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coral reef paper

Localized coral reef mortality event at East Flower Garden Bank, Gulf of Mexico

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ABSTRACT.—Flower Garden Banks National Marine Sanctuary contains the northernmost coral reef ecosystem in the Gulf of Mexico, with >50% living coral cover. Historically, this reef system has harbored a healthy coral community, relatively free of disease with limited mortality from bleaching or other factors. In July 2016 an unprecedented localized mortality event was documented at East Flower Garden Bank affecting an area of approximately 5.6 ha (2.6% of the coral reef). Within this area, up to 82% of the coral colonies succumbed to partial or total mortality, along with invertebrates spanning numerous taxa, including cnidarians, poriferans, echinoderms, crustaceans, and mollusks. Within the affected area, the impact was highly stratified, with many coral colonies exhibiting a clear line of delineation with polyps above appearing healthy, and those below exhibiting paling, bleaching, tissue sloughing, and/or mortality. The mortality of sessile invertebrates across multiple taxa was similar to observations from coral mortality events in other regions associated with low dissolved oxygen (DO) concentrations. While instrumentation for measuring DO was not in place on East Flower Garden Bank, DO sensors at similar depths located 50–70 km northwest of East Flower Garden Bank confirmed low DO levels (<3.5 mg L^{-1}) at the time of the event. The mortality event likely resulted from a combination of stressors, but localized low DO is implicated as the primary contributing factor.

East Flower Garden Bank and West Flower Garden Bank, part of the Flower Garden Banks National Marine Sanctuary located in the northwestern Gulf of Mexico, are approximately 190 km south of the Texas-Louisiana border and contain distinct reef habitats ranging from 16 to 150 m in depth (Fig. 1; Bright et al. 1985, Schmahl et al. 2008). The banks, positioned approximately 20 km apart, provide favorable conditions for colonization of hermatypic corals, sponges, algae, invertebrates, and fishes, similar to species common on Caribbean coral reefs (Bright et al. 1984). Well-developed tropical coral assemblages top the shallowest area of the East Flower Garden Bank and West Flower Garden Bank reef caps, ranging in depth from 16 to 46 m (Schmahl et al. 2008).

The coral reefs have been monitored annually at East Flower Garden Bank and West Flower Garden Bank since 1989 (Johnston et al. 2016). In spite of global coral cover decline in recent decades, mean coral cover has remained near or above 50% throughout the 27 yrs of monitoring with values that are significantly higher than other Caribbean reefs (Gardner et al. 2003, Jackson et al. 2014, Johnston et al. 2016). East West Flower Garden Bank and West Flower Garden Bank are also relatively protected from the effects of tropical storms, temperature and salinity variability, and disease due to their remoteness, depth, and the robust structure created by the predominant massive coral community (Aronson et al. 2005, Johnston et al. 2016). This buffers them from severe bleaching and mortality events that have impacted shallower, coastal reefs across the globe (Altieri et al. 2017, Hughes et al. 2018, Johnson et al. 2018). However, in 2016, a localized area of East Flower Garden Bank suffered from significant coral and invertebrate mortality that, to the best of our knowledge, was the first event of its nature documented at the Flower Garden Banks.

On 25 July, 2016, recreational divers reported signs of stress on the reef, including dying corals and sponges coated with white mats, along with low visibility and green coloration in the water column at East Flower Garden Bank. Coincidentally, sanctuary research divers were approximately 275 m away conducting annual coral reef monitoring activities and observed no signs of reef stress at the monitoring site. On 27 July, 2016, the research team conducted benthic surveys near the reported location and confirmed the observations of turbid, low visibility water column conditions and dying corals described by the recreational divers. A subsequent response cruise from 5–7 August, 2016, further documented the effects of the event. Here, we describe benthic and water quality data collected during the time of the event and a week after the event to determine the extent of the affected area and impacts to the benthic community.

Methods

Study Site Description.—East Flower Garden Bank (27°54.5´N, 93°36.0´W) is a pear-shaped dome located approximately 193 km southeast of Galveston, Texas. The bank (65.86 km^2) slopes from its shallowest point at 17 m to the seafloor at a depth of approximately 130 m (Fig. 1) and is capped by a well-developed coral reef covering 8.24 km^2. A 10,000 m^2 long-term monitoring site (herein referred to as LTM site), ranging in depth from 17 to 27 m, is located on the eastern side of the central portion of the cap (Fig. 2) and is monitored once a year to examine trends in the benthic cover and fish community. The affected area resulting from the mortality event was located near the center of the coral cap, approximately 275 m west of the LTM site (Fig. 2).

