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Localized bleaching and quick recovery in Hong Kong's coral communities

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ABSTRACT

During the summer of 2017 we visited 33 sites with substantial coral cover across Hong Kong waters. At six sites where coral bleaching was observed, video-transect surveys were conducted, which revealed 18.7% to 56.1% bleached colonies and 5.9% to 57.6% bleached coral covered area per site. Mainly affected were three plate-like and three massive coral species. Water quality parameters were analyzed, which indicated that hyposalinity might have triggered the bleaching event. Tagging and follow-up field observation revealed a pattern of recovery depending on coral growth form, with high recovery rates (> 93%) at five sites dominated by massive and submassive corals, but moderate (70%) at a site dominated by plate-like corals. Our study shows that the corals of Hong Kong exhibit differential susceptibility to bleaching and ability to recover, therefore it is imperative to establish a long-term monitoring programme to detect the changes in community structure over time.

1. Introduction

Coral bleaching, the whitening of coral tissues due to the loss of endosymbiontic *Symbiodinium*, has been widely recognized as a major cause of coral mass mortality and coral reef degradation worldwide (Hughes et al., 2017). There have been large-scale bleaching events over the last half century, including those that occurred during 1982–1983 in the Caribbean (Glynn, 1991), 1996–1998 in tropical Pacific, Caribbean and the Indian Ocean (Wilkinson, 1998), 2010 in tropical Pacific and the Caribbean (Doshi et al., 2012; Alemu and Clement, 2014), and 2014–2017 throughout the tropical oceans (Hughes et al., 2017; Eakin et al., 2018). In subtropical reefs, however, coral bleaching usually caused only minor impacts, affecting small areas and small percentage of coral colonies (Cook et al., 1990; Hagman and Gittings, 1992; Dalton and Carroll, 2011; Abdo et al., 2012). Nevertheless, such minor bleaching events can have serious consequences for subtropical coral communities because of their low recruitment success (Chiu and Ang, 2017) and slow growth rates hindering recovery after bleaching events (Goodkin et al., 2011; Harrison et al., 2011; Hoey et al., 2011). In addition, since abnormal weather conditions have become more frequent in recent decades, repeated minor bleaching events have been experienced in many subtropical reefs, which could lead to cumulative impact on coral communities (Beger et al., 2014). Furthermore, global warming has resulted in the range shift of some tropical species including fishes and corals to subtropical areas, having the potential to alter the species interactions among coral communities as well as their stress responses (Greenstein and Pandolfi, 2008; Beger et al., 2014).

Situated on China's southern coast at 22°20′N, Hong Kong has a monsoonal climate with two distinct seasons. The dry season (November–March) is characterized by low mean monthly precipitation (67 mm) and water temperature (17–21 °C), whereas the wet season (May–October) is characterized by high mean monthly precipitation (330 mm) and water temperature (25–29 °C). The Pearl River, located west of Hong Kong, is the third largest river in China. Huge amounts of freshwater (on average 1.06×10^4 m^3 s^{-1}) discharged from the Pearl River especially during the wet season could significantly affect the water quality, resulting in a distinct west-east gradient of salinity, turbidity and nutrient concentrations in Hong Kong's 1651 km^2 of coastal waters. The cold winter water temperatures thus render Hong Kong a marginal environment for the development of coral communities. Here corals do not grow into true reefs; they only form shallow fringing coral communities. Along the west-east direction, Hong Kong's coastal waters exhibit gradual transition from an estuarine zone to an

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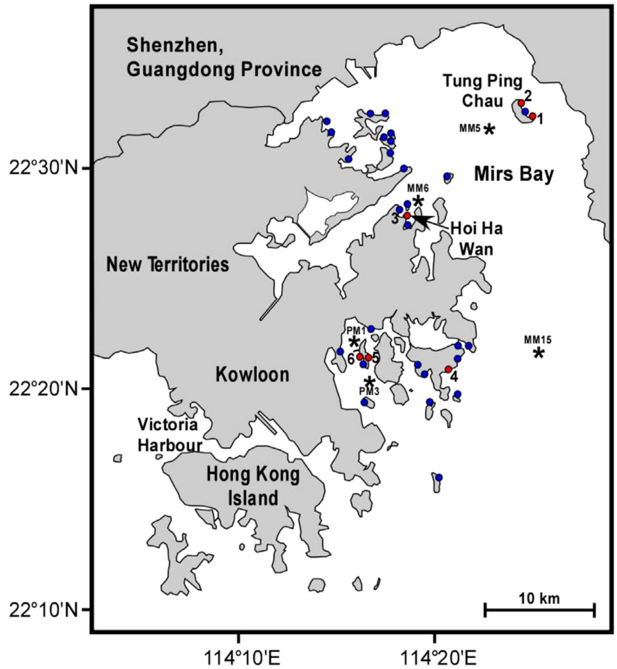

Fig. 1. Map of eastern Hong Kong showing the 33 coral communities surveyed in the summer of 2017; among these, six communities exhibited signs of bleaching which have been colored in red (1. A Ma Wan; 2. A Ye Wan; 3. Coral Beach; 4. Pak Lap Tsai; 5. Sharp Island East; 6. Sharp Island North). Five EPD water quality monitoring stations (PM1, PM3, MM5, MM6, MM15) that are closest to the identified bleaching sites are indicated by asterisks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

oceanic zone, with a transitional zone in the middle (Morton and Morton, 1983). Scleractinian corals are mostly restricted to the oceanic zones, although isolated colonies of a few species are also present in the transitional zone (Hodgson and Yau, 1997). Nevertheless, at least 84 species of scleractinian corals have been recorded from Hong Kong (Chan et al., 2005), which represent a significant percentage (88.4%) of the total number of scleractinian species recorded along the south-eastern coasts of China in Fujian and Guangdong Provinces (Huang et al., 2016).

