Int. J. Environ. Res., 9(3):1011-1022, Summer 2015
ISSN: 1735-6865

Survival of High Latitude Fringing Corals in Extreme Temperatures: Red Sea Meteorology

Moustafa, M.Z.[1*], Moustafa, Z.Q.[2] ,Moustafa, M.S.[1] ,Moustafa, S.E.[3] and Moustafa, Z.D.[4]

[1]H2O & Geo, Inc., 70 Whispering Oaks Trail, West Palm Beach, FL 33411, USA

[2]Wilson College, Princeton University, 110 West College P.O. Box 430. Princeton, NJ 08542-0430

[3]Department of Geography, Rutgers The State University of New Jersey, Piscataway, NJ 08854-8045

[4] Pratt School of Engineering, Duke University, Durham, NC 27708

Received 19 Sep. 2014; Revised 9 Dec. 2014; Accepted 13 Dec. 2014

ABSTRACT: Zaki's Reef is located in the Gulf of Suez, a narrow portion of the Red Sea, with exceptionally dry and hot climate and lacks almost all scientific data. This research intends to describe the area's unique climatology, which may reveal correlations between the reef's existence at high latitude and extreme climate conditions. Air temperature at Zaki's Reef fluctuated between 0.3 and 58.6°C with a daily range of 25°C and annual mean of 22.1°C ±0.075. Spectral analysis revealed half day, daily and yearly return periods, all of which have shown that daily and half daily cycles are dominating the local climate with amplitudes of approximately 5°C. Frequency histograms revealed a bimodal signal, one peak at 14-15°C and a second peak at 32-33°C, both represent nighttime and daytime temperatures half-day cycle. Meteorological data collected at Zaki's Reef were also compared to Hurghada's and Ismailia's, 400 and 200 km south and north of the study site, respectively, to reveal any anomalies. Although air temperature daily means at Zaki's Reef were similar to Hurghada's, maximum daily means exceeded Hurghada's by 7°C, while minimums were almost equal to Ismailia's. Unexpected temperature trends and short distance between mountain range and Zaki's Reef, prompted us to hypothesize that a Foehn wind may be responsible for the extremely high air temperatures. Air parcel trajectory model results further verified that local wind patterns matched signatures of a Foehn wind. The observed warmer than normal air temperatures may be responsible for securing the survival of these northernmost subtropical coral reefs.

Key words: Red Sea, Gulf of Suez, Fringing Reef, Air Temperature, Foehn Wind

INTRODUCTION

The Red Sea is truly one of the world's most exotic and fascinating natural environments. Located between Asia and Africa, its most northern point forms the Sinai Peninsula and stretches about 1000 miles south to join the Indian Ocean. The Red Sea is home to more than one thousand species of fish and over four hundred species of coral, more than any other proportionally sized body of water (Hanaur, 1988), and remains at an almost constant temperature, averaging 22°C year round.

Zaki's Reef (the study site) is an isolated, fringing coral reef that extends approximately one-kilometer parallel to shore, and lies 50-100 m offshore (Figure 1), and is located in the Red Sea's Gulf of Suez near the most northern latitude for subtropical coral reefs (29° 32'N and 32° 24'E). The very shallow (50-80m 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 Northwesterly trade winds and extreme temperatures result in high salinity (43-45 psu) as well as 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, only 35 species have been identified in the Gulf of Suez (Mustafa, 2000), and of these, only six species have been identified to dominate Zaki's Reef (Moustafa et al., 2008a), accounting for more than 95% of total coral coverage.

*Corresponding author E-mail: mzmocean@gmail.com

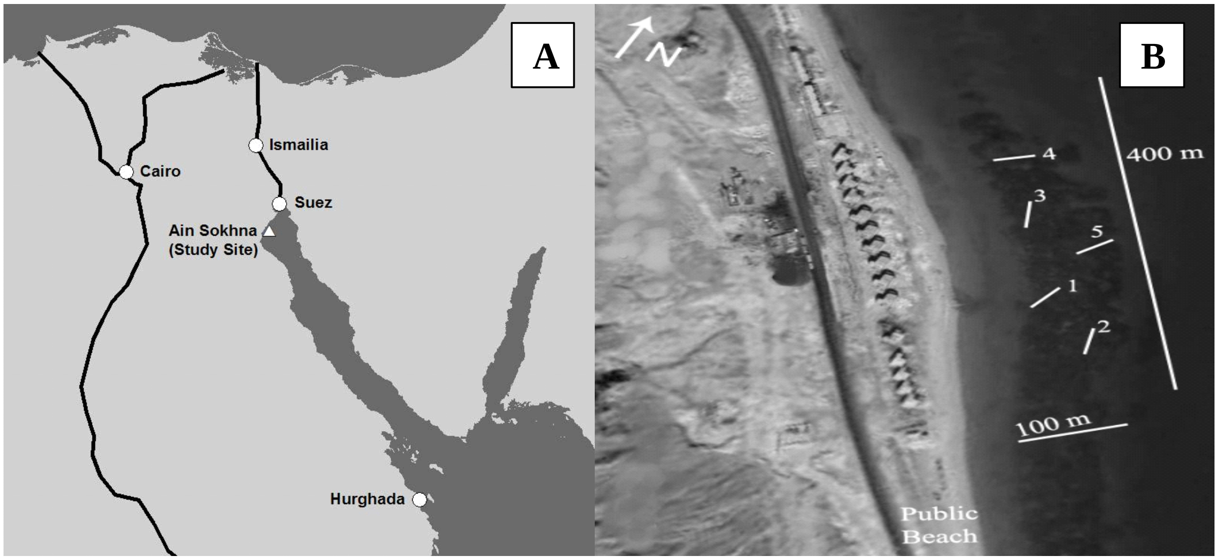


Fig. 1. Location of Zaki's Reef in the Red Sea's Gulf of Suez, approximately 80 km south of the highly trafficked Suez Canal. Panel A, general location of the study area; Zaki's reef is located approximately 60 km from Suez City, 200 km south of Ismailia, and 400 km north of Hurghada. Panel B: Location of Zaki's reef relative to Gabel Ataka mountain (distance is < 500 meters).

