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Coral Bleaching Mortality and Resilience at Stetson Bank, a High Latitude Coral Community in the Gulf of Mexico

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Abstract. Stetson Bank, located near 28.2° N, 94.3° W in the northwestern Gulf of Mexico, approximately 110 kilometers offshore of Galveston, Texas, is an uplifted claystone feature associated with an underlying salt dome. Due to the influence of the warm, clear waters of the Gulf Stream Loop Current, Stetson Bank supports a well-developed benthic community comprised of tropical marine sponges, coral and other invertebrates. Living coral cover, predominately *Millepora alcicornis*, can comprise up to 30% of the reef surface. A long-term monitoring program was initiated in 1993 consisting of 66 permanently marked stations on the reef surface that are photographed annually and analyzed for changes in community structure and benthic cover. In the summer of 2005, significant mortality of coral was documented in association with a major bleaching event in the Gulf of Mexico. In addition, the area was subject to significant coastal runoff resulting from two major hurricanes (Katrina and Rita). The synergistic effect of both coastal runoff and elevated temperature may have contributed to mortality in 2005. Here we present an analysis of monitoring data from 2004-2008 and evidence of possible resiliency of the coral-sponge community of Stetson Bank.

Key Words: coral bleaching, resiliency, Gulf of Mexico, Millepora, Stetson Bank

Introduction

Stetson Bank is one of a number of topographic features associated with underlying salt domes located in the northwestern Gulf of Mexico (Fig. 1; Rezak et al. 1985). Rising from surrounding water depths of over 55 meters, Stetson Bank crests to within 15 to 25 meters of the sea surface. The main feature of Stetson Bank is made up of uplifted claystone and siltstone pinnacle formations that harbor a well developed coral-sponge community. Stetson was first described in the 1950's (Carsey 1950; Stetson 1953; Neumann 1958) due to increasing interest of the oil and gas industry in offshore oil exploration along the continental shelf.

The clay/siltstone pinnacle structures of Stetson Bank support a unique coral and sponge community. Surrounded by a clay-mud bottom, the pinnacles rise to within 15 meters of the water's surface, providing structure above the turbid depths into the relatively clear, warm surface waters. The predominant benthic species on Stetson Bank is the hydrozoan *Millepora alcicornis* (fire coral) accounting for up to 30% of the reef surface in the pinnacle area. In addition, eleven other species of hermatypic corals have been documented, including *Diploria strigosa*, *Stephanocoenia intersepta*, *Madracis mirabilis*, *Madracis decactis*, and *Agaricia fragilis*. Sponges, primarily *Chondrilla nucula*, *Ircinia strobilina* and *Agelas clathrodes*, comprise up to another 30% of the benthic cover. A running total of 180 species of fish, including several species of sharks and rays (Pattengill 1998), 644 species of invertebrates, including mollusks and echinoderms, and 2 species of turtle (*Caretta caretta* and *Eretmochelys imbricata*) also inhabit this coral-sponge community (see http://www.flowergarden.noaa.gov/ document_library /science/recdivingspecieslist.pdf).

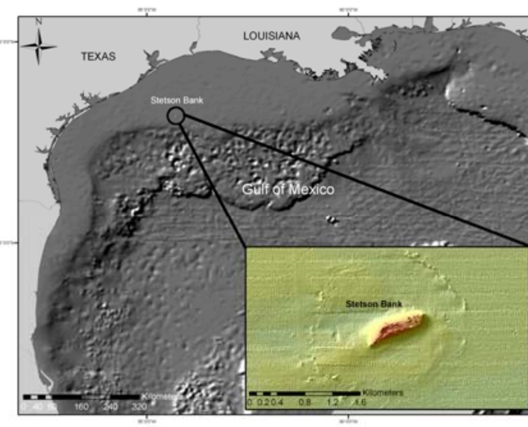

Figure 1: Location of Stetson Bank in the northwestern Gulf of Mexico. Inset shows bathymetry of Stetson Bank and surrounding deeper ring of siltstone pinnacles. Bathymetry provided by USGS/Gardner.

