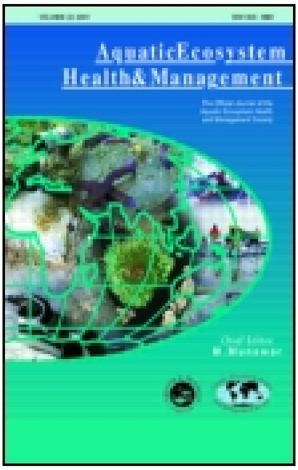

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Coral bleaching caused by an abnormal water temperature rise at Luhuitou fringing reef, Sanya Bay, China

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Coral bleaching caused by an abnormal water temperature rise at Luhuitou fringing reef, Sanya Bay, China

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Luhuitou fringing reef, which has been seriously affected by human activities and terrestrial runoff, has degraded quickly in recent decades. However, direct impact by hyperthermal stress has probably been minimal because of the influence of the Qiongdong upwelling in summer. Seawater temperature anomalies in 2010 resulted in mean monthly seawater temperatures in summer to be 1–2°C higher than in the same period of the 3 preceding years. Moderate coral bleaching at Luhuitou fringing reef was observed in the summer of 2010 due to high thermal stress. Montipora *was the most susceptible taxon, whereas* Galaxea fascicularis *and* Pocillopora damicornis *were among the least susceptible taxa. Mortality of* Montipora *was 21.7%, whereas for the remaining taxa it was less than 5%. No mortality was observed for tabular* Acropora, G. fascicularis, P. damicornis, Favites *and* Leptoria. *Most taxa showed relatively high bleaching in larger colonies compared with that in smaller ones. Juvenile coral colonies showed less bleaching (3%) than adult coral colonies (28%). Our study suggested that although most taxa in the survey area might recover from this moderate coral bleaching episode, coral reproduction in the year following bleaching may be adversely affected.*

Keywords: high thermal stress, Qiongdong upwelling, coral community, Sanya, Hainan Island, mortality, juvenile coral, coral recovery, temperature anomaly

Introduction

Global warming is an obvious fact at present. Sea surface temperature (SST), which has increased by about 0.5°C during the past 100 years (IPCC, 2007), is considered as the major threat to coral reefs (Wilkinson, 2008). Coral bleaching, in association with elevated sea temperatures over the past 20 years, has caused significant losses of live coral in many parts of the world (Hoegh-Guldberg, 1999). According to the National Oceanic and Atmospheric Administration, the first eight months of 2010 matched 1998 as the hottest January to August period on record (NOAA, 2010). Extensive coral bleaching in the Indian Ocean and throughout Southeast Asia was observed in 2010 (Dennis, 2010).

The Luhuitou fringing reef, located in Sanya Bay, Hainan Island, P. R. China, is an important ecosystem with high biodiversity. The corals at this reef

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have been severely damaged by human activities, and biodiversity has declined during the last few decades (Zhang et al., 2006). Coral cover decreased from 80–90% in the 1960s, to 30–40% in 1990s, and further to 11% in 2007 (Zhao, 2008). Human activities, such as reef block mining and curio collecting, destructive fishing and overfishing, as well as terrestrial runoff in the form of sedimentation, inorganic nutrients and other pollutants from coastal land and marine farms, caused the rapid deterioration of Luhuitou fringing reef (Shi et al., 2008). However, no coral bleaching at this reef in association with high thermal stress is recorded in the literature.

From 1961 to 1999, the average annual SST in Sanya Bay was 26.9°C. The average monthly SST reached a maximum of 29.5°C between May and September, and a minimum of 23.2°C between December and February (Shi et al., 2003). Long-term SST monitoring showed a rising trend of 0.17°C per decade during 1960–2002 at the Yinggehai oceanic hydrological station, 90 km from Luhuitou fringing reef. Huang et al. (2003) reported that Sanya Bay was affected by a cold-water upwelling (Qiongdong upwelling) and a clear thermocline was recorded during June–August. The strong Qiongdong upwelling (QDU) regions are located along the east coast of Hainan Island from the south of Sanya to the west of the Qizhou Archipelago (Jing et al., 2009). No coral bleaching episode has been reported in association with high thermal stress at Luhuitou fringing reef before 2010 (Shi et al., 2003; Zhang et al., 2006).

