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Monitoring of coral communities in the inner Gulf of Thailand influenced by the elevated seawater temperature and flooding

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Abstract

There were two severe coral bleaching events at Ko Khang Khao, the inner Gulf of Thailand, occurred during the prolonged period of the elevated sea surface temperature (SST) in 2010 and low salinity as well as turbidity due to heavy flooding in 2011. The bleaching index (*BI*) and mortality index (*MI*) are calculated to compare the susceptibilities of coral species in the two bleaching events. The *BI* and *MI* vary significantly among the study sites and bleaching events. The most susceptible corals during both bleaching events are *Acropora millepora*, *Pocillopora damicornis* and *Pavona decussate*, while the most resistant species were *Galaxea fascicularis*, *Fungia fungites*, *Pavona frondifera*, *Oulastrea crispate*, and *Symphyllia recta*. The corals *Favia favus*, *Goniopora columna*, *Platygyra pini*, *Symphyllia agaricia* were relatively more tolerant to high SST but they are relatively more susceptible to low salinity. Coral bleaching is a phenomenon that the dissociation stress of the symbiotic relationship between zooxanthellae and their cnidarian host results in the reduction in photosynthetic pigment concentration. Among stressors, both prolonged exposure of high SST and low salinity, above and below their thresholds, respectively. The long-term resilience of coral communities at Ko Khang Khao and other coral communities close to the mouth of large rivers may depend on the frequency and duration of the exposure on the elevated SST due to atmospheric heating and low salinity due to river flooding.

Key words: coral bleaching, salinity, temperature, mortality, flooding, Gulf of Thailand

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1 Introduction

Coral reefs are the most biologically diverse among marine ecosystems providing numerous ecosystem functions and services (Hoegh-Guldberg et al., 2007). However, coral reef ecosystem is also vulnerable and subject to a wide range of natural disturbances such as cyclones, corallivore outbreaks, and mass coral bleaching events (Karlson and Hurd 1993; Hughes et al., 2003; McClanahan et al., 2008; Sudek et al., 2012; Edmunds and Gray, 2014; Swain et al., 2017). These threats are increasingly compounded by climate change and direct human contact, leading to widespread degradation of coral reefs (Jackson et al., 2001; Bellwood et al., 2004; McClanahan et al., 2007b, 2012; Hoegh-Guldberg, 2011). The increased frequency and severity of disturbances affecting coral reefs ecosystems result in declining coral cover and changes in dominance among coral communities (Loya et al., 2001; Berumen and Pratchett, 2006; Yeemin et al., 2006; Hughes et al., 2007; Mumby et al., 2013). Coral bleaching is considered as a stress response that has many causes, however large scale phenomena are mainly caused by prolonged periods of high seawater temperatures (Brown, 1997; Hoegh-Guldberg, 1999; Yeemin et al., 2012; Yucharoen et al., 2015). Coral bleaching events have been documented with increasing frequency on coral communities around the world (Glynn, 1996; Wilkinson, 2008; Burke et al., 2011; Vargas-Ángel et al., 2011; Wooldridge, 2014; Barkley and Cohen, 2016).

A substantial loss of live coral cover due to coral bleaching phenomena has occurred on many coral reef communities during the past decades (Brown, 1997; Goreau et al., 2000; Sheppard et al., 2002; McClanahan et al., 2004; Saenghaisuk and Yeemin, 2011; Sutthacheep et al., 2013). It is hypothesized that most corals will not adapt rapidly enough to cope with the predicted rate of the rise in sea surface temperature (SST) from various climate-change models forecasting that SSTs will exceed the present thermal tolerance of corals by the year 2020. Coral bleaching is also predicted to occur annually in future 30–50 years' time (Hoegh-Guldberg, 1999; Baird et al., 2008). However, coral species are susceptible to various bleaching and certain environmental factors, especially irradiance, which can affect the outcome of SST anomalies that cause coral bleaching and possible subsequent coral mortality (Glynn, 1993; Mumby et al., 2011; Coles and Brown, 2003; McClanahan and Maina, 2003; Sutthacheep et al., 2012). Consistent differences in susceptibility among taxa have resulted in community-structural shifts on coral reefs due to an increase in the relative abundance of less susceptible massive and encrusting species (Loya et al., 2001; McClanahan et al., 2007a; Yeemin et al., 2013).

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While the effects of high seawater temperature on coral reefs have been widely studied in past decades to understand the climate change impacts, low salinity impacts have received relatively little attention. Coral reefs are generally considered to exist in habitats where salinity is stable over long timescales (Coles and Jokiel, 1992). However, major rainfall events are common in tropical countries that may affect corals by significant reductions in salinity. Decreases in salinity levels can also occur in shallow coral communities following the occurence of heavy rainfall with low tides or when coral communities are inundated by flood plumes of rivers, particularly in vicinities of major rivers (Goreau, 1964; Jokiel et al., 1993; van Woesik et al., 1995; Wadey et al., 2017). Some studies have reported short- and long-term impacts of low salinity on corals and coral communities (Coles and Jokiel, 1992; Moberg et al., 1997; Kerswell and Jones, 2003; Nakano et al., 2009; Berkelmans et al., 2012). The consistency of spatial patterns among consecutive coral bleaching years caused by different drivers has not been reported. Two coral bleaching events, caused by different stresses, were obviously observed at Ko Khang Khao, the inner Gulf of Thailand, i.e., elevated seawater temperature in 2010 and heavy flooding in 2011. Therefore, the two episodes provid a good case study for comparing the spatial variations of impacts of high seawater temperature and low salinity on corals and their adaptation at community levels in the inner Gulf of Thailand, with focus on developing the coral bleaching and the coral mortality indices for comparing the susceptibility of coral species for both coral bleaching events.