General Observations.—During initial observations at East Flower Garden Bank in July 2016, divers captured photographs and video in the reported affected

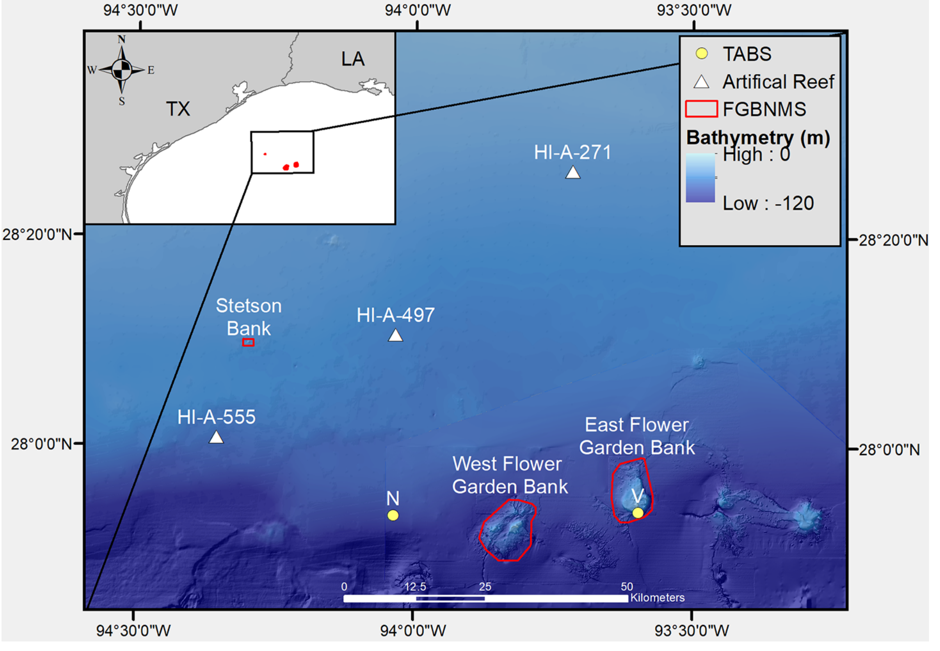

Figure 1. Outlined marine sanctuary boundaries of Stetson Bank (2.18 km^2), West Flower Garden Bank (77.54 km^2), and East Flower Garden Bank (65.86 km^2), located along the outer Texas-Louisiana continental shelf in the Gulf of Mexico (inset). Platforms with United States Geological Survey multi-parameter water quality data sondes are depicted as white triangles and TABS buoys as yellow circles.

area. Divers also conducted six random benthic photo-transect surveys, focusing on sites at or near the center of the reported affected area on 27 July, 2016. Divers also conducted 10 random benthic photo-transect surveys across the coral cap at the neighboring West Flower Garden Bank on 28 July, 2016, to inspect for signs of reef stress as observed at East Flower Garden Bank. A response specific cruise was executed 5–7 August, 2016, to conduct additional benthic surveys.

Benthic Surveys.—Diver propulsion vehicle (DPV) surveys were performed on 5 August, 2016, to map the extent of mortality. Latitude and longitude, along with estimates by divers of the percent of coral affected per location, were marked during DPV surveys to delineate the edges of the affected area.

Benthic percent cover surveys consisted of non-overlapping 8.16-m^2 photo-transects (13.6 × 0.6 m). A Canon Power Shot® G11 digital camera in an Ikelite® housing and 28-mm equivalent wet mount lens adaptor, mounted on a 0.65-m T-frame with bubble level and two Inon® Z240 strobes, was used to capture images along each transect. The mounted camera was placed at intervals marked along a 15-m measuring tape at 80 cm apart, producing 17 nonoverlapping images (each still frame image captured a 0.8 × 0.6 m area) along the transect.

