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Fringing Red Sea Corals Survival: Is It Tide or Local Wind?

Mohamed Zaki Moustafa, Mary Sue Moustafa

H_2O & Geo LLC, West Palm Beach, USA
Email: mzmocean@gmail.com

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Abstract

In this paper, we obtain tidal constituents and discuss observations of tidal and wind variations and its impact on water surface elevation at Zaki's Reef; a fringing coral reef located in the Red Sea-Gulf of Suez. This manuscript focuses on investigating if tidal forces are playing a key role to keep the area's unique coral reefs alive and well. Determining the reasons why coral species and community of organisms found here survive despite all stressors is critical, and such information may hold the key to the preservation of reefs elsewhere. Phase and amplitude for 35 tidal constituents were deducted from observations of water surface elevation at the study site (first of its kind). The main tidal constituents based on their amplitudes are: M_2, N_2, S_2, K_1, NU_2, K_2, $2N_s$, L_2, and MU_2. The first five tidal constituents of the aforementioned list are enough to reproduce accurate predictions of tides at this location (R^2 variance = 87.54% and RMS = 0.167). The Tidal Form number (0.07) at Zaki's Reef indicates a fully semidiurnal dominated tidal regime. Moreover, the S_a and S_{sa} constituents obtained from nearby stations made no improvements on tidal prediction results. Spectral analysis results of the white noise (residuals) from observed water surface elevation are dominated by daily frequency, suggesting that local wind plays a key role in circulation at study site. Local wind generated southerly long-shore and year-round offshore wind stress with a mean of −0.36 & 0.35 N_m^{-2}, respectively. The persistent longshore and offshore currents help transport oil patches/spills, from the two nearby ports, away from the reef. Yet, offshore wind stress, pushing water away from the shore, may cause more exposure of the reef to extreme atmospheric conditions. We hypothesize that the repeated reef exposure to the combined effect of tides and offshore wind stress over many years may have played a key role in selecting and then enhancing corals ability, through training, to become more adaptable to those harsh conditions. Training of corals over the years, may have led to the dominance of only six species, out of 35 coral species known to exist in the gulf. Those heat-adopted dominant species can be used to stimulate and revive impacted coral sites elsewhere.

Keywords

Tides, Red Sea, Gulf of Suez, Fringing Reef, Wind Stress

1. Introduction

Tidal motions of the Red Sea are important to the functioning of the coral reef located along its shores (*i.e.*, Fringing or Marginal reefs). Tidal currents create turbulence, which increases nutrients, phytoplankton, and zooplankton fluxes between corals ecosystem and overlying water column [1]. Changes in water surface elevations due to tidal forces can be important to shallow fringing reef features and occasionally exposing resident corals to wave action and increasing the likelihood of drying out at low tides [2]. Fringing coral reefs have been extensively studied in the Gulf of Aqaba; yet, tidal forces and wind actions and their impacts on fringing coral reefs along the Red Sea are the least studied, particularly in the Gulf of Suez ([3] [4] and [5]). There is only one tide station located near the entrance of the Suez Canal: approximately 60 km North of Zaki's Reef, the study site.

Zaki's Reef is located near the town of Ain Sokhna in the Red Sea's Gulf of Suez near the most northern latitude for any subtropical coral reefs (29˚32'N and 32˚24'E). 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 Northeasterly trade winds and extreme temperatures result in high salinity (43 - 45 psu) 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. Of the estimated 335 species of corals found in the Red Sea [6], only 35 species have been identified in the Gulf of Suez, and of these, only six species have been identified to dominate (94% of coral cover) Zaki's Reef [3]. The fact that only six coral species dominated the study site promoted us to investigate why those six at this location and what might be the reason(s) behind their survival in such an extreme environment?

The main goal of our research in the Gulf of Suez is to address the lack of almost all forms of scientific data in one of the least studied regions of the world's ocean [3] and [4]. Therefore, the overarching goal for this multi-year study was to establish a knowledge base for fringing coral reefs in the Gulf of Suez and provides basic information for current and future reef management, as reef-related activities generate a significant portion of the country's tourism revenue, accounting for approximately 11% of Egypt's GNP and providing 2.2 million jobs.

This research project intends on not only recording a variety of basic scientific data (*i.e.* air/water temperature, etc.), open and accessible to the public and for future researchers use, but also reveals the correlations, if any, between reef health, local climate and oceanographic conditions in this region. Realizing the reason(s) behind those coral survivals may also provide the critical information needed to protect and enhance the coral reef ecosystems in the Gulf of Suez in particular.

Specific objectives of this research are to apply the least square harmonic method to obtain tidal constants, investigate tidal characteristics and sea level fluctuation at Zaki's Reef, and the seasonal changes of mean sea level at the study site. We used observed water surface elevation and meteorological data collected at the study site from August 13, 2010 through August 25, 2011, to identify and deduce the major tidal constituents and investigate the physical parameters that control the seasonal changes of sea level. Ain Sokhna has an increasing potential for major future development (20 million by 2050), with two major ports currently in operation. However, no intensive study was reported in literature regarding sea level variabilities or tides (closest tide station is located at Suez City 60 km north of the study site). Therefore, the goals of this study are to 1) Determine tidal constituents and establish a set of constants that predicts water surface elevations in the Gulf of Suez at the northern limits of sub-tropical coral reef ecosystems, 2) Compare our research results to other similar studies along the Red Sea, and 3) Discuss and document tidal impacts on resident biotas on Zaki's reef (e.g., reef exposure to atmospheric conditions).

2. Data and Methods

2.1. Study Site

Zaki's Reef is an isolated, fringing coral reef that extends approximately one-kilometer parallel to shore, and 50 - 100 m offshore (**Figure 1**). At low tide, the average water depth is one to two meters. This 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). Geographic Positioning Systems (GPS) and Satellite image analysis were used to survey reef boundaries (**Figure 1**).

