

Relationship between environmental conditions and recovery of the coral reefs in the Andaman coast of Thailand

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ABSTRACT: The coral reef ecosystem in the Andaman sea was studied by monitoring aquatic environmental conditions and reef condition from years 2005–2009. Following the Asian tsunami in December 2004, the ammonium-nitrogen concentration in the surface water in Ranong province ranged from 8.45–14.08 μM , while in Phang Nga area, it was between 9.99 and 25.11 μM . Mean sea surface temperatures in Ranong and Phang Nga were $30.6 \pm 0.4^\circ\text{C}$ during the dry season. The growth rate of *Acropora* spp. in Chong Khat bay, Surin Marine National Park, was 1.0 cm/month during the first 5 months after the tsunami. After this five-month period, corals, especially *Acropora* spp., showed signs of recovery but then faced extensive bleaching in May 2005. Three years after the tsunami, the coral reefs in deep water areas could grow and recover rapidly although they faced serious bleaching while coral reefs in the shallower waters were in a poor condition after serious bleaching in May 2005. This phenomenon revealed that the mass mortality of corals in shallow waters was enhanced by high seawater temperature and high turbidity due to phytoplankton blooms. Overall results indicate that the relationships between environmental conditions and coral reef status in the Andaman sea is an issue of great concern and coastal corals may gradually degrade in the near future unless action is taken to alleviate coastal environmental problems.

KEYWORDS: coral bleaching, red tide, tsunami

INTRODUCTION

Many coral reefs, especially those along the Andaman shoreline and in adjacent narrow channels of Thai water, were severely damaged by the gigantic tsunami caused by the 9.3 Mw Sumatra-Andaman earthquake¹ which occurred on 26 December 2004. To evaluate the impacts of the tsunami, an emergency research team led by the Department of Marine and Coastal Resources (DMCR) of the Ministry of Natural Resources and Environment (MONRE), including nine educational institutions (Burapha University, Chulalongkorn University, Kasetsart University, Mahidol University, Prince of Songkhla University, Rajamangala Institute of Technology, Ramkhamhaeng University, and Walailak University) was formed. The assessment of the destructive impact of the tsunami on the coral reefs began within a couple of days after it occurred. The

results from that study showed that the destructive impact of the tsunami on coral reefs depended on the geographic location of shorelines, islands, and reefs. Most of the coral reefs in Ranong and Phang Nga were not damaged (less than 30% of corals were affected). The more severely damaged coral reefs (more than 50% affected) were found in Chong Khat bay (Surin Marine National Park, Phang Nga), Lan, Kam Yai, and Khang Khao islands, Ranong (unpublished English-language data). Half of the coral reef in the north-eastern part of Jolly Buoy island, Andaman and Nicobar islands died due to the tsunami². A few months after the tsunami, Ranong and Phang Nga reefs faced serious problems of coral bleaching and phytoplankton blooms, particular during our coastal surveys in May 2005.

Coral bleaching is not a new phenomenon in coastal areas with high incidences reported in several regions over the last two decades^{3–9}. Coral

bleaching in the Andaman sea has also been reported^{10–12}. Extensive coral mortality by coral bleaching in the Andaman sea was observed in 1991 and 1995. Pongsuwan¹¹ reported that 80% mortality of *Acropora* spp. occurred at Surin and Similan islands in 1995. Previous studies have suggested that coral bleaching were caused by high temperature or irradiance^{13–18}. Fitt¹⁹ suggested that it is caused by thermal tolerance limits and thermal thresholds in several tropical corals. However, quantitative and qualitative analysis of these factors, including anomaly excursion, length and exposure timing, has not been done¹⁸. Coral bleaching in the Andaman sea seemed to be an annual event²⁰.

In addition, coral reef along the Andaman coast line faced the problem of an increase in turbidity. In fact, the Andaman sea has faced problems of nutrient loading, red tide, and macroalgal blooms several times after the tsunami in 2004. Since phytoplankton bloom increases water turbidity and decreases the amount of light available to zooxanthellae in coral polyp, increases phytoplankton levels could have both direct and indirect effects on the growth rate of corals. Thus to understand the changes in the status of coral reefs exposed stressful environmental conditions, the physicochemical characteristics of sea water, degree of coral bleaching, and the growth of corals were examined from 2005–2009. The goal of this study is to clarify the relationships between the environmental conditions and coral reef status in the study area. The output from this study should contribute to coral reef management of the coastal areas.

MATERIALS AND METHODS

Sampling and site

This study focused on three topic areas. Firstly, seawater characteristic analysis was conducted in March 2005 (Ranong province) and in March 2006 (Phang Nga province). Secondly, the incidences of red tide were monitored in March 2005, 2006, and October 2009. Finally, the coral bleaching incident (in May 2005), growth, and recovery of coral (in May 2005, February 2007 and October 2009) were examined. One hundred and thirty two sampling stations covered all study areas (near shore and off shore) were designed as shown in Figs. 1 and 2.

