

Supplementary Material

Article Title: Bleaching threatens positive carbonate budgets on Bahraini reefs

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1 Supplementary Method

SST Satellite Data Acquisition and Processing

To characterise the thermal history of the two reefs weekly SST data was acquired from the CoRTAD¹ version 6 database. Data was extracted and assessed for thermal history of SST during the period 1982-2017. SST values derived from the CoRTAD database were converted from Kelvin (K) to Celsius (°C). Following the conversion, data was extracted for the specific reefs through their coordinates and calculations were conducted to determine the change in SST metrics over time to examine the thermal history of the bioregions over the 35-year period. Data was analysed using the “R” software (R, 2018) and “RStudio” version 1.1383 through which raster maps and plots were produced using the ggplot function in the “tidyverse” package in R (Wickham *et al.*, 2019). A time series analysis was conducted to determine change in SST over time and was decomposed to examine the trend and variation of SST. The time series data was further analysed using a linear regression to determine the direction and magnitude of the slope. To calculate the thermal history metrics, the below equations were used.

Definitions and Calculation Methods of SST Thermal History Metrics

SST Trends: Defined as the rate of change in SST over time.

Climatology: Defined as the long-term mean of SST conditions. Positive or negative values of SST that exceed long term mean SST (climatology) of a particular area, which indicates whether SST is warmer or cooler than usual (Heron *et al.*, 2016).

Climatology = Σ weekly SST over an extended period /n (total no. of weeks)

¹ **Coral Reef Temperature Anomaly Database (CoRTAD)** is a dataset of SST and related thermal stress metrics, which was developed by NOAA specifically for coral reef ecosystem applications. The CoRTAD Version 6 database used in this study contains global ~4km resolution SST data on a weekly time scale for the period 1982 – 2017. <[ftp://ftp.nodc.noaa.gov/pub/data.nodc/cortad/README.html](http://ftp.nodc.noaa.gov/pub/data.nodc/cortad/README.html)>

Thermal Stress Anomaly (TSA): Described as a positive SST anomaly above the maximum of the monthly mean SST climatology. TSA, also referred to as “Hotspots”, is calculated through examining the difference between the weekly SST and maximum long term SST mean (climatology; Pineda et al., 2013).

$$TSA = \text{Weekly SST} - \text{Maximum weekly Climatology}$$

Degree Heating Weeks (DHW): Defined as the accumulated thermal stress on corals whereby one DHW unit equals to when SST are 1°C above the expected mean summertime maximum for a period of one week (Wellington et al., 2001; Heron et al., 2016). Therefore, a DHW is calculated as the sum of accumulated daily hotspots over 12 consecutive weeks when the hotspot value (TSA) is $\geq 1^\circ\text{C}$ (Couch et al., 2017).

$$DHW = \sum TSA \geq 1^\circ\text{C for 12 consecutive weeks}$$

Bleaching Threshold: Described as the value where SST has exceeded maximum long-term mean by 1°C. It is calculated based on DHW combining magnitude and duration of temperature exceeding the long-term mean (climatology). DHW at $\geq 4^\circ\text{C-weeks}$ is used as an indicator of thermal stress of bleaching level whilst $\geq 8^\circ\text{C-weeks}$ is referred to as the threshold for thermal stress mortality-level (Liu et al., 2006; Heron et al., 2016; Couch et al., 2017).

$$\text{Bleaching Threshold} = \text{Max. weekly Climatology} + 1^\circ\text{C}$$

2 Supplementary Tables

Supplementary Table 1. Summary statistics of the generalized linear models (GLMs) to determine the main effects of year (pre- and post-bleaching) and sites (nearshore and offshore sites) on hard coral cover, crustose coralline algae (CCA) cover, rugosity, echinoid density, parrot fish density, gross carbonate production, gross carbonate erosion, and net carbonate production.

