

# Resilience of a high latitude Red Sea corals to extreme temperature

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## ABSTRACT

Our research objective was to expand the very limited knowledgebase pertaining to the ecology of fringing coral reefs in the Gulf of Suez, Egypt. Specifically, determine dominant coral species and investigate why this reef is capable of surviving at such a high-latitude (29° 32'N and 32° 24'E), and extreme harsh environment. Data collection included annual reef surveys, randomized quadrat sampling, five permanent video transects and *in situ* seawater temperature. Of the known Gulf of Suez 35 taxa, only six (*Acropora humilis*, *A. microclados*, *A. hemprichii*, *Litophyton arboretum*, *Stylophora pistillata*, *Porites columna*, and *P. plantulata*), compose 94% of the reef's coral cover. Coral dominance across species shifted drastically during the study period. However, the six coral dominance remained unchanged, while some decreased others increased. These six coral taxa regularly experience 4.0°C - 6.5°C daily changes in seawater temperature and seasonal variations that exceed 29°C. These extreme temperatures variation and the fact that only six coral taxa dominance remained unchanged, suggest that these corals may have developed a mechanism to cope with extreme seawater temperatures as evidenced by their continued growth and survival over the study period. We speculate that species dominance shift occurred largely as a result of a local oil spill rather than exposure to extreme temperatures. Further scrutiny of these species and the mechanisms by which they are able to thrive is recommended, as they hold the potential to benefit other coral communities as a resilient transplant species and model for understanding coral survivability in extreme environmental conditions.

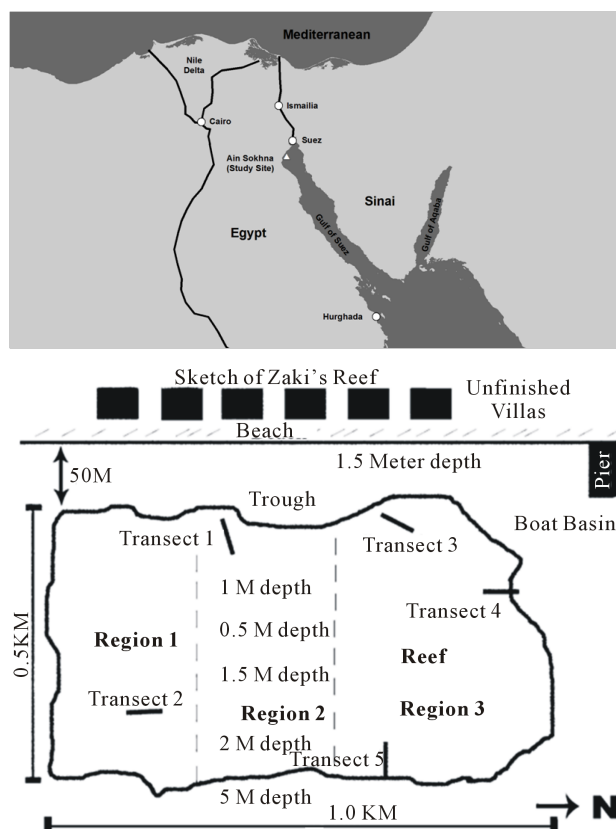
**Keywords:** Red Sea; Fringing Reef; Gulf of Suez; Coral Bleaching; Temperature Tolerance; Marginal Reef; Thermal Limits Omponent; Formatting; Style; Styling; Insert

## 1. INTRODUCTION

Coral reefs are among the most complex and diverse of all ecosystems. They are heavily utilized and considered economically valuable, providing shelter, food and breeding sites for numerous oceanic plants and animals. Fringing reefs form breakwaters for adjacent coasts, thus providing natural storm protection. Fringing reefs grow close to shore in relatively shallow water and often suffer due to their accessibility and proximity to sources of pollution as well as anthropogenic stressors. Although Red Sea reefs are among the most diverse in the world, Red Sea corals are not well studied [1-4], and of the estimated 335 species of corals that are found in the Red Sea, only 35 - 45 of those species have been identified in the Gulf of Suez [2].

Zaki's Reef (the study site) is located in the north-western arm of the Red Sea, in the Gulf of Suez, approximately 80 km south of the Suez Canal (**Figure 1**). This shallow gulf (~50 - 80 m deep) extends approximately 225 km by 14 - 45 km and is adjacent to an arid desert where rainfall is minimal, evaporation rates are high, and freshwater input is nearly non-existent. Persistent north-west trade winds, narrow connections to the oceans, and extreme temperatures result in average salinities of 43 - 45 ppt (part per thousand) and large daily and seasonal temperature fluctuations between 10°C - 15°C [5,6]. High temperatures and salinity reduce oxygen solubility and stress many species of reef-dwelling organisms, thus limiting the number of coral species in the region.

Seawater temperature is considered the primary factor controlling reef distribution worldwide [7-9] where optimum temperature for coral growth ranges between 26°C



**Figure 1.** Location of Zaki's Reef in the Red Sea Gulf of Suez, approximate 80 km south of the highly trafficked Suez Canal. Panel a, General location of the study area. Panel b: Location of five water monitoring stations at Zaki's reef.

27°C [10,11]. Distribution of coral reefs has been reported to be aligned with a monthly minimum seawater temperature of 18°C [12,13].

Cold seawater temperature also causes coral bleaching and mortality [14]. Coral bleaching commonly occurs when water temperatures get too high, but life-threatening stress and bleaching also occur when water temperatures drop too low. While cold-temperature tolerance is not well defined for all coral species, early experiments documenting the impact of prolonged exposure to low seawater temperatures (<16°C) found that they adversely affected coral health [14]. Exposure of corals to even lower seawater temperatures (e.g., <14°C for less than 9 hours) resulted in mortality [15-17].