Ranong and Phang Nga are located at the first and second southern provinces, respectively, on the Andaman coast of Thailand. The coast along these provinces is submerged with a narrow continental shelf. More than 160 islands belongs to Ranong

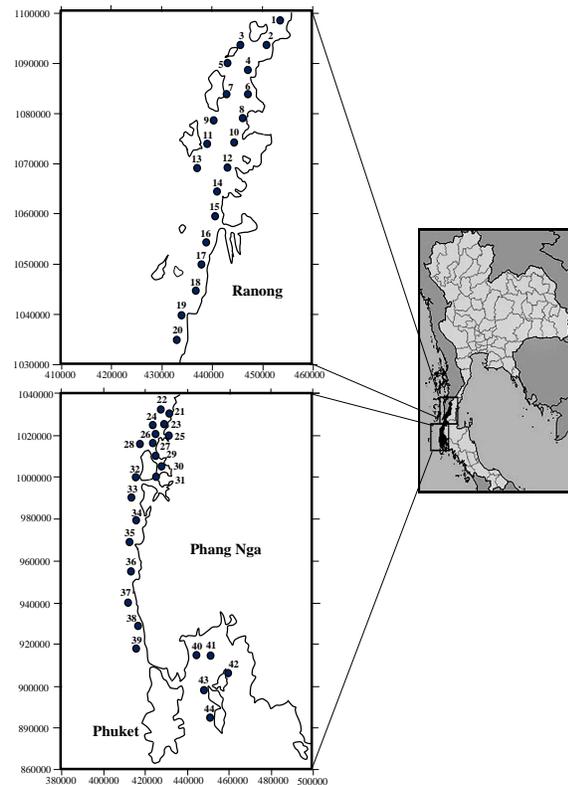


Fig. 1 Sampling locations (44 stations) for seawater characteristics in Ranong (March 2005) and Phang Nga provinces (March 2006).

and Phang Nga provinces. Phayam island is a large island with an area of approximately 35 square kilometres. We can find coral reef at both East and West coast of the island. The most beautiful and famous diving site of the near-shore area is Khang Khao island. Most of the coral reefs of near shore islands in study area are shallow fringing reefs. In our study area, rainy season span about 8 months (May–December) each year. High volume of water from rain compensates for the evaporation and results in an average salinity of less than 34 psu²¹. Suspended solids usually affect the water transparency especially along the coastal areas during rainy season. The appropriate time for scuba diving is only four months during the dry season.

The Andaman sea is generally clean and clear during the dry season. Surin Marine National Park has an aquatic area of 102 square kilometres with about 60 km far away from the main land (Phang Nga province). The most dominant genus of coral in this area is *Porites* followed by *Acropora*²².

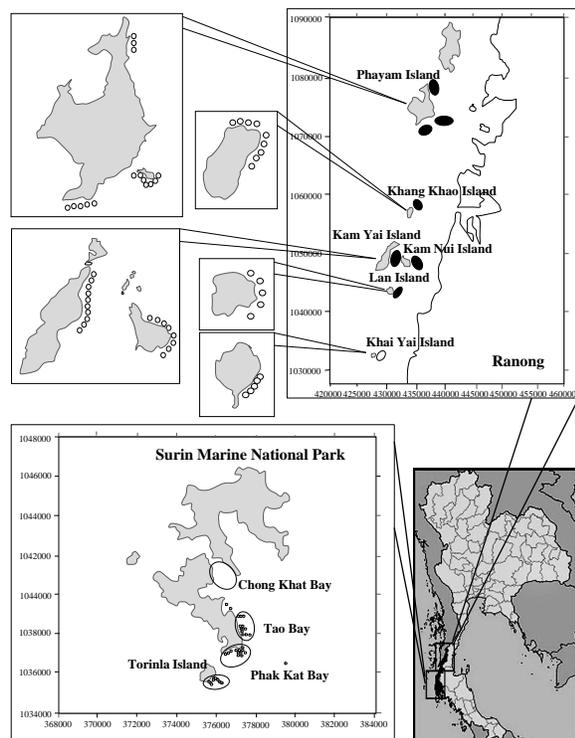


Fig. 2 Map of sampling area around Ranong (52 sampling stations (15 stations at Phayam island; 18 stations at Kam Yai and Kam Nui islands; 9 stations at Khang Khao island; 5 stations at Lan island; 5 stations at Khai Yai island (closed circle) for coral bleaching survey and 8 sites (dash ellipse) for coral growth measurement) and Surin Marine National Park (36 stations (open circle) for coral bleaching survey and 4 sites (dash ellipse) for coral growth measurement).

Environmental factors and red tide incidence

At least two water samples were obtained from each sampling station along the Andaman sea coasts in Ranong and Phang Nga provinces, Thailand. A total of 44 stations in Thai waters were sampled (Fig. 1). Water samples were collected at a depth of 30 cm with a Van-Dorn bottle sampler. Water temperature and salinity were also measured using a multi-parameter water quality monitor (YSI 6600). To avoid the impact of different stages of the tidal cycle on seawater characteristics, water sampling was conducted on a speed boat to complete the sample collections within three days, during flood tide only. The incidence of red tide was also recorded during the field survey.

Chemical analysis

For nutrient analysis, 20-ml aliquots of water samples were filtered through Whatman GF/F filter paper. All nutrient samples were kept frozen at -40°C . Concentrations of ammonium-nitrogen, silicate-silicon and orthophosphate-phosphorus were then analysed by a nutrient auto-analyser (Skalar San Plus) within one week after sampling.

For chlorophyll *a* analysis, approximately 100 ml of each water sample was filtered through Whatman GF/F filter paper and chlorophyll *a* was extracted from the filters with 90% acetone solution. Chlorophyll *a* concentration was then determined by spectrophotometric method²³.

Measurement of coral bleaching

Measurement of coral bleaching was conducted along the coastlines of Ranong and Phang Nga in May 2005 (Fig. 2). The surveys were performed using line transects of 20–60 m in length at Ranong province with a total of 52 sampling stations (15 stations at Phayam island, 18 stations at Kam Yai and Kam Nui islands, 9 stations at Khang Khao island, 5 stations at Lan island, and 5 stations at Khai Yai island). The length of line transects depended on the length of the reef flat and reef slope. The measurement of bleaching started from reef flat and ended at the end of reef slope. Since the coral reef of Surin and Torinla islands (Surin Marine National Park) at some stations have a long reef flat and very deep reef slope, the transect lines were set up at three depths (about 15, 20, and 25 m) parallel to the shoreline. The measurement of bleaching was conducted at 36 sampling stations in Surin Marine National Park. The percentage of coral bleaching was calculated by measuring the proportion of living coral and bleached coral, along the transect lines.