The extent and impact of historical coral bleaching events in Hong Kong have not been well-documented (Morton, 1995; McCorry, 2002; Ang et al., 2005; Xie et al., 2017). Among the few coral bleaching sightings reported anecdotally since the 1980s, the impact was usually confined to only a few colonies in small areas. Only two coral bleaching events have been described quantitatively: McCorry (2002) reported a territory-wide event that occurred in the summer of 1997, whereas Xie et al. (2017) reported an event in the summer of 2014 in Port Shelter, a bay surrounded by land on three sides in the eastern waters (Fig. 1).

Given the prediction of the third global coral bleaching event in 2014–2017 (Eakin et al., 2016), the Agriculture, Fisheries and Conservation Department commissioned a study, which required frequent spot checking of local coral communities to discover coral bleaching, and to provide quantitative data on coral bleaching and recovery. Our hypothesis, based on the prediction that Hong Kong will become warmer in the 21th century with more very hot days, higher number of rain days and higher average rainfall intensity (Environment Bureau, 2015), was that Hong Kong's coral communities might also be affected by this period that included an El Niño. When our spot checking detected signs of bleaching in July 2017, we set out to conduct full-scale surveys across 33 major coral communities in local waters to determine the extent of the coral bleaching and the recovery of bleached colonies. We also hypothesized that NOAA's Coral Reef Watch product (Liu et al., 2006) could be applied to predict coral bleaching in subtropical Hong Kong. To test this hypothesis we checked the timing of coral bleaching and recovery during the 2017 event and historical bleaching events in Hong Kong against degree heating week (DHW) data generated by NOAA from remote sensing derived sea surface temperature data. Since local water quality parameters including salinity, dissolved oxygen and chlorophyll *a* have been suggested to be involved in previous bleaching events in Hong Kong (McCorry, 2002; Xie et al., 2017), along with temperature data we analyzed these water quality parameters, based on data collected by the Environmental Protection Department's marine water monitoring programme (http://epic.epd.gov.hk/EPICRIVER/marine). The results can form the basis of informed management of local coral communities, as well as contribute to the prediction of "winners and losers" of coral species around the world in responses to global climate change.

2. Materials and methods

2.1. The extent of coral bleaching

Our spot checking first detected bleaching at three sites in the Port Shelter area (Fig. 1) in July 2017. Thirty three sites with substantial coral cover (> 10%) in the eastern waters were then selected for survey of possible occurrence of coral bleaching in July and August 2017 (Fig. 1). At each site, a permanent 100-m transect was laid in a water depth (1–5 m) with the highest coral cover, marked by a steel stake with a numbered tag at 0 m, 20 m, 25 m, 45 m, 50 m, 70 m, 75 m and 95 m. The same two SCUBA divers were deployed to conduct quick underwater observation. When bleaching (obvious whitening of coral tissue) was observed at > 1% colonies, a more detailed quantitative survey was conducted using a video-transect method (Xie et al., 2017) along this permanent transect. A video footage covering 0.75 m × 100 m of the substrate was captured using a Canon G7X Mark II digital camera inside a WP-DC55 underwater housing at 24 frames per second and a resolution of at least 1920 × 1080 pixels.

In the laboratory, the video footages were played back and analyzed to quantify the substrate composition as well as the extent of coral bleaching using a Dot Grid method (Hill and Wilkinson, 2004). During playback, the video was paused every 4 s to register the type of substrates recorded under 5 points marked on the computer monitor. Each footage contained, on average, 500 video frames with a total of 2500 points used to calculate the substrate composition following the Reef Check's benthic substrate classification scheme (https://reefcheck.org/PDFs/RCCAmanual9thedition.pdf) as live coral, dead coral, rock, rubble, sand, or others (e.g., mud, sponge). Each live coral was identified to genus level and whether it showed any sign of bleaching or not was recorded. The Coral Health Chart of CoralWatch (Siebeck et al., 2006) was used to help determine whether colonies were bleached, by comparing the color of the darkest colony against the other colonies of the same species along the transect and ranking them based on color intensity from 1 to 6, where 1 is the lightest and 6 is the darkest. A score difference > 2 indicated that the colony suffers from bleaching. Percent cover of a particular substrate was determined as the number of points that overlaid that substrate divided by the total number of points counted (i.e. 2500 points). Percent cover for a particular coral genus irrespective of whether the coral was bleached or not was determined as the number of points that overlaid that genus divided by the total number of points that overlaid all coral genera on the computer monitor.

The video footages were also played back to identify and count the number of coral colonies that exhibited bleaching as well as to classify the level of bleaching for each colony (Fig. 2). Colonies > 10 cm in the longest dimension were identified to the genus level, counted and scored as no bleaching (without obvious bleaching); mild bleaching (< 1/3 surface area bleached); moderate bleaching (1/3–2/3 surface area bleached); severe bleaching (> 2/3 surface area bleached).