At Luhuitou fringing reef, coral bleaching was observed for the first time on July 10, 2010. Because the study site lies in the upwelling zone, this investigation provides a case study to better understand whether upwelling zones protect reefs from rapid temperature rise. This study also investigated the bleaching response of different coral taxa and size groups to thermal stress, and the potential effect of the coral bleaching episode on coral community structure at Luhuitou fringing reef.

Methodology

Study sites

The study area was located at the Luhuitou fringing reef in Sanya Bay. The survey sites were away from the mouth of the Sanya River, about 1.6 km for site 1, 3.5 km for site 2 and 4.7 km for site 3 (Figure 1). Site 1 and site 2 were wave-protected areas, whereas site 3 was wave-exposed and far away from human habitation. The seawater was turbid at sites 1 and 2 with the transparency mostly between 2 to 3 m, whereas site 3 was relatively clear for inshore waters with a 3 to 5 m transparency.

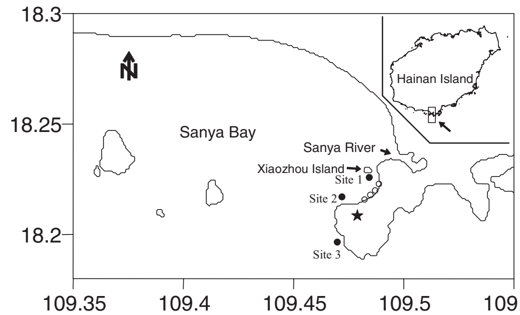

Figure 1. Location of the study sites at Luhuitou fringing reef. Bleaching surveys were conducted at sites 1 and 2. Solid circles indicate study sites. Open circles indicate human habitation around Luhuitou fringing reef. Star indicates the Tropical Marine Biological Research Station in Hainan, Chinese Academy of Sciences.

Temperature measurement

To measure seawater temperature, Hobo water temperature loggers (U22-001) were employed at site 1 from January 2010, site 2 from April 2007 and site 3 from April 2010 at 3 m depth. Site 3 was selected as a seawater temperature reference site. The seawater temperatures at site 2 during 2007–2009 were used to make comparisons between bleaching years and non-bleaching years.

Bleaching survey

There was no visible coral bleaching at site 3. Hence, bleaching surveys were conducted at sites 1 and 2 only. According to the coral bleaching, the investigation depth for adult coral colonies ranged from 1.5 to 4.5 m at site 1, and 1.5 to 3 m at site 2.

A single, simple and cost-effective system was used for monitoring bleaching. The system is based on haphazardly selecting coral colonies and categorizing them into seven categories of coral bleaching: normal, pale, 0–20%, 20–50%, 50–80%, 80–100% bleached and recently dead, as described in McClanahan et al. (2007). Corals, which had white exposed skeletons with no living tissue on the surface, were considered as recently dead (McClanahan, 2004). The mortality rate was calculated from the percentage of recently dead coral colonies. Bleaching responses (BRs) by taxa were calculated as weighted averages based on the percentage of colonies in each of the seven categories of bleaching intensity (McClanahan et al., 2007). A site-specific bleaching susceptibility index (BSI) was determined from the taxon-specific BR and multiplying this response by its relative density, summing for all taxa at the site, and dividing by the number of taxa (McClanahan et al., 2007). Most of the abundant corals were identified to genus level (except *Galaxea fascicularis* and *Pocillopora damicornis*). All colonies were allocated to one of four size classes (5–9.9 cm, 10–19.9 cm, 20–29.9 cm and ≥30 cm). A total of 1017 colonies at site 1 and 746 colonies at site 2 were surveyed during 10–14 August 2010, which was about 1 month after the beginning of coral bleaching, observed on 10 July 2010. Site 1 and site 2 were revisited qualitatively on September 2010 to check coral recovery and some thermally stressed colonies were photographed.