2.2. Data Collection

Water surface elevation data were recorded on a 25-minutes interval using an Onset, Inc. water level logger (ONSET, http://www.onsetcomp.com; U20-001-Ti) from August 13, 2010 through August 25, 2011. The self-contained pressure sensor collected water surface elevation and water temperature. In addition, high-frequency (30-minute interval) time series of atmospheric pressure, wind speed and direction, air temperature, dew point, and humidity were collected from a roof top weather station (https://www.onsetcomp.com/products/kits/u30-nrc-sys-c/) placed near Zaki's Reef at approximately ten-meter height above sea level. Weather data were collected between August 13, 2010 through August 25, 2011.

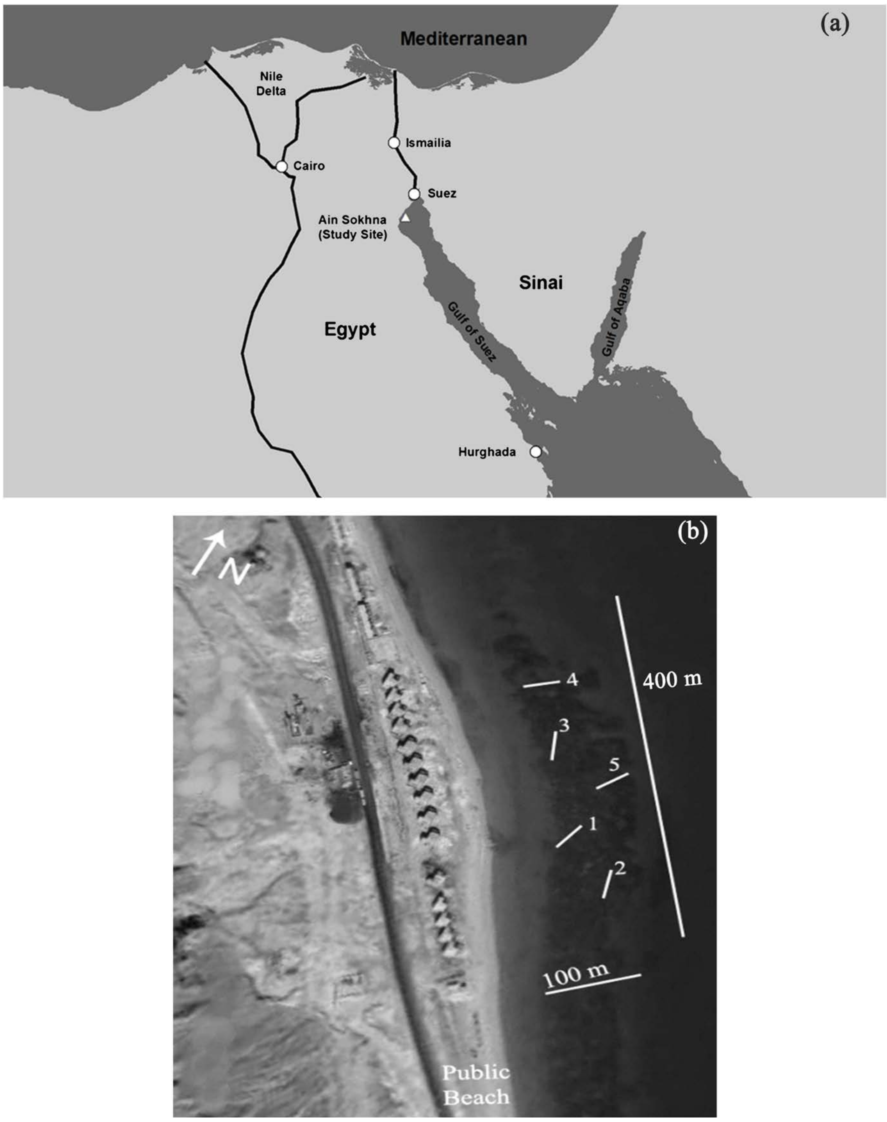

Figure 1. Location of Zaki's Reef in the Red Seas Gulf of Suez, approximate 60 km south of the highly trafficked Suez Canal. Panel A, General location of the study area; Zaki's reef is located approximately 60 km from Suez city and 400 km north of Hurghada. Panel B: Arial location of Zaki's reef monitored transects (water level logger was placed near transect 5). Numbers depicted (1, 2, 3, 4, and 5) mark Transect locations of coral reef surveys during this research study.

2.3. Data Analysis

A combination of descriptive statistics together with graphical techniques was employed to identify seasonality or trends, and describe relationships, if any, in time series observations. All analyses were performed with daily, monthly, and yearly means calculated from the original observations. Statistics were calculated with JMP (Version11, SAS Institute Inc., Cary, NC) and SigmaPlot (Version 12.5, SPSS, Inc. Chicago, IL). The level of significance (α) was set at 0.05 for all analyses. Wind probability plots were constructed following [7] and [8] and WRPLOT View Software was used to determine wind vector and wind classes from field observations. WRPLOT View provides displays of wind rose plots and frequency analysis (http://www.weblakes.com/company/index.html). A wind rose depicts the frequency of occurrence of winds in each of the specified wind direction sectors and wind speed classes for a given location and time period.

World Tides software (http://www.mathworks.com/matlabcentral/fileexchange/) developed by [9] was used to investigate the major tidal constituents (World Tides 2009 version1.0: MATLAB version 7.1.0 - 7.5.0 (R2007b)). In addition to the daily and monthly mean sea level, a 30-hour filter was used to eliminate high frequency observations and pre- and post-filter data were used to calculate the major tidal constituents. Pressure observations measured by the water level logger used for the analysis included atmospheric pressure. To eliminate weather related pressure fluctuations, atmospheric pressure was subtracted from the measured pressure time-series on a daily basis.

3. Results

3.1. Major Tidal Constituents

Defining Harmonic analysis of water surface elevation data resulted in 35 tidal constituents, and **Table 1** lists all major and the top ten constituents, period, and phase lag, whose amplitudes exceeded 4% of the M_2 amplitude.