In 1996, Stetson Bank was incorporated into the Flower Garden Banks National Marine Sanctuary under revisions to the Marine Protection, Research and Sanctuaries Act of 1972 (now the Marine Sanctuaries Act). Since 1993, a long-term monitoring program has been in place, utilizing permanent photographic stations, fish counts and random transects, as well as temperature and salinity probes. Initially, 66 long-term photographic stations were established, of which 44 station locations are currently known. Long-term monitoring cruises occur every summer, in June or July, weather permitting.

In 2005, a Caribbean wide bleaching event (for more information, see http://coralreefwatch.noaa.gov /caribbean2005/) severely impacted Stetson Bank, coupled with two hurricanes (Katrina and Rita) which caused mechanical damage as well as an increase in coastal runoff. A dark plume from the Mississippi River and coastal Louisiana encircled the banks for a few weeks after Hurricane Rita passed (Fig. 2). Here we present an investigation into the amount of change and degree of resiliency of Stetson Bank after this widespread bleaching event and repeated impacts from two hurricanes, through an analysis of five years of monitoring data, from June 2004 to June 2008.

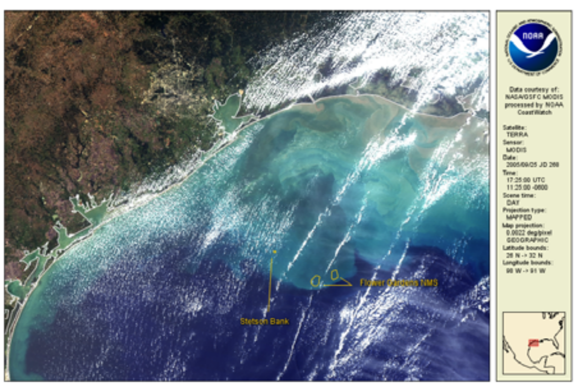

Figure 2: Satellite imagery showing the plume of coastal runoff elicited by Hurricanes Katrina and Rita. The plume moved over 100 miles south into the Gulf of Mexico, directly over Stetson and the Flower Garden Banks. This image is dated 25 September 2005, one day after Hurricane Rita's landfall. Data is courtesy of NASA/FSFC MODIS, processed by NOAA Coast Watch.

Material and Methods

Long-term monitoring cruises were conducted during the weeks of June 14 – 16, 2004, June 13 – 15, 2005, June 19 – 21, 2006, July 22 – 25, 2007, and June 16 – 18, 2008. From 2004 through 2007, a total of 51 different stations were photographed with a Nikonos V camera, with a 15mm lens, and two Ikelite 200 underwater strobes, mounted on a 1 meter T-frame with a bubble-leveler and compass. 100 ASA Fujichrome Sensia II film was used. The Nikonos was focused to 2.6 feet, f 8, on auto-exposure. The area of coverage was 1.6 m^2. Slides were commercially developed and scanned at 1200 pixels per inch (Nikon LS1000). In 2008, a Nikon Coolpix P5000 digital camera, housed in an Ikelite underwater housing, with two Ikelite DS125 sub-strobes and an Ikelite wide angle lens adapter, replaced the Nikonos V film camera. The digital camera was mounted on a modified T-frame (1.25 m in length), which provided a slightly larger coverage area than the Nikonos V. After digital images were downloaded, image distortion was removed using Photoshop CS2 software (V9.0.2, Adobe Systems Inc.), and then the image was cropped to maintain 1.6 m^2 coverage, the coverage obtained by the Nikonos V. Benthic cover was determined from a random overlay of 30 points using Coral Point Count with Excel extensions software (CPCe V3.5; National Coral Reef Institute (NCRI), Florida; Kohler and Gill 2006).

Sea surface temperature data were obtained from a National Data Buoy Center (NDBC) 3-meter discus buoy (Station 42019, 27.91˚ N, 95.36˚ W), located 60 nautical miles south of Freeport, Texas and 58 nautical miles west-southwest of Stetson Bank. The NDBC buoy reads the water temperature at 0.6 m below the water surface and is positioned over a water depth of 82.3 m. Bottom temperatures were obtained from HOBO temperature loggers (HOBO Water Temp Pro [H20-001]) and data sondes (YSI 6600 Series) placed on the crest of Stetson Bank at 23.5 m depth.