There are no known long-term studies investigating fringing coral reefs in the Gulf of Suez prior to the research reported here [18,19]. Further, the existence of oceanographic and biological data for this region is extremely limited. Therefore, the overarching goal for this multi-year study (2004-2007) was to establish a knowledge base for fringing coral reefs in the Gulf of Suez and provide the basic information necessary for current and future reef management, as reef-related activities generate a significant portion of the country's tourism revenue.

Specific objectives of this research are:

- Determine resident species and their abundance,
- Determine resident coral's vulnerability to reported worldwide bleaching events, resident coral's thermal limits vulnerability, and compare them to other high-latitude coral reefs, and,
- Discuss why this fringing coral reef is able to thrive at this northernmost limit for subtropical reefs.

Annual reef surveys, which included random quadrat digital photos and fixed video transects, were used to determine baseline conditions (2004) including dominant coral populations and resident reef inhabitants. We expanded our original data collection effort to include *in situ* air and water temperature, mainly to investigate resident biota thermal susceptibility and their tolerance to worldwide bleaching events. Data collected under this research create a knowledge base for fringing coral reefs in the Gulf of Suez and provide the basic information necessary for current and future reef management

## 2. MATERIAL AND METHODS

### 2.1. Study Site

Zaki's reef is located in the Gulf of Suez in the Red Sea off the coast of Egypt, near a town called Ain Sokhna (29° 32'N and 32° 24'E). Zaki's reef is an isolated fringing coral reef that extends approximately one-kilometer parallel to shore and located 100 - 200 m offshore (Figure 1). Global Positioning Systems (GPS) and satellite image analysis were used to survey the reef and determine the exact reef boundaries. We discovered that what was thought to be a separate fringing reef to the south is actually part of the same reef system. The southern extension of this ecosystem (a very popular public beach) is completely destroyed.

### 2.2. Data Collection

#### 2.2.1. Digital Photo Quadrat

Annual random quadrat digital photo surveys recorded the bottom substrate from across the reef to establish spatial variation, percent coral cover and species dominance. Approximately 30 - 40 quadrats were taken in each of the three reef regions (Figure 1). Swim direction and distance of travel for each quadrat sample was determined from the roll of two die where the first roll represents a direction and the second number multiplied by a constant factor of three represents the number of kicks to be taken by the swimmer. A 0.25 m<sup>2</sup> quadrat frame was then tossed and allowed to settle to the bottom, and the contents were subsequently photographed. Two to three digital photos were taken for each quadrat sample and the highest quality one was later selected for computer analysis.

### 2.2.2. Video Transect Survey

Underwater video surveys were performed annually using methods adapted from [20], and involved filming along each of five fixed 10-meter long transects placed randomly across the reef to document coral species, coral cover, benthic invertebrates, and to capture changes over time (**Figure 1**). Transects were staked and their GPS positions were recorded. Before photographing, a one-meter incremented line and tape measure was strung across the transect endpoints to use as a reference while video recording. The photographer then swam slowly along the center line of a transect while video recording. The process was repeated on the swim back to the start point several times to ensure data quality at each of the five established transect locations.

### 2.2.3. *In Situ* Seawater Temperature

High frequency underwater temperature observations was measured by deploying a minimum of five *in situ* temperature sensors (*i.e.*, T1, T2, T3, T4, T5 and T6) across the reef to sample every 15 minutes for two weeks in the summer of 2005 and 2006 (**Table 1**). In addition, a total of four temperature sensors were deployed and recovered after 14 months between June 2006, and August, 2007, with a sampling frequency of 30 minutes. Another four temperature sensors were deployed with 30-minute sampling intervals between August 2007 and June 2008 (**Table 1**). All temperature sensors were deployed at each of the five permanent 10-meter transects.

The temperature sensor (Optic Stow Away-TEMP(C) ONSET) has an operating range between  $-20^{\circ}\text{C}$  to  $70^{\circ}\text{C}$ .

**Table 1.** Temperature sensors deployment dates at Zaki's reef. Vandalism and losses are a major issue at the study site for illegal tropical fish catching/selling. For example, all short duration sensors listed in **Table 1** (*i.e.*, T1, T2, T3, and T4) were re-deployed after the two weeks testing period. Yet, T1 and T2 were not recovered the following year.

Transect (2006-2007)	Start	End	Duration (days)	Sampling Interval
T1	06/21/2006	07/05/2006	14	15
T2	06/21/2006	07/05/2006	14	15
T3 (short)	06/21/2006	07/05/2006	14	15
T4 (short)	06/21/2006	06/27/2006	5	15
T3 (long)	07/06/2006	08/09/2007	399	30
T4 (long)	07/06/2006	08/07/2007	397	30
T5	06/21/2006	08/08/2007	413	30
T6	07/06/2006	08/21/2007	411	30
2007-2008				
T1	08/09/2007	06/19/2008	315	30
T2	08/09/2007	06/19/2008	315	30
T3	08/09/2007	06/21/2008	316	30
T4	08/09/2007	08/15/2007	5	15 seconds
T5	08/09/2007	06/21/2008	316	30

Sensor accuracy is  $0.2^{\circ}\text{C}$  over a  $0^{\circ}$  to  $50^{\circ}\text{C}$  range, with a resolution of  $0.02^{\circ}\text{C}$  at  $25^{\circ}\text{C}$ , and stability of  $0.1^{\circ}\text{C}$  per year. All sensors were deployed approximately 0.25 m from the bottom in 1.5 - 2.5 m water depth. Temperature readings during deployment and retrieval days (first and last day observations) were excluded from our analysis (mainly the time it took to deploy or retrieve all sensors). We calculated and used daily seawater temperature means as the main dataset for all statistical analysis conducted in this research.

We defined the cold and hot temperature season to be the period between January 1<sup>st</sup> through March 31<sup>st</sup> (92 days) and July 1<sup>st</sup> and September 30<sup>th</sup> (92 days), respectively. This definition is based on observed temperature values and the extent of these two periods may differ from typical summer and winter season extents elsewhere. Since cold-temperature tolerances are not well defined for corals, we decided to use both  $16^{\circ}\text{C}$  and  $18^{\circ}\text{C}$  as reference points in our analyses and for comparisons with extreme temperatures reported for high-latitude subtropical coral reef sites.