The character of the tide is determined by the ratio $(K_1 + O_1)/(M_2 + S_2)$. This ratio is 0.07 at Zaki's Reef, which indicates that tide at the study site is strongly semidiurnal. The RSM error (square root of the mean square difference between observed and predicted water levels) is a measure of the expected error associated with tidal predictions, and in this case RMS = 0.167. Percent reduction in variance is the percentage of the total variance in water level explained by the astronomic tide model (R^2 = 87.54%). **Figure 2** depicts observed and predicted water surface elevations based on the all 35 tidal constituents at Zaki's Reef (**Table 1**).

As shown in **Table 2**, results were remarkably similar to each other when using all or first six or first eleven tidal constituents (based on the order of magnitude of amplitude) to predict tides at this location.

Tidal Form number (0.07) at Zaki's Reef indicates a fully semidiurnal dominated tidal regime. The lunar tidal constituent M_2 shows the largest amplitude (57.5 cm), followed by N_2 and S_2 (**Table 1**), while the diurnal components such as O_1, K_1, S_1, and P_1 show some of the smallest amplitudes among major tidal constituents. For longer period constituents such as solar semi-annual and annual (S_a, and S_{sa}), several years of observations are required to determine amplitude and phase angle. If these constituents are not available, they can be used and applied from nearby stations ([9] Boon, 2011). In calculating tidal constituents (World Tides), we used S_a and S_{sa} values provided by the United Kingdom Hydrographic Office (http://www.admiralty.co.uk/) from the nearest available tide station (Suez Port, approximately 60 km north of the study area). Including S_a and S_{sa} values obtained from nearby station constituents resulted in no improvement

Table 1. Major Tidal constituents, amplitudes, and phase lag relative to local time (GMT + 3) at Ain Sokhna, Egyptian Red Sea obtained from a 376 days of water surface elevation observations. Complete definition of all listed tidal constituents is located at: (https://en.wikipedia.org/wiki/Theory_of_tides#Semi-diurnal).

ID	Constituents	Amplitude (cm)	Phase Lag (˚)	Frequency (cycle/day)	% of M_2
1	M_2	57.5	298.2	1.932	100.00
2	N_2	19.8	185.0	1.896	34.43
3	S_2	14.3	21.8	2.000	24.87
4	K_1	4.2	195.1	1.003	7.30
5	NU_2	4.1	306.0	1.901	7.13
6	K_2	4.1	180.0	2.006	7.13
7	$2N_2$	3.4	32.3	1.860	5.91
8	L_2	3.4	326.6	1.969	5.91
9	MU_2	3.0	114.9	1.865	5.22
10	S_1	2.6	258.2	1.000	4.52
11	O_1	1.2	159.3	0.930	2.09
12	P_1	1.2	163.9	0.997	2.09
13	T_2	1.1	35.4	1.997	1.91
14	LAM_2	0.9	125.8	1.964	1.57
15	Q_1	0.7	55.7	0.893	1.22
16	M_4	0.7	72.5	3.865	1.22
17	OO_1	0.6	154.6	1.076	1.04
18	MNS_2	0.6	312.0	1.828	1.04
19	M_3	0.5	133.6	2.898	0.87
20	MN_4	0.5	323.1	3.828	0.87
21	MS_4	0.5	167.7	3.932	0.87
22	R_2	0.4	130.0	2.003	0.70
23	$2SM_2$	0.4	327.7	2.068	0.70
24	MK_3	0.4	50.7	2.935	0.70
25	RHO_1	0.1	66.1	0.898	0.17
26	M_1	0.1	75.8	0.966	0.17
27	J_1	0.1	58.7	1.039	0.17
28	$2MK_3$	0.1	358.6	2.862	0.17
29	S_4	0.1	124.1	4.000	0.17
30	$2MN_6$	0.1	192.3	5.761	0.17
31	M_6	0.1	300.1	5.797	0.17
32	$2MS_6$	0.1	39.5	5.865	0.17
33	S_6	0.0	40.0	6.000	0.00
34	M_8	0.0	49.1	7.729	0.00
35	$3MS_8$	0.0	294.8	7.797	0.00