2 Materials and methods

Quantitative surveys on coral bleaching and subsequent coral mortality were conducted at three coral communities around Ko Khang Khao Island (13°06′46.40″N, 100°48′18.40″E, Fig. 1), the inner Gulf of Thailand, during and after the two bleaching events in 2010 and 2011. The coral communities around the island are characterized by high turbidity and *Porites* spp. being the most dominant corals (Sakai et al., 1986). The study sites located on the north, west and southeast sides of the island that were affected by freshwater runoff as they were nearby two major rivers (the Bang Pakong River and the Chao Phraya River). The coral communities experienced relatively low salinity, 24–32. Live coral covered at the study sites before the 2010 coral bleaching event was in the range of 20%–60%. The coral communities were generally found at 1–6 m in depth. Circulations were clockwise during the southwest monsoon (May–August) and anti-clockwise during the northeast monsoon (November–January).

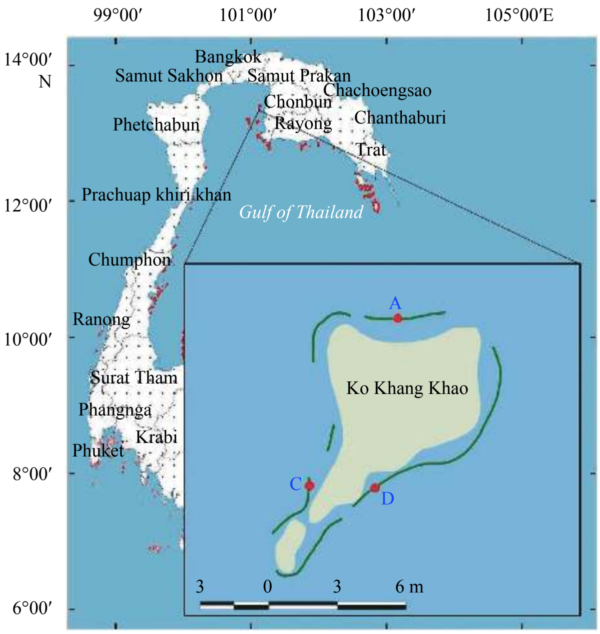

Fig. 1. Location of the study sites, the inner Gulf of Thailand.

Seawater temperatures have been recorded hourly by *in situ* deploying of HOBO Data Loggers (UA-002-64) on the substrate of coral communities since April 2010. The salinity data were obtained from the Aquatic Resources Research Institute, Chulalongkorn University. Seawater quality (viz. temperature, salinity, dissolved oxygen, conductivity and pH) was also measured monthly near bottom of the sea in the morning and at noon in three replicates by using a portable digital instrument (YSI 556 Multi-Probe System). At each station, three belt transects, 50 m× 1 m each, were used to quantify and assess the extent of coral bleaching and coral mortality at the study sites in July–September 2010 (high temperature) and August–November 2011 (low salinity). The belt transects were placed perpendicularly to the shoreline. The distance between each transect was about 20 m. All coral colonies within the belt transects were identified to the species level, counted, and had their bleaching and mortality conditions recorded.

We calculated the coral bleaching index (*BI*) by assigning each coral colony into one of the six categories: (1) unbleached (normal coloration), (2) <25% bleached, (3) 25%–50% bleached, (4) 51%–75% bleached, (5) >75% bleached, and (6) whole colony bleached (modified from McClanahan, 2004). The *BI* was then calculated from the percentage of observations in each of the six bleaching categories (Fig. 2) as follow:

$$BI = (0c_1 + 1c_2 + 2c_3 + 3c_4 + 4c_5 + 5c_6)/5, \qquad (1)$$

where c_i is the percentage of observations in each of the six bleaching categories.

Each coral colony was categorized into the six categories: (1) live, (2) <25% died, (3) 25%–50% died, (4) 51%–75% died, (5) >75% died, and (6) whole colony had died. Based on this, the mortality index (*MI*) was calculated from the percentage of observations in each of the six mortality categories (Fig. 2) as follow:

$$MI = (0c_1 + 1c_2 + 2c_3 + 3c_4 + 4c_5 + 5c_6)/5, \qquad (2)$$

where c_i is the percentage of observations in each of the six mortality categories.

The quantitative data gathered from the field survey was tested for normality and homogeneity of variances using the Shapiro-Wilk test. A two-way ANOVA was used to test the influence of time and location on live coral coverage, *BI* and *MI*. Where significant differences were established, Scheffe's Test was employed to determine which group(s) differed. Cluster analysis was also performed on the coral bleaching and mortality indices data to find groupings of coral species affected by high seawater temperature and low salinity.