## 2.3. Data Analysis and Presentation

A combination of descriptive statistics together with graphical techniques [21,22] was employed to reveal data characteristics and describe relationships among variables. Statistics were calculated with JMP (John's Macintosh Project's a computer program for statistics developed by the JMP business unit of SAS Institute Version 7, SAS Institute Inc., Cary, NC), or SigmaPlot (Version 11.0, SPSS, Inc. Chicago, IL). The level of significance ( $\alpha$ ) was set at 0.05 for all analyses. In addition, multiple techniques were used to scrutinize the data for bi-variate and multivariate relationships. Correlations (JMP; Pearson product-moments coefficients) quantified the strength of association between pairs of variables. Seawater temperature probability plots were constructed following [23, 24].

### 2.3.1. Quadrat/Transect Analysis

Each year, statistics for percent bottom coverage by coral taxa were derived from the analysis of approximately 120 random quadrat digital images. Coral Point Count (CPCe) software [25] was employed to determine coverage area for each species. Coverage analysis categories included bottom/sand, long and short-spine sea urchins, as well as various other sessile organisms. A Red Sea comprehensive guidebook (Myers & Lieske 2004) was used to identify coral taxa and reef inhabitants.

The sharpest digital images were extracted from all transect and quadrat survey data to identify coral taxa and calculate percent benthic coverage. Coral Point Count was used to evaluate coral coverage along each 10-m transect by analyzing 25 consecutive frames representing

a strip approximately 0.5 m × 2 m wide area. Percent coral cover was calculated by identifying the bottom type at 60 randomly generated points projected onto each frame as analysis showed that data from 60 points were statistically identical to identifying the total coverage area from each photo. For each quadrat photo the total surface area (in cm<sup>2</sup>) covered by each coral taxa was determined using CPCe software.

### 3. RESULTS

#### 3.1. Coral Diversity and Dominance

##### 3.1.1. Quadrat Survey (Photo)

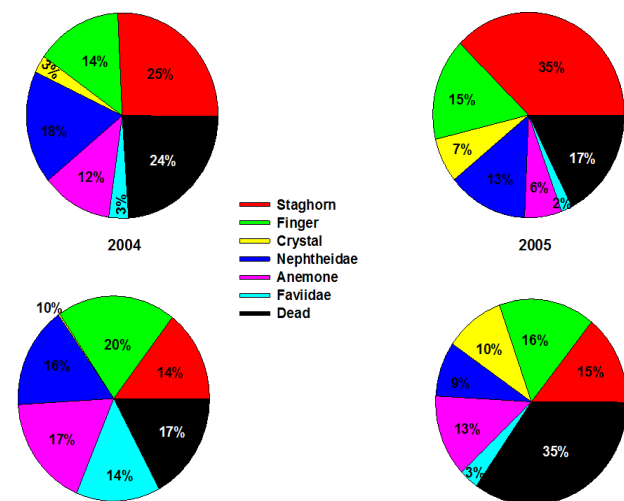
A total of 35 - 40 coral taxa were identified in the Gulf of Suez [2]. Only six of these 35 taxa make up 94% of the coral cover on Zaki's Reef including *Acropora humilis*, *A. microclados*, *A. hemprichii*, *Litophyton arboretum*, *Stylophora pistillata*, *Porites columnna*, and *P. plantulata*, approximately 80% hard corals and 20% soft corals (**Table 2**). Dominant hard corals included Staghorn (*Acropora*), Nephtheidae (*Litophyton*), as well as Finger (*Stylophora*) and Anemone (*Porites*) corals. On average, 24% of the coral (primarily *Acropora*) was dead in 2004. This value increased significantly to 35% dead by 2007 (**Table 2**). The percentage of dead coral varied over time, and the dominant bottom-coverage types have shifted depending on location on the reef. In general, spatial patterns of coral coverage and health indicate that the off-shore regions of the reef where the water is deepest are healthiest.

Based on quadrat survey results, staghorn was the dominant species (25%) at the outset of this research and continued to grow to more than 35% in 2005 (**Figure 2**). However, both staghorn (down to 14% from 35%) and crystal coral (down to <0.3% from 7%) declined dramatically between 2005 and 2006. Yet there was no observed change in the percentage of dead coral that year,

suggesting that the loss of staghorn and crystal corals was compensated for by the growth of other species (**Figure 2**).

##### 3.1.2. Transect Survey (Video)

At all five transects Faviidae, anemone, finger, Nephtheidae, and staghorn were the dominant species (**Table 3**). When the 2007 coral coverage was compared to previous years, a net loss in coral was observed at Transects 2 and 4 while overall growth was observed at the other three transects (**Table 3**). The Kruskal-Wallis statistical test for population equality [26] validated the null hypothesis of no significant differences ( $\alpha \leq 0.05$ ) in coral coverage at all transects. Therefore, despite noted differences in species coverage between years (**Table 3**), differences remained statistically insignificant ( $\alpha = 0.05$ ); as some



**Figure 2.** Percent change in coral coverage over the four years based on the random 0.25 m squared quadrat survey of the reef conducted each year. Note the increase in dead corals by 2007. Values are reported to the nearest whole number.

**Table 2.** Dominant coral species at the study site for all surveyed years (2004-2007), and percent change in coral coverage at each of the five permanent transects monitored since 2004; baseline observation year.