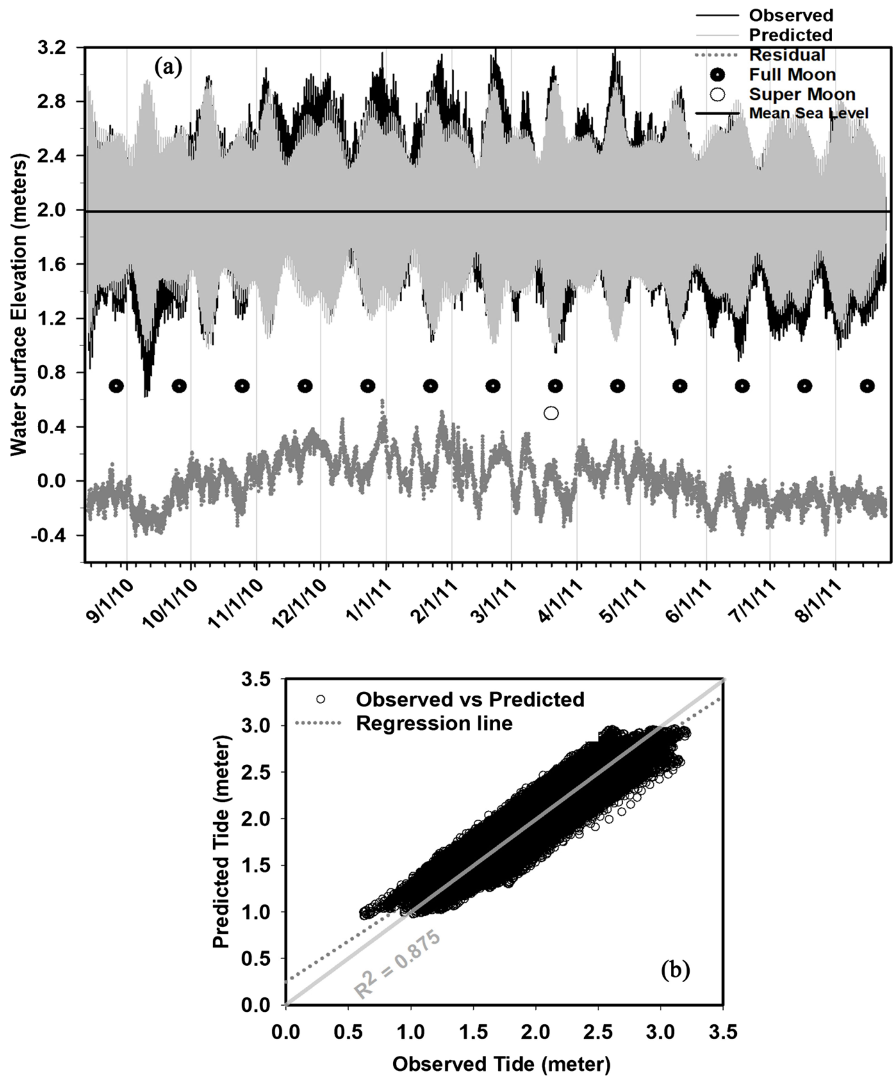

Figure 2. Observed vs. predicted tides at Zaki's Reef (Ain Sokhna, Red Sea, Egypt) from August 2010 through August 2011. Panel A: Observed (Black continuous line), predicted (gray continuous line), residuals (dark gray dotted line), and Mean Sea level during this period (black line). Panel B: Regression line displayed (dotted grey line).

Table 2. Tidal prediction results using all, eleven, and six tidal constituents included in the World Tide program.

# of constituents	HAT[a]	LAT[b]	RMS Error	R^2 (%)
35	1.098	−1.222	0.167	87.54
11	1.034	−1.067	0.168	87.39
6	1.020	−1.046	0.172	86.67

[a]Highest astronomical tide; [b]Lowest astronomical tide.

as measured by RSM or R^2. This suggests the need for multi-year water surface elevations observations at the study site and the current period of record (376 days) is not long enough to calculate S_a and S_{sa} characteristics (*i.e.*, amplitude and phase angle), or both constituent contributions to tide is negligible; the latter (no major contribution) is more likely at Zaki's Reef.

The resulting low pass filtered daily records were averaged to calculate the monthly sea levels (Figure 3). Seasonal changes in monthly mean sea levels fluctuated between higher levels (above average mean annual sea level) for six months (October through April) and lower levels for six months (March and May through September). Maximum monthly sea level was 19.0 cm and was reached during November (2010), and the lowest monthly mean sea level (18.0 cm) was reached during September (Figure 3). Monthly mean sea levels were almost constant during the following summer months June, July, August 2010, and August 2011 (Figure 3). The seasonal change in monthly mean sea levels resulted in an annual tidal range of 37.0 cm, with minimum and maximum changes during summer and winter, respectively.

3.2. Barometric Pressure

The standard pressure is 1013.25 mbar (millibar), and the rate of change of less than 2 mbar per three hours (mbar/3hr) are within expected ranges associated with barometric "station" pressure variation due to diurnal oscillation in temperate climates. The barometric pressure in the tropics simply does not change a lot from day to day and in the tropics, barometric pressure (corrected to sea level) should vary from about 1008.7 mbar to 1018.9 mbar. Barometric pressure at Miami, Florida, for example, might change from 1002.0 mbar to 1032.4 mbar (range is about 30 mbar). In higher latitudes, variation from 981.65 mbar to 1049.4 mbar is not uncommon (range = 68 mbar). However, in sub-tropical locations such as Zaki's Reef, barometric pressure varied between 998.85 and 1026.25 (range = 27.4), with a median of 1012.05. The observed range is a little

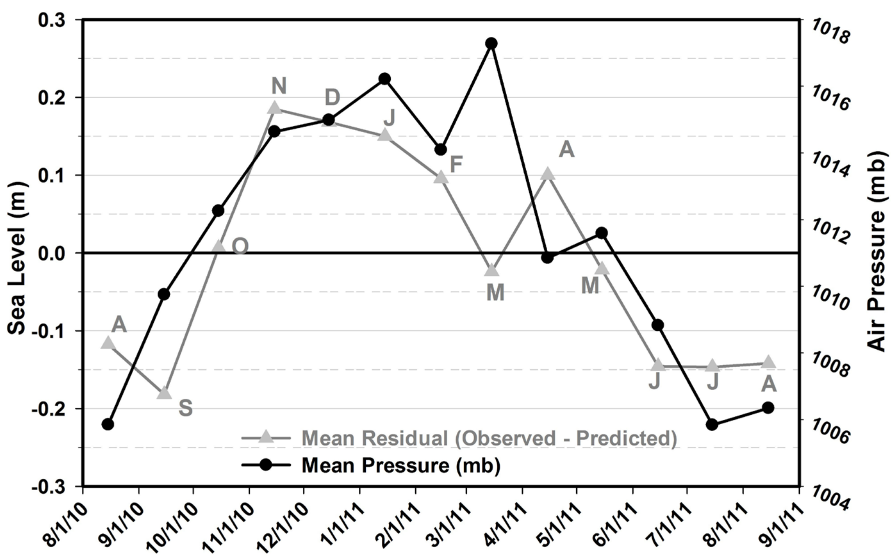

Figure 3. Monthly mean sea level (black line with solid circles) and air pressure changes (gray line with solid triangles) at Zaki's Reef (Ain Sokhna, Red Sea, Egypt) From August 2010 through August 2011. A, B, C …A, represents "month"; A = August, S = September, …).

more than the ones observed in tropical areas, which was expected. Monthly means of air pressure adjusted to sea level at Zaki's Reef followed the monthly mean sea level changes with an annual range of 11.54 mbar. Similar to sea level, monthly means of air pressure at Zaki's Reef reached its maximum during winter and minimum during summer (**Figure 3**). A maximum barometric pressure was observed in March (1017.37 mbar) and a minimum (1005.84 mbar) in July (**Figure 3**).