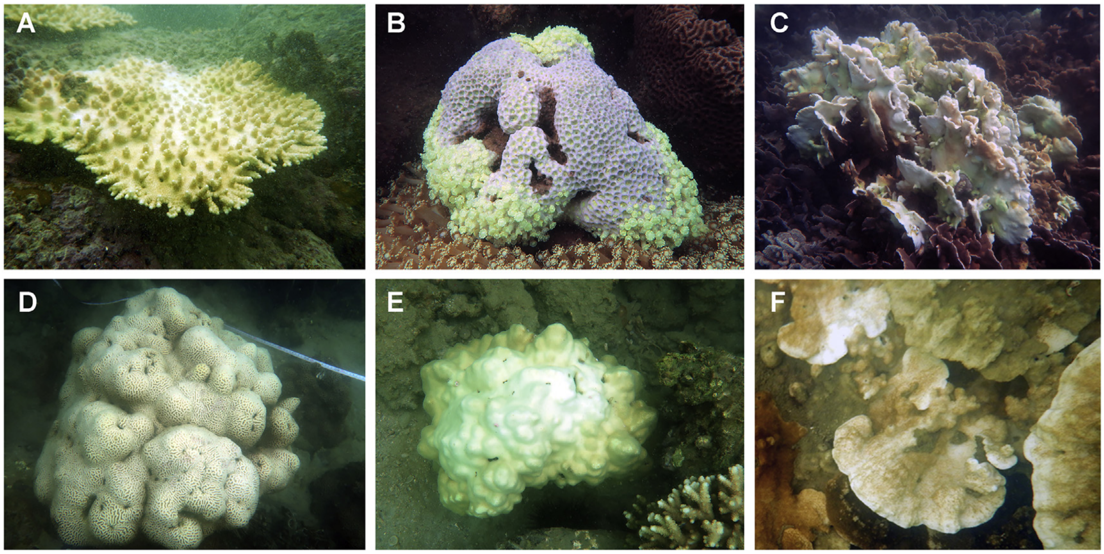

Fig. 2. Selected in situ photographs of coral species showing bleaching during the summer of 2017 in Hong Kong: (A) *Acropora solitaryensis,* (B) *Goniopora columna* (C) *Pavona decussata,* (D) *Platygyra carnosa,* (E) *Porites lutea,* and (F) *Montipora peltiformis*.
Photographs taken by J.Y. Xie.

2.2. Bleaching recovery

To quantify the impact of the bleaching event, a total of 200 bleached colonies from the six sites were selected for follow-up observation. Each selected colony was marked by a number tagged steel stake hammered partially into the substrate next to the colony, or by placing a numbered tag on the colony directly using a cable tie. The colonies were photographed and their GPS locations recorded immediately after the video-transect survey at the site. Three months later, these colonies were photographed again during revisit. In addition, a video-transect survey was also conducted for use in detection of possible change in substrate composition. In the laboratory, photographs taken during and after the bleaching event were compared side by side on a computer monitor to determine the level of recovery.

2.3. Environmental parameters

To understand the temperature conditions that might have triggered the observed coral bleaching in 2017, NOAA's Coral Reef Watch website (https://coralreefwatch.noaa.gov/satellite/index.php) was visited and the sea surface temperature and degree heating week (DHW) data corresponding to the remote sensing area that covered Hong Kong waters for 2007 to 2017 were downloaded. A DHW curve for this period was then plotted and the time points corresponding to our empirical observation of bleach and recovery were determined.

To understand the contribution of local water quality parameters to coral bleaching, the database from the Water Quality Monitoring Programme of the Environmental Protection Department (EPD) was consulted (http://epic.epd.gov.hk/EPICRIVER/marine). This database contains water quality data taken monthly from 90 marine stations around Hong Kong. Although several stations in this monitoring network are within the sites monitored for coral bleaching in the present study, these stations are mainly located in more open waters, rather than directly over or near the shallow-water coral communities. We selected stations PM1 and PM3 in Port Shelter (Fig. 1) which correspond to the bleaching sites Sharp Island East and Sharp Island West, MM5 in Mirs Bay which corresponds to the bleaching sites A Ye Wan and A Ma Wan in Tung Ping Chau, MM6 in Mirs Bay which corresponds to the bleaching site Hoi Ha Wan Coral Beach, and MM15 which corresponds to the bleaching site Pak Lap Tsai to provide clues about abnormal environmental conditions that might have prevailed before, during and after the bleaching incident in the summer of 2017. Four environmental parameters (salinity, water temperature, chlorophyll-*a* (Chl-*a*) and dissolved oxygen (DO) concentration) from 2007 to 2017 were downloaded from the website. These parameters were selected because they were previously linked to reported bleaching events in Hong Kong (salinity in 1997, Chl-a and DO in 2014). Measurements of these environmental parameters were taken from 1 m below sea surface, middle, and 1 m above seabed. For each parameter, two tailed *t*-test was performed between the July 2017 values and the averages of each other month in 2017, as well as between the July 2017 values and the values in 2007–2016. These tests allowed us to determine whether the July 2017 values were abnormal.

3. Results

Of the 33 sites surveyed, only six sites showed signs of coral bleaching, so these six sites were monitored more closely with respect to substrate composition, coral community structure, coral bleaching and recovery patterns, as well as the association between coral bleaching and water quality parameters.

3.1. Benthic substrate and level of coral bleaching estimated by the Dot Grid method

Live coral cover was high at five of the six sites, ranging from 34.6% at A Ye Wan to 94.0% at Coral Beach; but at Pak Lap Tsai, a relatively open site, live coral cover was only 18.6% (left panel in Fig. 3). Dead coral cover in general was low, ranging from 0.6% at Coral Beach to 12% at Sharp Island East. Rock cover varied substantially from 0.4% at Coral Beach to 69.4% at Pak Lap Tsai, and sand cover from 5% at Coral Beach to 32.2% at A Ye Wan.