Year/Species	Staghorn Coral (Acropora)	Finger Coral (Stylophra)	Crystal Coral (Galaxea fascicularis)	Nephtheidae (Litophyton)	Anemone Coral (Porites)	Faviidae (Favia lacuna)	Dead Coral
2004	25.19	14.07	2.7	17.38	11.6	3.24	23.44
2005	35.33	15.02	6.58	12.68	5.91	1.74	16.46
2006	14.13	19.3	0.26	15.52	17.11	13.77	16.61
2007	14.25	16.14	9.94	8.58	12.87	3.23	34.74
Mean	22.23	16.13	4.87	13.54	11.87	5.50	22.81
Standard Error	5.08	1.14	2.13	1.92	2.31	2.78	4.30
% change since 2004-2005	40.25	6.75	143.70	-27.04	-49.05	-46.30	-29.78
% change since 2004-2006	-43.91	37.17	-90.37	-10.70	47.50	325.00	-29.14
% change since 2004-2007	-43.43	14.71	268.15	-50.63	10.95	-0.31	48.21



**Table 3.** Percent change in coral coverage at each of the five permanent transects monitored since 2004. Transects 1, 3, and 5 show a net increase in coral coverage, while Transects 2 and 4 indicate an overall decrease.

	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5
Location on Reef	Near shore S.	Mid-reef S.	Near shore N.	Mid-reef N.	Offshore Mid-reef
	2005-07	2004-07	2004-07	2005-07	2005-07
Faviidae ( <i>Favia lacuna</i> )		3.87	-19.80	1.53	0.33
Anemone Coral ( <i>Litophyton arboretum</i> )	9.71	0.47	10.73	11.13	3.61
Finger Coral ( <i>Stylophora pistillata</i> )	1.98	-12.93	9.87	18.45	-1.19
Mushroom			0.27	0.80	
Crystal Coral ( <i>Galaxea fascicularis</i> )				-32.34	5.27
Nephtheidae ( <i>Litophyton arboretum</i> )	-0.08	0.13	-4.93	-15.30	-8.66
Staghorn Coral ( <i>Acropora humilis</i> )	-1.64	-9.93	8.80	7.81	2.41
Leaf Coral		0.00			6.47
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

species declined, others may have grown (**Table 3**).

### 3.2. Seawater Temperature

The highest (>29.0°C) and lowest (>16°C) monthly means for water temperature occurred in August and February at all transects during both sampling years (**Table 4**). Monthly mean seawater temperature ranged between a minimum of 15.76°C during February 2007 at T4 to a maximum of 29.68°C during August 2006 at T6. In the second sampling year T3 registered the lowest monthly mean at 13.11°C followed by T2 and T1 at 16.56°C and 16.57°C, respectively.

Observed seawater temperature seasonal variability is large, ranging from a low of 13.00°C in February to a high of 30.00°C in August (**Table 4**). Monthly seawater temperature range fluctuated widely between a minimum of 2.06°C at T5 (February of 2008) to a maximum of 12.95°C at T6 transect (March of 2007). Seawater temperature variability and extremes are a function of transect location on the reef (**Table 4**).

#### 3.2.1. Cold Season Temperature

Minimum daily means of seawater temperature fluctuated widely at all transects and ranged between a minimum of 14.90°C and 12.10°C at T3 to a daily maximum of 19.64°C and 21.08°C at T6 and T1 during 2007 and 2008, respectively (**Table 5**). Observed minimum daily temperatures were less than 16°C for both years (2007 and 2008) and daily temperature ranges were less than 3.48°C and 5.64°C at almost all transects for the two consecutive sampling years. It should be noted that the medians of observed seawater temperatures designate, by definition, that 50% of these observations are less than the reported median, which is less than 17.64°C at all

transects and during both winters (**Table 5**).

Daily mean temperature remained above 14.0°C and 11.2°C for the 2006-2007 and 2007-2008 sampling years, respectively (**Figure 3**). The lowest temperature was observed at T3 for both sampling years, followed by T4. However, during the second sampling year, the low temperature at T3 was lower than all other recorded values by at least 3.00°C.

Temperature at T3 remained equal to or less than 16.00°C for 18% of the time during the first sampling year and 57% of the time during the second sampling year (**Figure 3**).

During 2007, daily mean temperature fell below 16.00°C during the cold season for extended periods of time (**Figure 3**). Seawater daily mean temperature less than 16.00°C were prevalent at Mid-reef and T5 for approximately 1% of the time, and lasted longer (*i.e.*, 9% to 16% of time) at T4 and T3, respectively (**Figure 3**). Yet, daily mean seawater temperature fell below 16.00°C less frequently during winter of 2008 compared to 2007 and was also based on transect location (**Figure 1**). For example, temperatures below 16°C were prevalent at T1 and T2 for approximately 5% of the time, less than 3% at T5, and 58% of the time at T3.

In general, minimum observed seawater temperatures were practically less than 17.00°C the entire winter period at all transects (**Figure 4**). The extent of the cold period (less than 16.00°C) is evident by observing the minimum half-hourly temperature values (**Figure 4**). For example, minimum observed seawater temperature at T4 in 2007 was less than 16.00°C starting at January 1, and remained less or equal to 16.00°C from January 14 until February 22, 2007; a total of 32 days where seawater temperature is less than or equal to 16°C and a total of 21

**Table 4.** Summary statistics of monthly seawater temperature collected between June 2006 and August 2007 at T3, T4, T5, and T6 temperature sensors, and summary statistics of monthly seawater temperature collected between August 2007 and June 2008 at T1, T2, T3 & T5 temperature sensors.