The Gulf of Suez is a narrow portion of the Red Sea, surrounded on all sides by mountain ranges. Almost all forms of scientific data are lacking for this region (Moustafa *et al.*, 2008a, b). Therefore, the overarching goal of this multi-year study was to establish a knowledge base for fringing coral reefs in the Gulf of Suez and provide 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 (Hanaur, 1988; UNESCO, 2005).

In situ observations from the study site and two additional stations located north and south of the study site spanning over a two year period (2007–2009) were collected and analyzed to describe prevailing conditions and reveal any existing anomalies in this region's climatology. Long-term data collection provides evidence of seasonal and interannual variability and may reveal correlations between a tropical reef's existence at such high latitude and climate conditions of this region. Specific objectives of this research were:

1. Establish observed meteorological data ranges and trends at the northern limits of sub-tropical coral reef ecosystems; the nearest available historical weather station is more than 200 km away,

2. Determine the cyclic nature of all univariate time series to reveal natural forces/phenomena that exist in this region, and

3. Compare our results to other similar studies and localities, which may explain and identify the most likely reasons why this fringing coral reef survives at the northernmost latitude of subtropical reefs; i.e., investigate if the local climate is responsible, as a whole or in part, for this reef's survivalship.

MATERIALS & METHODS

A roof top weather station was placed near Zaki's Reef at a height of ten meters above sea level. High frequency time series of air temperature, dew point, and humidity were collected with highly sensitive sensors for two years between August 20, 2007 and September 16, 2009 (Onset Computer Corporation, 2014).

We were also able to obtain daily-mean observations from two nearby stations, Ismailia and Hurghada located 200 and 400km away north and south of the study site, respectively (Wunderground, 2010). Daily data included air temperature, dew point, and relative humidity at these locations (Figure 1).

A combination of descriptive statistics together with graphical techniques was employed to identify seasonality or trends, and describe relationships between air temperatures and local climate near Zaki's Reef. All analyses were performed with daily, monthly, and yearly means calculated from 30 minute observations (48 samples per day). Statistics were calculated with JMP (Version 7, SAS Institute Inc., Cary, NC), or SigmaPlot (Version 11.0, SPSS, Inc. Chicago, IL). The level of significance (α) was set at 0.05 for all

Table 1. Daily descriptive statistics for air temperature, humidity, and dew point temperature data collected at the study site from August 21, 2007 through June 20, 2008 and from June 20, 2008 through September 16, 2009. All daily statistics are based on 48 daily observations.

	2007-2008				2008-2009				2007-2009			
2007-2008	Temp. (ºC)	Dew Point (ºC)	Abs Humidity (gm/M³)	Relative Humidity (%)	Temp. (ºC)	Dew Point (ºC)	Abs Humidity (gm/M³)	Relative Humidity (%)	Temp. (ºC)	Dew Point (ºC)	Abs Humidity (gm/M³)	Relative Humidity (%)
Mean	22.14	12.69	11.45	62.27	25.60	20.21	18.44	79.18	24.21	17.19	15.64	72.40
Standard Error	0.07	0.05	0.03	0.22	0.06	0.05	0.05	0.17	0.05	0.04	0.04	0.14
Minimum	0.29	-14.64	1.40	5.90	3.31	-1.64	4.00	10.10	0.29	-14.64	1.40	5.90
Maximum	50.66	36.13	41.90	103.80	58.55	38.77	47.90	103.80	58.55	38.77	47.90	103.80
Count	14583	14583	14583	14583	21763	21763	21763	21763	36346	36346	36346	36346

analyses. Box and whisker plots were also developed and summarized.

Spectral analysis was used as the primary technique for assessing the cyclic nature of all univariate time series in the frequency domain, and was applied to all time series after filtering the original data with a 30 hour filter to exclude high frequency signals. Spectral analysis was applied to the raw datasets with no filtering and for the original half hourly and hourly observations. Spectral analysis was also applied to a new generated dataset that was created by subtracting the overall mean from the original half-hourly observations.

HYSPLIT model was used to investigate local circulation patterns. Wind-patterns were modeled using the National Ocean and Atmospheric Association's (NOAA's) HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph 2013). The HYSPLIT model provides a variety of different forms of quantitative information such as meteorological, topographical, and environmental factors involved in the region's weather patterns. This model was used to investigate trends and patterns regarding the movement of wind and weather around the Gulf of Suez region. Model run input data were based on archived meteorological data trajectories extracted from the National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) datasets available from 2006-present (Okamoto and Derber, 2006). The HYSPLIT model runs were based on single starting point trajectories. Point locations were selected based on regions of known dominant wind patterns (i.e., trade winds) and exact boundaries between mean sea level and Gebel Ataka Mountain (located approximately < 500 m west of Zaki's Reef) derived from a Digital Elevation Model (DEM). Identifying precise topographic variations in the region was crucial in order to distinguish model-predicted air mass spatio-temporal patterns, which are formed as a result of orthographic uplift

RESULTS & DISCUSSION

Observed air temperatures in this arid environment reached as high as 59ºC in a single day, yet the annual means were 22.1 and 25.6ºC for first and second sampling year, respectively (Table 1). Observed minimums were as low as 0.3 and 3.3ºC, while maximum values reached as high as 50.7 and 58.6ºC, for 2008 and 2009, respectively (Table 1). These wide temperature fluctuations translate to an average daily range in excess of 25°C.

Overall air temperature means for the two year period, were 22.3ºC (±0.22 SE) for Ismailia, 24.2ºC (±0.24 SE) at the study site, and 25.2ºC (±0.22 SE) for

Table 2. Statistical summary of daily air temperatures at Ain Sokhna, Hurghada, and Ismailia from 08/21/2007 through 09/16/2009. Study site is located 200km south of Ismailia and 400km north of Hurghada. Daily observations at study site are based on half-hourly sampling frequency, while daily means for the remaining two nearby stations were reported and obtained from: http://www.wunderground.com/global/EG.html