The coral communities were characterized by high dominance by one to three genera (middle panel in Fig. 3). Specifically, Coral Beach was dominated by *Pavona* only (i.e. 98.9%). A Ma Wan and Sharp Island East were both co-dominated by *Pavona (*45.9–48.9%) and *Platygyra* (31.8–39.1%). A Ye Wan was co-dominated by *Platygyra (*37.6%) and *Porites* (40.5%). Pak Lap Tsai was co-dominated by *Acropora* (45.2%), *Montipora* (28.0%), and *Porites* (19.4%). Sharp Island North was co-dominated by *Pavona* (35.2%) and *Porites* (46.7%).

Bleaching was observed mainly in six of the common coral genera (*Acropora, Goniopora, Montipora, Pavona, Platygyra* and *Porites*) (Fig. 2).

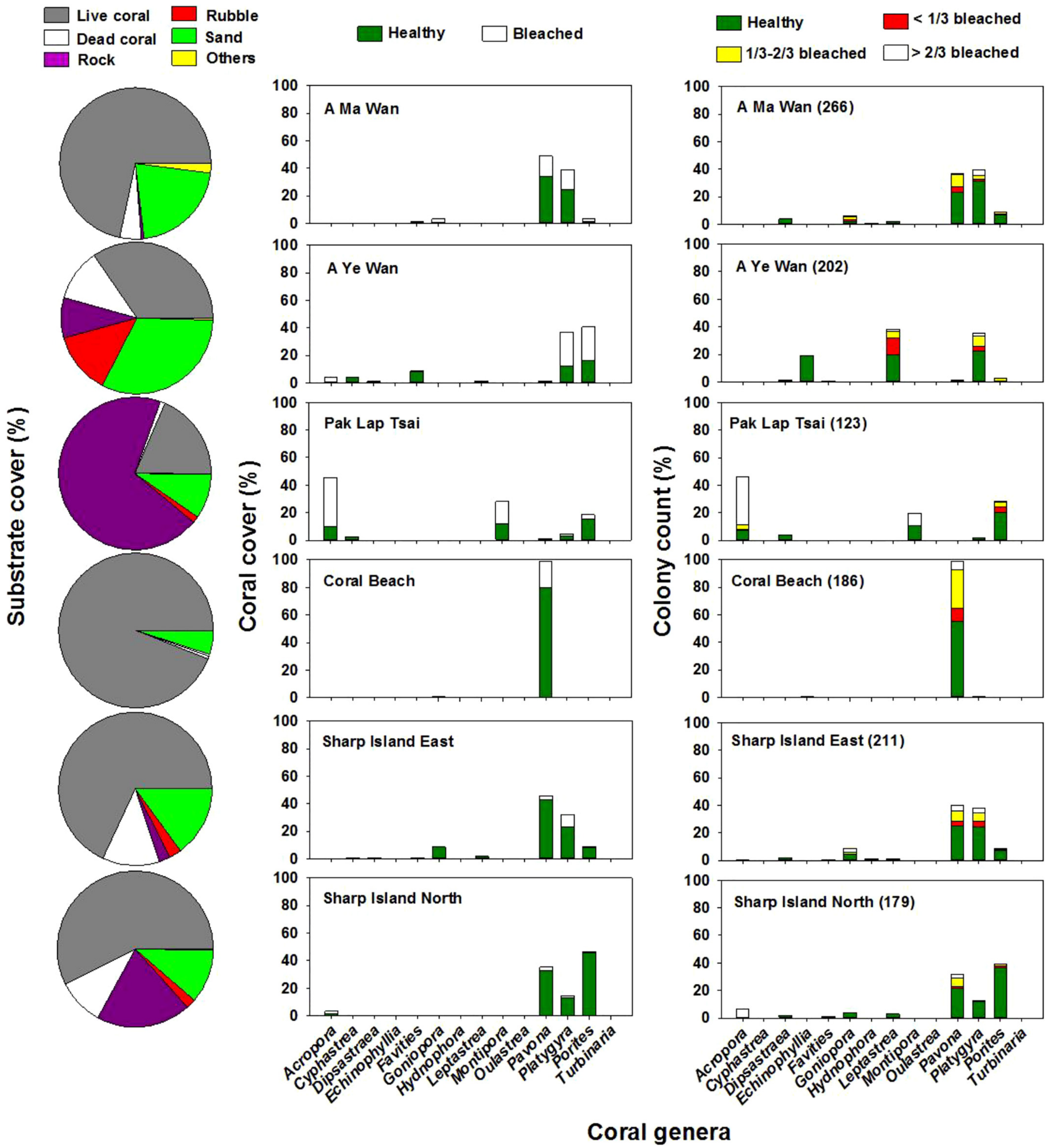

Fig. 3. Community composition and coral bleaching status at the six sites that were surveyed quantitatively during this study. The left panel shows the substrate composition. The middle panel shows the coral community composition by genera estimated using the 5-point method, with healthy and bleached surface area illustrated in green and white respectively. The right panel shows the coral community composition estimated by the colony count method, with healthy and bleached colonies shown in different colors. At each site, the total number of colonies scored is shown inside the parentheses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The level of coral bleaching varied substantially among the six sites (middle panel in Fig. 3). At Sharp Island North and Sharp Island East, bleaching was mild with bleached area accounting for only 5.9% and 13.0% of the total coral covered area respectively. Here, the bleached colonies were mainly *Pavona* and *Platygyra*. Coral Beach and A Ma Wan suffered from moderate coral bleaching, with a value of 19.4% and 34.9% respectively. Since Coral Beach was dominated by *Pavona*, the percent cover of bleached corals was mainly contributed by this genus. In comparison, *Platygyra* (14.8%) and *Pavona* (14.5%) contributed most heavily to the total bleached coral area in A Ma Wan. A Ye Wan and Pak

Lap Tsai suffered from moderate coral bleaching. At A Ye Wan, *Platygyra* (25.0%) and *Porites* (24.4%) were responsible for most of the total of 54.7% of the bleached coral area. At Pak Lap Tsai, *Acropora, Montipora* and *Porites* were responsible for 35.9%, 16.3% and 3.3% of the 57.6% of the bleached coral covered area, respectively.