3 Results

The peak of high seawater temperatures recorded from data loggers was 33.0°C in May 2010. There were no seawater temperature anomalies in the year 2011 (Fig. 3). The heavy flooding in Thailand in 2011 resulted in the impact of flood plumes on coral

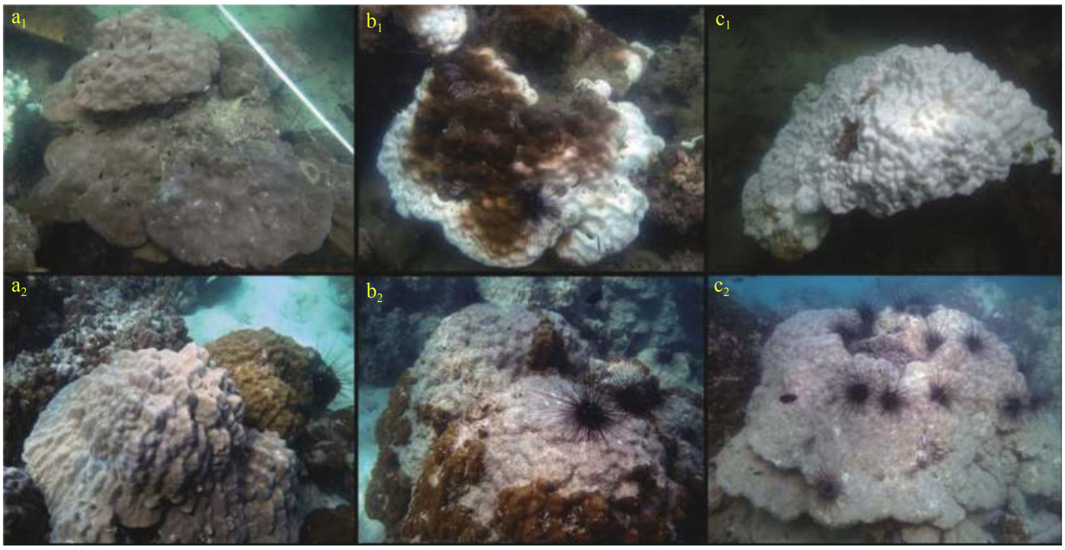

Fig. 2. Coral bleaching: unbleached or normal coloration (a_1), 51%–75% bleached colony (b_1), whole colony bleached (c_1); coral mortality: living colony (a_2), 51%–75% died colony (b_2), whole colony died (c_2).

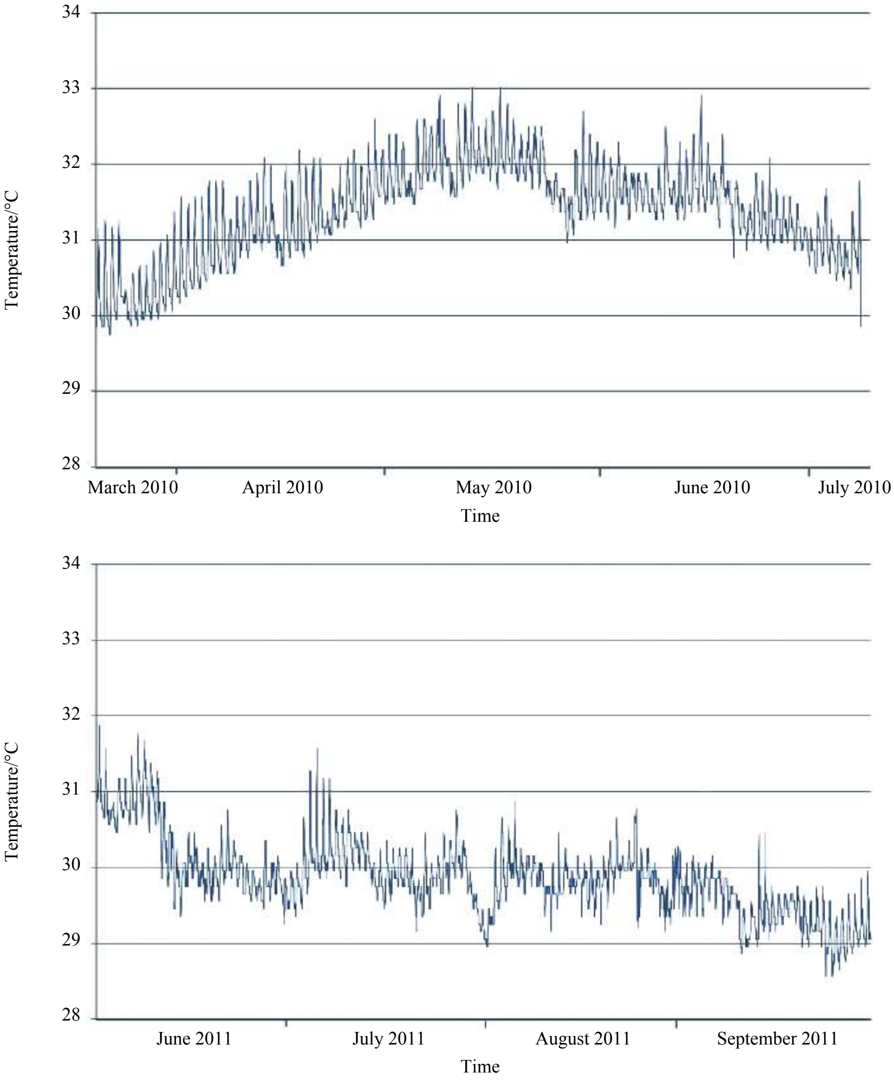

Fig. 3. Seawater temperatures recorded from data loggers in 2010 and 2011.

communities of Ko Khang Khao. The recorded salinities indicate sharp drops in August 2011 from that recorded in 2010 (Table 1, Fig. 4). The DO values were very low (2.33–2.71 mg/L) during the flooding period (Table 1).