The bleached colonies and density of juvenile corals were investigated by a visual census method (Edmunds et al., 1998) at sites 1 and 2. At each site, four 10-m transects were laid out parallel to the shoreline at 3 m depth. The distance between transects was at least 5 m. Juveniles (0.4 cm ≤ diameter ≤ 5 cm) were carefully counted in at least eight random quadrants (0.5 m × 0.5 m) along each 10 m transect. A total of 84 juvenile colonies at site 1 and 98 colonies at site 2 were surveyed.

Results

Temperature anomaly

During 2007–2010, the seawater temperature at Luhuitou fringing reef varied from 19.9°C to 33.4°C. In general, low mean monthly seawater temperatures were observed in August during 2007–2009 (Figure 2a), whereas clear increases in seawater temperature occurred in August 2010. Compared with the 3 preceding years, such temperature anomalies began from May 2010 and the monthly mean seawater temperatures increased by about 2°C at sites 1 and 2, and 1.5°C at site 3 in August 2010 (Figure 2b).

In 2010, the seawater temperature varied greatly among sites (Figure 2b). During April to September 2010, the average daily seawater temperature at site 1 (28.5 ± 1.4°C, mean ± SE) was significantly higher than at site 3 (28.3 ± 1.3°C) (n = 169, p = 0.028), whereas there were no significant differences between site 1 and site 2 (28.4 ± 1.3°C) or between site 2 and site 3 (n = 169, p > 0.05). Coral bleaching at site 1 and 2 was observed on July 10, 2010 (Figure 3). However, no visible coral bleaching was observed at site 3. Extremely high seawater temperature (greater than 32°C) occurred in 2010 and lasted 17 days, 1 day and 0 days at sites 1, 2 and 3, respectively. The extremely high seawater temperature appeared mostly during low tides ranging from 105 cm to 8 cm in the late afternoon. Water exchange capacity decreased during ebb tides, and this exacerbated the seawater temperature anomalies on some hot days.

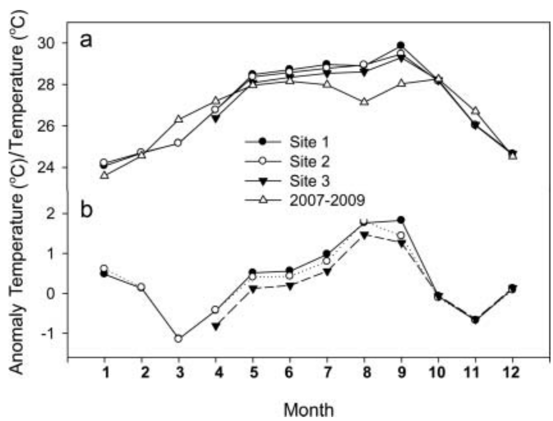

Figure 2. (a) Monthly means of seawater temperature (°C) at a depth of 3 m at site 1 to site 3 in 2010, and average of the 3 preceding years (2007–2009) at site 2. (b) Anomalies in 2010 monthly seawater temperature (°C) compared with the mean seawater temperature of the 3 preceding years (2007–2009).

Coral bleaching

The visible coral bleaching area was about 5000 m^2 at site 1 and 3000 m^2 at site 2. The visible bleaching depth ranged from 1.5 to 4.5 m at site 1, and 1.5 to 3 m at site 2 during high tides. The bleaching susceptibility index (BSI) was slightly higher at site 1 (2.0%) than at site 2 (1.8%). *Montipora* was the most susceptible taxon, whereas *G. fascicularis* and *P. damicornis* were the least susceptible, with bleaching responses (BRs) of 50%, 9.3% and 7%, respectively (Figure 4). BRs of other taxa ranged from 11.7 % to 27.4%. The mortality for *Montipora* was 21.7%, whereas it was less than 5% for the remaining taxa. No mortality was observed for tabular *Acropora* (ACT), *G. fascicularis*, *P. damicornis, Favites*, and *Leptoria*.