3.2. Community characteristics and bleaching estimated by the colony count method

Coral community composition was also quantified by the colony count method (right panel in Fig. 3). Coral Beach was absolutely dominated by *Pavona*, which accounted for 99.5% of the total number of colonies. A Ma Wan and Sharp Island East were co-dominated by *Pavona* (36.8% and 46.9% respectively) and *Platygyra* (39.5% and 44.7% respectively). A Ye Wan was co-dominated by *Leptastrea* (38.5%), *Platygyra* (35.1%) and *Echinophyllia* (19.3%). Pak Lap Tsai was co-dominated by *Acropora* (46.3%), *Montipora* (19.5%), and *Porites* (28.4%). Sharp Island North was co-dominated by *Pavona* (31.8%) and *Porites* (39.1%). Overall, the coral head count method and the Dot Plot method gave a very similar result at five of the six sites.

There was substantial variation in coral bleaching among the six sites (right panel in Fig. 3). Sites suffered from mild bleaching included Sharp Island North and A Ma Wan, with 21.2% and 28.9% of bleached colonies, respectively; here the bleached colonies were mainly *Pavona, Platygyra* and *Porites*. However, at Sharp Island North all 12 colonies of *Acropora* also bleached. At the other four sites, coral bleaching was moderate to severe. At Sharp Island East, 36.5% of the colonies were bleached, and the affected colonies mainly belong to *Pavona* (15.2%), *Platygyra* (13.7%) and *Porites* (7.1%). At A Ye Wan*,* 34.5% of the colonies were bleached, in which *Platygyra* (12.0%) and *Leptastrea* (18.5%) contributed most heavily to the total number of bleaching colonies. At Pak Lap Tsai, *Acropora, Montipora* and *Porites* was responsible for 39.0%, 8.9% and 8.1% of the 56.1% of bleached colonies, respectively. At Coral Beach, bleaching affected 43.5% of the colonies, essentially *Pavona*.

Comparing the results of the two survey methods showed that they provide complementary information about coral bleaching. For instance, at Pak Lap Tsai where most of the bleaching was caused by *Montipora*, the area cover data showed that this genus accounted for ~32% of the overall coral substrate at the site, and ~ 62% of the area covered by *Montipora* suffered from bleaching. The colony count data, on the other hand, showed that there were only 20 *Montipora* colonies along the surveyed transect, and that a majority of them suffered from at least some level of bleaching. Putting these two set of data together (20 colonies accounting for 32% coral area cover), we can infer that these colonies were big ones, and therefore, despite the small number of colonies, their death after bleaching may have disproportionally large impact on the coral community structure at this site.

3.3. Bleaching observation

A total of 200 bleached colonies were tagged at the six sites immediately after the video-transect survey in July–August, and observed three months later for their recovery. During the revisit 143 of the tagged colonies were found. Among them, 132 had fully recovered, including 38 colonies of *Platygyra*, 35 colonies of *Acropora*, 41 colonies of *Pavona*, 11 colonies of *Porites*, 5 colonies of *Goniopora*, and 2 colonies of *Leptastrea*. The colonies that were found dead included 3 *Acropora*, 2 *Goniopora*, 3 *Pavona*, 1 *Porites* and 2 *Platygyra*. No partially recovered colonies were found. Overall, at five of the six sites the corals appeared to have recovered well, with over 93% colonies fully recovered. At Pak Lap Tsai where the corals had a moderate recovery rate of 70%. The dead corals at Pak Lap Tsai were all large plate-like *Acropora solitaryensis.*

Failure to find the tagged colonies might be a function of the loss of tags cable-tied to coral colonies due to coral breakage, or loss of the steel stakes together with the tags, making it difficult to determine the status of coral recovery. Both could have occurred, but unfortunately in most of the sites we could not determine which was the case. Comparing the transect videos taken during the bleaching event and the revisit three months later did not show obvious changes in coral community composition at five of the six sites (Qiu et al., 2019). However, at Pak Lap Tsai, the contribution of plate-like corals to the total coral covered area had declined, from 45.2% during the bleaching event to 29.0% during the revisit for *A. solitaryensis* and 28.0% to 22.6% for *Montipora peltiformis.*

3.4. Environmental conditions

Data from NOAA's Coral Reef Watch (Supplementary Fig. S1) for the area that covers Hong Kong waters showed that, in most years from 2007 to 2017, except 2013, there was a period in summer that exceeded 4 °C-weeks, a threshold that is likely to trigger bleaching in tropical waters (Liu et al., 2006; Eakin et al., 2016, 2018). Nevertheless, over this 11-year period, substantial bleaching, and in general good recovery, have been found only in the Port Shelter area in 2014 and the six sites across eastern Hong Kong waters in 2017. The summer of these two years indeed showed the highest abnormal temperatures, with DHW values exceeding 8 °C-weeks, a threshold that is generally consider to result in widespread bleaching and mortality in tropical waters (Liu et al., 2006; Eakin et al., 2016, 2018), for around 4 months in 2014 and around 5 months in 2017. Overall, these data appear to indicate that Hong Kong corals are in general resistant to heat stress. The fact that in July 2017, when coral beaching was first discovered, the DHW values were only 2 °C-weeks may indicate that factors other than temperature, as we will discuss below, might be the main trigger for the bleaching event. Furthermore, our observation that, in October when DHW reached its peak of > 12 °C-weeks, most bleached colonies have recovered may also infer that local corals are resistant to heat and this stressor might not be the main contributing factor to the 2017 bleaching event in Hong Kong.