Table 1. Water quality at the stations (*in situ* measurement)

Parameter	Station					
	July 2010			August 2011		
	A	C	D	A	C	D
Salinity	30.74±0.01	31.45±0.02	30.98±0.01	13.01±0.03	11.18±0.02	17.78±0.02
Temperature/°C	31.40±0.03	31.71±0.01	30.37±0.04	29.65±0.01	29.98±0.03	29.69±0.01
Conductivity/mS·cm^{-1}	48.42±0.01	48.81±0.03	46.90±0.02	21.74±0.04	18.63±0.03	29.05±0.01
Dissolved oxygen/mg·L^{-1}	5.34±0.01	5.61±0.02	5.70±0.01	2.70±0.01	2.32±0.01	2.62±0.02
pH	8.28±0.04	8.37±0.02	8.26±0.03	7.54±0.02	7.23±0.02	7.27±0.01

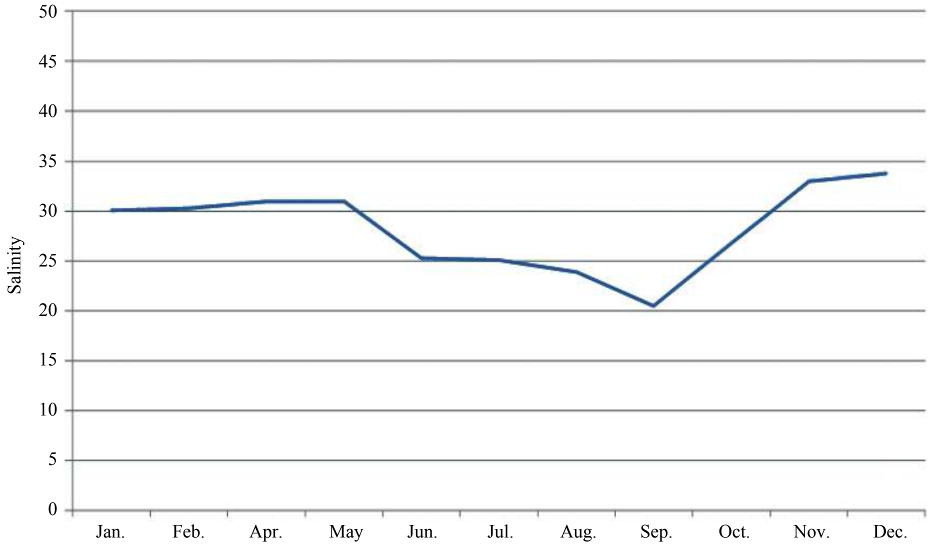

Fig. 4. Seawater salinity recorded during 2011 at the monitoring station for water quality (data from Aquatic Resourses Research Institute, Chulalongkorn University).

The percentages of live coral cover vary significantly both between the three stations and the years (Table 2, ANOVA, $P<0.05$). The coral survey before the 2010 bleaching (March 2010, Fig. 5) shows that the live coral percentage at Sta. D is the highest (55%), whereas Sta. C has the lowest (15%). The highest coral mortality rate was found at Sta. C either in 2010 (27%) and in 2011 (34%), while the lowest was at Sta. A for the year 2010 (14%) and Sta. D for the year 2011 (16%). After the 2011 bleaching, Sta. D still had the highest percentage of live coral cover (34%) while Sta. C had the lowest (7%). The taxa *Pocillopora damicornis*, *Acropora millepora* and *Porites lutea* experienced high mortality rates either in 2010 or in 2011. The taxa *Montipora turtlensis* showed high mortality rates only in 2010, while *Favites abdita*, *Goniopora columna*, *Platygyra sinensis* and *P. pini* exhibited high mortality rates only in 2011.

Table 2. Results of two-way ANOVA and Scheffe's test examining the effect of time and location on live coral coverage

Source of variation	Degree of freedom	Mean square	*F*-statistic	Significant difference
Two-way ANOVA test				
Time	2	365.466	100.021	<0.001
Location	2	2 419.311	662.117	<0.001
Location×time	4	47.104	12.891	<0.001
Errors	18	3.654		
Total	27			
Scheffe' s test				
Mar. 2010 vs Feb. 2011				<0.001
Mar. 2010 vs Nov. 2011				<0.001
Feb. 2011 vs Nov. 2011				<0.001
Sta. A vs Sta. C				<0.001
Sta. A vs Sta. D				<0.001
Sta. C vs Sta. D				<0.001

Note: Significant difference ($p<0.05$).

The *BI* for the 18 taxa from the 2010 and 2011 coral bleaching events were categorized into four groups as: (1) no significant bleaching in 2010 and 2011 ($BI = 0$): *Fungia fungites*, *Galaxea fascicularis*, *Oulastrea crispata*, *Pavona frondifera* and *Symphyllia recta*; (2) significant bleaching in 2010 only ($BI>20$); *Montipora turtlensis*, *Favites abdita*, *Podabacia crustacean*, *Platygyra daedalea*; (3) significant bleaching in 2011 only ($BI>20$); *Goniopora columna*, *Favia favus*, *Platygyra pini*, *Porites lutea*, *Symphyllia agaricia*; (4) significant bleaching in both 2010 and 2011 ($BI>80$): *Acropora millepora*, *Pocillopora damicornis*, *Pavona decussata*, *Platygyra sinensis* (Figs 6 and 7a). The *BI* varied significantly between the three stations and the years (Table 3, ANOVA, $P<0.05$). The *BI* values for each station in 2010 were higher than those in 2011. The *BI* values at Sta. C were the highest in both years while the lowest was at Sta. A in 2010 and at Sta. D in 2011.