Statistical analysis

Percent cover values for major species categories (i.e., Coral, Sponge, Algae, Coralline Algae, and Other) could not be transformed to conform to a normal distribution. Therefore, percent cover data for each major species category were analyzed using non-parametric Friedman's ANOVA. Photographic stations which were not consistently photographed for all five years were not included, which left 39 out of 51 stations for the analysis. All tests were performed using Statistica software (6.0; StatSoft, Inc.).

Results

Changes in percent benthic cover

Percent coral cover changed significantly between 2004 and 2008 (Friedman's ANOVA; $\chi_{37,4} = 85.63$, $P < 0.001$), decreasing dramatically after 2005 (Table 1). Specifically, *Millepora alcicornis* decreased by 80% from 2005 levels and has not recovered as of 2008 (Fig. 3). Other hermatypic coral species have shown minor fluctuations in percent cover from 2004-2008, but were generally stable (3.5% in 2005; 4.2% in 2008).

Algal cover also changed significantly over the five years ($\chi_{37,4} = 82.93$, $P < 0.001$). In general, algal cover increased since 2005, from 29% to a peak of 63% in 2007, but decreased to near 2004 levels at 49% in 2008. Specifically, percent cover of *Dictyota* fell from a high of 26% in 2006 to 3% in 2008, while turf-algae matrix increased to a high of 36% in 2007, and then decreased to 5% in 2008. Coralline algae (Corallinaceae) increased from 2% in 2004 to almost 9% in 2008 ($\chi_{37,4} = 29.58$, $P < 0.001$).

Sponge cover also changed significantly over time ($\chi_{37,4} = 19.72$, $P < 0.001$), decreasing from 27% in 2005 to a low of 18% in 2007. However, in 2008, overall sponge cover increased to 23%. Sponge species showed differing trends in cover. *Chondrilla nucula* decreased from 5% in 2005 to 0.2% cover in 2008. In contrast, *Ircinia strobilina* remained between 8-10% cover, and *Agelas clathrodes* between 1-2% cover between 2004 and 2008.

'Other' percent cover, which includes bare substrate, substrate rubble and mobile organisms, also changed significantly over time ($\chi_{37,4} = 15.74$, $P = 0.003$), decreasing from 10% to 6% in 2006, and then increasing to 12% in 2008.

	June 2004		June 2005		June 2006		July 2007		June 2008	
	% cover	s.e.m.	% cover	s.e.m.	% cover	s.e.m.	% cover	s.e.m.	% cover	s.e.m.
Millepora alcicornis	22.90	2.69	24.82	2.68	5.79	1.12	5.52	1.04	3.43	0.82
other corals	3.66	0.18	4.53	0.21	3.35	0.19	3.75	0.21	4.14	0.20
Chondrilla nucula	5.28	0.40	3.65	0.31	0.63	0.08	0.98	0.10	0.26	0.07
other sponges	15.39	0.09	23.26	0.13	18.81	0.12	16.81	0.11	22.89	0.13
Dictyota spp.	25.74	3.46	19.62	2.84	26.04	3.37	22.60	2.65	2.20	0.56
Turf-algae matrix	7.64	1.52	4.17	1.44	29.20	2.88	36.30	2.64	4.58	1.01
other algae	11.77	0.51	6.34	0.30	4.97	0.32	3.74	0.29	40.67	1.36
Coralline algae	1.79	0.28	2.86	0.33	4.25	0.41	4.09	0.39	8.71	0.73
Bare substrate	4.30	0.65	7.46	1.09	5.33	1.01	5.25	0.89	10.65	1.31
Substrate rubble	0.73	0.73	3.21	1.17	0.54	0.33	0.53	0.37	1.67	0.84
Other	0.65	0.09	0.09	0.02	1.08	0.08	0.44	0.05	0.79	0.07

Table 1: Percent benthic cover, averaged over all photostations, (± standard error, s.e.m.) from 2004 through 2008. The bleaching event occurred during the summer of 2005. Category 'other' in the table represents urchins, fish and other organisms which appeared under the random point generated by CPCe software.