Twenty-five benthic photo-transects were completed in a grid pattern starting from the point of highest observed reef stress (centroid) during the initial surveys and moving outward in eight directions (cardinal and primary intercardinal directions). Survey sites were located every 50 m within 100 m of the centroid and every

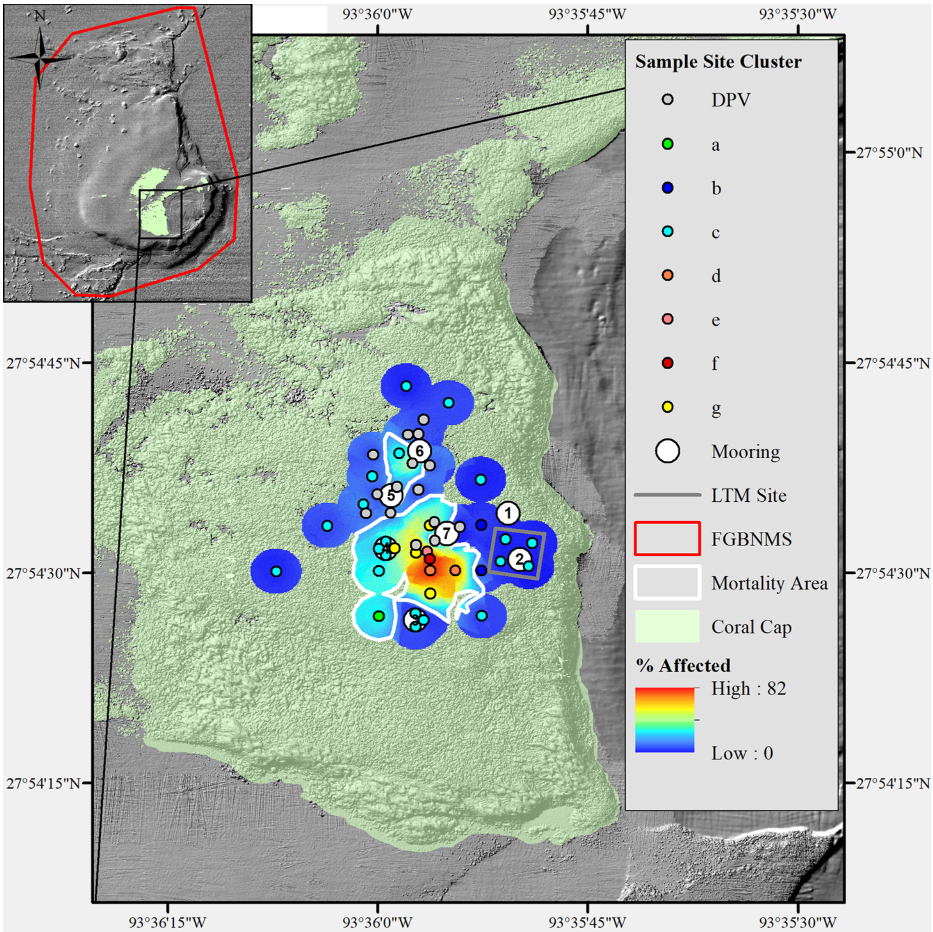

Figure 2. Spatial distribution of the affected area (outlined in white) centered in the middle of the East Flower Garden Bank coral reef cap (colored light green). Numbered white circles represent mooring buoys and the 1-ha long-term monitoring site (LTM site) is outlined in gray. Survey sites are small circles and color coordinated to match significant similarity profile permutation clusters. Percent coral affected from high to low (based on the inverse distance weighted model) ranges in color from red to blue. Map inset shows the Flower Garden Banks National Marine Sanctuary (FGBNMS) boundaries (outlined in red) and coral reef cap.

200 m through the remaining area on the coral cap shallower than 30.5 m (Fig. 2). Benthic photo-transect data collected from the unaffected East Flower Garden Bank LTM site in July 2016 (Johnston et al. 2017) were used for comparison to surveys taken in the affected area.

Benthic cover and the percentage of impacted coral were determined by analyzing the photo-transects. Mean percent benthic cover was determined using Coral Point Count with Microsoft® Excel® extensions (CPCe) v4.1 with a 500 random point overlay distributed among all images within a transect (Kohler and Gill 2006). Organisms positioned beneath each random point were identified to the lowest possible taxonomic level and grouped into primary functional groups: (1) coral; (2) sponge; (3) macroalgae; (4) sand; and (5) colonizable substrate, a composite substrate category that included crustose coralline algae, fine turf algae, and bare rock (Aronson and

Precht 2000, Aronson et al. 2005). Macroalgae included algae longer than approximately 3 mm and thick algal turfs covering underlying substrate.