Data from five EPD monitoring stations were also examined to understand the environmental parameters that might have affected local corals (Supplementary Table S1). Since the trends was very similar across the five sites, the data from PM3 in the middle of Port Shelter were presented in a figure to illustrate the monthly changes of the four parameters in the different water depths in 2017 (Fig. 4). At all these stations, as shown by the data from PM3, during July–August 2017 when the bleaching occurred, there was an obvious thermocline, with the surface water (27.2–29.8 °C) being substantially warmer than the bottom water (22.3–27.6 °C). However, this thermal stratification phenomenon occurs every year in Hong Kong. Dissolved oxygen varied slightly during most of the months in 2017, but in July there was a notable difference between the surface (6.3 mg/L) and bottom (1.1 mg/L) readings, indicating hypoxia in the bottom water. Nevertheless, the same hypoxia condition also developed years when no bleaching was reported, and thus was not a likely cause of bleaching in 2017. *Chl-a*, a parameter indicating water column productivity, varied between 1.1 and 1.4 mg l^{-1} in 2017; there was no indication of algal bloom preceding or during the bleaching event. Salinity changed only very slightly throughout most months of 2017 with only minor differences between the surface and bottom values; however in July there was a huge difference between the surface (average of 22.6 psu across 5 stations) and bottom (31.1 psu across 5 stations) salinity values, indicating substantial dilution of the surface water and development of a pycnocline in the water column.

Consistent with our visual inspection of the environmental data, two-tailed *t*-test showed that the surface and mid-water salinity values in July were significantly lower than those in other months of 2017 across the five sites, and were significantly lower than the salinity values in July of all other years from 2007 to 2016 ($P < 0.05$; Supplementary Table S2). No significant difference was detected for Chl

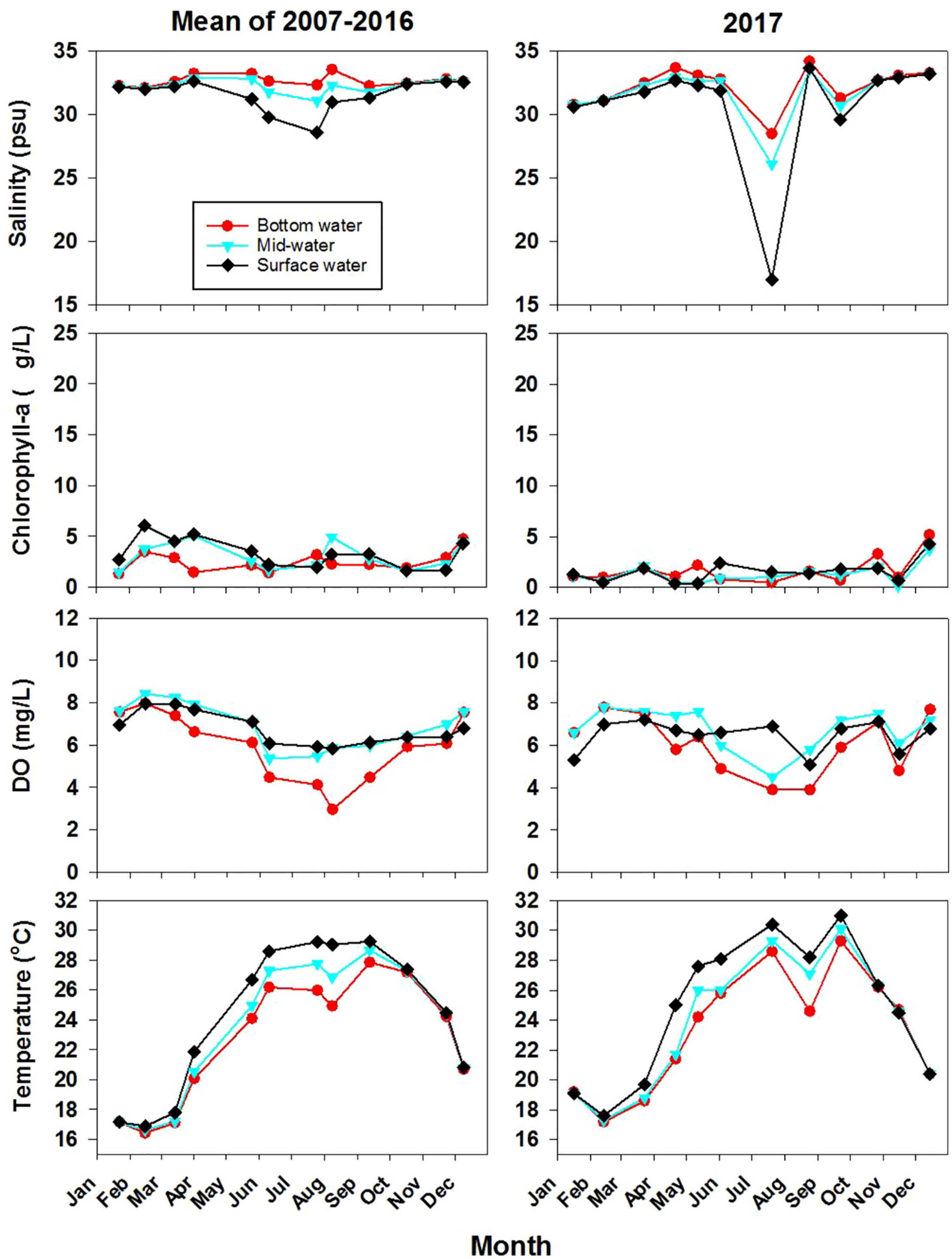

Fig. 4. Comparison of monthly changes in four environmental parameters between 2007 and 2016 and 2017 in the water column of EPD water quality monitoring station PM3 inside Port Shelter.

a and DO between July 2017 and July 2007–2016, as well as salinity or any other parameters between other months of 2017 and 2007–2016 (Supplementary Table S2). As expected, however, in July the temperatures were higher than the temperatures in winter months, but July was not the month with the highest temperatures (Supplementary Table S1).