Ain Sokhna				Hurghada			Ismailia[1]		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Mean	**24.22**	**36.90**	**16.06**	**25.20**	**30.02**	**20.39**	**22.29**	**28.20**	**16.39**
Standard Error	0.24	0.28	0.23	0.22	0.22	0.23	0.22	0.24	0.22
Standard Deviation	6.72	7.73	6.30	6.07	5.99	6.36	6.09	6.55	5.90
Median	25.06	37.44	16.76	25.56	30.56	20.56	23.33	28.89	16.67
Mode	17.55	**41.52**	24.01	31.11	**36.67**	27.78	30.00	**35.00**	23.89
Minimum	9.57	17.52	0.29	11.67	15.56	1.67	8.89	11.67	0.56
Maximum	**36.44**	**58.55**	**27.12**	**35.56**	**41.67**	**30.56**	**33.33**	**42.78**	**26.67**
Count	758	758	758	758	758	758	747	747	747

[1] = Missing a total of 11 points; 8 beginning of May 2009; 2 beginning of August 2009, and 1 July 12, 2009

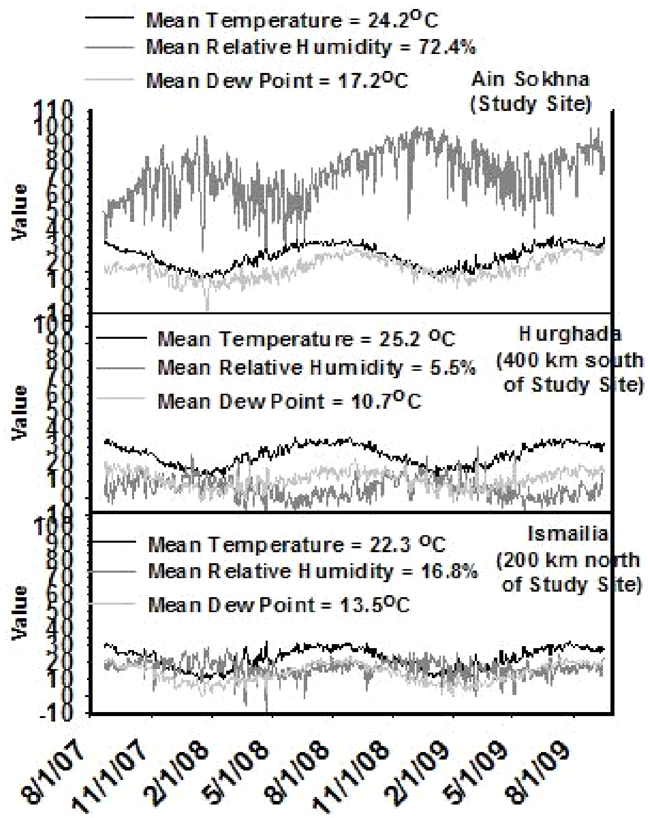


Fig. 2. Daily mean temperature, relative humidity, and dew points at study site (Ain Sokhna), Hurghada, and Ismailia from August 21, 2007 through September 16, 2009. Solid line air temperature, dotted line relative humidity, and dashed line dew point temperature. Mean values for the entire period of record.

Hurghada (Table 2). Air temperature daily means at the study site were similar to daily means observed at Hurghada (south of the study by approximately 400km), yet lower than Ismailia.

Relative humidity daily means at the study site were significantly higher compared to values from the other two sites. Their means were 72.4 (±0.13 SE), 16.8 (±0.18 SE), and 5.5% (±0.22 SE), for Ain Sokhna, Ismailia, and Hurghada, respectively (Fig 2). Dew point daily means were very close to observed daily mean temperatures at the study site, and higher than those recorded at the two other sites (Fig 2).

Dew point daily means were 17.2 (±0.24 SE), 13.5 (±0.20 SE), and 10.7°C (±0.18 SE), for Ain Sokhna, Ismailia, and Hurghada, respectively (Fig. 2). Air temperature monthly means had a well-defined annual

Table 3. Yearly descriptive statistics for meteorological data collected at the study site for year 2007-2008, 2008-2009 (only matching dates for previous year; i.e., equal number of observations), and 2007-2009. All statistical values are calculated based on 48 samples per day.

2007-2008	Mean Temp. (ºC)	Minimum Temp. (ºC)	Maximum Temp. (ºC)	Mean Humidity (%)	Minimum Humidity (%)	Maximum Humidity (%)	Mean Dew Point (oC)	Minimum Dew Point (ºC)	Maximum Dew Point (ºC)
Mean	22.19	14.47	34.05	62.23	25.47	95.16	12.70	6.82	18.44
Standard Error	0.36	0.34	0.41	0.76	0.57	0.68	0.29	0.32	0.29
Minimum	9.57	0.29	17.52	27.30	5.90	48.30	-8.75	-14.64	-0.98
Maximum	34.60	27.12	50.66	96.03	54.00	100.00	23.66	17.39	36.13
Count	305	305	305	305	305	305	305	305	305
2008-2009									
Mean	25.61	17.15	38.84	79.16	38.25	102.98	20.22	14.33	27.36
Standard Error	0.31	0.30	0.35	0.58	0.69	0.18	0.28	0.29	0.29
Minimum	11.10	3.31	20.57	34.55	10.10	70.40	5.32	-1.64	11.03
Maximum	36.44	26.34	58.55	100.00	78.70	100.00	29.85	25.54	38.77
Count	454	454	454	454	454	454	454	454	454

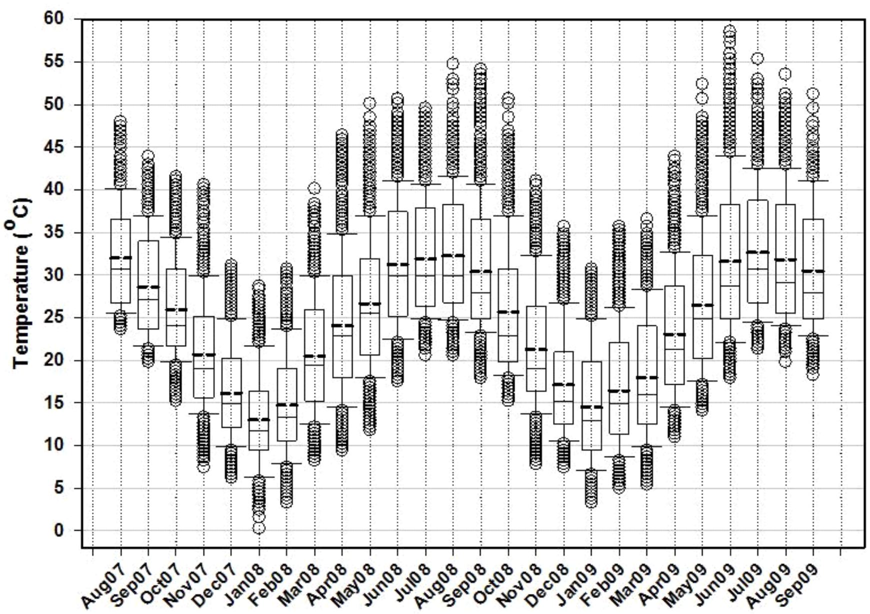


Fig. 3. Monthly Box and whisker plots for temperature for Ain Sokhna from August 21, 2007 through September 16, 2009: top and bottom of box = 75th, 25th percentiles, respectively, black solid midline in box = median; dashed midline in box = mean values; ends of whiskers denote 5th and 95th, respectively.