The *MI* for the 18 taxa from the 2010 and 2011 coral bleaching events were categorized into four groups as: (1) no significant mortality in 2010 and 2011($MI = 0$): *Galaxea fascicularis*, *Fungia*

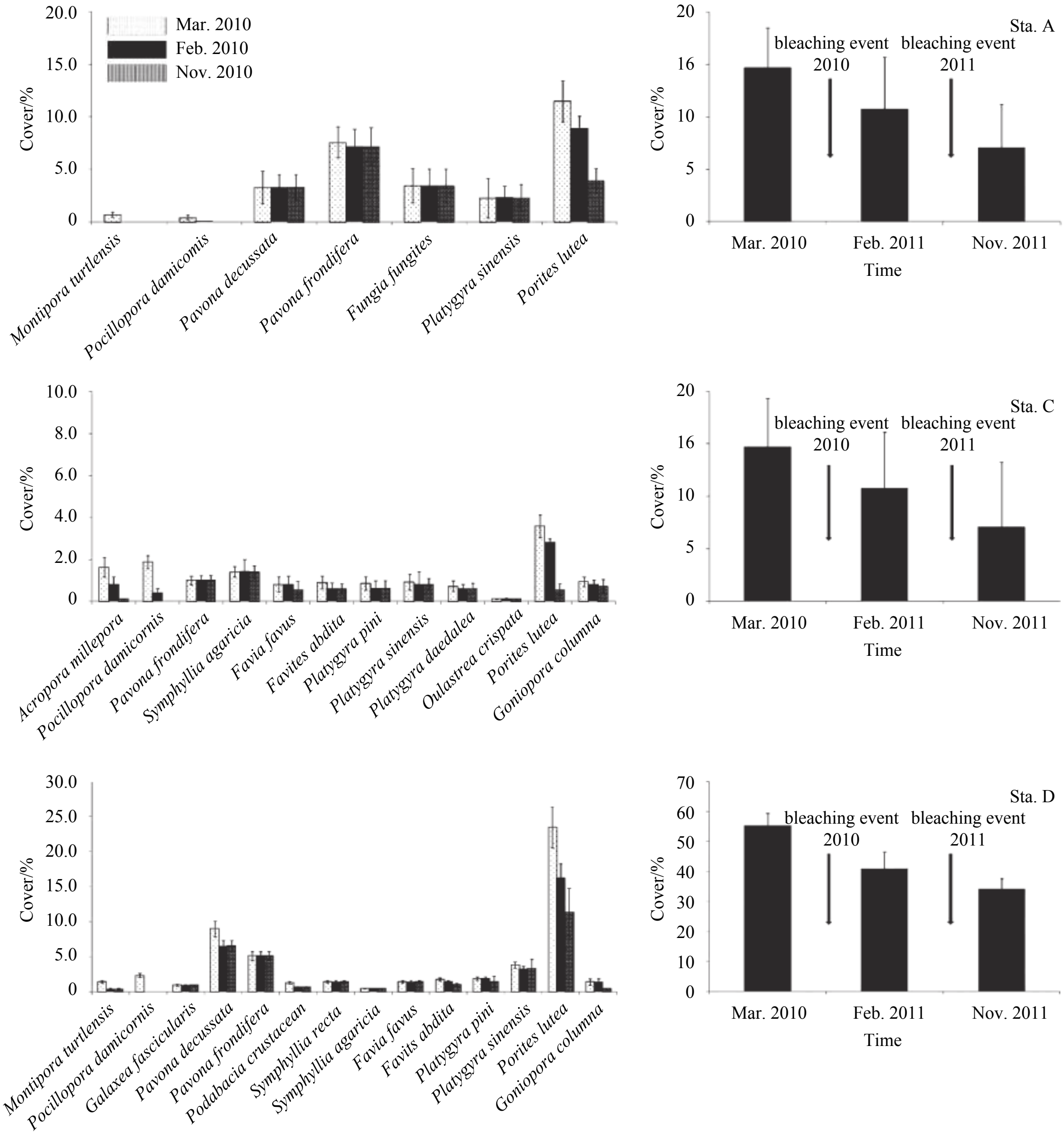

Fig. 5. Live coral cover at three stations in 2010–2011.

fungites, *Pavona frondifera*, *Oulastrea crispata*, *Platygyra pini* and *Symphyllia recta*; (2) significant mortality in 2010 only (*MI*>15): *Favites abdita*, *Platygyra sinensis*, *P. daedalea*, *Podabacia crustacean*, *Montipora turtlensis*, *Pavona decussata*; (3) significant mortality in 2011 only (*MI*>15): *Goniopora columna*, *Symphyllia agaricia, Favia favus* and *Porites lutea*; (4) significant mortality in both 2010 and 2011 (*MI*>40): *Acropora millepora* and *Pocillopora damicornis* (Figs 6 and 7b).

The *MI* varied significantly both between the three stations and the years (Table 4, ANOVA, P<0.05). The *MI* values for all stations in 2010 were higher than those in 2011. Station C showed the highest *MI* value whereas Sta. A exhibited the lowest either in 2010 and 2011.