Changes in temperature and salinity regime

Sea surface temperatures reached a peak in 2005, with water temperatures spiking to 30°C or greater on 67 days of the year (Table 2). Winter temperatures were also considerably milder than other years, with only 27 days falling below 20°C. In comparison, 2006 reached similar high, as well as low, sea surface temperatures, though for not as many days as in 2005.

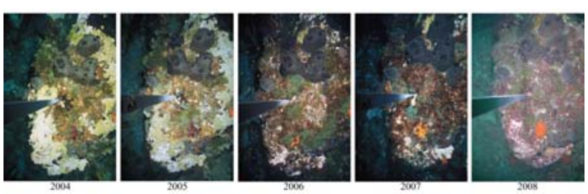

Figure 3: An example from one long-term photostation from 2004 to 2008. An obvious shift from *Millepora* to algae and sponge-dominated substrate is apparent in this series of photographs. In 2004 and 2005, *Millepora* (yellow coloration) is shown in relative abundance on the pinnacle, but is overgrown by algae in 2006 and 2007.

Sea surface and HOBO temperatures showed seasonal fluctuations over the mid-shelf area and Stetson Bank, respectively (Fig. 4 A, B). HOBO probes reported lower temperatures on the crest of Stetson than nearby, mid-shelf sea surface temperatures obtained from the NDBC surface buoy (e.g., August 7, 2005; Fig. 4A: 31.29°C SST; Fig. 4B: 29.26°C HOBO). Further, there were several sudden drops in temperature evidenced by the HOBO dataset, which were not reflected in the SST dataset (e.g., July 15, 2005: 29.8°C SST, 24.6°C HOBO). These discrepancies could be explained by the occurrence of cold water thermoclines over Stetson Bank during the summer months.

Year	Number of days SST reached 30 C	Number of days SST fell below 20 C	Mean temperature (± s.e.)	HIGH	LOW
2004	34	63	24.980 ± 0.044	31.6	15.2
2005	67	27	25.157 ± 0.040	33.1	18.8
2006	40	19	25.036 ± 0.037	33.1	18.8
2007	27	59	24.881 ± 0.039	31.8	18
2008*	7	48	22.977 ± 0.049	31.9	18.3

Table 2: Temperature records from Stetson Bank from 2004-2008. Asterisk denotes temperature data was not calculated from a full year; data is shown up to June 30, 2008.

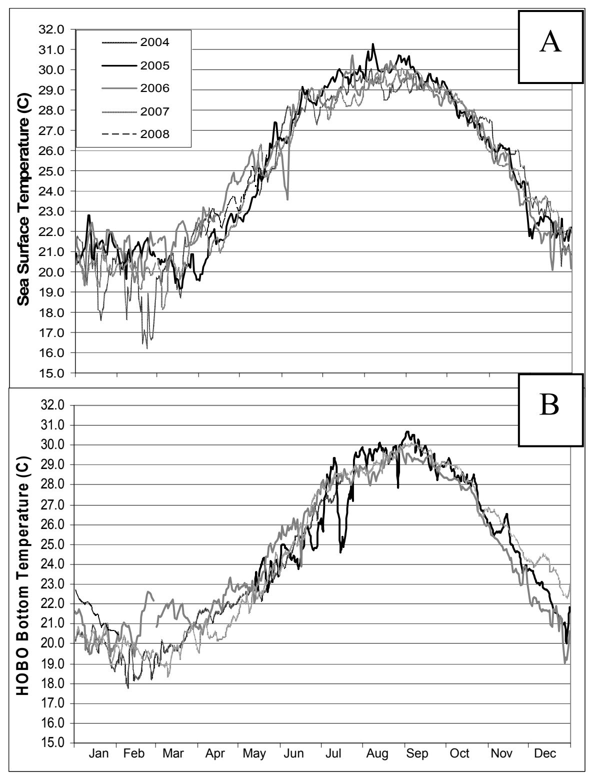

Figure 4: Average daily temperatures from 2004 – 2008. (A) Sea surface temperatures from NDBC Buoy 42019. (B) Bottom temperatures from the surface of Stetson Bank (23.5 m depth) from HOBO temperature probes.