3.3. Water and Air Temperature

Water temperature monthly means at Zaki's Reef followed the same trends as air temperature monthly means with a minimum during winter and maximum during summer season (**Figure 4**). Minimum air and water temperatures (18.47˚C, 16.38˚C) occurred in January and February, respectively, while maximum of both air and water temperatures (31.90˚C and 29.97˚C) occurred in August, respectively (**Figure 4**). The correlation coefficient between monthly air and water temperatures is $R^2 = 0.92$.

Wind effect: March is an interesting month to say the least (letter "M" on mean residual gray solid line in **Figure 3**), with a marked depression in sea level during the winter month accompanied with a marked peak in barometric pressure (**Figure 3**). Also, during March, both water and air temperature monthly means (18.91˚C and 19.02˚C for water and air, respectively) were almost identical (**Figure 4**). This marked depression in sea level during March, where sea level in general is higher during the winter season, was unexpected. Yet, its cause may be well defined, and most likely is due to the sudden increase in air pressure (**Figure 3**). According to the hydrostatic hypothesis, external forces such as gravity are balanced by a pressure gradient force [10]; *i.e.*, the sea surface reacts

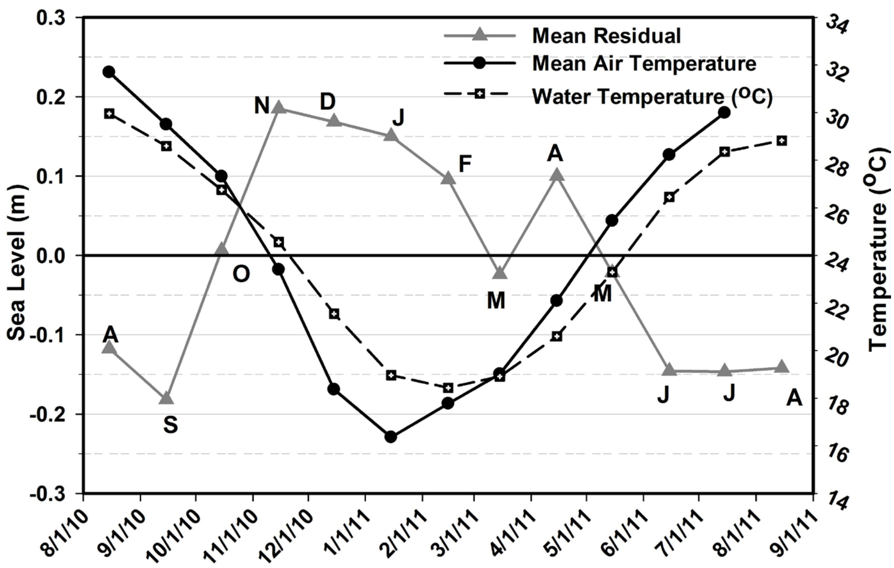

Figure 4. Monthly mean sea level (gray line with solid triangles), monthly mean air (black line with solid circles), and water temperature (dashed black line with solid squares) at Ain Sokhna. A, B, C …A, represents "month"; A = August, S = September…).

like an inverted barometer that lowers the sea level by 1 cm for each millibar increase in atmospheric pressure. In this case, sea surface was lowered 10 cm accompanied by an increase of 5 mb during marsh, which may partially explain the sudden drop in sea level. In addition, this increase in air pressure may possibly be due to another local phenomenon. During that month (March), wind speed and air temperature increases drastically and abruptly due to the Khamaseen wind system, which originates in the western desert during March and last for fifty days, hence the name.

Wind exceedance probability analysis, based on the 30-minutes observations, indicated that wind speed and gust wind speed during the observation period were almost 100% less than 4 and 10 ms^{-1}, respectively (data not shown). Wind stress along the shore was directed north-west 38% and towards south-east 62% of the time, and cross shore wind stress was directed offshore more than 62% and on shore less than 37% of the time.

The effect of wind stress is to raise or lower the sea level causing positive or negative surge. Analysis of the wind field at Zaki's Reef revealed that the prevailing winds blow from the West and East and SES (**Figure 5**). The most frequent winds are from the E, SE, and W (**Figure 5**).

The most frequent wind class (0.5 - 2.1 $m \cdot s^{-1}$) was more than 64% of the time followed by wind class (2.1 - 3.6 $m \cdot s^{-1}$) with more than 24% of the time, 88% of wind speed were in the range of 0.5 - 3.6 $m \cdot sec^{-1}$. The resultant wind vector for