Analyses of the *BI* and *MI* for the two bleaching events revealed that the coral taxa could be categorized into four groups: (1) no bleaching and no mortality either in 2010 or in 2011 (*BI* = 0, *MI* = 0): *Fungia fungites*, *Galaxea fascicularis*, *Oulastrea crispata*, *Symphyllia recta*, *Pavona frondifera*; (2) significant bleaching and mortality in 2010 only (*BI*>20, *MI*>15): *Favites abdita*, *Montipora turtlensis*, *Podabacia crustacean*, *Platygyra daedalea*, *Platygyra sinensis*; (3) significant bleaching and mortality in 2011 only (*BI*>20, *MI*>15): *Favia favus*, *Goniopora columna*, *Platygyra pini*, *Porites lutea* and *Symphyllia agaricia*; (4) significant bleaching and mortality in both 2010 and 2011 (*BI*>80, *MI*>40): *Acropora millepora*, *Pavona decussata* and *Pocillopora damicornis* (Fig. 7c).

4 Discussion

The coral bleaching event in 2010 at Ko Khang Khao corresponded to a period of anomalous seawater surface temperatures during May–August. Coral communities at other locations in the Gulf of Thailand, e.g., Kut Island, also experienced coral bleaching which led to subsequent mortality between 26% and 45% (Sutthacheep et al., 2012). The mortality rates at Kut Island (the eastern Gulf of Thailand) were much higher than those at Ko Khang Khao (the inner Gulf of Thailand). This was in agreement with Yeemin et al. (2012) who reported that the 2010 mass coral bleaching event caused a more severe and extensive coral degradation in the Andaman Sea than in the Gulf of Thailand, with the inner Gulf of Thailand exhibiting the lowest bleaching im-

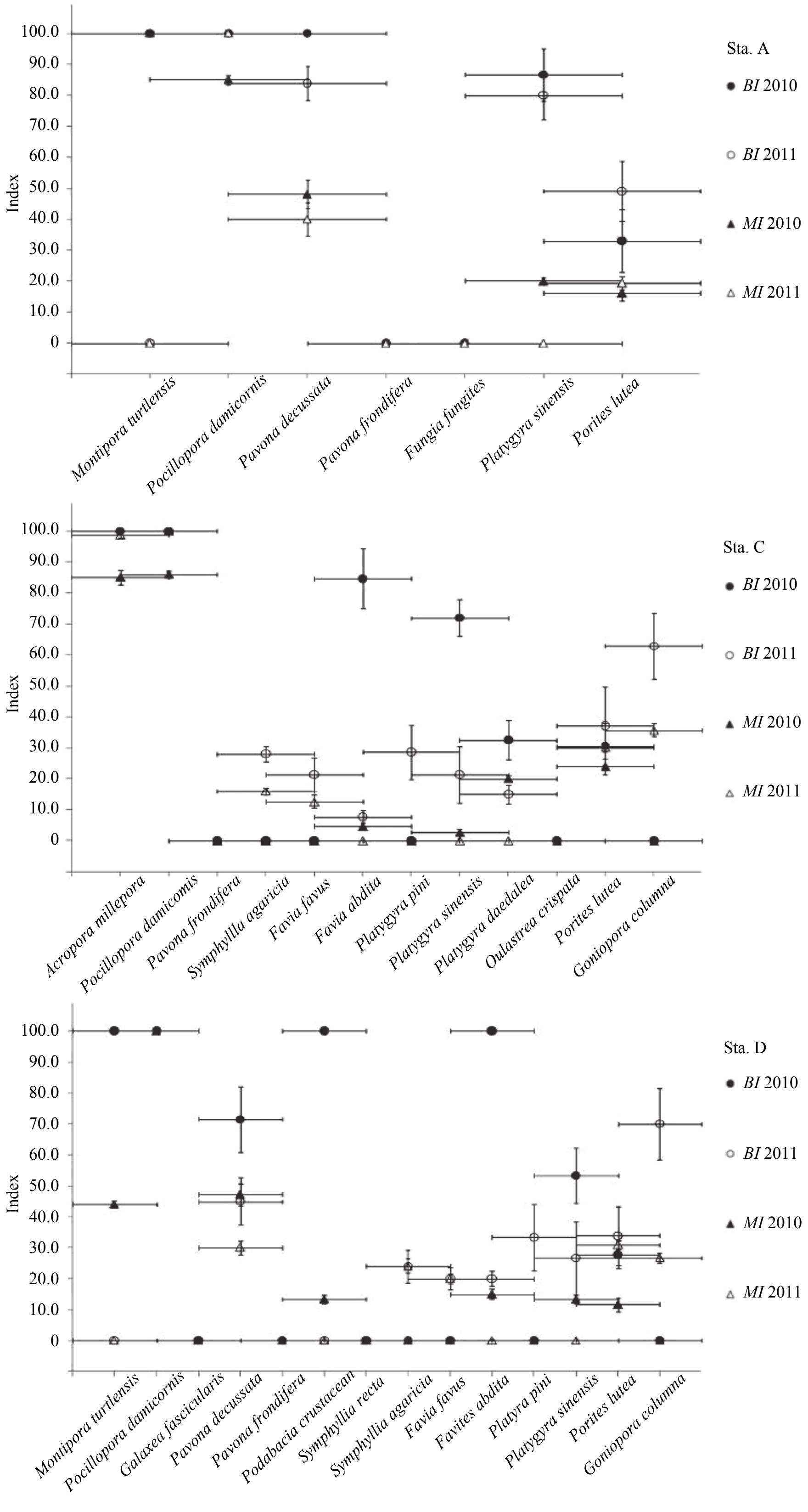

Fig. 6. Bleaching index (*BI*) and mortality index (*MI*) at three stations in 2010–2011.