Month/Year	Mean	Minimum	Maximum	Range	Mean	Minimum	Maximum	Range
T3				T4				
6/15/2006	27.65	25.33	29.68	4.35				
7/15/2006	28.51	25.66	31.43	5.77	28.18	25.47	29.79	4.32
8/15/2006	29.54	27.31	32.15	4.84	29.38	27.76	31.54	3.78
9/15/2006	27.95	25.99	31.08	5.09	27.49	25.14	30.49	5.35
10/15/2006	25.82	23.41	28.65	5.24	25.52	23.55	27.76	4.21
11/15/2006	22.40	19.69	25.01	5.32	22.40	20.14	24.82	4.68
12/15/2006	19.24	16.12	22.15	6.03	18.98	16.27	21.37	5.10
1/15/2007	16.87	15.24	18.49	3.25	16.31	14.81	18.04	3.23
2/15/2007	16.42	14.36	19.09	4.73	15.76	13.94	18.04	4.10
3/15/2007	17.52	15.24	19.99	4.75	16.95	15.11	18.94	3.83
4/15/2007	18.99	16.71	22.47	5.76	18.58	16.86	21.06	4.20
5/15/2007	21.67	18.49	25.01	6.52	21.43	18.34	23.87	5.53
6/15/2007	24.15	21.22	27.97	6.75	24.10	21.37	27.09	5.72
7/15/2007	25.93	23.09	29.33	6.24	26.03	23.55	28.43	4.88
8/15/2007	26.20	24.69	29.33	4.64	26.50	25.47	27.76	2.29
	Mean	Minimum	Maximum	Range	Mean	Minimum	Maximum	Range
T5				T6				
6/15/2006	27.01	25.02	28.99	3.97				
7/15/2006	28.05	25.99	29.67	3.68	28.52	25.44	31.93	6.49
8/15/2006	29.16	27.31	31.07	3.76	29.68	27.42	32.66	5.24
9/15/2006	27.72	26.32	29.67	3.35	28.18	21.94	34.89	12.95
10/15/2006	26.05	24.06	27.97	3.91	26.19	23.84	29.81	5.97
11/15/2006	23.09	20.62	25.34	4.72	22.89	20.41	25.44	5.03
12/15/2006	20.07	17.33	22.17	4.84	19.83	16.51	22.57	6.06
1/15/2007	17.73	16.44	19.42	2.98	17.53	15.92	19.19	3.27
2/15/2007	17.17	15.56	19.12	3.56	17.17	15.03	20.10	5.07
3/15/2007	18.38	16.74	20.32	3.58	18.49	9.82	21.33	11.51
4/15/2007	20.02	18.52	22.79	4.27	20.34	18.29	24.48	6.19
5/15/2007	23.05	20.32	25.34	5.02	23.51	19.79	27.42	7.63
6/15/2007	25.99	23.43	28.31	4.88	26.68	23.20	31.21	8.01
7/15/2007	28.43	26.65	31.07	4.42	29.05	26.10	33.02	6.92
8/15/2007	29.36	28.31	30.72	2.41	29.60	27.76	33.39	5.63
Month/Year	Mean	Minimum	Maximum	Range	Mean	Minimum	Maximum	Range
T1				T2				
08/15/2007	29.62	27.56	31.71	4.15	29.50	27.72	31.17	3.45
09/15/2007	28.05	24.62	32.07	7.45	28.03	24.44	31.53	7.09
10/15/2007	26.13	23.98	28.91	4.93	26.13	24.12	28.39	4.27
11/15/2007	23.58	21.16	26.90	5.74	23.68	20.67	26.39	5.72
12/15/2007	20.47	18.13	23.03	4.90	20.64	18.26	22.86	4.60
01/15/2008	17.64	14.60	19.93	5.33	17.73	14.71	20.06	5.35
02/15/2008	16.57	14.31	18.43	4.12	16.56	14.41	18.26	3.85
03/15/2008	19.12	16.35	22.40	6.05	19.09	16.47	22.22	5.75
04/15/2008	21.46	17.84	24.94	7.10	21.52	17.96	24.77	6.81
05/15/2008	23.75	20.54	28.23	7.69	23.75	20.67	27.38	6.71
06/15/2008	26.29	23.98	28.57	4.59	26.34	24.12	28.06	3.94

## Continued

08/15/2007	26.19	23.41	28.31	4.90	29.34	28.24	30.65	2.41
09/15/2007	24.63	21.53	28.99	7.46	27.97	25.59	30.65	5.06
10/15/2007	22.65	20.61	25.33	4.72	26.01	24.62	27.57	2.95
11/15/2007	20.05	17.30	23.09	5.79	23.69	21.77	25.27	3.50
12/15/2007	17.04	14.94	19.39	4.45	20.70	19.03	22.40	3.37
01/15/2008	14.20	11.47	16.42	4.95	17.80	15.18	19.63	4.45
02/15/2008	13.11	11.18	14.94	3.76	16.47	15.18	17.24	2.06
03/15/2008	15.59	13.20	18.49	5.29	18.76	16.65	21.16	4.51
04/15/2008	17.81	14.36	21.22	6.86	21.12	18.43	24.62	6.19
05/15/2008	20.00	17.01	24.37	7.36	23.33	20.85	26.24	5.39
06/15/2008	22.40	19.99	27.31	7.32	25.90	24.30	27.23	2.93

**Table 5.** Summary statistics of daily seawater temperature collected during winter season (January 1, through end of March) for 2007 and 2008 sampling years.

January-March (2007)	T3	T4	T6	T5
Mean	16.36	16.96	17.75	16.96
Standard Error	0.07	0.08	0.08	0.08
Median	16.32	16.95	17.64	16.95
Range	3.11	3.11	3.48	3.11
Minimum	14.90	15.42	16.16	15.42
Maximum	18.00	18.54	19.64	18.54
Count	90	90	90	90
January-March (2008)	T1	T2	T3	T5
Mean	17.80	17.82	14.33	17.70
Standard Error	0.14	0.14	0.13	0.13
Median	17.46	17.43	13.99	17.61
Range	5.62	5.64	5.51	4.75
Minimum	15.45	15.43	12.10	15.70
Maximum	21.08	21.08	17.61	20.46
Count	91	91	91	91

days less than or equal to 15.00°C (**Figure 3**). The longest cold period (temperature < 16.00°C) was observed at T3 and lasted from January 1, 2008 through March 24, 2008 (**Figure 3**).