Measurement of coral growth

Measurement of the growth of corals was conducted in various sites along the Andaman coast in May 2005, February 2007, and October 2009 (Fig. 2). Long term measurement of coral growth in the entire study area was very difficult to conduct using a permanent grid due to a high current speed and turbidity except at Surin Marine National Park. Hence 58 samples of *Acropora* spp. in Surin Marine National Park and 10 samples at near shore islands were selected randomly to measure the length of its primary branch (Fig. 3). In this current study, the growth rate of *Acropora* spp. in which the length of the branch of coral which had been overturned

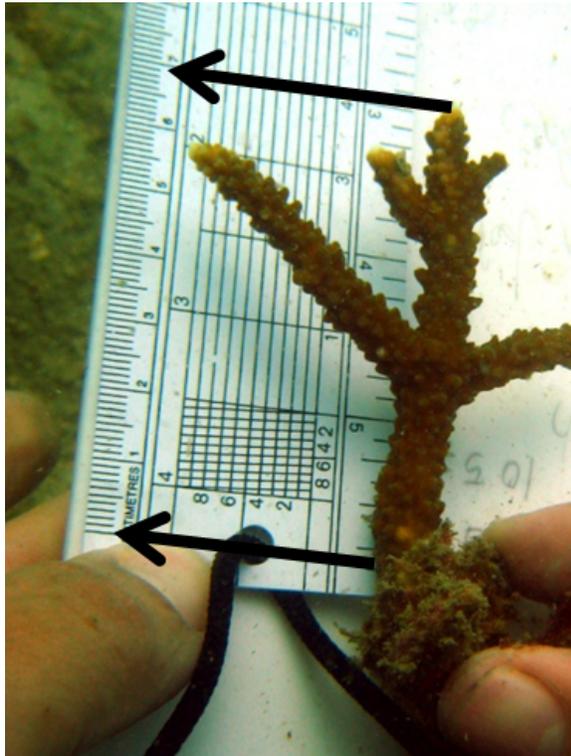


Fig. 3 Measurement of the length of *Acropora*'s primary branch.

by the 2004 tsunami was monitored. Some parts of corals were brought back to the laboratory for species identification. Classification systems for corals was done according to Veron²⁴.

Data analysis

Data from all measurements were compared using one-way ANOVA and *t*-tests after checking for normality and homoscedasticity. Coefficients of determinations were calculated where appropriate.

RESULTS

Seawater characteristic

Surface (depth of 30 cm) water temperatures in Ranong ranged from 30.05–31.90 °C while in Phang Nga, they ranged from 30.01–31.25 °C. The highest sea surface temperatures were found in the western part of Khao Bang Chang (station 6) and Khao Phing Kan (station 40) (Tables 1 and 2). The sea surface temperatures in 37 of the 44 sampling stations were higher than 30 °C. The mean sea surface temperature in Ranong and Phang Nga was 30.6 ± 0.4 °C. Fig. 4 shows the vertical profile of the water temperatures at stations 6 (water depth

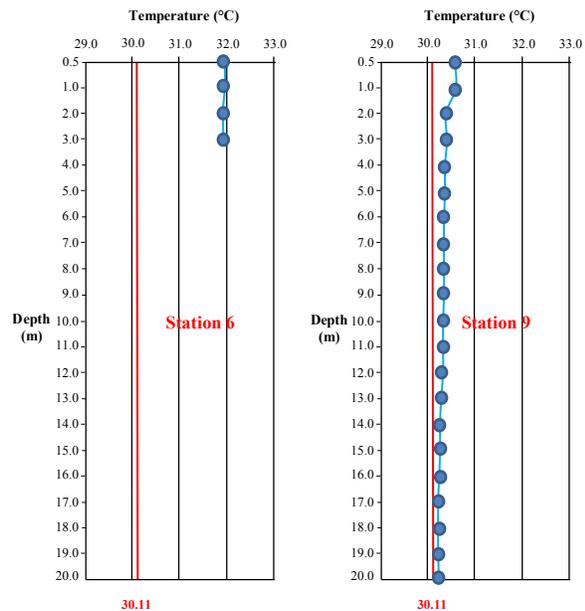


Fig. 4 Vertical profiles of temperature at stations 6 (left) and 9 (right).

2.5 m) and 9 (water depth 20 m). These profiles indicate vertical mixing of water occurring around the study area.

Surface salinity in Ranong and Phang Nga ranged from 32.98–34.80 and 32.90–33.41 psu, respectively, (Tables 1 and 2). During the dry season, all sampling stations had a surface salinity higher than 32 psu. The lowest salinity in Ranong and Phang Nga was found at the Ranong river mouth (station 1) and Khao Phing Kan (station 40), respectively. In the case of silicate-silicon concentration, results showed that the highest concentration in surface waters was found at the mouth of Ranong river (Table 1). In Phang Nga, the concentration of silicate-silicon varied from 3.77–25.23 μM (Table 2). The highest concentration was found at Khao Phing Kan (station 40) where the lowest salinity was also found.

Ammonium-nitrogen concentration in surface water in Ranong ranged between 8.45 and 14.08 μM , while in Phang Nga, it ranged from 9.99–25.11 μM (Tables 1 and 2). The highest concentration in Phang Nga was found at Ban Thai Mueang (station 38), an area which suffered severe damage from the 2004 tsunami. Orthophosphate-phosphorus concentrations of surface water in Ranong ranged between 0.34 and 0.77 μM , while in Phang Nga the values ranged from 0.13–0.49 μM . The highest concentration was found at the mouth

Table 1 Seawater characteristics of surface water in Ranong water (March 2005), the Andaman sea, Thailand.