GLMs	Coefficients	Estimate	SE	t-value	p-value	AIC	Residual (df)	Null (df)
Hard Coral Cover ~ Year + Site	Intercept	10.38	3.76	2.76	0.01	186.34	2370.43 (21)	2923.40 (23)
	Year	-5.80	4.34	-1.34	0.20			
	Site	7.65	4.34	1.76	0.09			
Crustose Coralline Algae Cover ~ Year + Site	Intercept	37.09	6.68	5.55	<0.01	213.97	7497.63 (21)	12448.46 (23)
	Year	-18.67	7.71	-2.42	0.02			
	Site	-21.83	7.71	-2.83	0.01			
Rugosity ~ Year + Site	Intercept	1.66	0.10	16.35	<0.01	13.122	1.74 (21)	2.11 (23)
	Year	-0.17	0.12	-1.43	0.17			
	Site	0.18	0.12	1.57	0.13			
Echinoid Density ~ Year + Site	Intercept	1.02	0.16	6.22	<0.01	36.04	4.52 (21)	9.52 (23)
	Year	-0.42	0.19	-2.24	0.04			
	Site	-0.81	0.19	-4.27	<0.01			
Parrot Fish Density ~ Year + Site	Intercept	0.03	0.02	1.84	0.08	-68.31	0.06 (21)	0.12 (23)
	Year	-0.07	0.02	-3.19	<0.01			
	Site	0.07	0.02	3.39	<0.01			
Gross Carbonate Production ~ Year + Site	Intercept	3.13	1.17	2.67	0.01	130.49	231.32 (21)	267.91 (23)
	Year	-1.67	1.35	-1.23	0.23			
	Site	1.82	1.35	1.34	0.19			
Gross Carbonate Erosion ~ Year + Site	Intercept	0.48	0.05	9.54	<0.01	-20.47	0.43 (21)	1.13 (23)
	Year	-0.27	0.06	-4.61	<0.01			
	Site	-0.21	0.06	-3.58	<0.01			
	Intercept	2.65	1.15	2.30	0.03	129.63	223.21	259.65

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Net Carbonate Production ~ Year + Site	Year	-1.40	1.33	-1.05	0.30		(21)	(23)
	Site	2.03	1.33	1.52	0.14			

Supplementary Table 2. Summary statistics of the generalized linear models (GLMs) to determine the main and interaction effects of years (pre- and post-bleaching event) and sites (nearshore and offshore) on hard coral cover, crustose coralline algae cover, rugosity, echinoid density, parrot fish density, gross carbonate production, gross carbonate erosion, and net carbonate production.

GLMs	Coefficients	Estimate	SE	t-value	p-value	AIC	Residual (df)	Null (df)
Hard Coral Cover ~ Year * Site	Intercept	13.60	4.20	3.24	<0.01	185.67	2120.81 (20)	2923.40 (23)
	Year	-12.25	5.95	-2.06	0.05			
	Site	1.20	5.95	0.20	0.84			
	Year:Site	12.90	8.41	1.53	0.14			
Crustose Coralline Algae Cover ~ Year * Site	Intercept	42.23	7.56	5.58	<0.01	213.85	6863.14 (20)	12448.46 (23)
	Year	-28.95	10.70	-2.71	0.01			
	Site	-32.12	10.70	-3.00	0.01			
	Year:Site	20.57	15.13	1.36	0.19			
Rugosity ~ Year * Site	Intercept	1.73	0.12	14.84	<0.01	13.58	1.63 (20)	2.11 (23)
	Year	-0.30	0.16	-1.83	0.08			
	Site	0.05	0.16	0.30	0.76			
	Year:Site	0.27	0.23	1.15	0.26			
Echinoid Density ~ Year * Site	Intercept	1.23	0.17	7.29	<0.01	31.46	3.44 (20)	9.52 (23)
	Year	-0.85	0.24	-3.55	<0.01			
	Site	-1.23	0.24	-5.15	<0.01			
	Year:Site	0.85	0.34	2.51	0.02			
Parrot Fish Density ~ Year * Site	Intercept	3.40×10^{-17}	0.02	2.15×10^{-15}	1.00	-82.24	0.03 (20)	0.12 (23)
	Year	-6.80×10^{-17}	0.02	-3.04×10^{-15}	1.00			
	Site	0.14	0.02	6.32	<0.01			
	Year:Site	-0.14	0.03	-4.34	<0.01			
Gross Carbonate Production ~ Year * Site	Intercept	4.07	1.32	3.07	0.01	130.18	210.13 (20)	267.91 (23)
	Year	-3.55	1.87	-1.90	0.07			
	Site	-0.06	1.87	-0.03	0.97			
	Year:Site	3.76	2.65	1.42	0.17			

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Gross Carbonate Erosion ~ Year * Site	Intercept	0.49	0.06	8.21	<0.01	-18.55	0.43 (20)	1.13 (23)
	Year	-0.29	0.08	-3.38	<0.01			
	Site	-0.22	0.08	-2.66	0.01			
	Year:Site	0.03	0.12	0.26	0.79			
Net Carbonate Production ~ Year * Site	Intercept	3.58	1.30	2.75	0.01	129.28	202.37 (20)	259.65 (23)
	Year	-3.27	1.84	-1.78	0.09			
	Site	0.16	1.84	0.09	0.93			
	Year:Site	3.73	2.60	1.44	0.17			

Supplementary Table 3. Summary statistics of likelihood ratio test to compare generalized linear models (GLMs) without the interaction effect (dependent variable ~ Year + Site) and with interaction effect (dependent variable ~ Year * Site).