cycle (Fig. 3). Air temperature monthly means increased during the summer (June through September), reaching as high as 32.2ºC in August every year. Air temperature minimum monthly means decreased during winter months (December through February) every year reaching as low as 13.0ºC. Air temperature monthly and daily mean ranges fluctuated widely and ranged between 24 and 55ºC and 30-41ºC over the entire period of record, yet followed the same annual cycle (Fig. 3). Monthly means ranged between 30 to 32 and 35 to 41ºC for winter and summer season, respectively.

Air temperature monthly means for the nearby stations are based on reported daily means. Air temperature monthly means from all three stations followed the same trends, with air temperature peaking during summer months, reaching their lowest values during winter months. Monthly means from the study site were higher and significantly different from Hurghada's measurements. Observed daily maximums from the study site were also higher than Hurghada's during hot summer months, yet very similar to Ismailia. Dew point temperature followed the same annual cycle as air temperature, decreasing as air temperature

Table 4. Results of spectral analysis for air temperature (07-08, 08-09, and 07-09) measured at the study site, based on half-hourly sampling intervals. Regardless of the selected sampling intervals (i.e., half-hour vs. hourly), filtering the raw data (30-hours cut off frequency), vs. no filter, dominant cycles are yearly, daily, and half-daily.

Frequency	Period = (1/Frequency); days (2007_2008)	Amplitude = (Variance)$^{0.5}$ (2007_2008)	Period = (1/Frequency); in days (2008_2009)	Amplitude = (Variance)$^{0.5}$ (2008_2009)	Period = (1/Frequency); days	Amplitude = (Variance)$^{0.5}$ 2007-2009
Mean	0.00	19.70	0.00	23.64	0.00	23.37
Yearly	341.3	1.48	341.33	6.30	341.33	6.05
Daily	1.00	3.93	1.00	4.62	1.00	4.89
Daily	1.00	2.18	1.00	2.23	1.00	1.76
Daily	1.00	1.42	1.00	1.39	1.00	1.31
Daily	0.99	0.73	1.00	1.23	1.00	0.88
Half-day	0.50	1.59	0.50	1.92	0.50	1.43
Half-day	0.50	0.98	0.50	1.19	0.50	1.35

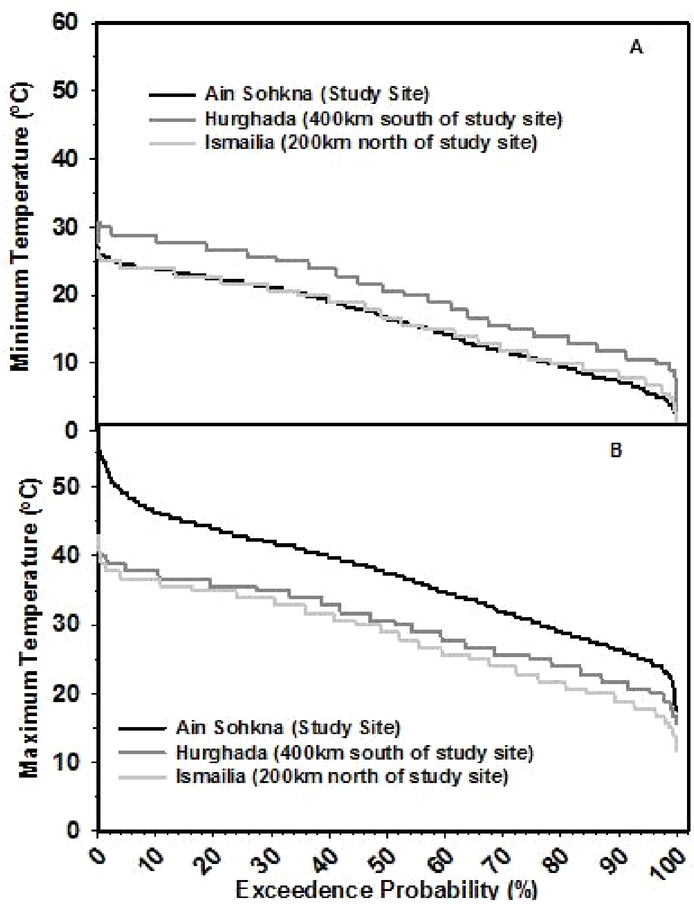


Fig. 4. Exceedence probability curves for observed daily minimum (Panel A) and maximum (Panel B) air temperatures at Ain Sokhna (solid black), Hurghada (dark grey) and Ismailia (light grey). Minimum daily temperature almost the same at study site and Ismailia located 200km north of study site and lower than Hurghada south of the study site by 400km by approximately 5°C. Maximum air temperature at study site exceeds Hurghada's observed maximum temperature by an average of 7°C.

decreased, and increasing as air temperature increased (Fig. 2). Dew point monthly means at the study site were significantly different for the entire period of record with the exception of August of 2007 (due to short record at the study site) and July 2007 (Fig. 2).