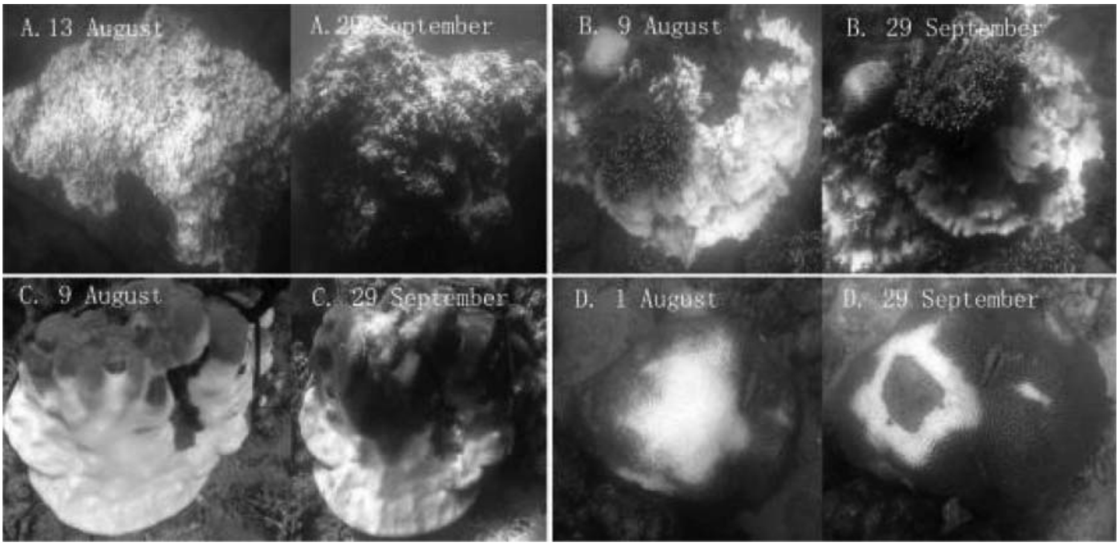

Figure 3. Photographs of thermally stressed colonies. Site 1: A. *Montipora*; Site 2: B. *Montipora*, C. *Porites* and D. *Platygyra*.

There were significant correlations between BRs among adult colonies and the four size classes for the 11 abundant taxa with relative abundances above 1% ($p < 0.05$). However, no significant difference among the four size-specific BRs was observed ($P > 0.05$). This indicated that size specific susceptibility among taxa to the seawater temperature anomaly varied inconsistently. Most taxa (e.g. *Platygyra*, branching *Acropora* (ACB), ACT, *Leptoria*, *Favia*, *Favites* and *Porites*) showed relatively higher BRs in large size classes. However, relatively higher BRs in small size classes were found in *Montipora* and *Goniastrea*, and relatively lower BRs in medium size classes in *G. fascicularis* and *P. damicornis*.

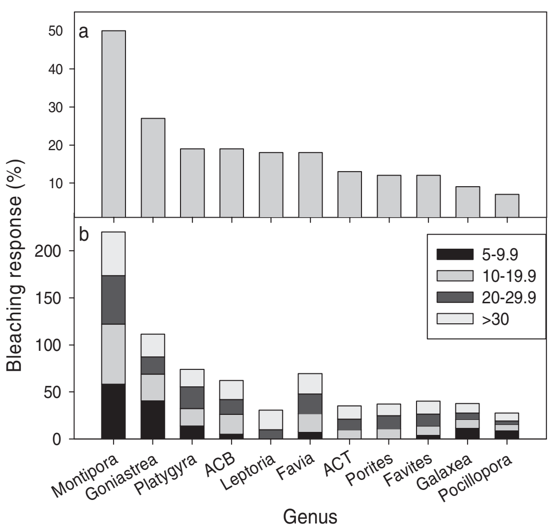

Figure 4. The bleaching responses in combined data from sites 1 and 2 for the 11 most abundant taxa. (a) taxa-specific responses; (b) size (cm)-specific responses. ACB: branching *Acoropora*; ACT: tabular *Acoropora*.