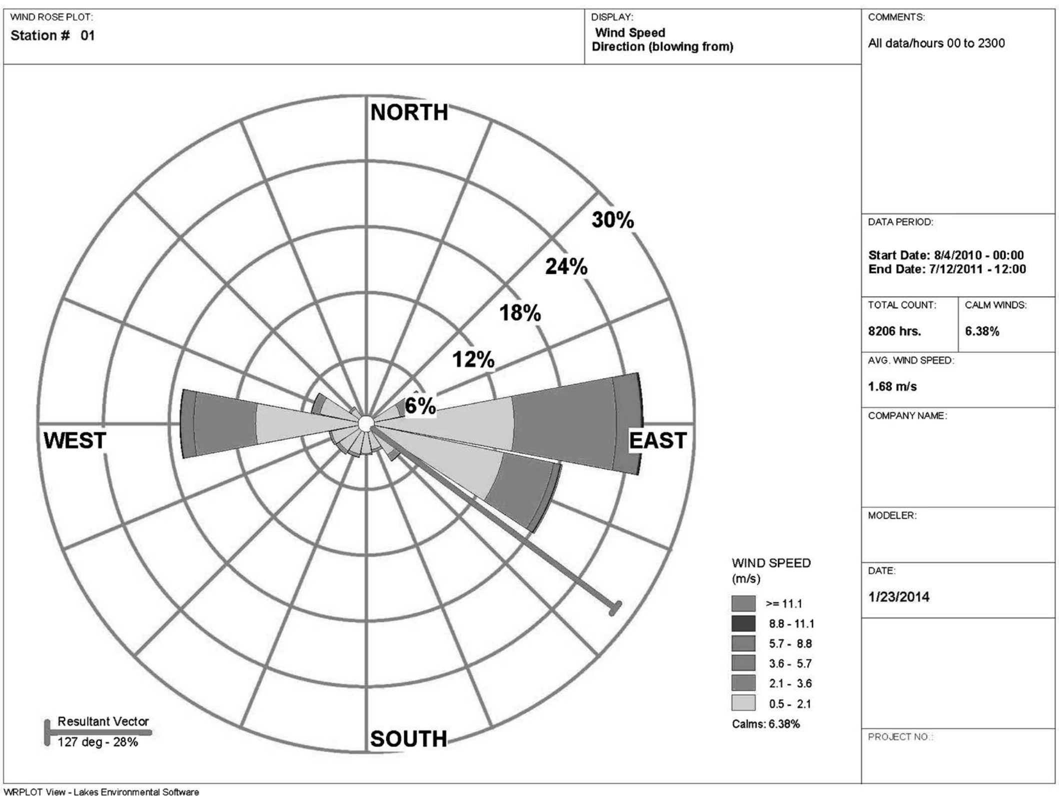

Figure 5. Wind speed and direction (blowing from) at Zaki's Reef from August 13, 2010 through August 25, 2011.

the entire period was at 127˚ (**Figure 5**). The overall wind speed mean was 1.68 $m \cdot s^{-1}$ with a minimum of 2.88 $m \cdot s^{-1}$ and a maximum of 7.70 $m \cdot s^{-1}$, all of which justify the use of a wind drag coefficient of $C_D = 0.0013$ to calculate wind stress. For practical applications in oceanography, it is enough to use an empirical formula to calculate wind stress from wind speed such as:

$$\tau = C_D \rho_{air} U_{10}^2 \quad (1)$$

where

U_{10} = wind speed at 10 m above the sea surface

ρ_{air} = 1.22 $kg \cdot m^{-3}$

C_D = 0.0013 dimensionless drag coefficient; a typical value might be 0.0013, this gives t in units of $N \cdot m^{-2}$, or Pascals (Pa).

The Gulf of Suez heading is 330˚ (or 30˚ west from true North). Wind stress vector decomposition resulted in an on-shore and cross-shore currents indicating that both components are almost equal in strength and persistent year around (**Table 3**), yet in completely opposite direction (**Figure 6**). Wind stress along shore is persistent year-round and towards southeast, while wind generated surge is always (the entire observation period) persistent towards offshore. Wind stress along shore, in general, is higher in values than the offshore wind stress (**Figure 6**). Wind stress calculated from wind gust data (**Table 3**) also followed the same direction, with a much stronger offshore gust wind stress compared to alongshore (southeast) component. Those wind gusts may be attributed

Table 3. Monthly average of the entire period of record results of wind vector decomposition to alongshore and offshore components. Gulf of Suez orientation is 330˚ or 30˚ west of true North.

Month	Average of Wind Speed ($m \cdot s^{-1}$)	Average of Gust Speed, ($m \cdot s^{-1}$)	Average of Wind Direction ($\emptyset$)	Average Pressure (mbar)	Average of Wind Gust Stress Long-shore	Average of Wind Gust Stress cross-shore	Average of Long-shore: negative is south-east	Average of Cross-shore: negative is onshore
08[a]	2.70	7.70	171.67	1005.5	−2.08	1.20	−0.69	0.39
09	1.47	3.35	167.44	1009.7	−0.76	0.41	−0.32	0.20
10	1.32	2.94	175.14	1012.3	−0.41	0.30	−0.15	0.10
11	1.30	2.88	152.80	1014.6	−0.76	1.15	−0.34	0.50
12	1.68	3.64	127.18	1015.0	−1.01	2.11	−0.45	0.94
01[b]	1.55	3.31	133.29	1016.2	−1.07	1.58	−0.49	0.72
02	1.88	4.05	151.32	1014.1	−0.99	1.78	−0.44	0.78
03	1.66	3.61	160.09	1017.3	−1.09	1.26	−0.49	0.56
04	1.94	3.92	174.86	1010.9	−0.57	0.51	−0.22	0.17
05	1.84	3.75	195.39	1011.6	−0.32	−0.08	−0.10	−0.10
06	1.78	3.63	183.70	1008.8	−0.81	0.12	−0.33	0.01
07	1.79	3.58	186.66	1005.8	−0.59	0.15	−0.24	0.01
08[c]	1.84	3.71	174.16	1006.3	−0.84	0.61	−0.38	0.25

[a]17 days average; Year 2010; [b]Year 2011; [c]24 days average.