Salinity was not measured as consistently as temperature due to instrument difficulties. However, a particular salinity regime emerged from the datasonde measurements. There were repeated freshwater influxes to Stetson Bank between 2004 and 2008 (data not shown). However, freshwater influxes in 2005 seemed to be of greater duration and extent than in the other years of this study. To contrast the extent of the lower salinity regime in 2005, in 2006 the average yearly salinity was 35.3 ppt, compared to 32.9 ppt in 2005. Throughout the end of July and August of 2005, daily average salinity measurements were as low as 27 ppt, and with the passage of Hurricane Rita, salinity again decreased from an average in September of 35 ppt to an average daily low of 32 ppt on October 2 (see Fig. 5).

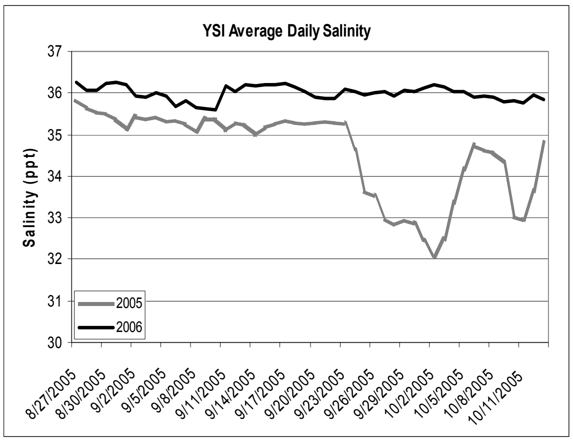

Figure 5: Average daily salinity measured between August and October, 2005 and 2006. Salinity was measured with a datasonde/YSI on the surface of Stetson Bank (23.5 m depth). Hurricane Katrina passed through the Gulf of Mexico on August 28, 2005; while Hurricane Rita passed through the Gulf on September 23, 2005.

Discussion

Though previous studies have suggested that the benthic community of Stetson Bank is relatively stable (Bernhardt 2000), this study is the first to report a dramatic change in percent cover of Stetson Bank's benthic community. This analysis allows for investigation into questions regarding the mechanisms of recovery or resiliency of this high-latitude coral-sponge community.

Several trends in percent cover are apparent from the analysis of the five years surrounding the bleaching event of 2005. Prior to the Caribbean wide bleaching event in 2005, Stetson Bank supported 27% coral cover. After 2005, overall coral cover fell to 7%, with *Millepora* suffering the largest decrease and not recovering as of the 2008 monitoring effort. The other hermatypic coral species of Stetson Bank (e.g., *Diploria strigosa, Stephanocoenia intersepta, Madracis decactis, Madracis mirabilis*, and *Siderastrea radians*) appeared stable, remaining at around 4% of the benthic cover throughout 2004 to 2008. This demonstrates the significant differential response of *Millepora* to bleaching compared with other species of hermatypic coral. The composition of sponge species varied between 18-27% throughout the five years. However, there was a dramatic decrease in *Chondrilla nucula* percent cover after 2005. Bleaching in sponges is not well documented (see Vicente 1990; Fromont and Garson 1999) and though we can not say from this dataset that the mortality of *C. nucula* was due to bleaching, *C. nucula* virtually disappeared between the 2005 and 2006 monitoring cruises. Further, the disappearance of *C. nucula* at Stetson Bank is an opposite response from the increase in *C. nucula* cover reported from the reefs of Belize after the 1998 coral bleaching episode (Aronson et al. 2006). Along with the varied success of the sponge species, there was an initial increase and subsequent decrease in algal cover. Concomitant with this decrease in filamentous and macro-algae, coralline algae and turf-algae matrix has steadily increased since 2005.