Generalized Linear Models (GLMs)	Residual df	Residual Deviance	df	Deviance	p-value
Hard Coral Cover ~ Year + Site	21	2370.40	1	249.62	0.13
Hard Coral Cover ~ Year * Site	20	2120.80			
Crustose Coralline Algae Cover ~ Year + Site	21	7497.60	1	634.48	0.17
Crustose Coralline Algae Cover ~ Year * Site	20	6863.10			
Rugosity ~ Year + Site	21	1.73	1	0.11	0.25
Rugosity ~ Year * Site	20	1.63			
Echinoid Density ~ Year + Site	21	4.52	1	1.08	0.01
Echinoid Density ~ Year * Site	20	3.44			
Parrot Fish Density ~ Year + Site	21	0.06	1	0.028	<0.01
Parrot Fish Density ~ Year * Site	20	0.03			
Gross Carbonate Production ~ Year + Site	21	231.32	1	21.20	0.16
Gross Carbonate Production ~ Year * Site	20	210.13			
Gross Carbonate Erosion ~ Year + Site	21	0.43	1	1.50×10^{-3}	0.79
Gross Carbonate Erosion ~ Year * Site	20	0.43			
Net Carbonate Production ~ Year + Site	21	223.21	1	20.84	0.15
Net Carbonate Production ~ Year * Site	20	202.37			

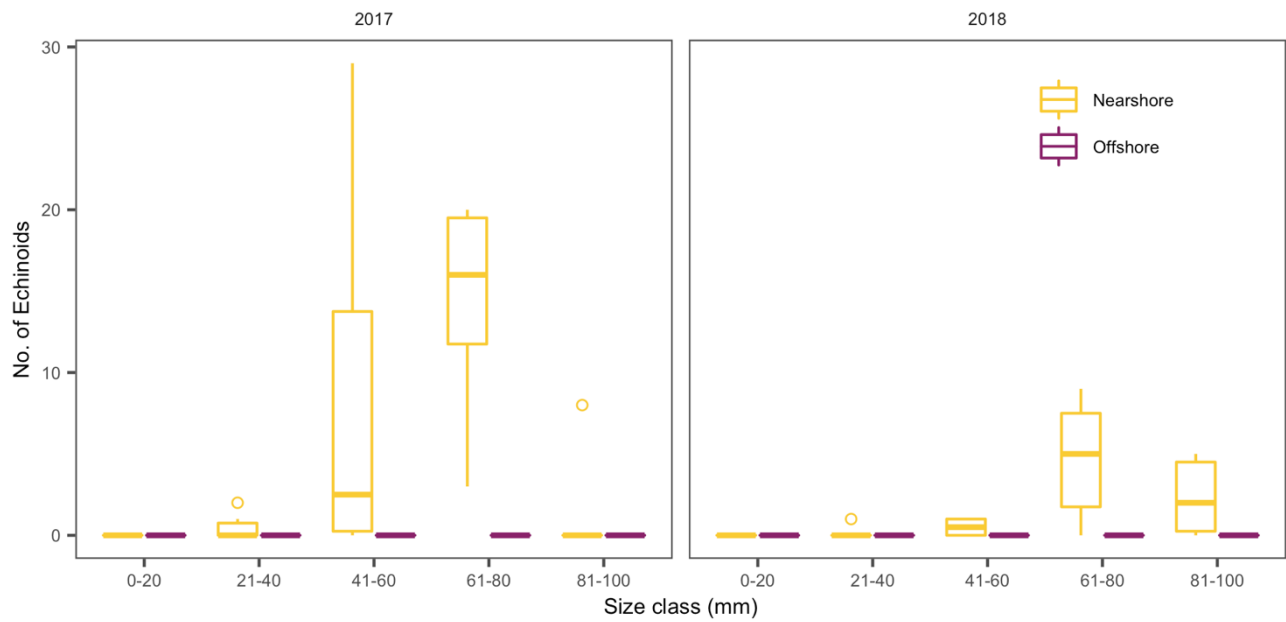
Supplementary Table 4. Summary statistics of post-hoc multiple comparison tests to determine differences in hard coral cover, crustose coralline algae (CCA) cover, rugosity, echinoid density, parrot fish density, gross carbon production, gross carbon erosion, and net carbon production between pre- and post-bleaching period at each site.