### 3.2.2. Hot/Summer Season Temperature

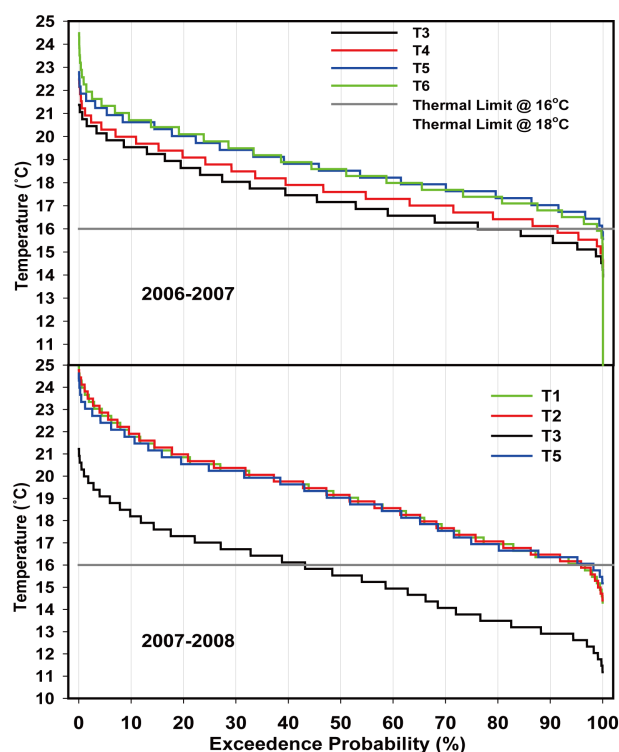
Frequency of coral bleaching temperatures at the study site occurred almost every year. *In situ* maximum daily seawater temperatures at the study site were above the coral bleaching temperature of 28.00°C during all four summers: 2005 (world-wide bleaching event), 2006, 2007, and 2008 (**Figure 5**). For the most part, observed seawater temperature remained above 28.00°C and reached as high as 32.00°C for the two week deployment time during the summer of 2005; a total of six continuous days of temperatures exceeding 30.00°C (**Figure 5**). During the summer of 2006, which was not reported as a world-wide bleaching event, the maximum temperature remained above 28.00°C from June 26<sup>th</sup> through September 5<sup>th</sup> at all transects (**Figure 5**). At T6 (mid-region)

on September 12<sup>th</sup>, 2006, *in situ* seawater temperature reached 34.90°C and remained above 30.00°C between September 12 and September 17, 2006 (**Figure 5**). This location is more prone to extreme low tide episodes, where corals are directly exposed to prevailing air temperatures (**Figure 6**). Similarly and during the summer of 2007, maximum temperatures remained far above previously reported lethal temperature coral limits (>28.00°C) for an extended period of time, reaching as high as 33°C almost every two weeks, synchronized with extreme low tide episodes (**Figure 5**).

## 4. DISCUSSION

### 4.1. Resident Coral Vulnerability and Thermal Limits

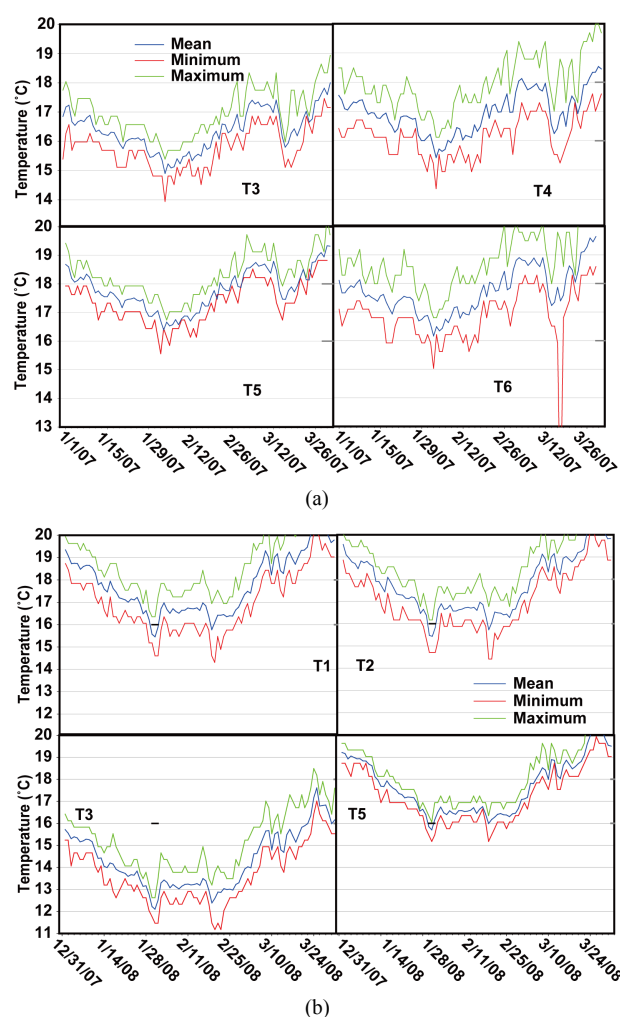
Water temperatures and elevated salinity are vitally important environmental stressors to consider when evaluating coral health, made even more so by the fact that it has been shown that excessive warming can en-



**Figure 3.** Seawater temperature duration curves during 2006-2007 (T3, T4, T5, & T6 temperature sensors) and during 2007-2008 (T1, T2, T3, & T5). Temperature values are based on 30-minutes observations.

hance the effects of pollution [27-29]. The Gulf of Suez's subtropical location means that it is warm enough to harbor a wealth of tropical biota, however, its high-latitude results in significant seasonal variations, and a marked amplitude of summer and winter temperature differences (**Tables 4** and **5**). Seawater temperatures on Zaki's reef remained above their means (ranging between 19.20°C at T3 2007-2008 and 24.00°C at Mid-reef), and most importantly remained higher than the highest monthly mean temperature (August), for approximately 10% of the time during 1<sup>st</sup> and 2<sup>nd</sup> year of sampling, with the exception of T3 during 2007-2008 (**Figure 3**). Temperatures at T5 were much closer to T6, and corals at this location experienced wider fluctuations and were more susceptible to potential bleaching events than the remaining transects due to extreme tidal episodes. Mid-reef region (T5 & T6) has been observed to experience extreme low-tide events, where corals are exposed directly to the atmosphere. These minimum and maximum temperatures at this extreme northern latitude greatly exceed the coral tolerance limits documented at other tropical reef sites [30].

