was stressed by the 2005 oil-spill and bleaching, corals appeared to be more susceptible to observed diseases and fish bites, similar to observations of Goreau and Wolf (2004). As petroleum hydrocarbons remain present in reef sediment, prolonged injury to this community could continue for years and may explain much of the apparent decrease in overall reef health. The significant increase in short-spined urchins in 2007 is likely attributed to an increase in algae coverage.

We compared SRP and DIN in reef water samples to values reported in the literature (Lapointe et al. 1997). At nearly all locations, SRP levels were close to literature-reported values, while all DIN measurement, whose likely source is wastewater, exceeded literature's values by more than a factor of ten. The increased algal cover may be a response to these nutrients. Coral and mucus sampling for coliform bacteria were also positive.

Survival of this reef despite extreme environmental conditions clearly demonstrates its resilience over time. At the start of the study, results indicated that the reef was healthy and near pristine. Water visibility was high and sea urchin population counts were moderate. The sediment biogenic index initially suggested a healthy reef, and little coral disease was noted. Data from 2004/2005, prior to the oil spill, serves as a reference point, not only for this study, but also for any future coral reef studies in this region.

As man encroaches, human impact is no longer in question. Fishermen have relocated closer to the reef, beach houses that were under construction are being occupied, and with the new port, local shipping and oil offloading traffic has increased. Enormous tanker ships transiting less than 2 km away in very shallow water are displacing great amounts of sediment that appear to be contributing to reef sedimentation. The Gulf of Suez coastline to the north and south of Zaki's Reef is developing at an alarming rate without concern for the impact on the local environment.

Based on the existence of reefs in this region for the historic past, we can infer that select corals and their inhabitants can successfully thrive under extreme conditions. Corals and inhabitants here have adapted and appear more resilient to the large daily, seasonal, and interannual temperature variations and extreme salinities. Our results suggest that so far corals here are adapted to environmental variation and able to survive newly introduced stressors. Eventually, we anticipate that this reef will reach a point where it will no longer be able to recover from insults, and the community will succumb to the cumulative environmental impacts.

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