For each coral point, the incidence of coral paling, bleaching, and mortality was recorded based on Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocols (Lang et al. 2012). Any point that landed on coral that was pale or discolored relative to what was considered normal for the species was characterized as paling; any point that landed on a portion of coral with bright white polyp tissue was characterized as bleaching; and any point that landed on recently dead coral (exposed bare skeleton) where polyp tissue was sloughing or decomposing and the underlying skeletal structure was visible and identifiable to species was classified as mortality (Lang et al. 2012). Because corals were observed to be in various stages of stress, the three categories representing coral paling, bleaching, and mortality were combined to determine the total coral affected percentage.

Benthic transect data were evaluated with non-parametric distance based analyses (Primer® v7.0, Plymouth, United Kingdom; Anderson et al. 2008). Euclidean distance resemblance matrices were calculated using untransformed percent cover data (coral, sponge, macroalgae, sand, colonizable substrate) and percent affected coral data from random transects. Cluster analysis comparing benthic cover groups and percent affected coral was performed with similarity profile permutation tests (SIMPROF) to identify significant ($\alpha = 0.05$) clusters (Table 1; Clarke et al. 2014). Groups contributing to observed dissimilarities were identified using similarity percentages (SIMPER) (Clarke et al. 2014).

Modeling.—To visualize and estimate the extent of the affected area caused by the mortality event, DPV survey estimates and affected percent coral cover for each benthic transect were used in an inverse distance weighted (IDW) interpolation in ESRI ArcGIS® (Fig. 2). IDW predictions were created using variable distance referencing up to three data points, restricted to within 100-m radius, and clipped with a 50 m sample site buffer. The affected area was defined as possessing >15% percent coral paling, bleaching and mortality, combined. The model output was a map helping to visualize and estimate the size of the affected area on the reef cap.

Water Quality.—While no instrumentation was installed within the immediate affected area, water quality instrumentation was present on the reef as part of the long-term monitoring program. Temperature and salinity are recorded every hour by data sondes (SBE 37 MicroCAT, Sea-Bird Electronics, Bellevue, Washington) installed on the reef cap at both East Flower Garden Bank and West Flower Garden Bank. At East Flower Garden Bank, the instrument is located within the LTM site at 24 m depth, approximately 275 m east from the affected area. Flower Garden Banks National Marine Sanctuary baseline long-term monitoring temperature data at depth from 1990 to 2015 were used to compare to seawater temperature data in 2016.

Hourly surface temperature and salinity data were downloaded from the Texas Automated Buoy System (TABS) database (TABS 2018) for Buoy V located within East Flower Garden Bank marine sanctuary boundaries (27°53.796´N, 93°35.838´W; 1.4 km south of the East Flower Garden Bank reef cap) and Buoy N located 21.8 km west of West Flower Garden Bank (27°53.418´N, 94°02.202´W) (Fig. 1).

To further investigate water quality dynamics in the northwestern Gulf of Mexico at the time of the event, additional water quality parameters at depth (21–30 m), including dissolved oxygen (DO) concentration, pH, chlorophyll, turbidity, and blue-green algae were examined. Data were collected with United States Geological Survey (USGS) multi-parameter water quality data sondes on three artificial reefed petroleum platforms (High Island-A-271, High Island-A-497, and High Island-A-555) located within 50–70 km of East Flower Garden Bank (Fig. 1) from mid-July to mid-September 2016.

Results

Initial observations and general photography in July 2016 documented affected invertebrates including cnidarians, poriferans, echinoderms, crustaceans, and mollusks (Fig. 3). Dead bivalves, sea urchins, brittle stars, and crabs were observed on the seafloor under coral overhangs throughout the affected area at approximately 23 m. The highest level of mortality appeared to be concentrated in the lower portions of the reef, associated with sand channels and flats, which intersect the area. Many affected coral colonies had a clear line of delineation, with coral polyps above appearing healthy and those below exhibiting paling, bleaching, tissue sloughing, and/or mortality (Fig 3.). The mortality was indiscriminate, affecting all sessile or slow-moving invertebrates in a number of sand flats and depressions in the area. Nine days after initial observations, many coral colonies originally showing signs of bleaching stress had succumbed to mortality and active tissue necrosis was no longer present. It appeared that numerous corals were under stress, bleached due to stress, and quickly died as a result of the event (Fig. 3).