Monthly mean and minimum temperatures observed at Zaki's reef provided a clear picture of what resident biota regularly experience on a yearly basis (**Figures 4** and **5**). Unlike other locations where resident biota are rarely

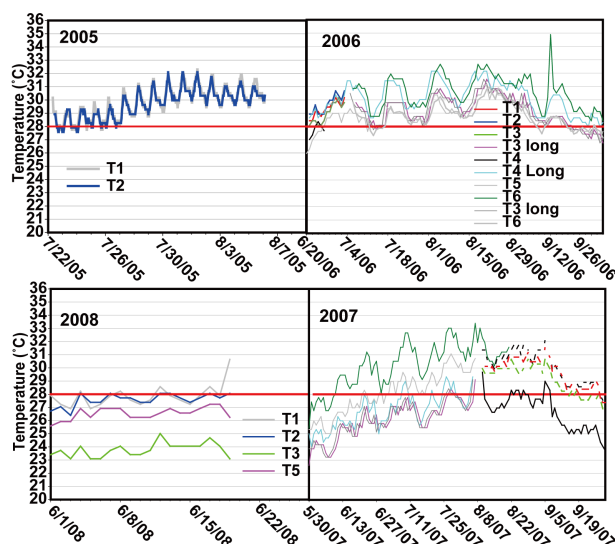


**Figure 4.** Observed mean, minimum, and maximum seawater sea water temperature during winter seasons at all available temperature sensors. Panel A depicts seawater temperature in 2007 (T3, T4, T5, and T6) and Panel B depicts seawater temperature in 2008 at T1, T2, T3, & T5.

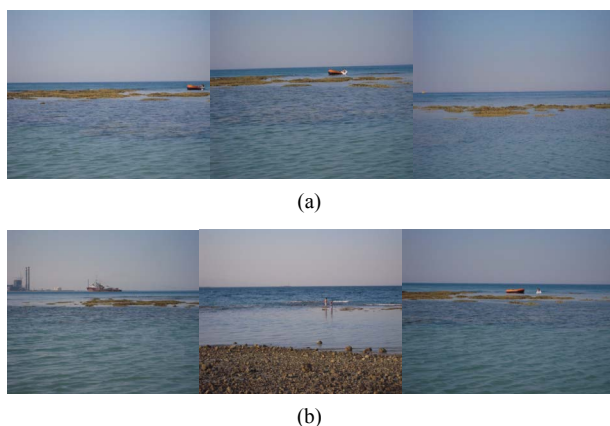
exposed to extreme events [14,31-32], resident biota at Zaki's reef are exposed to these extremes (both hot and cold seawater temperature) on a yearly basis. Winter season (January through March) monthly minimums of seawater temperature reached as low as 12.00°C or 14.00°C for several days, while the summer season maximum monthly temperatures reached as high as 32.00°C or 33.00°C for extended periods of time (**Tables 4** and **5**). Resident biota at Zaki's reef not only are exposed to extreme hot and cold temperatures, but are also exposed to these extremes for extended periods of time (>10 consecutive days), and on a regular yearly basis.

Cold-temperature tolerances are still being defined for corals (e.g., 16.00°C or 18.00°C). However, previously documented results showed that prolonged exposure to 16.00°C is stressful to most coral species and exposure to temperature < 14.00°C, even for a short period of time (<





**Figure 5.** Observed seawater temperature during summer seasons at all available temperature sensors. Note that during 2005 and 2006 summers, only two and five sensors were deployed, respectively, for a two-week period. Vandalism and sensor losses due to breakage are the main reasons for not recovering all deployed sensors, the following year.



**Figure 6.** Example of a low-tide episode at Zaki's reef in June, 2012. Panel (a) depicts a massive area of Zaki's reef, from middle to south portion, being exposed directly to air temperature, which is much higher than seawater temperature, and a co-author conducting our annual reef survey. Panel (b) depicts newly introduced stresses to Zaki's reef, including the nearby new oil shipping port and local workers standing on top of the reef. (a) middle to south (row 1); (b) north to middle (row 2).

9 hours) can result in coral mortality [33-35]. *In situ* temperatures were less than 15.00°C at T3 between 1 January and 10 February 2007 and at T4 between 2 and 4 February 2007. In 2008, *in situ* temperatures remained lower than 16.00°C between 28 January and 27 February, and less than 15.00°C at two separate times, 30 January through 2 February 2008 and 18 February through 22 February 2008 at T1. At T2 during 2008, *in situ* temperatures remained below 16.00°C from 27 January

through 26 February 2008 with very short exceptions and below 15.00°C from 29 January through 1 February 2008 and 18 - 20 February 2008. Seawater temperatures at T3 fell below 16.00°C from 1 January through 31 March 2008 except two days. Yet, with all the observed exposure to low temperatures, changes in reef dominance of the six most prominent coral species remain practically the same during the study (**Tables 2 and 3**).

As reef building corals live near their upper thermal tolerance limits, small increases in sea temperature (0.5°C - 1.5°C) over several weeks or large increases (3°C - 4°C) over a few days may lead to coral death. A conservative temperature increase of 1°C - 2°C would cause regions between 20 - 30 degrees north to experience sustained warming that falls within the lethal limits of most reef-building coral species. Our temperature data indicated that for a five-day period (**Figure 5**, 2005) seawater temperatures at this site exceeded 30.00°C, and on five occasions equaled or exceeded 32.00°C (**Figure 5**, 2006). In all summer and winter seasons' observations, corals at the study were clearly exposed to hot and cold temperatures lethal limits (e.g., 16°C - 18°C) as reported by others. Yet reef conditions in 2007 provided enough evidence that corals at this location adapted to these extreme conditions, and those six taxa thrived in spite of all other anthropogenic stresses.