Relative humidity monthly means were also significantly different for most of the study period, starting January of 2008, peaked during winter months, decreased during summer months, and remained below 100% throughout the two year period (Fig. 2). Relative

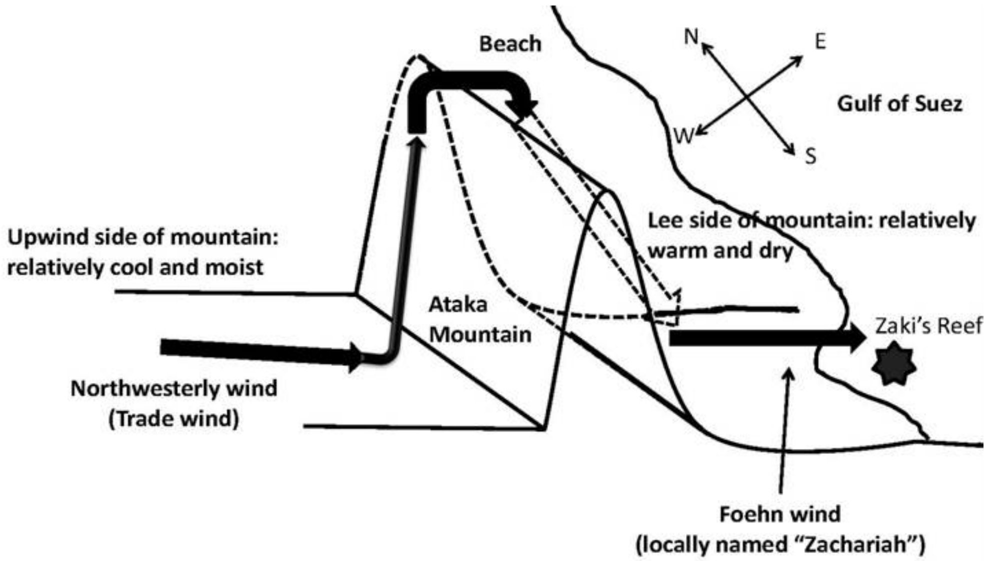


Fig. 5. Schematic illustrating the hypothesized Katabatic/Foehn winds at the study site. This wind system is derived based on co-existence of a persistent year-round trade wind (north westerly wind) and Gebel Ataka, < 500m away from Zaki's Reef at Ain Sokhna.

humidity annual cycle was opposite to air temperature cycle; increased when temperature decreased and decreased when temperature increased. However, observed relative humidity values remained within the comfort zone for humans (30-60% relative humidity range) for more than 50% and 75% of the time during the first and second study years, respectively (data not shown).

Yearly air temperature means were 22.1 (±0.07SE) and 25.6°C (±0.08SE) during 2007-2008 and 2008-2009, with an overall mean of 24.2°C (±0.05SE) during 2007-2009 (Table 3). Observed differences between the two means is due to record length, where number of observations for the first and second years was 14,583 and 21,762, respectively. However, means calculated based on the same number of observations (N = 14583) from each year were almost identical at 22.1 (±0.07SE) and 22.4 (±0.07SE).

We used spectral analysis as the primary technique for assessing the cyclic nature of all univariate time series in the frequency domain. At zero frequency (i.e., temperature spectrum $^oC^2$), the value is 504 corresponding to mean square of the series (Table 4; amplitude = 22.5°C). At the next frequency, 0.292969E-02, the value is 18.9, which approximately represents annual variations (1.5 and 6.3°C for 1st and 2nd year, respectively), since 16,384 data points at 30 minutes cover 8,192 hours (approximately 11.5 months). Remaining frequencies were dominated by daily cycles with amplitudes ranging between 0.7 and 4.6°C, followed by half-daily cycles with an amplitude of 1.0°C (Table 4). The strongest signals were yearly, daily and half-daily frequencies based on the resultant amplitudes. Air temperature from the combined two-year data set revealed the same half day, daily and yearly return periods, all of which reveal that daily and half daily cycles are dominating the local climate with an amplitude of approximately 5°C**.** Regardless of the data set used (1st, 2nd, or the two-year combined), all spectral results are nearly identical showing the variance at low frequency of yearly, half-daily and daily. Further, all results are unaffected by sampling intervals (half-hourly, hourly, and de-seasonalized datasets; Table 4).

Frequency histograms revealed a bimodal signal, with one peak around 14-15°C and a second peak around 32-33°C. This bimodal signal was present in first, second, and the two-year combined data sets. Those two peaks represent the half-day cycle from spectral analysis representing night (14-15°C) and daytime (32-33°C) temperatures.

The main reasons for the prolific development of reef systems along the Red Sea proper are because of its great depths (> 1,800 m) and efficient water circulation pattern (Mustafa, 2000). Very high surface temperatures coupled with high salinities make the Red Sea one of the warmest and saltiest bodies of seawater in the world. The average surface water temperature of the Red Sea during the summer is about 26°C in the north and 30°C in the south. Rainfall along the Red Sea is extremely low, averaging 0.06 m per year, mostly in the form of short spell showers. There is virtually no surface water runoff because no river enters the Red Sea (Shahin 1989; Morcos, 1970). The scarcity of rainfall and lack of a major source of fresh water result in evaporation rates as high as 205 cm/yr, and high salinity with minimal seasonal variation (Red Sea, 2011).

It should be noted that of the approximately 35 coral taxa known to survive in the Gulf of Suez, only six (*Acropora humilis*, *A. microclados*, *A. hemprichii*, *Litophyton arboretum*, *Stylophora pistillata*, *Porites columna*, and *P. plantulata* (approximately 80% hard corals and 20% soft corals), compose 94% of the reef's coral cover. Coral dominance shifted over a four-year period (2004-2007), mainly due to an oil spill in 2005, global bleaching event (2005), and high (>30°C) and low (<16°C) seawater temperature (Moustafa *et al*., 2008). Yet, the six corals dominance remained unchanged. These corals regularly experience 4-6.5°C daily changes in seawater temperature and seasonal variations that exceed 29°C (Moustafa *et al*., 2008).