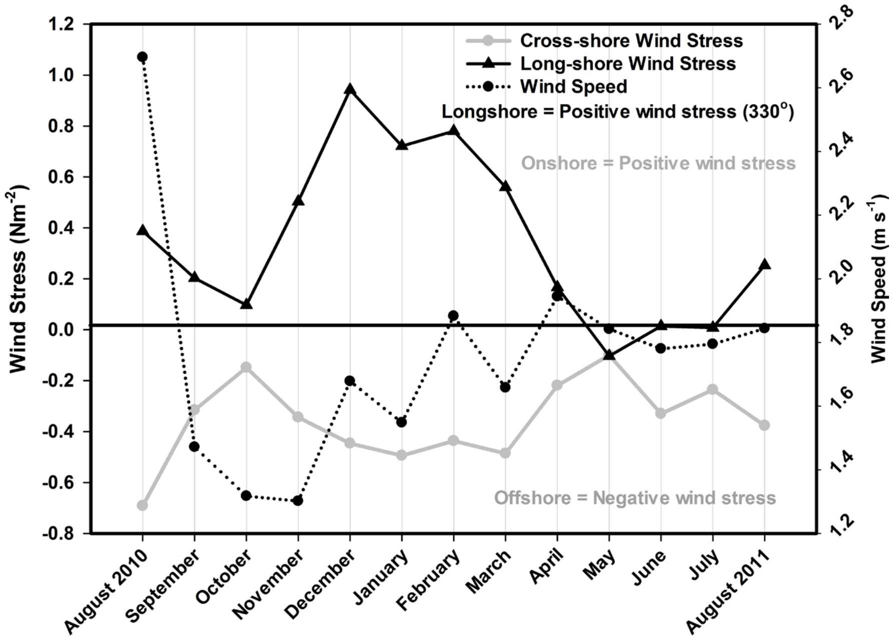

Figure 6. Monthly mean wind stress component along shore (black line with solid triangles), cross shore (gray line with solid circles), and monthly mean wind speed (black dotted line with solid circles) at Ain Sokhna from August 13, 2010 through August 25, 2011. Shoreline is aligned at 330˚ from true north. Positive alongshore stress is directed northwest and positive cross shore is shoreward.

to two natural phenomenon, land-sea breeze or local Foehn wind, which results from the nearby Gebel Ataka [11].

4. Discussion

There are no long-term studies, particularly for fringing coral reefs, in the Gulf of Suez prior to the research reported here [3]. This multi-year study was set out to establish linkages between fringing coral reefs in the northern Gulf of Suez and prevailing environmental conditions such as local climate, oceanographic conditions, as well as other factors (e.g., oil spells, human encroachment in this region) at Zaki's Reef. Insight into local meteorological and oceanographic processes may provide a better understanding of the direct or indirect influence of environmental conditions may have on resident biotas. Determining the reasons why coral species and community of organisms found here survive despite all stressors is critical, and such information may hold the key to the preservation of reefs elsewhere.

There are several major reasons behind expanding our data collection to include meteorological data, water temperature and water surface elevation observations. First, it was pure scientific curiosity to discover why corals at Zaki's Reef survived at extremely high latitude, or are those corals truly heat-adopted? Second, does the local weather create suitable water temperatures and possibly the reason behind Zaki's Reef survival at this location? Third, do tidal forces have any impacts on corals and their survival at the study site?

All major species of hard and soft corals that survived in the study area and the dominant ones were identified by [3]. They pointed out that of all known coral reef species that exist in the Gulf of Suez, only six dominated Zaki's Reef; more than 94% of coral coverage. They also examined and discussed in details other environmental factors such as meteorology and oceanography that may have enhanced the survivalship of corals at this location ([11] and [12]). In this manuscript, the focus is on local tides and its impacts on the resident biotas. Previous researchers [1] reported that tidal motions of the Red Sea are important to the functioning of fringing or marginal reefs located along its shores. Tidal currents create turbulence, which increases nutrients, phytoplankton, and zooplankton fluxes between corals ecosystem and overlying water column. Studying fringing corals in the Gulf of Aqaba, [2] reported that changes in water surface elevations due to tidal forces can be important to shallow fringing reef features, occasionally exposing resident corals to wave action, and increasing the likelihood of drying out at low tides.

The major tidal constituents identified from a tide gauge at Zaki's Reef (2010-2011) were dominated by the semi-diurnal components (**Table 1**) and resulted in classifying tidal characteristics as strongly semi-diurnal (Form number = 0.07). Monthly mean sea level variations (non-tidal components) show higher and lower levels in winter and summer, respectively, with a range of 38 cm (**Figure 3** and **Figure 4**). Pre- and post-filtered water surface elevation data analysis (using World Tides software) are identical, which means higher frequency present in those observations (<30 hours) are the main reason to achieve only 87% agreement. Analysis of those high frequency residual data (residual = observed – predicted water surface elevations, *i.e.*, white noise) was dominated by daily frequency, indicating possible wind-dominance.

Results of tidal constituents are similar to results obtained by [13] at Gizan, Saudi Arabia (1800 km south of study site), where tides are defined as strongly semi-diurnal (0.07 vs. 0.07). Tidal ranges were 40 and 37 cm at Gizan and Zaki's Reef, respectively. Dominant constituents were M_2, N_2, and S_2 at Gizan and Zaki's Reef. Yet, amplitudes of those constituents at Zaki's Reef are almost twice as much as the ones found in Gizan. Unlike the similarity in tides between Zaki's Reef and Gizan, tides at Jeddah (1100 km south of Zaki's Reef), Saudi Arabia, is mixed, mainly semi-diurnal with large diurnal inequalities, while at Port Sudan (1200 km south of Zaki's Reef) the tide is diurnal [14]. Yet, co-tidal range as reported by [14] over-predicted, doubled, the observed tidal range at Zaki's Reef. It should be noted that Jeddah and Gizan are located on the eastern shore, while Port Sudan is located on the western shores of the Red Sea. The fact that the Gulf of Suez is shallow (average water depth is approximately 25 m) may explain the increase in the semi-diurnal amplitudes observed at Zaki's Reef compared to the ones in Gizan, Jeddah, or Port Sudan. Yet, over tide constituents at Zaki's Reef were irrelevant as well as daily constituents.