Station	UTM zone 47		Temp (°C)	Salinity (psu)	NH ₄ ⁺ -N (μM)	Si(OH) ₄ -Si (μM)	PO ₄ ³⁻ -P (μM)	Chl <i>a</i> (μg/l)
	E	N						
1	453 571	1 100 210	30.05	32.98	11.40	10.54	0.77	3.17
2	450 648	1 095 140	30.15	33.48	11.26	8.43	0.60	4.67
3	445 484	1 095 140	30.24	33.67	10.56	6.32	0.44	2.00
4	446 945	1 090 120	31.06	33.76	11.61	6.32	0.47	2.10
5	442 951	1 091 290	30.36	33.89	9.85	6.32	0.34	2.50
6	447 092	1 085 110	31.90	34.54	11.96	6.32	0.43	3.00
7	442 707	1 085 060	31.02	34.32	11.61	6.32	0.43	2.84
8	445 874	1 080 230	30.68	34.80	10.56	6.32	0.43	2.94
9	440 174	1 079 800	30.40	34.14	11.26	5.27	0.43	1.84
10	444 412	1 075 170	30.42	34.37	11.26	6.32	0.34	2.00
11	438 859	1 074 880	30.33	34.29	11.61	5.27	0.34	2.17
12	442 999	1 070 050	30.08	34.14	9.85	5.27	0.34	1.93
13	436 861	1 070 150	30.06	34.36	10.56	4.22	0.34	3.00
14	440 856	1 065 280	30.25	34.14	9.15	6.32	0.34	1.72
15	440 612	1 059 970	30.05	34.33	8.45	6.32	0.34	1.34
16	438 615	1 054 800	30.49	34.29	11.26	6.32	0.34	2.29
17	437 689	1 050 080	30.83	34.40	11.26	6.32	0.38	2.29
18	436 764	1 044 910	30.69	34.34	14.08	6.32	0.36	2.00
19	433 743	1 039 990	30.64	34.04	10.91	6.32	0.43	2.00
20	432 818	1 034 980	30.60	33.98	9.71	6.32	0.34	1.50

Table 2 Seawater characteristics of surface water in Phang Nga water (March 2006), the Andaman sea, Thailand.

Station	UTM zone 47		Temp (°C)	Salinity (psu)	NH ₄ ⁺ -N (μM)	Si(OH) ₄ -Si (μM)	PO ₄ ³⁻ -P (μM)	Chl <i>a</i> (μg/l)
	E	N						
21	431 356	1 030 110	30.76	33.91	10.56	6.32	0.30	2.17
22	427 540	1 031 926	30.47	33.85	11.26	6.32	0.38	0.83
23	429 115	1 025 180	30.14	33.82	9.99	6.32	0.26	1.17
24	423 694	1 024 281	30.51	33.31	19.56	5.66	0.49	1.34
25	431 521	1 019 691	30.63	34.41	16.19	7.38	0.47	6.45
26	425 267	1 019 920	30.60	33.86	10.56	6.32	0.26	1.63
27	423 853	1 016 095	30.10	33.95	11.26	5.27	0.26	1.34
28	418 074	1 014 906	30.46	33.47	18.37	6.76	0.41	0.95
29	425 121	1 010 230	30.66	34.24	10.91	6.32	0.34	2.00
30	428 287	1 004 920	30.18	34.32	11.96	6.32	0.34	2.00
31	425 364	1 000 050	30.38	34.13	10.56	6.32	0.26	1.17
32	415 679	999 668	30.59	33.53	20.81	13.00	0.37	1.67
33	413 681	989 878	30.01	33.52	18.17	4.81	0.32	0.67
34	415 960	978 904	30.82	33.48	16.65	4.68	0.23	0.67
35	412 908	968 564	30.84	33.56	16.39	5.40	0.13	0.57
36	413 486	954 635	30.73	33.41	17.84	5.85	0.27	0.50
37	411 733	939 455	30.62	33.48	14.54	5.72	0.45	1.11
38	416 527	928 633	30.67	33.49	25.11	3.77	0.23	1.07
39	416 126	917 281	30.54	33.46	14.21	5.85	0.33	0.57
40	444 675	914 388	31.25	32.90	15.73	25.23	0.39	5.34
41	451 532	914 518	31.12	33.20	16.52	19.38	0.26	4.01
42	459 710	905 397	30.80	33.25	17.77	9.10	0.34	3.13
43	448 451	897 409	30.85	33.12	17.84	10.99	0.36	4.01
44	450 947	884 464	30.39	33.16	21.67	7.28	0.37	2.67

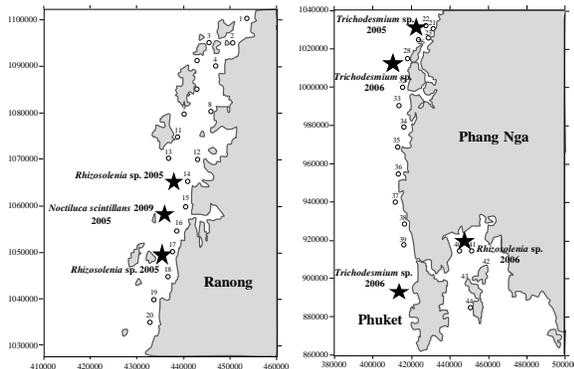


Fig. 5 Map of red tide incident locations in Ranong, Phang Nga, and Phuket provinces during field surveys from 2004–2009.

of Ranong River (station 1) and the eastern part of Ra island (station 24).