Based on percent cover analysis of benthic photo-transects within the area surveyed, the percent coral affected (paling, bleaching, and mortality categories combined) ranged from 19% to 82% within the main affected area, and from 0% to 14% outside the area. SIMPROF analysis detected seven significant clusters among benthic transect surveys (Table 1, Fig. 2), where significant differences among surveys were due to percent affected coral (SIMPER 36%) and not the benthic community. Based on the IDW model with a 15% coral affected threshold, the affected area was centrally located on the East Flower Garden Bank reef cap and spread across approximately 5.6 ha, totaling 2.6% of the coral reef cap (Fig. 2). At the time of the event, there was minimal bleaching and no evidence of coral mortality within the LTM site benthic transect surveys (mean coral cover ranging from 33% to 64%). There was also minimal bleaching and no evidence of coral mortality on the neighboring West Flower Garden Bank coral cap.

A total of 17 species of coral were observed in the benthic transects, and all coral species were affected by the event. Within transects where coral was affected, 41% of *Orbicella franksi* (Gregory, 1895), 20% of *Pseudodiploria strigosa* (Dana, 1846), and 14% of *Porites astreoides* Lamarck, 1816 coral cover was impacted. Where a distinct depth band was observed on numerous affected coral colonies, the corals were often located on/near sand patches on the seafloor (23 m) and mortality occurred vertically up to approximately 1–2 m, while the remaining top portion of the colonies appeared unaffected (Fig. 3).

During the period leading up to the event, higher than average seawater temperature and lower than average salinity were detected offshore. Surface seawater temperatures recorded by TABS Buoy V within East Flower Garden Bank sanctuary boundaries (1.4 km from the bank reef cap) were unseasonably warm, reaching