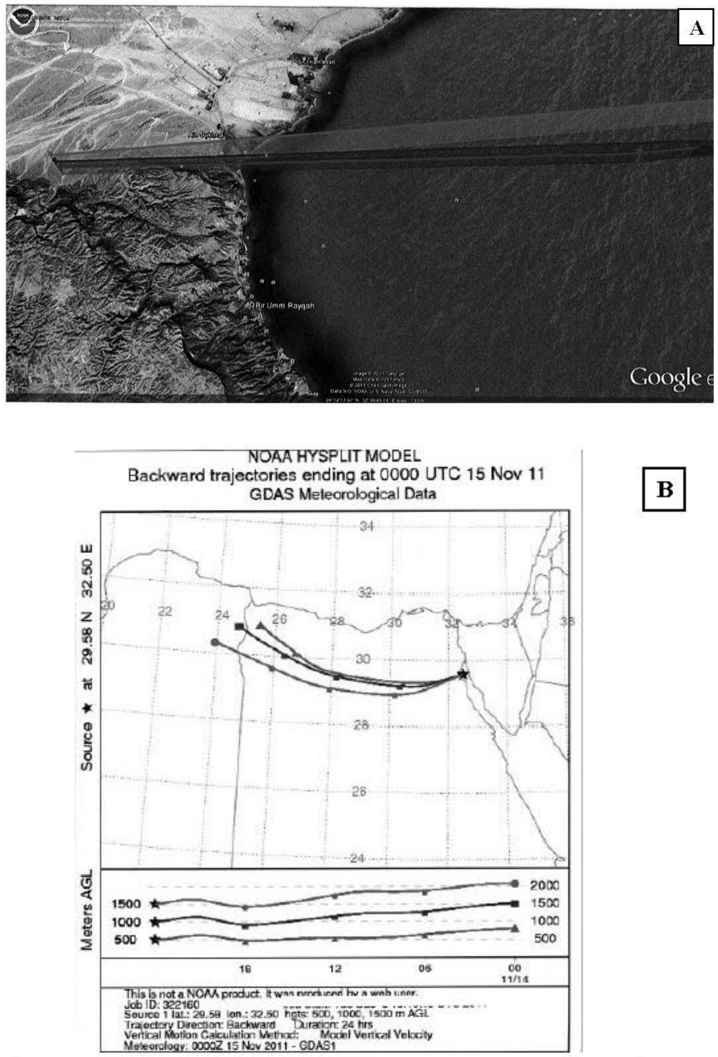
There are no long-term studies in this region prior to the research reported here (Moustafa *et al*., 2008a). This multi-year study set out to study the health of Zaki's Reef and its dominant coral species. The fact that only six of the identified Gulf of Suez 35-40 coral species remained dominant for a five-year study (Moustafa *et al*., 2008a) made us wonder what it was about these six species that allowed them to survive in such a harsh environment. Are these six species heat tolerant or is there a linkage between fringing coral reefs located in the Gulf of Suez and the local climate? Insight into local climate may provide a better understanding of the direct influence weather has, if any, on fringing coral reef health.

What was found regarding air temperature at the study site and the two other locations was puzzling at first. The fact that daily mean air temperature at the study site was less than the mean observed at Ismailia was expected since the climatic trend in Egypt is that air temperature increases going farther south. However, it was not expected that air temperature daily means at the study site and Hurghada would be very similar (Table 2), particularly if one considers how far Hurghada is from the study site (>400 km south). Air temperature daily maximums at the study site exceeded both Hurghada's and Ismailia's by almost 7 and 9°C, respectively (Fig. 4). While air temperature minimum daily means are almost equal to Ismailia's, the minimums were less than Hurghada's by 4 degrees. These observed trends were not expected considering the three stations' geographic locations, suggesting that other natural phenomena may be influencing air temperature at the study site.

Ain Sokhna, Arabic for "hot spring," was named after the nearby sulfur springs. These springs originate at Gebel Ataka (<500 m West of Zaki's Reef), the northern most mountains in the eastern desert. When the year-round trade wind approaches the study area it finds its first obstacle, Gebel Ataka; the mountain range that starts at the study site and continues almost all the way south to Hurghada with an average elevation of approximately 300m. Gebel Ataka was the first factor that we believed may be influencing the local climate. We hypothesized that these high plateauing mountains force the trade winds upward, and as a result it loses its moisture content and decreases in temperature. Air parcels reaching the highest point on top of Gebel Ataka start descending due to gravity (dense air) on the leeside (down-wind) and towards the study site. This wind pattern at the study site mimics a Katabatic wind system (Fig. 5).

Katabatic wind is the technical name for a wind that carries high density air from a higher elevation down a slope under the force of gravity. Katabatic winds originate from radiational cooling of air atop a plateau, a mountain, or even a hill. Since the density of air is inversely proportional to temperature, the air will flow downwards, warming adiabatically as it descends. The temperature of the wind depends on the temperature in the source region and height of descent. At Ain Sokhna, it is possible that due to the presence of this local mountain, an adiabatic wind pattern exists locally and causes the air temperature to rise at the study site, as becomes evident when one compares the study site air temperature observations with those from Hurghada.

The entire near-surface wind field and air temperature at sea level at the study site may be heavily influenced by the Katabatic winds. What differentiates the study site from the other two stations is the fact that the mountain range is less than 500m from the study site and no major obstacles exist between Ataka Mountain and Zaki's Reef (Fig. 1b). The close proximity of the study site to the mountain means that elevated temperatures air parcels descending from Gebel Ataka are likely to cause a marked increase of air temperature at the study site. In contrast, one of the main reasons that Hurghada's temperatures are less than those observed at the study site is because Ataka mountain range is located very far (>30 km) from the Red Sea coast. For example mean observations at the study site are very close to temperature means at Hurghada (24.2 vs. 25.2°C; Table 2), yet daily maximum observations at the study site exceed Hurghada and Ismailia by almost 7 and 9 degrees, respectively (Fig. 4). Furthermore, during winter time, the existence of the warm dry Katabatic (Foehn) wind increases air temperature at the study site and consequently causes the minimum daily means at the study site and Ismailia to be almost equal (Fig. 4). Those warm air parcels are



Vertical Motion: Model vertical velocity	
Start time (UTC): 11/15/11; Nov.2011.wk3)	
Total run time (hours)	24 hours
Start a new trajectory every (hours)	0 hours
Start 1 latitude	29.58°
Start 1 longitude	32.50°
Start 2 latitude	29.58°
Start 2 longitude	32.50°
Start 3 latitude	29.58°
Start 3 longitude	32.50°
Level 1 height (meters Above Ground Level)	500.00
Level 2 height	1000.00
Level 3 height	1500.00

Fig. 6. NOAA's HySplit Model results. Panel A depicts forward trajectory which represents air movement over a one week time span, originating at a point approximately 10km away from Zaki's Reef (behind the western mountain), and shows that the winds at the reef's vicinity originated from behind the western mountain, all of which confirm the ascending and descending wind pattern required for a Foehn wind. Panel B depicts backward trajectory of air movement where Zaki's Reef location is the reference point. This image highlights the distance traveled from the wind's point of origin to the chosen endpoint (Zaki's Reef) and highlights the presence of a dominant westerly wind in the region. Both forward and backward trajectories depicted further support the existence of a Foehn wind near the reef as a result of the consistent westerly wind and the surmounting of the preceding mountain range

likely to raise water temperature, particularly during winter season, and help resident corals to survive at this location.