## 4.2. Comparisons with Other Reef Locations

Seawater temperature is a key indicator of coral reef health. Seawater temperature influences ecological processes and is considered the primary factor limiting coral reef survival and development throughout the world [36, 37]. Seawater temperature affects coral breeding, spawning, larval settlement and growth [38,39], and coral recruitment [40].

It is evident that Zaki's coral species have a relatively higher thermal tolerance compared to similar species at other locations (**Table 6**); only the most hot and cold-tolerant few have been identified at this site. The worldwide bleaching event in 2005 resulted in lethal heat conditions to coral species worldwide, yet coral species found at Zaki's reef survive temperatures more extreme than most every year. Regardless of all exposures to lethal or near-lethal limits of hot and cold, the six coral species at Zaki's reef remained dominant (>94%).

Lirman *et al.* [14] suggested that the only coral taxa that survive the cold event with limited mortality were those that are also found in other habitats that often experience low temperatures on a regular basis, suggesting species-specific adaptive resistance mechanisms. Corals on Zaki's reef experience these extreme seawater temperatures annually, as evident from our seawater temperature observations for both summer and winter (**Figures 4 and 5**). Exposure to these high- and low-temperature

**Table 6.** Observed annual minimum, maximum, and temperature ranges for high latitude coral reef sites and Zaki's reef study site. All temperature sensors (T1 through T6) for all available years from Zaki's reef are listed.

Count	Location	Latitude	Longitude	Temperature (°C)		
				Minimum	Maximum	Range
1	Saudi Arabia	27 N	50 E	11.4	36.2	24.8
2	Qatar	25	51	14.1	36.0	21.9
3	Abu Dhabi	24	54	16.0	36.0	20.0
4	Florida	25	80W	13.3	32.8	19.5
5	Heron Island	23	152° E	16.0	35.0	19.0
6	Kuwait	29	48	13.2	31.5	18.3
7	Japan	35	140	18.0	29.5	16.5
8	Abrolhos Island	29	113	17.0	28.0	11.0
9	Midway Island	28	177	18.2	28.3	10.6
10	Gulf of Aqaba	29	35	20.0	28.0	6.0
	<b>Zaki's Reef (Gulf of Suez)</b>	<b>29.58 N</b>	<b>32.36 E</b>	<b>Minimum</b>	<b>Maximum</b>	<b>Range</b>
11	T6 (2006-2007)			9.8	34.89	25.1
12	T3			14.4	32.2	17.8
13	T4			13.9	31.5	17.6
14	T5			15.6	31.1	15.5
15	T1 (2007-2008)			14.3	32.07	26.8
15	T2			14.4	31.53	29.2
16	T3			11.2	29.68	25.9
15	T5			15.2	30.65	21.4

anomalies on a yearly basis may have caused corals at Zaki's reef to develop an adaptive resistance mechanism. It is no surprise that only six out of the 35 identified coral species in the Gulf of Suez dominate Zaki's reef (>94%), and can be attributed to their adaptive resistance mechanisms to both low and high extreme temperatures. These corals have been living at the study site for hundreds of years, and may have the capacity to acclimatize or adapt to external stresses better than others. For example, previous comparisons among plants [38] and animals [39-41] have shown that some population or species are far more resilient compared to others with marked influences on growth, survival, and disease resistance [41-43]. Furthermore, Barshis *et al.* [44] studied coral genes and concluded that some of these genes may bestow resilience through faster reaction during transient heat stress, which may prepare corals for frequently encountered stress.

Coles and Fadlallah [31] reported that *Acropora pharaonis* and *Porites compressa* in the Arabian Gulf suffered severe mortality when the water temperature fell below 11.50°C. Furthermore they reported that *Porites compressa* (the dominant species at their reef) and Faviidae corals showed sign of sub-lethal effects when temperature was below 12.00°C for two consecutive days, yet recovered after six months. Some of the coral genera found in the Arabian Gulf are also found in Zaki's reef (e.g., *Acropora humilis* and *Porites columna*). Unlike the Ara-

bian Gulf counterpart, resident *Acropora* in Zaki's reef survived well during the worldwide bleaching event in 2005, as well as during cold temperatures measured in the 2006 and 2007 winter seasons. However, *Acropora* on Zaki's reef declined from 35% in 2004 to 14% in 2006 and 15% in 2007 (**Figure 2**). Based on the ability for *Acropora* to survive on Zaki's reef during these extreme temperature events, we attribute this decline to a local oil spill, which occurred in 2005 (personal observation), and not to exposure to lethal thermal limits. Temperatures on Zaki's reef did not reach the same low temperatures (11.50°C) as reported by Coles and Fadlallah [31], where all the *Acropora* colonies died.

## 5. CONCLUSIONS

For four years (2004 through 2007), annual reef assessments via fixed video transect and random quadrat digital photo surveys were conducted to determine baseline conditions, assess the rate of reef recovery after the 2005 oil spill, and to evaluate the effects of increasing coastal development in the region. The data collected provided estimates of the number of coral species, percentage of total living coverage, and diversity of coral. This unique and large data set will serve as a baseline for any future coral study in this region as it is the first of its kind.

Coral thermal lethal limits are suggested first at water temperatures of 18°C and second at 16°C. Regardless of

the currently known thermal lethal limits, corals at Zaki's reef appear to be more resilient to extreme low and high seawater temperatures. Coral species at this location have adapted to those extreme seawater temperatures, and their wide range of temperature tolerance can be beneficial to local eco-tourism. Further scrutiny of these species and the mechanisms by which they are able to thrive is recommended, as they hold the potential to benefit other coral communities as a resilient transplant species and model for understanding coral survivability in extreme environmental conditions. Transplants of coral species from Zaki's reef to other reef locations (e.g., Hurghada a divers' haven approximately 400 km south of the study site) can help restore some of the impacted reef sites, because of their proven resilience and ability to survive exposure to both high and low temperatures.

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