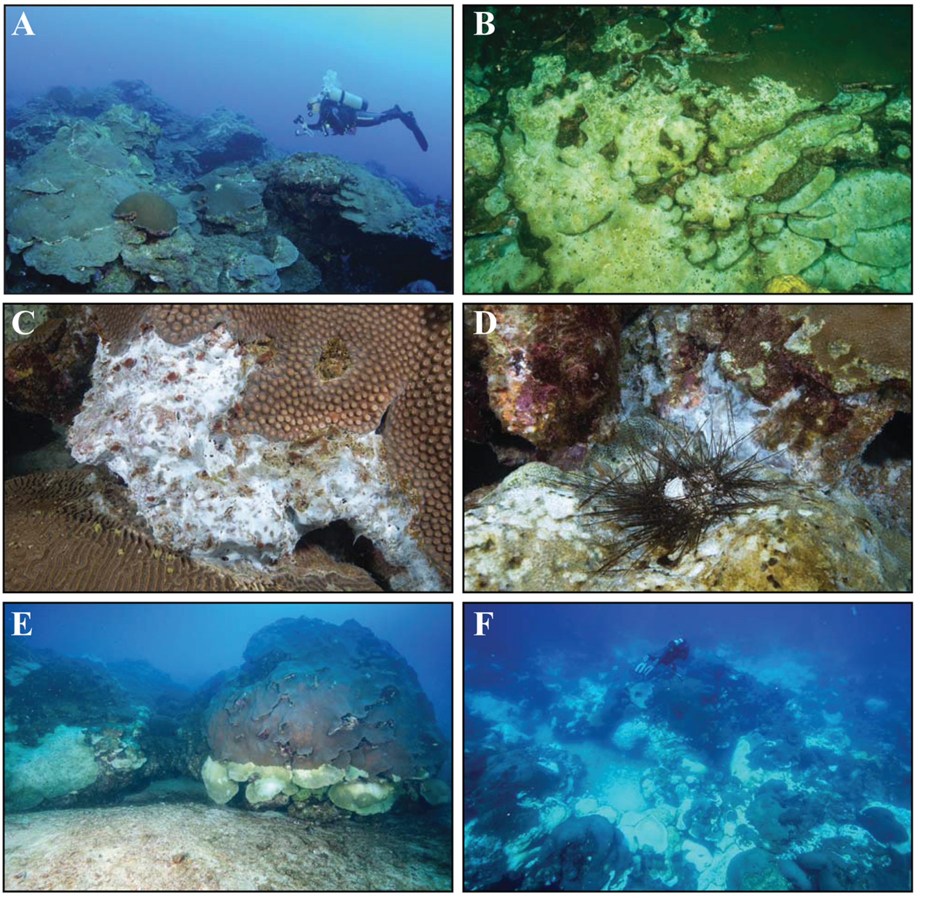

Figure 3. Mortality effects on the coral reef at East Flower Garden Bank. (A) Healthy reef community at East Flower Garden Bank including *Orbicella franksi*, the dominant coral species at the bank; (B) an affected *O. franksi* colony during the event; (C) white mat covering a portion of a *Montastraea cavernosa* (Linnaeus, 1767) colony; (D) dead *Diadema antillarum* Philippi, 1845 on the reef within the affected area; (E) distinct line of mortality on an *Orbicella faveolata* (Ellis and Solander, 1786) colony near a sand flat; and (F) a scuba diver hovers above the affected area between benthic surveys.

a maximum temperature of 31.29 °C on 10 August, 2016, and totaling 31 d >30 °C (Fig. 4) from 21 June to 27 July, 2016. At the East Flower Garden Bank SBE 37 instrument on the reef (24 m), the maximum temperature was recorded on 10 August, 2016 (30.73 °C), and a total of 4 d were >30 °C (Fig. 4) from 23 July to 27 July, 2016, right before and during the event. These temperatures were warmer than historic averages based on long-term monitoring baseline data, where East Flower Garden Bank daily seawater temperature at depth (24 m) from 1990 to 2015 averaged 28.62 °C for July and 29.34 °C for August, compared to July (29.26 °C) and August (29.99 °C) temperatures at depth in 2016. Near the neighboring West Flower Garden Bank, seawater temperatures were slightly cooler in 2016. Sea surface temperatures recorded by TABS Buoy N (21.8 km west of the West Flower Garden Bank reef cap) reached 31.07 °C on 10 August, 2016, with a total of 30 d >30 °C from 21 June to 27 July, 2016

Table 1. Mean percent benthic cover and percent of coral affected (percent paling, bleaching, and mortality combined) per similarity profile permutation (SIMPROF) group from benthic photo transect surveys. SIMPROF groups represent significant data clusters. CTB = colonizable substrate.

SIMPROF	Living coral (%)	Macroalgae (%)	Sand (%)	Sponge (%)	CTB (%)	Other (%)	Paling (%)	Bleached (%)	Mortality (%)	Coral affected (%)
a	79.84	10.25	2.67	0.00	7.03	0.21	26.68	0.00	0.84	27.52
b	38.66	47.86	1.33	1.03	10.81	0.31	1.85	0.23	0.27	2.34
c	58.99	27.59	1.73	0.58	10.71	0.39	3.80	1.01	1.90	6.72
d	32.12	26.63	1.60	1.34	37.68	0.63	13.45	1.78	47.86	63.09
e	27.25	15.57	10.19	0.20	45.55	1.24	12.75	0.39	59.90	73.04
f	22.64	29.85	2.45	2.14	41.97	0.95	17.38	0.35	62.66	80.39
g	42.16	30.81	0.63	0.41	25.38	0.61	16.32	6.30	23.03	45.64

(Fig. 4). At the West Flower Garden Bank 24-m instrument on the reef, there were 0 d >30 °C on the reef from 21 June to 27 July, 2016 (Fig. 4).