Warm dry Katabatic winds occur on the leeside of a mountain range. These Katabatic winds that descend on the leeside of a mountain (e.g., Gebel Ataka) and warmed adiabatically, are called Foehn winds (also Chinook or Bergwind; Fig. 5). As a consequence of the different adiabatic lapse rates of moist and dry air, the air on the leeward slopes becomes warmer than equivalent elevations on the windward slopes, and can raise temperatures by as much as 30°C in just a matter of hours (Hess and McKnight, 2000). For example, one of the main reasons that central Europe enjoys a warmer climate is due to the Foehn, as moisture-filled winds off the Mediterranean Sea blow over the Alps. In our case, the end result is that conditions on the upwind side of Gebel Ataka will be relatively moist and cool while conditions on the leeward side of the mountain, corresponding to the study site, will be relatively warm and dry. As the air flow descends on the leeward side of Gebel Ataka, it becomes compressed by atmospheric pressure, which raises the air-flow temperature. In addition to compression, the air flow also gains more heat directly from the sun (particularly during summer months), when the skies are typically clear.

The increase in air temperature at sea level may have some positive consequences for corals at this location. Warmer than normal air temperature due to this local wind pattern is more likely to increase seawater temperature at Zaki's Reef. Comparisons between air and seawater temperature collected at Zaki's Reef reveal that their means are almost identical (Moustafa *et al***.,** 2008b; 2013; 2014). We speculate that the two yearly means of air and seawater temperatures are almost identical as a result of the local wind pattern. This warm mountain air elevates seawater temperature, all of which may help explain the existence and survival of Zaki's Reef at such a high latitude.

HYSPLIT trajectory model was used to serve as an independent validation for the existence of the newly identified Foehn wind. Model runs ranged from daily to weekly traces and quantified average flow rate of the air masses and temperature rates of change as they encountered resistances caused by natural obstructions (e.g., mountain ranges). After initializing model runs, model parameters were adjusted (e.g., number of starting points, temporal scale of trajectories, and frequency of extraction) in order to observe resulting model outputs. These extractions were projected and utilized in Google Earth to serve as a visual aid of model run outputs. The resulting HYSPLIT model data served as independent validation to support the proposed hypothesis regarding the existence of Foehn winds in the Red Sea region, near the study site (Fig. 6).

Two HYSPLIT model run results are displayed in Fig. 6. The first trajectory (Fig. 6a) is a forward trajectory of air movement over a one week period, originating at a point approximately 10 km West of Gabel Ataka Mountain (29° 22' 30.47" N and 32° 15' 10.25" E). This model run predicts that the winds in Zaki's Reef vicinity originate from a point behind the westward mountain range, likely confirming the rising/falling wind pattern **-** a signature of a Foehn wind. The backward trajectory in Fig. 6b illustrates the distance traveled from the wind's point of origin to the predefined end point (Zaki's Reef), and depicts the presence of a dominant westerly wind in the region. These two trajectories depicted in Fig. 6 further support the existence of a Foehn wind near Zaki's reef, as a result of the consistent westerly wind and the surmounting of the Ataka mountain range.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 (Szmant & Gassman, 1990; Goreau & Hayes, 2005). Seawater temperature affects coral breeding, spawning, larval settlement and growth (Szmant & Gassman 1990; Mendes & Woody, 2002), and coral recruitment (Jokiel & Coles, 1990).

It is evident that Zaki's coral species have a relatively higher thermal tolerance compared to similar species at other locations; only the most hot and cold-tolerant few have been identified at this site (Moustafa *et al*., 2008a; 2013). The world-wide 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*., (2011) 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 reported by Moustafa *et al*., (2014) for both summer and winter. 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. 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 (Ingram & Bartels, 1996) and animals (Huey & Kingsolver, 1993; Somero, 2002; Hochachka & Somero, 2002) have shown that some population or species are far more resilient compared to others with marked influences on growth, survival, and disease resistance (Nevo, 2001; Hochachka & Somero, 2002; Parsons, 2005). Furthermore, Barshis *et al*., (2012) 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 (1991) reported that *Acropora pharaonis* and *Porites compressa* in the Arabian Gulf suffered severe mortality when the water temperature fell below 11.5^{o}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^{o}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 Arabian 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 (Moustafa *et al.*, 2014).

CONCLUSIONS

The current study was driven mainly by scientific curiosity regarding the discovery of a fringing coral reef ecosystem that thrived at one of the highest latitudes of any sub-tropical reef system in the world. We quickly learned that there are no significant environmental databases for this region except for the very different Gulf of Aqaba. We therefore integrated other environmental data to help us find out why this ecosystem is flourishing at such a high latitude.

Our data collection and analysis lead to several note-worthy discoveries, most importantly the existence of a Katabatic/Foehn wind system caused by the co-existence of the high mountain range and the dominant trade winds at the study site. This wind system causes elevated temperatures during the hot summer and winter months at the study site. This location is the only one where the mountains are very close to the coast along the entire Egyptian Red Sea. As air temperature increases, water temperature at the study site may also increase. Consequently, temperature rise, particularly during winter seasons, enhances Zaki's Reef's chances of survival at such high latitude. Furthermore, this warm local wind may have also helped the corals at this location evolve/ acclimate to the extreme conditions prevalent during summer months. The entire Gulf of Suez fringing coral reef ecosystem may be reliant for survival, particularly during winter months, on this newly discovered local wind pattern.