Chlorophyll *a* concentrations in Ranong ranged between 1.34 and 4.67 $\mu\text{g/l}$ with a mean value of $2.37 \pm 0.75 \mu\text{g/l}$. The highest concentration of chlorophyll *a* was found at the river mouth and in the adjacent area. In Phang Nga waters, chlorophyll *a* concentrations ranged from 0.57–6.45 $\mu\text{g/l}$ with a mean value of $2.0 \pm 1.6 \mu\text{g/l}$. Chlorophyll *a* concentration at Khao Phing Kan (station 40), where the highest concentration of silicate-silicon and the lowest salinity were found, was 5.34 $\mu\text{g/l}$.

Statistical analysis (*t*-test, 0.99 confidence coefficient) showed that the seawater parameters in Ranong were significantly different from those in Phang Nga, except for water temperature, silicate-silicon, and chlorophyll *a* concentrations.

Red tide incidence

The outbreaks of red tide were observed along the coastline areas during the field survey from 2005–2009 (Fig. 5). *Rhizosolenia* spp. red tides were found between stations 13 and 14, as well as between stations 17 and 18 during a 2005 survey. Furthermore, *Trichodesmium erythraeum* red tides were found at Ra island (nearby station 24) and western coast of Phuket island during a survey in 2006. The widespread occurrence of red tide caused by *Noctiluca scintillans* was also observed in the eastern part of Khang Khao island during the October 2009 survey.

Coral bleaching

Five months after the tsunami, the corals, especially *Acropora* spp., showed slight signs of recovery, but the corals here faced serious coral bleaching

Table 3 Length (in cm) of primary branch of *Acropora* spp. around the study areas after 2004 tsunami.

Location	May 2005		February 2007	
	Length	Average	Length	Average
Torinla island	2.0–4.1	3.0 ± 1.2	13.0–15.5	14.5 ± 1.3
Tao Bay	1.9–4.5	2.9 ± 0.9	–	–
Phak Kat Bay	3.7–4.1	3.9 ± 0.3	7.0–25.0	14.2 ± 5.8
Chong Khat	3.6–8.8	5.2 ± 2.2	7.0–18.0	14.2 ± 4.6
Khang Khao	1.2–7.6	3.9 ± 2.7	–	–
Lan island	3.8	3.8 ± 0.0	–	–

again (Fig. 6). The coral bleaching levels (survey in May 2005) could be categorized into four groups, namely, severe bleaching (bleaching of more than 80%), moderate bleaching (bleaching of 50–79%), slight bleaching (bleaching of 20–49%), and minimal bleaching (bleaching less than 20%). Fig. 7 shows the percentage of coral bleaching at 15 sampling sites around Phayam island. Both corals in the northern and southern parts of Phayam island were severely bleached whereas corals in the eastern part of this island were moderately bleached. The coral bleaching level at Khang Khao island ranged between slight to moderate bleaching (Fig. 7). Corals in all sampling sites in the eastern part of this island were slightly bleached. In addition, slightly bleached corals in this area were found during the survey in October 2009 (Fig. 6h).

Coral bleaching at Kam Yai, Kam Nui, and Lan islands ranged widely from minimal to severe bleaching (Fig. 8). The coral bleaching around Khaiyai island ranged from slight to severe bleaching. Fig. 9 shows the percentage of coral bleaching at 36 sampling stations around South-Surin and Torinla islands. Coral bleaching in these two islands ranged from slight to severe. At Torinla island, severe bleaching was observed where water depth was over 20 m.

Coral growth

The growth of *Acropora* spp. (*A. cytherea*, *A. formosa*, *A. tenuis*, *A. vauhani*) in Surin Marine National Park, measured in May 2005, showed that corals at Torinla island could grow between 2.0 and 4.1 cm in 5 months, while the mean value was about 3.0 ± 1.2 cm (Table 3). Around Tao bay and Phak Kat bay, corals could grow between 1.9 and 4.5 and 3.7–4.1 cm, with mean growth of 2.9 ± 0.9 cm and 3.9 ± 0.3 cm, respectively. At Chong Khat bay, the most severely damaged by the tsunami, corals could grow between 3.6 and 8.8 cm with a mean