pact. The coral communities in the Gulf of Thailand, which were affected by the severe coral bleaching event in 1998 (Yeemin et al., 1998), had shown recovery at several locations (Yeemin et al., 2009). Spatial differences in coral mortality following the bleaching event at Ko Khang Khao may, in part, be the result of differences in waterflow rates that induce varying rates of passive diffusion (Nakamura and van Woesik, 2001) and interactive effects of various environmental factors such as hydrodynamic condi-

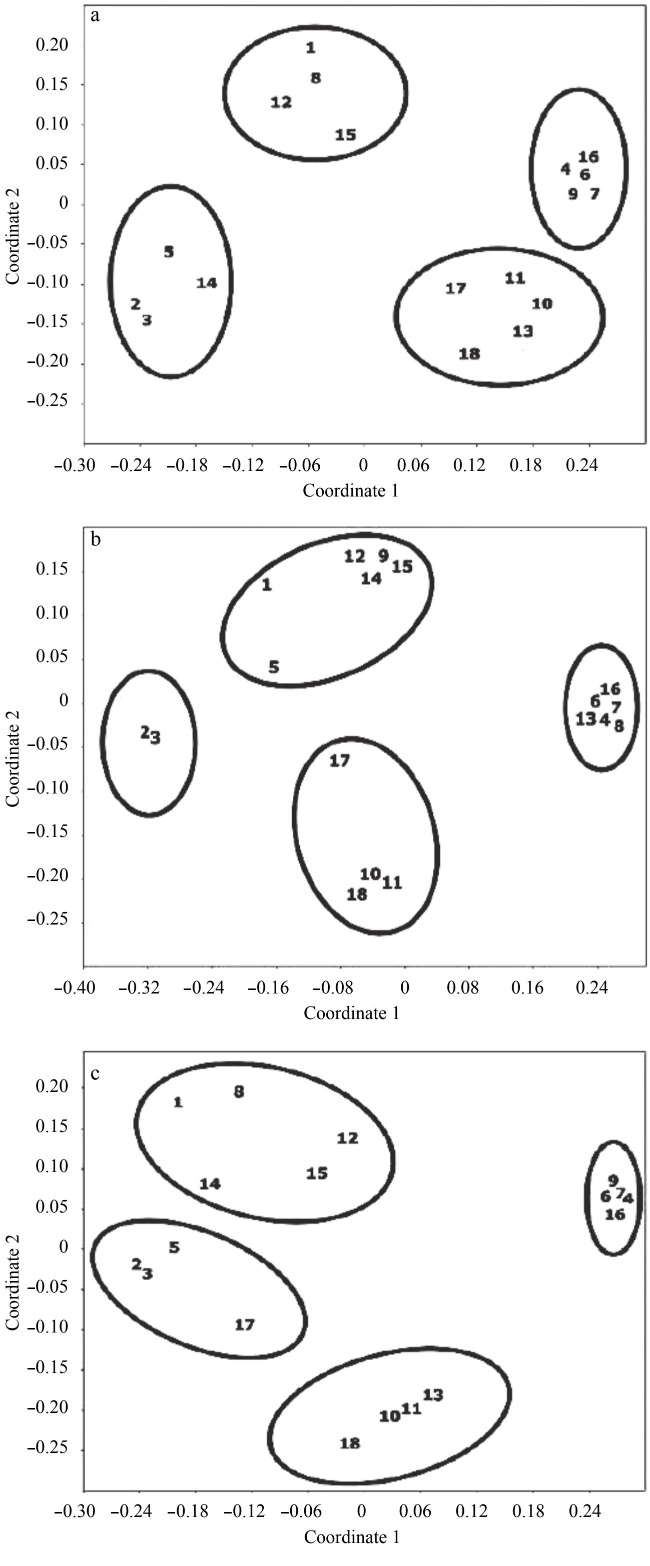

Fig. 7. Multidimenttional scaling analysis: bleaching index (a), mortality index (b), combination of the bleaching index and the mortality index at three stations in 2010–2011 (c). 1 represents *Montipora turtlensis*, 2 *Acropora millepora*, 3 *Pocillopora damicornis*, 4 *Galaxea fascicularis*, 5 *Pavona decussata*, 6 *Pavona frondifera*, 7 *Fungia fungites*, 8 *Podabacia crustacea*, 9 *Symphyllia recta*, 10 *Symphyllia agaricia*, 11 *Favia favus*, 12 *Favites abdita*, 13 *Platygyra pini*, 14 *Platygyra sinensis*, 15 *Platygyra daedalea*, 16 *Oulastrea crispata*, 17 *Porites lutea*, 18 *Goniopora columna*.

tions, differential adaptation and/or acclimatization of the coral/algal symbiosis (Penin et al., 2013; Yucharoen et al., 2015)

The results of the present study indicate that the 2011 coral bleaching phenomenon, caused by low salinity and subsequent mortality between 16% and 34%, was more severe than that in 2010 which was caused by high seawater temperature and sub-

Table 3. Results of two-way ANOVA and Scheffe's test examining the effect of time and location on bleaching index

Source of variation	Degree of freedom	Mean square	*F*-statistic	Significant difference
Two-way ANOVA test				
Time	1	168.912	25.560	<0.001
Location	2	43.876	6.639	0.011
Location×time	2	39.352	5.955	0.016
Errors	12	6.609		
Total	18			
Scheffe's test				
Sta. A vs Sta. C				0.046
Sta. A vs Sta. D				0.851
Sta. C vs Sta. D				0.017