Although the benthic community has not recovered to pre-2005 levels, trends observed in this study suggest possible signs of resiliency of the reef ecosystem of Stetson Bank. An increase in coralline algae, relatively stable hermatypic coral and sponge cover and decreasing macroalgal cover (after an initial spike) have been cited as possible signs of reef resiliency elsewhere (see Birrell et al. 2005; Smith et al. 2008). However, understanding the details of the disappearance of both *Millepora alcicornis* and *Chondrilla nucula* and the interaction of the overall biological community with trends in temperature and salinity regimes is equally important in determining the overall resiliency of Stetson's *Millepora*-dominated community.

The temperature data from Stetson Bank demonstrate differences in accuracy between the sea surface (SST) and bottom (HOBO) temperature measurements. There was a dramatic decrease in summertime bottom temperature in July 2005, coupled with bottom and sea surface temperatures which repeatedly reached over 30°C. Temperatures of 30°C and above are considered to signal the probable onset of bleaching for tropical corals, depending on the latitude of the reef system and seasonal maximum SST (Manzello et al. 2007). Further, Degree Heating Week (DHW) data, which is a proxy for thermal stress and represents the number of weeks during which the average weekly sea surface temperature is greater than the expected average monthly maximum temperature, also showed 2005 to be remarkable in the temperature regime over Stetson Bank (for a more thorough explanation of DHW, see http://coralreefwatch.noaa.gov/satellite/methodology/methodology.html#dhw). Specifically, compared to 2004, with 24 weeks at 0.55 DHWs, there was a dramatic increase to 32 weeks at a maximum of 6.05 DHWs in 2005. In 2006, there were only 6 weeks at

0.5 DHW; 2007 increased to 25 weeks at 0.8 DHW. As of September, there were no DHW in 2008 (data courtesy of NOAA Coral Reef Watch).

Coupled with the high, prolonged temperatures of 2005, coastal runoff from the passage of Hurricanes Katrina and Rita also reached Stetson Bank. Though Stetson Bank is subject to repeated influxes of freshwater, none of the documented influx events between 2004 and 2008 rivaled the events which occurred in 2005. The lower salinity regime instigated by two hurricanes passing through the northern Gulf of Mexico lasted several weeks, from August to October (see Fig. 5). Though water quality was not specifically tested at the FGBNMS, this plume of freshwater originating from the Gulf Coast and Mississippi River and driven southwestward by the winds of Hurricane Rita and spinoff eddies from the Loop Current, might have carried pollutants, chemicals, and nutrients to an already stressed reef community (see Rabalais et al. 1996; for review of effects of coastal discharge on corals, see Fabricius 2005).

The lack of quick recovery of *Millepora* following the bleaching event might be attributed to the dependence of the population on larval recruitment, rather than colony regrowth. Due to the severity of the 2005 bleaching event, most *Millepora* colonies exhibited total mortality, so that regeneration from remaining live tissue was not possible. An initial image assessment of a subset of randomly selected photostations exhibited only one or two new colonies between 2007 and 2008. *Millepora* spawning has not been reported from the FGBNMS, and little is known about its reproductive ecology (see Soong and Cho 1998). Depending on local *Millepora* behavior and larval duration, the resiliency of the *Millepora* population of Stetson Bank might depend on larval recruits from other coral communities in the Gulf of Mexico. However, there is limited research on the extent of population connectivity among the reefs and banks of the northwestern Gulf of Mexico (but see Lugo-Fernandez 1998; Lugo-Fernandez et al. 2001).

High seawater temperatures and major hurricane impacts (with associated freshwater influxes) in 2005, followed by an increase in recruitment-inhibiting macroalgae species (e.g., see Kuffner et al. 2006), and a dependence on larval recruitment, might explain why the reef community of Stetson Bank has not yet recovered to pre-bleaching benthic species assemblage patterns. However, as of 2008, the reef ecosystem of Stetson Bank may be exhibiting signs of resiliency, as evidenced by a subsequent decrease of macroalgae and an increase in coralline algae, the degree of which will be established through continued monitoring efforts.

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