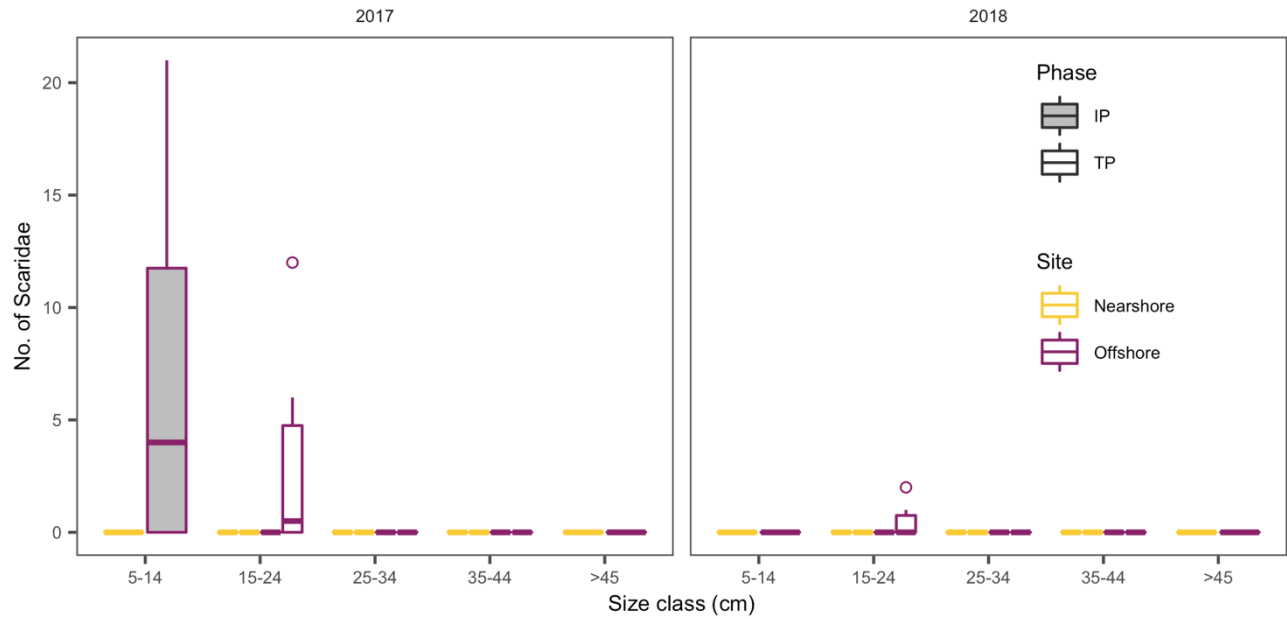
Generalised Linear Models (GLMs)	Post-hoc Multiple Comparison Test Statistics				
	Linear Hypotheses :	Estimate	SE	z value	p value
Hard Coral Cover ~ Year * Site	Nearshore : Post - Pre = 0	-12.3	6.0	-2.1	0.08
	Offshore : Post - Pre = 0	0.7	6.0	0.1	0.99
Crustose Coralline Algae Cover ~ Year * Site	Nearshore : Post - Pre = 0	-29.0	10.7	-2.7	0.01
	Offshore : Post - Pre = 0	-8.4	10.7	-0.8	0.68
Rugosity ~ Year * Site	Nearshore : Post - Pre = 0	0.033	0.16	0.20	0.97
	Offshore : Post - Pre = 0	0.30	0.16	1.83	0.13
Echinoid Density ~ Year * Site	Nearshore : Post - Pre = 0	0.9	0.2	3.6	<0.01
	Offshore : Post - Pre = 0	-2.2×10^{-16}	0.2	0	1.00
Parrot Fish Density ~ Year * Site	Nearshore : Post - Pre = 0	6.8×10^{-17}	0.02	0	1.00
	Offshore : Post - Pre = 0	0.1	0.02	6.1	<0.01
Gross Carbonate Production ~ Year * Site	Nearshore : Post - Pre = 0	-3.5	1.9	-1.9	0.11
	Offshore : Post - Pre = 0	0.2	1.9	0.1	0.99
Gross Carbonate Erosion ~ Year * Site	Nearshore : Post - Pre = 0	-0.3	0.08	-3.4	<0.01
	Offshore : Post - Pre = 0	-0.3	0.08	-3.0	<0.01
Net Carbonate Production ~ Year * Site	Nearshore : Post - Pre = 0	-3.3	1.8	-1.8	0.15
	Offshore : Post - Pre = 0	0.5	1.8	0.3	0.96

Supplementary Table 5. Erosion rates ($\text{kg CaCO}_3 \text{ m}^{-2} \text{ y}^{-1}$ expressed as G) by major bio-eroders i.e. echinoids and parrotfish at study sites (2017-2018)

	Nearshore		Offshore	
	2017	2018	2017	2018
Echinoids	0.5 ± 0.08	0.2 ± 0.06	0	0
Parrotfish	0	0	0.3 ± 0.06	0.009 ± 0.009

3 Supplementary Figures

**Supplementary Figure 1.** Total abundance of echinoids recorded based on size class pre- and post- bleaching at both study sites (n=6)



Supplementary Figure 2. Total abundance of Scaridae recorded in 2017 and 2018 based on size class (IP = initial phase / juveniles; TP = terminal phase / adults) pre- and post- bleaching at both study sites (n=6)