4. Discussion

4.1. Patterns and possible causes of the bleaching in 2017

In this paper we documented the coral bleaching and recovery occurred in 2017 in Hong Kong's subtropical coral communities. Bleaching was first observed in July. Subsequent visits to the 33 sites (Fig. 1) revealed only six sites with obvious signs of coral bleaching, with 18.7% to 56.1% bleached colonies and 5.9% to 57.6% bleached coral covered area. These sites spread across the northeastern and eastern waters, which did not seem to correspond to a clear environmental gradient. Among the six sites, five are located in either protected bays (Coral Beach, Sharp Island East, Sharp Island North), or the more protected concave side of Tung Ping Chau (A Ma Wan, A Ye Wan) (Hodgson and Yau, 1997), indicating insufficient water exchange with the open ocean might have created stressful conditions for the corals. At these sites that are relatively protected from tidal surges and wave actions, the dominant corals are the massive *Platygyra* and *Porites*, as well as the submassive *Pavona* with upright laminae, and most of the bleached corals also belonged to these three dominant genera. At these protected sites, branching corals, mainly *Acropora digitifera* and *Acropora pruinosa*, are uncommon (14 colonies in total), but they suffered from a disproportionately high percentage (85.7%) of bleaching. It is unknown why corals at Pak Lap Tsai, a relatively open site, also suffered from bleaching. This site has a relatively high percentage of rock substrate, and the community is unique in that it is co-dominated by the plate-like *A. solitaryensis* and *M. peltiformis*; these plate-like corals were responsible for most of the beaching at this site.

While it is unknown why only corals at the six sites bleached, the timing of the bleaching event (July–August) and high precipitation during the summer time in Hong Kong indicates water temperature and salinity might have played a role in triggering the bleaching. However, both the monthly mean air temperature preceding and during the bleaching event deviated only slightly from the 1981–2010 normal value (+0.9 °C in June, −0.15 °C in July and +0.6 °C in August) (http://www.hko.gov.hk/cis/climat_e.htm), indicating high temperature during the summer time might not be the triggering factor for the bleaching event. In fact, surface water temperatures and water column stratification in the summer of 2017 did not seem to differ substantially from those in 2007 to 2016 (Fig. 4). On the other hand, there was much heavier precipitation during the period from June to August (1751 mm) in 2017 than the mean monthly rainfall for this period between 2007 and 2016 (1183.8 mm); and the value in 2017 was 38% higher than the 1981–2010 mean precipitation in these three months. The heavy rainfall, which brought the surface water salinities down to as low as 19 psu in some stations could have created a hyposaline stress leading to coral bleaching. Overall, the EPD data indicated that low salinity might be the main triggering factor for the bleaching event, although we should be cautious about the interpretation because the data were taken only on monthly intervals and thus might not have captured short-term abnormal environmental conditions.

Degree Heating Week (DHW) has been widely used to predict the bleaching hotspots around the world (Liu et al., 2006; Eakin et al., 2016, 2018), but their applicability in subtropical reefs of Hong Kong have not widely validated. Our observation that Hong Kong corals are quite resistant to thermal stress as they were recovering in October 2017 when DHW reached > 12 °C-weeks, well exceeding 8 °C-weeks that are known to cause widespread bleaching and mortality in tropical reefs. The fact that in July when the beaching was first discover, DHW was only 2 °C-weeks, a value that did not to trigger bleaching in most years over the last decade, also indicated heat stress might not be the causal factor for the 2017 bleaching event in Hong Kong.

4.2. Comparison with previous bleaching events in Hong Kong and elsewhere

The coral bleaching occurred in 2017 in Hong Kong was less extensive than the one reported in 1997 by McCorry (2002). Among the nine sites visited, McCorry (2002) found total mortality of corals at one site, and severe bleaching at six sites, which affected 15 genera of corals with different growth forms. The 1997 bleaching event coincided with a prolonged period of heavy rainfall (i.e., 2359 mm in June–August) which brought the surface water salinity at some locations down to 19 psu in some locations (McCorry, 2002). Meanwhile, the surface water temperature values collected by EPD during the bleaching event were below the long-term mean, and the bottom dissolved oxygen levels were similar to the corresponding values in the summer of 1996 and 1998. Based on the analysis of climate and water quality data, McCorry (2002) concluded that the 1997 bleaching event was caused by low salinity, rather than other environmental conditions including high summer temperature that is known to have resulted in coral bleaching in several other high-latitude coral communities (Cook et al., 1990; Hagman and Gittings, 1992).

Xie et al. (2017) reported a summer bleaching in Hong Kong that occurred in 2014, but it was less extensive than the one in 2017, impacting coral communities in the Port Shelter area only. Among the eight sites they surveyed, seven experienced only minor bleaching (0.8–10.0% coral covered area and 0.4–5.2% colonies). Only at Sharp Island East was the bleaching moderate, with 30.6% bleached coral covered area and 13.1% colonies. The triggering factors for the bleaching in 2014 was unclear (Xie et al., 2017), but could involve abnormal environmental conditions preceding the event (heavy rainfall) and during the event (high temperature, high algal biomass and hypoxia).