ACKNOWLEDGEMENTS

Special thanks to all family members, particularly my son Zachariah Moustafa for providing field assistance and being the cause for expanding our research. In 2007, Zachariah's expression, caught in a photograph, from the incredible summer heat at the study site (registered at 135 Fahrenheit), caused us to re-evaluate our plans and start collecting meteorological data. Catherine Miller from Dreyfoos School of the Arts provided lab equipment and helped find funding. It is with great appreciations to PADI and North Carolina research consortium for their financial support of this research. Without the support of Onset and YSI Corporation, graciously donating and loaning field equipment, the culmination of this research would not been possible, particularly the dedicated staff, especially Kory Wagner, from Onset and their technical support throughout this research project.

REFERENCES

Stein, A. F., Isakov, V. Godowitch, J. and Draxler, R. R. (2007). A hybrid modeling approach to resolve pollutant concentrations in an urban area. Atmospheric Environment, **41 (40),** 9410-9428.

Barshis, D.J., Lander, J.T., Oliver, T.A., Seneca, F.O., Taylor-knowles, N., and Palumbi, S.R. (2012). Genomic basis for coral resilience to climate change. Proceedings of the National Academy of Sciences of the United States of America. **110 (4),** 1387-1392.

Coles, S.L., and Fadlallah, Y.H. (1991). Reef coral survival and mortality at low temperatures in the Arabian Gulf: New species-specific lower temperature limits. Coral Reefs, **9(4),** 231-237.

Draxler, R. R. and Rolph. G. D. (2013). HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website: http:// ready.arl.noaa.gov/HYSPLIT.php. NOAA Air Resources Laboratory, Silver Spring, MD.

Jokiel, P. L., and Coles, S. L. (1990). Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature. Coral Reefs, **8,** 155-162.

Goreau, T.J.F. and Hayes, R.L. (2005). Global coral reef bleaching and sea surface temperature trends from satellite-derived hotspot analysis. World Resource Review, **17(2),** 254-293.

Hanaur, E. 1(988). *The Egyptian Red Sea: A Diver's Guide*. (San Diego, CA: Watersport Publishing, Inc).

Hess, D. and McKnight, T.L. (2000). Foehn/Chinook Winds. In *Physical Geography: A Landscape Appreciation*. Upper Saddle River, Prentice Hall, NJ.

Hochachka, P. W. and Somero, G. N. (2002). Biochemical Adaptation: Mechanism and Process in Physiological Evolution. (New York: Oxford Univ. Press).

Huey, R. B. and Kingsolver, J.G. (1993). Evolution of resistance to high-temperatures in ectotherms. Am Nat 142 (Suppl), S21–S46.

Ingram, J. and Bartels, D. (1996). The molecular basis of dehydration tolerance in plants. Annu Rev Plant Physiol Plant Mol Biol., **47,** 377–403.

Lirman, D., Schopmeyer, S., Manzello, D., Gramer, L.J., Precht, W.F., *et al*. (2011). Severe Cold-Water Event Caused Unprecedented Mortality to Corals of the Florida Reef Tract and Reversed Previous Survivorship Patterns. PLoS ONE **6(8),** e23047.

Mendes, J. M. and Woodley, J.D. (2002). Effect of the 1995-1996 bleaching event on polyp tissue depth, growth, reproduction and skeletal band formation in Montastraea annularis. Mar Ecol Prog Ser, **235,** 93–102.

Morcos, S. A. (1970). Physical and chemical oceanography of the Red Sea. Oceanogr. Mar. Bio. Ann. Rev., **8,** 73-202.

Mustafa, F. (2000). Status of Coral Reefs in the Middle East, AIMS, http://www.aims.gov.au Accessed 6/2007.

Moustafa, Z. D., Hallock, P. Moustafa, M. S. and Moustafa, M. Z. (2008a). Survivalship of a Red Sea Fringing Coral Reef under Extreme Environmental Conditions, Proc. of the *11th International Coral Reef Symposium, Ft. Lauderdale*, Florida.

Moustafa, Z. D., Moustafa, M. S. and Moustafa, M. Z. (2008b). What is Normal? Extreme Temperature Variability on a High Latitude, Fringing Red Sea Coral Reef," ASLO/ AGU *Ocean Science Meeting, Orlando* FL.

Moustafa, M. Z., Moustafa, M. S. Moustafa, Z. D. and Moustafa, S.E. (2014). Survival of high latitude fringing corals in extreme temperatures: Red Sea Oceanography. Journal of sea research, **88,** 144-151.

Moustafa, M. Z., Moustafa, Z. D. and Moustafa, M. S. (2013). Resilience of high latitude Res Sea Corals to extreme temperature. OJE, **3(3),** 242-253. doi: 10.4236/oje/2013.33028

Nevo, E. (2001). Evolution of genome-phenome diversity under environmental stress. Proc Natl Acad Sci., **98(11),** 6233–6240.

Okamoto, K. and Derber, J.C. (2006). Assimilation of SSM/ I Radiances in the NCEP Global Data Assimilation System. Monthly Weather Review, **134,** 2612-2631. http:// ready.arl.noaa.gov/gdas1.php

Onset Computer Corporation (2014). Onset HOBO Data Loggers, Product Catalog, Data Loggers, External Sensors, and Software. http://www.onsetcomp.com/files/catalog-2014-lr.pdf.

Parsons, P.A. (2005). Environments and evolution: Interactions between stress, resource inadequacy and energetic efficiency. Biol Rev Camb Philos Soc., **80 (4),** 589–610.

Red Sea (2011). In Encyclopedia Britannica. Retrieved June 11, 2011, from Encyclopedia Britannica Online: http:// www.britannica.com/EBchecked/topic/494479/Red-Sea

Shahin M. (1989). Review and assessment of water resources in the Arab region. *Water Int*., **14,** 206–219.

Somero, G. N. (2002). Thermal physiology and vertical zonation of intertidal animals: Optima, limits, and costs of living. Integr Comp Biol., **42(4),** 780–789.

Szmant, A. M. and Gassman, N. J. (1990). The effects of prolonged ''bleaching '' on the tissue biomass and reproduction of the reef coral Montastrea annularis. Coral Reefs, **8,** 217–224.

UNESCO (2005). Regional Workshop on Impact of Ecotourism on Biosphere reserves Sharm El Sheikh, Egypt, 13-15 November, 2005, http://www.unesco.org/new/ fileadmin/MULTIMEDIA/FIELD/Cairo/images/ FinalReport_Ecotourism.pdf.

Wunderground (2010). Weather data web site: (http:// www.wunderground.com/global/EG.html).