Due to a battery malfunction, salinity data from the 24-m moored SBE 37 in the East Flower Garden Bank LTM site was not available from 18 February to 6 August, 2016. Typical oceanic salinity values average between 35 and 36; however, surface salinity recorded at TABS Buoy V averaged 30 for July 2016, dropping to a minimum of 13.26 on 5 August, 2016, at East Flower Garden Bank (Fig. 4). Surface salinity recorded by TABS Buoy N near West Flower Garden Bank reached a minimum of 23.23 on 24 August, 2016 (Fig. 4). At the West Flower Garden Bank 24-m moored SBE 37, the salinity values were within normal ranges (approximately 36) in July and August (Fig. 4). While DO sensors were not installed on the East Flower Garden

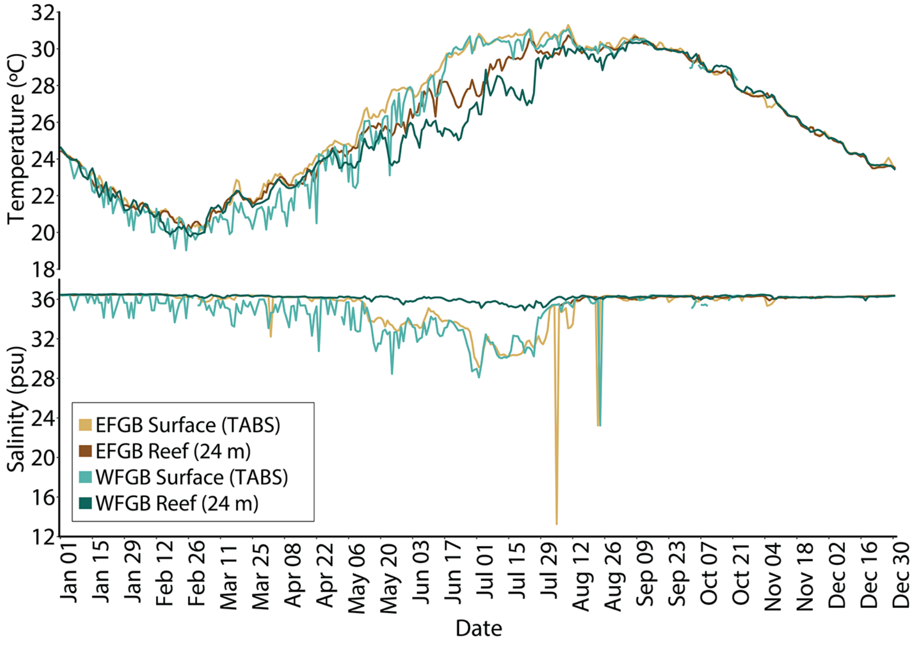

Figure 4. Daily mean seawater temperature (°C) and salinity at East Flower Garden Bank (EFGB) and West Flower Garden Bank (WFGB) from surface TABS buoys and water quality instruments at depth (24 m) on the reef.

Bank reef cap at the time of the event, USGS data sondes on three artificial reefs (High Island-A-271, High Island-A-497, and High Island-A-555) located 50–70 km from East Flower Garden Bank (Fig. 1) recorded decreases in DO concentrations at similar depths to the East Flower Garden Bank coral cap in late July and early August. During the timeframe from 20 July to 13 September, 2016, DO concentrations ranged from 2.0 to 6.9 mg L^{-1} at High Island-A-271, 2.9 to 9.3 mg L^{-1} at High Island-A-555, and 3.8 to 7.2 mg L^{-1} at High Island-A-497. All concentrations <3.5 mg L^{-1} were recorded between 20 July and 9 August, 2016, coinciding with the time of the event at East Flower Garden Bank. As a whole, these deployments indicate substantial spatial variability in general water quality parameters during the deployment period in the northwestern Gulf of Mexico.

Discussion

Based on observations, the mortality event at East Flower Garden Bank occurred rapidly, as a recreational dive was conducted at the same location 2 d prior to initial observations near the affected area and nothing abnormal was reported. The event at East Flower Garden Bank was also highly localized, affecting a small area in the center of the coral cap, while other areas were not affected, such as the nearby LTM site, or the neighboring West Flower Garden Bank. Instrumentation on and around the reef at East Flower Garden Bank documented low surface salinity and higher than average seawater temperature at the surface and at depth. At the time of the event, the surface water atop East Flower Garden Bank was relatively fresh compared to that at West Flower Garden Bank, and seawater temperatures were higher at depth, suggesting that conditions can be highly variable between the banks, and even vary between different locations on the same bank. While the mortality event likely resulted from a combination of stressors, localized low dissolved oxygen (DO) is hypothesized to be the primary contributing factor.