The three bleaching events in Hong Kong were all related to abnormal global climate phenomena. In 1997–1998 a strong El Niño developed, with many reefs across the tropics experiencing the hottest water in the 20th century in the summer of 1998, leading to mass coral bleaching (Wilkinson, 1998). The 2014–2017 global coral bleaching event was unprecedented due to its long duration as well as its extent of coral damage, affecting 51% of coral reefs around the world (Eakin et al., 2016, 2018). Bleaching-level heat stress started in 2014, reaching a peak during the El Niño in 2015 and 2016, and extending into early 2017. Although in many places heat stress was the main cause of coral bleaching (Hughes et al., 2017), other stressors, which might interact with high temperature, could have a stronger impact on corals. For instance, Ampou et al. (2017) found that the 2015–2016 El Niño that caused a fall in sea surface level, which exposed shallow-water corals to air, was the main stressor for corals in Indonesia, resulting in as much as 85% coral mortality on some reef flats. Bahr et al. (2015) and Cunning et al. (2016) reported that both abnormal precipitation and temperature conditions contributed to the 2014 coral bleaching event in Kāne'ohe Bay, Hawaii. Heavy rainfall in the early summer reduced 22.5% of the coral cover in a shallow area of Kāne'ohe Bay, and later high temperatures in Autumn caused additional 60.0% reduction in coral cover in the area. Therefore multiple environmental factors need to be accounted for in order to determine the susceptibility of subtropical coral communities to climate change.

4.3. Bleaching recovery

Whether bleached corals can recover depends on the severity and duration of the stress, as well as the resilience of the coral. Our follow-up observation of tagged colonies showed that only 0–6.7% of the colonies died at the five relatively enclosed study sites, indicating that local massive (*Platygyra, Porites*) and submassive (*Pavona*) corals are resilient to bleaching. Unfortunately, the plate-like *M. peltiformis* and *A. solitaryensis* in the more open Pak Lap Tsai suffered from a moderate level of mortality, indicating these species might be more susceptible to bleaching. Such a differential mortality between growth forms following the bleaching event may have consequences on coral dominancy pattern in local waters. Perhaps due to their higher susceptibility to environmental stressors including flooding as well as recreational activities (Au et al., 2014), branching corals have become very rare in recent decades (Morton, 1995), and plate-like corals are now restricted to only a few eastern locations (i.e., Pak Lap Tsai, High Island Dam and Bluff Island) that are relatively open and thus may experience smaller fluctuation in environmental conditions. In fact, McCorry (2002) reported that *A. pruinosa* and *M. peltiformis* were the most susceptible species during the 1997 bleaching event. Both Hodgson and Yau (1997) and McCorry (2002) showed that *M. peltiformis* was quite common at Tung Ping Chau and Sharp Island until 1990s, but it is now very rare in these and other relatively protected locations, based on quantitative substrate surveys conducted in recent years (Dumont et al., 2013; Qiu et al., 2014; Xie et al., 2017; This study).

4.4. Mechanisms behind growth-form differences in bleaching susceptibility and management implications

Field observations during bleaching events in Okinawa have shown that coral morphology is associated with their differential resistance to bleaching (Fujioka, 1999; Kayanne et al., 1999; Loya et al., 2001), with branching species suffering from more severe bleaching and higher bleaching mortality than massive and encrusting species. Loya et al. (2001) found that massive and encrusting corals have thicker tissues, and hypothesized that these species can retract their tissues during stress and thus are less susceptible to bleaching. In addition, they proposed that the thick-tissued species have higher mass-transfer capacity that will allow more efficient removal of oxidative radicals produced during stress, therefore promoting coral health. Putnam et al. (2017) further proposed that the thicker tissues provide a greater spatial and temporal variations in physiochemical parameters, therefore may allow massive corals to enhance their tolerance to adverse environmental conditions through priming.

Consistent with the above observations and hypotheses, our study reveals that massive and submassive coral species in Hong Kong are more resistant by showing high bleaching recovery rates. Since these growth forms dominate most of Hong Kong's coral communities, one may infer that local coral communities are resilient. Nevertheless, the moderate death rate of the bleached plate-like corals at Pak Lap Tsai should not be overlooked. Since the affected plate-like species were usually large and the substrate at Pak Lap Tsai was already dominated by rocks, the death of these colonies was alarming. Given that Hong Kong's climate is becoming warmer and wetter with more extreme rainfall events in the 21st Century (www.epd.gov.hk/epd/english/climate_change), a long-term coral monitoring programme should be established to provide continuous records of environmental parameters in the coral communities, and track the spatial and temporal changes in health status and community structure of local corals. Moreover, because local corals have already faced various threats including coastal development (Morton, 1995; Hodgson and Yau, 1997; Ang et al., 2005), nutrient pollution (Duprey et al., 2016), bioerosion (Qiu et al., 2014; Xie et al., 2016) and abnormal coral growth (Chiu et al., 2012; Sun et al., 2013; Zhang et al., 2017), and recreational activities (Chung et al., 2013; Au et al., 2014), studies should be conducted to understand how such stressors may interact with bleaching to compromise the coral health, and whether regulating certain human activities at marine parks during severe bleaching events (Yeemin et al., 2012), can lessen the impact of bleaching.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Author statement

JWQ, WKC, KK, LLC and PA designed the study, JYX, YHY and CKK conducted field surveys, JYX and JWQ drafted the manuscript, all authors edited the manuscript and approved it for publication.

Appendix A. Supplementary data

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