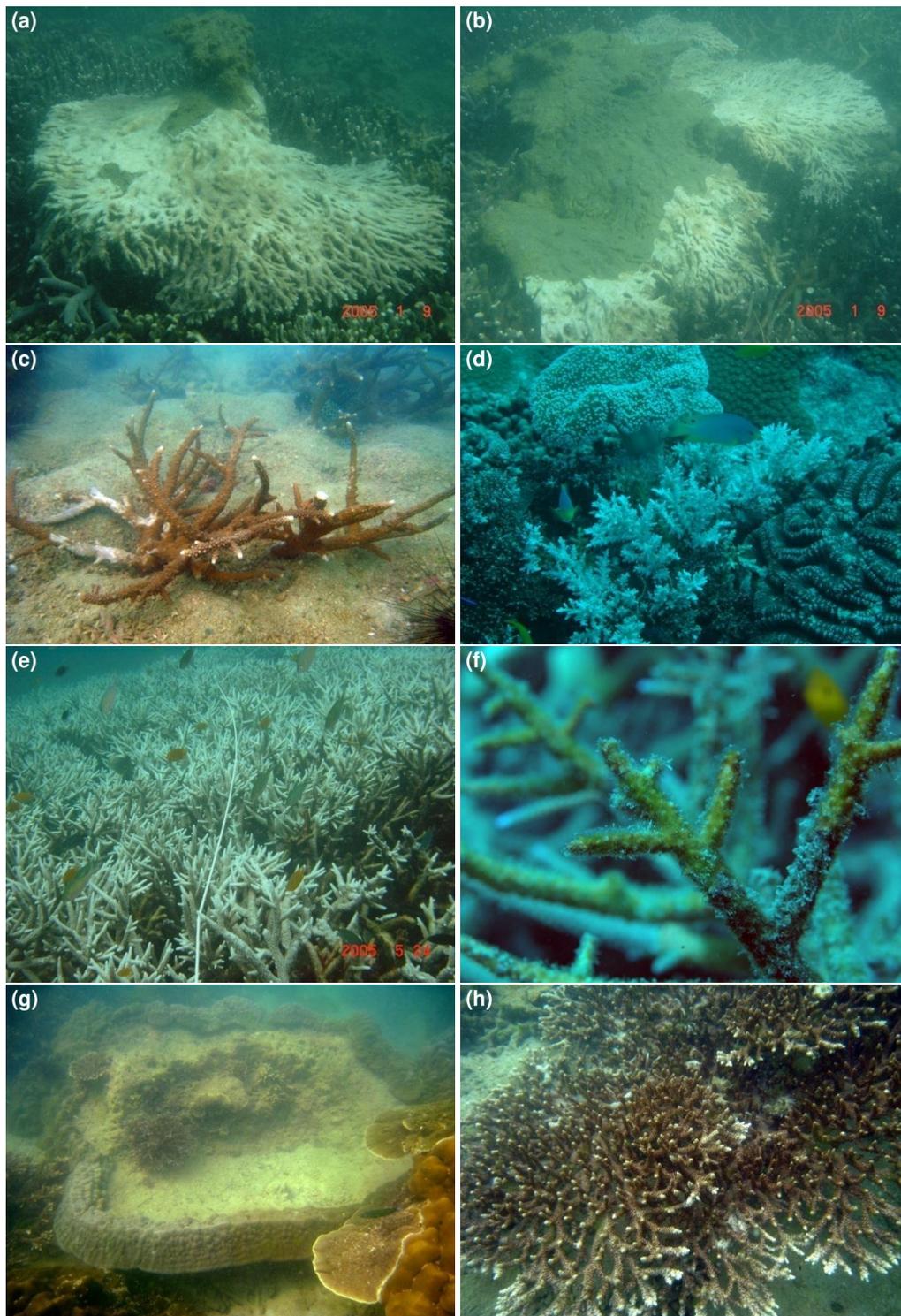


Fig. 6 (a, b, c) Morphology of *Acropora* spp. after attack by tsunami for 5 months; (d, e) coral bleaching occurring in both massive and branching corals in May 2005; (f) dead corals covered with macro algae and settled particulates in February 2007; (g) coral morphology at Khang Khao island in October 2009; (h) coral bleaching at Khang Khao island in October 2009.

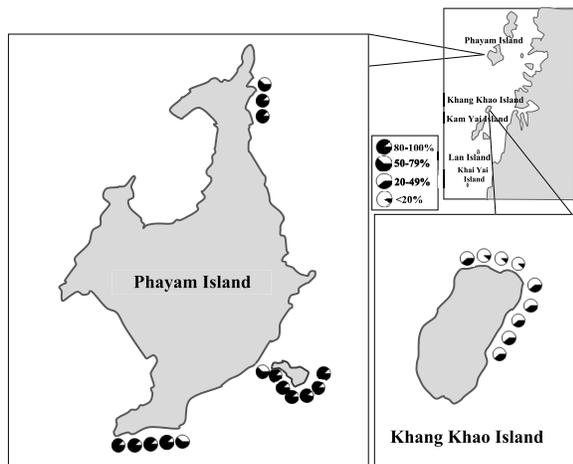


Fig. 7 Percentage of coral bleaching around Phayam and Khang Khao islands, Ranong, Thailand.

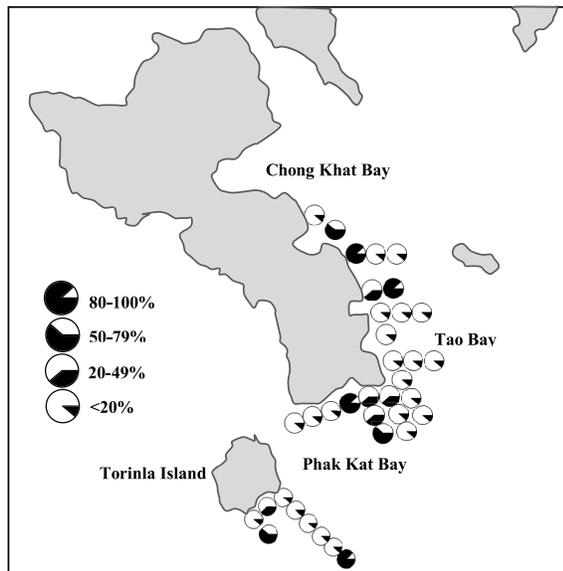


Fig. 9 Percentage of coral bleaching around Surin Marine National Park.

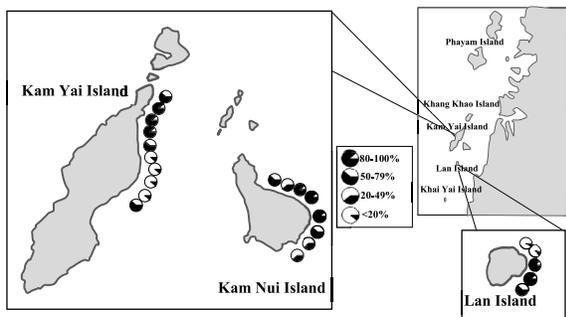


Fig. 8 Percentage of coral bleaching around Kam Yai, Kam Nui and Lan islands, Ranong, Thailand.

value of 5.2 ± 2.2 cm. Statistical tests (ANOVA, 0.95 confidence coefficient) carried out 5 months after the tsunami indicated that the coral growth rate at Chong Khat bay was significantly different from those at Tao bay and Phak Kat bay, while no significant difference was found between Tao bay and Phak Kat bay. In near shore areas such as Khang Khao and Lan islands, the growth of coral (determined in May 2005) were at a mean value of 3.9 ± 2.7 cm and 3.8 ± 0.0 cm, respectively.