The density of juvenile corals was 10.5 colonies m^{-2} at site 1 and 12.3 colonies m^{-2} at site 2, with no significant differences between them ($n = 4$, $P = 0.546$). The percentage of bleaching for juvenile coral colonies (3%) was lower than the adult coral colonies (28%).

Discussion

Temperature anomaly and the cause of coral bleaching

Some studies suggested that upwelling areas are possible refuges for reefs, because they are protected from rapid temperature rise (Glynn, 1996; Riegl and Piller, 2003). However, Chollett et al. (2010) suggested that upwelling areas do not guarantee refuge for coral reefs in a warming ocean. Upwelling can only provide defense against warming events if: (1) the threat and the upwelling coincide, and (2) this overlap produces a meaningful decrease in thermal stress in upwelling areas (Chollett et al., 2010). The strong QDU occurred in summer (July and August) and could influence Sanya sea areas (Jing et al., 2009). Moreover, the low mean monthly seawater temperatures in August 2007–2009 at Luhuitou fringing reef were probably caused by the strong QDU. This suggested that QDU is in accord with the two assumptions and might play an important role in cooling down seawater temperature at Luhuitou fringing reef in summer. The above viewpoint was also indirectly supported by the long-term SST data that shows a rising trend mostly in spring and winter, rather than summer (Zhao, 2008).

1998 is considered as the most severe coral bleaching year in history in Southeast Asia (Hoegh-Guldberg, 1999). However, the QDU was significantly strengthened in the summer of 1998 as a result of the dramatically enhanced long-shore wind stress over the region (Jing et al., 2011). The NOAA/NESDIS coral bleaching hotspot in 1998 also showed that low temperature areas were observed along the east coast of Hainan Island in summer. No bleaching warning (hotspot $\geq$1°C) was observed along the inshore areas of Sanya Bay (http://www.osdpd.noaa.gov/ml/ocean/cb/hotspots_1998.html). The results indicated that Luhuitou fringing reef was protected by the QDU from high thermal stress in the summer of 1998. This might partly explain why no coral bleaching due to high thermal stress had been recorded in this area (Shi et al., 2003; Zhang et al., 2006).

A slight increase in seawater temperature at the survey area in August 2010 (Figure 2a) indicated that Luhuitou fringing reef was less impacted by upwelling in 2010. Extremely high seawater temperature of more than 32°C was observed at site 1 and 2. The abnormal seawater temperature induced coral bleaching at the two sites. The NOAA/NESDIS coral bleaching hotspot on 5 and 8 July 2010 also showed that bleaching warning (hotspot $\geq$1°C) was observed along the inshore areas of Sanya (http://www.osdpd.noaa.gov/ml/ocean/cb/hotspots.html). Therefore, if the upwelling weakened at Luhuitou fringing reef in summer, coral bleaching could be observed in some shallow regions of this area.

Some studies have suggested that oceanic banks or island shores exposed to vigorous circulation are possible refuges for reefs (Glynn, 1996; Riegl and Piller, 2003). Site 1 and site 2 belonged to wave-protected areas and site 3 was wave-exposed. The average daily seawater temperature at site 3 was significantly lower than at site 1 during April to September 2010. At site 3, seawater temperatures never exceeded 32°C and just 2 days of more than 31°C were recorded. This might explain why no coral bleaching was observed at site 3. The results also indicated that island shores (e.g. site 3) exposed to vigorous circulation would influence the seawater temperature and decrease the potential of coral bleaching. Similarly, it was concluded that man-made ocean engineering (e.g. building a road between Xiaozhou Island and the shoreline) which decreased the hydrodynamic environment in shallow reef areas might increase coral bleaching.