Tides during full moon phase has a profound impact on Zaki's Reef, particularly during high off-shore wind that causes the reef to be exposed directly to the atmosphere, sun, and wave action (**Figure 2**). During March, for example, the long-shore wind stress (currents are southeast direction) was high (third highest value of the year) and cross offshore wind stress was the lowest value of the year (**Figure 6**). The offshore wind tends to push water away from the beach (Zaki's Reef), and the Super Full Moon (occurred on Saturday March 19, 2011; https://www.timeanddate.com/astronomy/moon/blue-moon.html), have the largest tidal range during the year, which tends to cause the largest changes in water surface elevation. Such combination exposes resident biotas at Zaki's Reef directly to the atmosphere and the detrimental effect of direct exposure to the hot sun and wave action (**Figure 2**).

The offshore wind stress (and consequently wind generated currents) is persistent year around (**Figure 6**), suggesting that moon (weather super or not super moon) may play a major role of exposing corals at Zaki's Reef to the atmosphere, more hot and cold air temperatures (depending on the season) compared to water temperatures (**Figure 4**). Exposures of corals at this location to such temperature changes, colder in winter and hotter in summer (**Figure 4**), may have either detrimental (coral bleaching and die off) or beneficial (resident biotas get "trained" to be more heat tolerant to a wider range of temperatures) effects. For example, it has been reported that exposure to cold water temperature tends to increase coral tolerance to higher water temperature [15], which may be the reason why Zaki's Reef have shown resilience and survived for many decades at this very high latitude; probably the highest sub-tropical coral reef in the world.

Researchers [15] reported that only coral taxa that survive cold temperature 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 repeatedly, as evident from our seawater temperature observations (see also **Figure 3** [12]). Exposure to these high- and low-temperature anomalies on a yearly basis may have caused corals at Zaki's Reef to develop an adaptive resistance mechanism, as suggested by [15]. The fact that only six (out of 35 identified in the Gulf of Suez) coral species dominate Zaki's Reef further suggest that their resilience may be attributed to their adaptive resistance mechanisms to extreme temperatures.

Previous comparisons among plants [16] and animals [17] [18] and [19] have shown that some population or species are far more resilient compared to others with marked influences on growth, survival, and disease resistance ([19] [20] and [21]). Corals at Zaki's Reef may have been living at the study site for several decades (as coral generally exhibit slow growth, particularly outside their temperature-optimum conditions of 25˚C to 27˚C) and may have the capacity to acclimatize or adapt to external stresses better than others.

If one assumes that Zaki's Reef existed for several decades, one may conclude then that predominant environmental factors collectively enhanced corals' survivalship and to exist in such harsh and extreme temperature conditions. This reef may have started out, historically, with the 35 coral species identified by [6] in the Gulf of Suez (*i.e.*, with more than the currently observed and dominated six species at this location) during more favorable and optimum conditions for coral reef to thrive. Over the years, resident biotas at Zaki's Reef experience frequent exposures to both cold and hot water temperatures and for extended period of times [12], due to the combined effects of offshore and tidal actions, which exposed those 35 species of corals to even hotter and colder temperatures. Yet, more recently, [3] [4] and [12] reported that after four years of studying resident biotas at this location, the same six species (out of 35 species known to exist in the Gulf of Suez) remained dominant. They also reported that, even after the world-wide bleaching event combined with an oil spill in 2005, those six species remained dominant.

Offshore winds at Zaki's Reef causes the hot nutrient depleted surface water to move offshore, and consequently a return flow supplies the needed nutrients for those corals to survive at this extremely high latitude of sub-tropical reefs. Wind setup, pushing water away from the beach/reef causes an imbalance in the barotropic pressure in the water column. Consequently, a return sub-surface (no current data are available at this location) flow takes place trying to balance this inequality (upwelling). Upwelling are often characterized with enrich nutrients and may provide additional nutrient supply to corals at this location. Upwelling is an oceanographic phenomenon that involves wind-driven motion of dense, cooler, and usually nutrient-rich water towards the ocean surface, replacing the warmer, usually nutrient-depleted surface water. It is also no surprise to see all fishermen boats (personal observations) are parked/fishing at and near this reef, no other fishing ports are near this area for many kilometers.

Current coral conditions of only six dominant species at Zaki's Reef are the results of many years and cycles of exposures to those extreme conditions; training, adaptation, or one might say "survival of the most adaptive/tolerant." It is important to recognize that the final six and dominant species at Zaki's Reef, not only manage to survive, but also are more adoptable to these harsh/extreme conditions, which make them an ideal specimen for relocation to increase the chances of reviving impacted reefs elsewhere.

5. Conclusions

The current study was driven mainly by scientific curiosity regarding the discovery of a fringing coral reef ecosystem that thrived at extremely high latitude (one of only few coral reefs that exist at such high latitudes). We quickly learned that there are no significant databases for this region, previous published or un-published research around the study site, except for the vastly different Gulf of Aqaba environment. We therefore integrated other environmental data collection to investigate, why this fringing coral reef is flourishing at such high latitude? Such

Figure 7. 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.

information may hold the key to the preservation of reefs elsewhere.

We concluded that it is not a single reason behind Zaki's Reef survival at this location. We believe as our data indicated that a combined effect of several factors may have contributed to the survival and resilience of corals at Zaki's Reef to thrive at one of the most northern latitudes for sub-tropical reefs. The combination of tidal motions, particularly Super Moon, offshore and longshore currents generated by the prevailing local winds, may have played a major role in selecting those six species out of the 35 species known to exist in the Gulf of Suez, and over the decades "trained" those six species to become heat and cold temperature adopted. Air temperature played a key role at this location, causing water temperature to be remarkably similar to air temperature. Furthermore, when the reef is exposed during super moon (Figure 7), or when offshore current is strong (offshore wind stress is persistent year around at this location), air temperature enhances the ability of those six selected species to become more heat and cold tolerant. This mechanism, through the combined forces of wind and tides, may be responsible of "training" or causing the entire community in the Gulf of Suez to survive such extreme conditions. Those "trained" corals can be used/relocated to areas experiencing deteriorating conditions due to overuse by divers, such as Hurghada (400 km south of the study site and a heaven for divers).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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