Three years after the 2004 tsunami, the corals in Surin Marine National Park was able to grow rapidly, while corals in near shore areas were found in a poor condition covered with macroalgae and settled particulates (Fig. 6f). The estimated growth of corals at Phak Kat bay in February 2007 indicated that corals (primary branch) could grow at the mean length of 14.2 ± 5.8 cm while the mean length of whole areas of Surin Marine National Park was estimated to be

13.4 ± 5.2 cm. Corals in near shore areas, such as Lan island, were almost dead and have been covered with macroalgae and settled particulates for three years after the tsunami. However, the corals around Khang Khao island (near shore area) showed slight signs of recovery in October 2009 (Fig. 6g).

DISCUSSION

Seawater characteristics

Elevation of sea temperature has long been suggested as an important factor inducing coral bleaching^{10,13}. The results from current study on seawater characteristic demonstrated that the surface water temperature of the Andaman sea was higher than those of the water temperature in the past. Brown¹⁰ revealed the seasonal variation of water temperature of the Andaman sea during 1946–1996. They also proposed a relationship between seawater temperature and coral bleaching around the coast of Phuket, Thailand, and concluded that the critical seawater temperature for coral bleaching was 30.11 °C. According to this study, the average seawater temperature at Ranong and Phang Nga, areas close to Phuket, was estimated to be 30.56 ± 0.37 °C greater than the critical seawater temperature reported by Brown¹⁰. Recently, the frequency and distribution of coral bleaching in the Andaman coastline of Thailand has increased, especially during April and May. This could be one of the important reasons for the gradual decline of

corals and reef areas over the years.

Corals can tolerate a wide range of salinities, i.e., between 15 and 50 psu²⁵. Our results indicate that the salinity of Andaman sea is still in the optimal range for coral growth, although freshwater runoff is gradually increasing due to the destruction of mangrove and inland forests along the Andaman coastline. The mangrove area in Ranong and Phang Nga Provinces was estimated to be from 21 800–36 700 ha²⁶. Thereafter, it has decreased to 19 237 ha in 1998, then it increased to 25 092 ha in 2004 due to the reforestation programme of the Royal Forestry Department. However, the natural inland forest was still reduced and substituted with monoculture of rubber trees. Silicate-silicon concentration in some study areas was quite high (over 25 μM). High concentrations of silicate-silicon can potentially stimulate the growth of benthic diatoms, which covers the coral and bottom sediments. Concentrations of ammonium-nitrogen ($\text{NH}_4^+\text{-N}$) and orthophosphate-phosphorus ($\text{PO}_4^{3-}\text{-P}$) in Ranong and Phang Nga waters were slightly low compared to the values in the Gulf of Thailand. Concentrations of $\text{PO}_4^{3-}\text{-P}$ in Ranong was markedly high (0.34–0.77 μM) compared to the value obtained from the same area in 1992²⁴. The results from Limpsaichol²⁷ indicated that the average concentration of $\text{PO}_4^{3-}\text{-P}$ in Ranong area ranged from 0.13–0.24 μM during December 1990 to December 1992. Pollution Control Department reported that average concentrations of $\text{PO}_4^{3-}\text{-P}$ throughout the year in the southern part of Ranong (stations 19 and 20) were 0.03 and 0.07 μM in 1997 and 2002, respectively. Our results confirmed that the nutrient concentration in the Andaman sea has soared. Although incidences of red tide are rare in the Andaman sea, outbreaks of *Rhizosolenia* spp. were found along the Andaman coastline during a survey in 2005, as well as *T. erythraeum* in the Phang Nga area during a survey in 2006. In addition, an occurrence of *N. scintillans* red tide covered the eastern part of Khang Khao island in 2009. Recent blooms of macroalgae such as *Cladophora* and *Enteromorpha* have been observed at Patong beach, Phuket island, during January and February 2005 and 2006, respectively. Tsunami run-up is also an issue regarding the nutrient enrichment of the Andaman sea. Thus after the tsunami in 2004, the frequency of the outbreak of red tide and macroalgal bloom seem to be increasing in the Andaman coastline.

The Andaman sea of Thailand has been well known for its clean and clear water. Nowadays, the

Andaman sea, especially in areas near the shore, is quite turbid and abundant in nutrients. Chlorophyll *a* concentration in the water column represents the turbidity and nutrient concentration in seawater. Limpsaichol²⁷ reported that the average chlorophyll *a* content of seawater in the Ranong area was 0.47 $\mu\text{g/l}$. However, our result suggested that the average chlorophyll *a* content of seawater in Ranong increased to 2.37 ± 0.75 $\mu\text{g/l}$. Moreover, the chlorophyll *a* content at Khao Phing Kan (station 40), a well-known tourist area, was higher than 5.0 $\mu\text{g/l}$. These results show that water quality around this area has deteriorated. The increase in nutrient concentration in the Andaman sea is caused by both human activities and natural disasters. Social community expansion and an increase in the number of tourists are the main causes of nutrient enrichment in the Andaman sea. Although nutrient concentration and some seawater characteristics in Ranong and Phang Nga waters have significant differences, they had similar chlorophyll *a* concentrations. This phenomenon suggests that the nutrient concentration of both study areas is enough and/or in excess, to support phytoplankton growth.