Coral bleaching and coral recovery

The susceptibility for coral taxa to high thermal stress varied greatly. *Montipora* was the most susceptible taxon at Luhuitou fringing reef. This was in accordance with many other studies (McClanahan, 2004; Sebastian et al., 2009). Sebastian et al. (2009) reported that *Montipora* was the most susceptible taxon with a BR of 56.3% in southern Africa. This study also indicated that *G. fascicularis* and *P. damicornis* were the least susceptible taxa. Sebastian et al. (2009) also reported that *P. damicornis* was the least susceptible coral in southern Africa. The type of algal symbiont showed different resistance to temperature rise. Clade D algal symbiont was more tolerant than Clade C in response to thermal stress (Rowan, 2004). One colony of *P. damicornis* was found to harbor Clade-D *Symbiodinium* and three colonies of *G. fascicularis* were found to harbor Clade-C and Clade-D *Symbiodinium* at site 2 (Dong et al., 2008). Results from laboratory experiments also suggested that *G. fascicularis* could endure high thermal stress (Dong et al., 2009; Li et al., 2009). Hence, the tolerance of *G. fascicularis* and *P. damicornis* to thermal stress might be connected with the type of algal symbiont at Luhuitou fringing reef.

This study revealed that the large size classes of most taxa had higher BRs in comparison with the smaller size classes. Juvenile coral colonies were less impacted and showed less bleaching (3%) than adult coral colonies (28%). These results are consistent with many other studies (Loya et al., 2001; Shenkar et al., 2005; Wagner et al., 2010). Wagner et al. (2010) reported that the most extensive bleaching was recorded for large colonies ($\geq$30 cm) in southern Florida. Shenkar et al. (2005) reported that small colony size of *Oculina patagonica* was advantageous in the case of bleaching in the Mediterranean. Loya et al. (2001) reported that juvenile *Acoropora* colonies survived the severe 1998 bleaching event at Sesoko Island while adult *Acoropora* colonies all died. This was probably linked to juvenile corals with high mass transfer, facilitating the removal of potentially damaging cellular toxins (Loya et al., 2001; Baker et al., 2008).

The BSI at Luhuitou fringing reef indicated that this was a moderate bleaching episode compared with the study of McClanahan et al. (2007). Low mortality (less than 5%, except *Montipora*) was observed at Luhuitou fringing reef. *Montipora* had the highest mortality (21.7%), although this is lower than the 70% mortality reported from Mombasa (McClanahan et al., 2007). Revisiting the bleaching areas and some bleaching colonies at site 1 and 2 between September 28 and 29 2010 indicated poor recovery of all taxa at site 1; whereas almost all taxa showed good recovery at site 2 except *Montipora* (Figure 3). This was supported by the increase in mean monthly seawater temperatures from August to September 2010, and 6 d of extremely high seawater temperature (e.g. 32°C) in September 2010 at site 1 (Figure 2a). However, although a slight increase of mean monthly seawater temperatures was observed from August to September 2010 at site 2, there were no days of extremely high temperature in September 2010. Some dead bleached colonies of *Montipora* were partially occupied by macroalgae while fewer colonies of other taxa were occupied by macroalgae. This also suggested that the most thermally stressed colonies might recover after this moderate coral bleaching episode, especially at site 2.

Conclusions

This is the first study to report coral bleaching due to high thermal stress at Luhuitou fringing reef in Sanya of Hainan Island. The rise of 1–2°C of mean monthly seawater temperatures at 3 m appeared to be a critical value for predicting coral bleaching at Luhutou fringing reef. Coral community in response to high thermal stress differed in coral taxa and size groups. *Montipora* was the most susceptible taxon; whereas *Galaxea fascicularis* and *Pocillopora damicornis* were among the least susceptible taxa. Relatively high bleaching in larger colonies was observed in comparison with that in smaller ones, while juvenile coral colonies showed less bleaching (3%) than adult coral colonies (28%). Our study suggested that although most taxa in the survey area might recover from this moderate coral bleaching episode, local stresses to Luhuitou fringing reef from declining water quality and overexploitation were probably exacerbated by high thermal stress. Therefore, further studies on the effects of coral bleaching are highly recommended.

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