Table 4. Result of two-way ANOVA and Scheffe's test examining the effect of time and location on Mortality index

Source of variation	Degree of freedom	Mean square	*F*-statistic	Significant difference
Two-way ANOVA test				
Time	1	49.302	14.342	0.003
Location	2	184.943	53.799	<0.001
Location×time	2	3.297	0.959	0.411
Errors	12	3.438		
Total	18			
Scheffe' s test				
Sta. A vs Sta. C				<0.001
Sta. A vs Sta. D				0.002
Sta. C vs Sta. D				<0.001

sequent mortality was between 14% and 27%. Nakano et al. (2009) hypothesized, based on the field observation in 1995 and laboratory experiments, that low salinity caused by severe runoff during the rainy season was an equally important factor as turbidity in influencing the characteristics of the coral community around Ko Khang Khao. The present study clearly shows empirical scientific evidence to support their hypothesis and might be used as a model for explaining the characteristics of coral communities around tropical nearshores close to river mouths. Berkelmans et al. (2012) proposed an empirically derived salinity threshold for sensitive *Acropora* species from the southern inshore Great Barrier Reef, based on *in situ* salinity exposure and coral responses during a major flood event in 2010–2011. The threshold was presented as a dose-time response for a salinity-sensitive range of 22–28 and an exposure time of 3–16 d at the lowest and highest salinities, respectively. We found that the salinity on coral communities of Ko Khang Khao during the field survey in August 2011 was much lower (salinity 11) than the above threshold. Several studies have reported short- and long-term reductions in salinity on coral communities (Cole, 1992). Moberg et al. (1997) reported a salinity level of 10 in coral-containing tidal pools on the reefs of the inner Gulf of Thailand. The coral communities in the inner Gulf of Thailand may frequently experience salinity reduction in the long-term. Therefore, our data on the high mortality rates of corals during the heavy flooding imply that the reduction in susceptibility to low salinity stress may not occur.

The present study shows that the taxa *Acropora millepora*, *Favia favus*, *Favites abdita*, *Goniopora columna*, *Pavona decussata*, *Pocillopora damicornis*, *Platygyra sinensis*, *P. pini* and *Porites lutea* are highly susceptible to coral bleaching caused by low salinity. Other studies show that *P. damicornis* and *Acropora* spp. are more sensitive to low salinity, while *Porites* is among the least sensitive to salinity reduction (Cole, 1992; Jokiel et al., 1993; Moberg et al., 1997; Nakano et al., 2009). As the heavy flooding in Thailand in the year 2011 occurred over a prolonged period of time, the corals at Ko Khang Khao might have suffered from salinity reduction more severely than in the previous reports. *Acropora* was not a dominant species at any study stations around Ko Khang Khao (Yuchareon and Sutthacheep, 2011). This may be partly explained by the impacts of seawater temperature anomalies and low salinity. Sudara et al. (1991) also stated that moisture brought by the southwest monsoon from the Indian Ocean caused rain along the western coast of the Gulf of Thailand, during which widespread coral mortality in the shallow reefs.

The present study intends to investigate the combined impacts of both high seawater temperature and low salinity on corals. The most tolerant corals to bleaching, caused by both high seawater temperature and low salinity, are *Galaxea fascicularis*, *Fungia fungites*, *Pavona frondifera*, *Oulastrea crispata* and *Symphyllia recta*. In contrast, *Acropora millepora*, *Pavona decussata*, and *Pocillopora damicornis* are the most susceptible to coral bleaching caused by the two factors. This finding agrees with previous studies reporting that branching coral species are among the first to bleach and exposed to the subsequent mortality (Yamazato, 1981; Glynn, 1988; Brown and Suharsono, 1990; Hoegh-Guldberg and Salvat, 1995; Sheppard, 1999; McClanahan, 2000; Edwards et al., 2001; Sutthacheep et al., 2012). The coral *Goniopora columna* is the most tolerant to high seawater temperature (Yeemin et al., 2009), but it is more sensitive to salinity reduction. This taxon may be a good study model for a physiological response of marine animals to temperature and salinity.

The present study demonstrates how exposure to low salinity can lead to some of the symptoms commonly attributed to seawater temperature anomalies and other anthropogenic disturbances on coral communities. Identifying the areas impacted by salinity reduction will be important in the implementation of conservation plans as proposed by several studies to cope with global climate change (Obura and Grimsdith, 2009; Mumby et al., 2011; McClanahan et al., 2012). Our findings highlight the difficulty of differentiating between the impacts of high seawater temperature, low salinity and pollutants on corals when exposure is in the same period. Moreover the impacts of low dissolved oxygen on corals should be investigated in details. Besides, the synergistic effects could be existed depending on various factors such as tolerance of coral species (Howells et al., 2016; Torda et al., 2017), types of zooxanthellae (Chakravarti et al., 2017), and roles of other microorganisms such as bacteria, viruses etc. (Sharp et al., 2012; Hernandez-Agreda et al., 2017; Röthig et al., 2017; Sweet and Bythell, 2017). To comprehend the synergistic effects, further detailed studies related to those factors are required. The long-term resilience of coral communities at Ko Khang Khao and other coral communities close to major rivers may depend on the frequency and severity of coral bleaching events caused by elevated seawater temperature and heavy flooding. Future research should be focused on detailed investigations of the symbiotic algae in the different coral species that might help explain differential susceptibility to high temperature and low salinity. Genetic analyses of the host corals themselves would also be an important task.

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