Coral bleaching

Coral bleaching in the Andaman sea has been reported by several authors over the last two decades^{11,21,22}. In the past coral bleaching mostly affected branching corals, but in this study bleaching was found to have affected both branching and massive corals. Although coral bleaching is associated with a variety of physiological stresses, the most important cause is elevated water temperature. Phongsuwan¹¹ noted that about 80% of *Acropora* spp. in Surin islands died after bleaching in May 1995 when seawater temperature was 0.7 °C higher than the critical temperature suggested by Brown¹⁰. In this study, some areas had seawater temperatures which were more than 1.4 °C higher than the critical temperature, resulting in the bleaching of more than 80% of both branching and massive corals in near shore and offshore areas.

Serious coral bleaching also occurred in the eastern part of the Gulf of Thailand in 1995 resulting in the mortality of more than 70% of branching corals around shallow water areas. In the Andaman sea, coral bleaching phenomenon was an annual event even before the 2004 tsunami, although some corals were able to recover. However, the coral bleaching phenomenon in 2005 was different from former incidences, with mass coral mortality occur-

ring along the Andaman coastline. Interestingly, after the 2004 tsunami, the coral reefs in deep areas (ca 25 m depth such as in Surin Marine National Park) could grow and recover very fast although they also faced serious bleaching. The coral reefs in the shallower waters along the Andaman coastal zones however was unable to recover within three years after serious bleaching. This situation could be due to light limitation from high turbidity in shallower zones, resulting in limited growth of symbiotic dinoflagellate in the coral. Recently, the high density of phytoplankton in the shallower waters along the Andaman coastal zones usually covered the reef areas leading to reduced light intensity. Moreover, red tide outbreaks have also occurred more frequently around the study site. As a consequence, the growth of symbiotic dinoflagellate in coral polyps was restricted.

Growth of corals

Since the corals along the Andaman coastline had been damaged over a vast area, a great number of samples were collected from each area. Although many *Acropora* species included in the samples might have caused variability in the growth between species, exactly settlement time, and those of individual branches due to their alignment or shading effects of one branch upon another, the data collected could demonstrate the sign of recovery and degeneration of coral reefs in the study areas. The growth of *Acropora* spp. around Surin Marine National Park, determined in May 2005, demonstrated that during the early period (5 months after tsunami) the growth rate of corals at Chong Khat bay (1.0 cm/month) was significantly different from the other study sites. There was no significant difference in growth rate of corals in Torinla island, Tao bay, and Phak Kat bay. Mean growth rate at all three sampling sites was estimated to be 0.6 cm/month. At Chong Khat bay, the most severely damaged area by the tsunami, corals were able to grow faster than at any other study site during the 5 months after tsunami. In the case of near shore areas, the growth of corals at both Khang Khao and Lan islands, determined in May 2005, had mean values of 0.8 cm/month. For long term monitoring, the growth of corals estimated around Surin Marine National Park in February 2007 showed that they had no significant differences in growth rates between sampling sites.

The mean length of the primary branch of corals at Phak Kat bay was estimated to be 3.9 ± 0.3 cm 5 months after the tsunami (about

0.8 cm/month), and the mean length was estimated to be 14.2 ± 5.8 cm three years after the tsunami (about 0.4 cm/month). Results indicate that corals around Surin Marine National Park were able to grow at a faster rate during the dry season (November–April) than during the wet season. Charuchinda and Hylleberg²⁸ also reported that the growth rate of *Acropora formosa* in Phuket during the north-East monsoon (November–April) was about twice faster (0.31 ± 0.08 mm/day or about 0.9 cm/month) than during the South-West monsoon (April–October). This phenomenon is also similar to the growth of *A. pulchra* in the Philippines, reported by Yap and Gomez²⁹, who suggested that the growth rate of *A. pulchra* was faster during the cool season (November–January) and was affected by the North-East Monsoon. They estimated the average growth rate of *A. pulchra* to be 15.3 cm/year. Previous studies reported a higher growth rate compared to the results of this study. This might be due to their short monitoring period or omitting some warm months^{30–32}. Strömögren³³ compared the growth rate of *A. pulchra* around Phuket Province, Thailand, as well as in the Philippines. He suggested that the growth rate of *A. pulchra* in the Philippines was markedly higher than that in Phuket due to higher water temperatures and stronger solar radiation.

Conclusions

After the occurrence of the tsunami in 2004, the concentration of nutrients (silicate-silicon, ammonium-nitrogen and orthophosphate-phosphorus) in the study areas increased due to tsunami run-up. Thereafter, chlorophyll *a* in the water column gradually increased due to rapid growth of phytoplankton (red tide outbreak a few months after the tsunami), and severe coral bleaching also occurred due to the increase in seawater temperatures to levels higher than the critical temperature. These conditions resulted in a mass mortality of corals in shallow waters. Three years after the 2004 tsunami, the coral reefs in deep water areas could grow and recover rapidly although they faced serious bleaching. Whereas, coral reefs in the shallower waters were in a poor condition after serious bleaching in May 2005. Mass mortality of corals in shallow waters was enhanced by high seawater temperature and high turbidity due to phytoplankton blooms. Turbidity is thus considered to be the most important factor leading to the degradation of corals in near shore shallow areas. Our results indicated that the future of corals in the Andaman sea, especially in shallow

coastal zones, is threatened. Although it is difficult to reduce seawater temperature levels caused by global warming in this region, it is possible to reduce phytoplankton density and other suspended particles in water column by decreasing nutrient loading and sediment runoff caused by domestic waste sediment and/or local deforestation. The coral population could vanish in the near future if stakeholders do not take action to tackle these problems.

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