A similar mortality event was documented on a coral reef in Almirante Bay, Bocas del Toro Province, Panama, in 2010 and again in 2017, where corals turned white and died in association with the mortality of other benthic macroinvertebrates across multiple taxa (Altieri et al. 2017, Johnson et al. 2018). Observations of white bacterial mats and a distinct mortality depth delineation were observed, comparable to observations at East Flower Garden Bank. Studies stemming from the Panamanian event determined that persistent low DO concentrations (<1.5 mg L^{-1}) in deeper waters contrasted with higher DO levels in shallower waters, resulted in a hypoxic event in the deeper areas of the bay (Altieri et al. 2017). Similar conditions as seen at East Flower Garden Bank were documented at Almirante Bay and included turbid water column conditions, higher than average seawater temperatures, and reduced salinity; however, impacted reef sites were in a shallow coastal lagoon at Almirante Bay vs the deeper open ocean setting at East Flower Garden Bank.

Preceding the event at East Flower Garden Bank, the Midwest region of the US experienced heavy precipitation and flooding events in the spring of 2016, causing freshwater runoff and discharge into the Gulf of Mexico from Texas and Louisiana waterways (Breaker et al. 2016). While discharge from major gulf watershed rivers, including the Atchafalaya and Mississippi, fell within normal ranges, discharge from at least four major Texas and Louisiana waterways (Brazos River, Colorado River, Sabine River, and Trinity River) were above long-term daily means for an approximate

4–6-mo period (measured from USGS gauging stations in the Texas coastal plain) (Breaker et al. 2016). It was clear from the water quality data that surface salinity levels around East Flower Garden Bank were low during July 2016; however, there is not enough data to link surface conditions to the mortality event observed at depth. While two-thirds of the water from US waterways drains into the Gulf of Mexico, large freshwater plumes rich with nutrients are uncommon in offshore locations, as runoff from storm events primarily affects coastal areas as plumes decay (Bianchi et al. 2010). However, this increase in fresh water coupled with elevated variable seawater temperatures and decreased oxygen concentrations in the gulf region may all have been contributing factors to the mortality event. It remains unclear as to why only a small area of the East Flower Garden Bank coral cap was affected, as there was no evidence of coral stress and mortality on other areas of East Flower Garden Bank, or at West Flower Garden Bank. It is hypothesized that most mortality within the area affected was confined to depressions and sand flats on the center of the bank where water circulation was possibly reduced, as opposed to the sloping shelf along the bank circumference where water movement is more dynamic (Jarosz et al. 2014).

While the impacts of low DO conditions are well documented in the coastal areas of the northern Gulf of Mexico (Diaz and Rosenberg 1995, Turner et al. 2008, Bianchi et al 2010, Zhang et al 2015), little is known about the frequency and occurrence of similar conditions on coral reefs around the world (Altieri et al. 2017, Baird et al. 2018, Blakeway 2018), much less the reefs and banks in the Gulf of Mexico. Low DO may have been one potential contributing factor to the mortality event; however, lack of in situ evidence prevents a definitive conclusion. Even though many of the mortality event symptoms suggest low DO, we cannot rule out the possibility that other drivers caused the event. The East Flower Garden Bank coral reef has developed on top of features formed by underlying salt domes, and while there was no instrumentation on this area of the reef capturing salinity values at the time of the event, the possibility of natural brine discharge cannot be ruled out. Alternate hypotheses include a spill of toxic chemicals, vessel discharge, or an unknown pathogen; however, data are lacking to evaluate these alternatives.

Altieri and Gedan (2015) suggest that temperature driven climate change will exacerbate low DO areas in the marine environment and expand the prevalence of dead zones, which would cause disastrous impacts to coral reefs that are already facing numerous anthropogenic threats (Gardner et al. 2003, Diaz and Rosenberg 2008, Jackson et al. 2014). This localized event has shown that, despite their remoteness, East Flower Garden Bank and West Flower Garden Bank are not immune to impacts; and regardless of their proximity, conditions between the two can vary significantly. Further, the fine-scale localization of this event highlights the need to increase the frequency and resolution of water quality data collection, as hypoxic conditions in the Gulf of Mexico may be variable and not just be limited to coastal areas. Despite the severity of the localized mortality event, in general, the coral reefs of Flower Garden Banks National Marine Sanctuary remain healthy and thriving, exhibiting some of the highest coral cover of massive boulder corals in the western Atlantic region.

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