Differential bleaching patterns in corals of Palk Bay and the Gulf of Mannar

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The status of reefs in Palk Bay and the Gulf of Mannar was studied during April–May 2016 following a bleach alert, as the sea surface temperature recorded a sudden increase from 30.5°C to 34.0°C in Gulf of Mannar. About 71.48% ± 8.9% of the corals in Palk Bay and 46.04% ± 3.78% in Thoothukkudi group of Islands in Gulf of Mannar were found bleached, showing a clearly decreasing trend from north to south, which could be attributed to the corresponding pattern in intensity of SST recorded in the study sites. Observations of bleaching patterns among different life-forms showed 68% of the bleached corals were massive forms. It was observed that 22 out of the 26 massive forms were bleached, while the *Acropora* corymbose (ACC), digitate (ACD) and encrusting coral (CE) forms were not bleached in any of the study sites in Palk Bay and Gulf of Mannar. The study suggests that the ACC, ACD and CE forms have adapted to thermal stress, subsequent to the earlier mass bleaching events. The study highlights the need for understanding the molecular mechanism of the association between corals and the symbiotic algae, for further understanding on coral bleaching in Indian waters.

Keywords: Adaptive coral bleaching, Gulf of Mannar, Palk Bay.

CORALS are among the most susceptible marine organisms to environmental anomalies, particularly temperature changes. During 1981–2010, the mean, maximum and minimum atmospheric temperatures increased at a rate of around 0.2°C per decade, which is several fold higher than that for the entire century (1901–2010). Mean sea surface temperatures (SSTs) in tropical regions have increased by almost 1°C over the past 100 years and are currently increasing at the rate of 1–2°C per century[1]. Sustained SST increase causes the zooxanthellae, a symbiotic microalgae providing pigmentation to coral tissues and 90% of nutritional needs of the corals[2], to leave the host, leading to whitening of corals, also termed as 'bleaching'. This is one of the major threats, which significantly affects reefs across the globe. It is estimated that 30% of the world's coral reefs are severely damaged and about 60% of those remaining may be lost by 2030 (ref. 3).

The Gulf of Mannar (GoM) and Palk Bay located in the southeast coast of India, are among the major reef systems in the country. GoM has 21 islands comprising four groups, viz. Mandapam (seven islands), Keelakarai (seven islands), Vembar (three islands) and Thoothukkudi (four islands), based on geographic proximity to locations on the mainland (Figure 1).

Coral reefs of GoM are under various threats, including pollution, sedimentation, destructive fishing practices and biological invasion[4,5]. Since 1998, GoM and Palk Bay reefs have experienced seven severe bleaching events[6]. The present study was conducted during April–May 2016, following a bleaching alert from the National Centre for Sustainable Coastal Management (NCSCM) for GoM determined based on the data buoy deployed at Krusadai Island, GoM (9°14′44.61″N; 79°14′3.13″E). This was further corroborated with degree heating week (DHW) alerts on coral bleaching issued by MoES-Indian National Centre for Ocean Information Services (INCOIS), Hyderabad using satellite-derived SST data, following NOAA Coral Reef Watch (CRW).

In order to assess the impact of elevated SST on the reefs in these areas, field surveys were conducted during April 2016 at two sites in Palk Bay (Thonithurai and Olaikuda) and six islands in GoM, spanning from north to south, viz. Mandapam Island group (MG – Kurusadai and Shingle); Keelakarai Island group (KG – Valimunai and Anaipar) and Thoothukkudi Island group (TG – Vaan and Koswari; Figure 1).

In each of the study sites, 20 m transects were laid in triplicate, running parallel to each other at 5 m interval, along the depth contour in order to assess the benthic community of the reefs[7]. The coral substrate was classified under 11 life-form categories (*Acropora*, branching: ACB; *Acropora*, corymbose: ACC; *Acropora*, digitate: ACD; *Acropora*, tabular: ACT; branching coral (non-*Acropora*): CB; encrusting coral: CE; massive-platy coral: CMP; massive coral: CM; foliose coral: CF; tabular coral (non-*Acropora*): CT and sub-massive coral: CSM)[8]. The bleaching status (unbleached, partially bleached, bleached) of corals was recorded following Marshall and Schuttenberg[9]. The life-forms were expressed as per cent cover of transect, while the extent of bleaching was expressed as percentage of live coral cover. The percentage benthic cover, thus determined, was then considered to be an unbiased estimate of the proportion of total area covered by the particular life-form. Coral species were identified based on field observations and using video transects recorded from the study sites following Veron[10].

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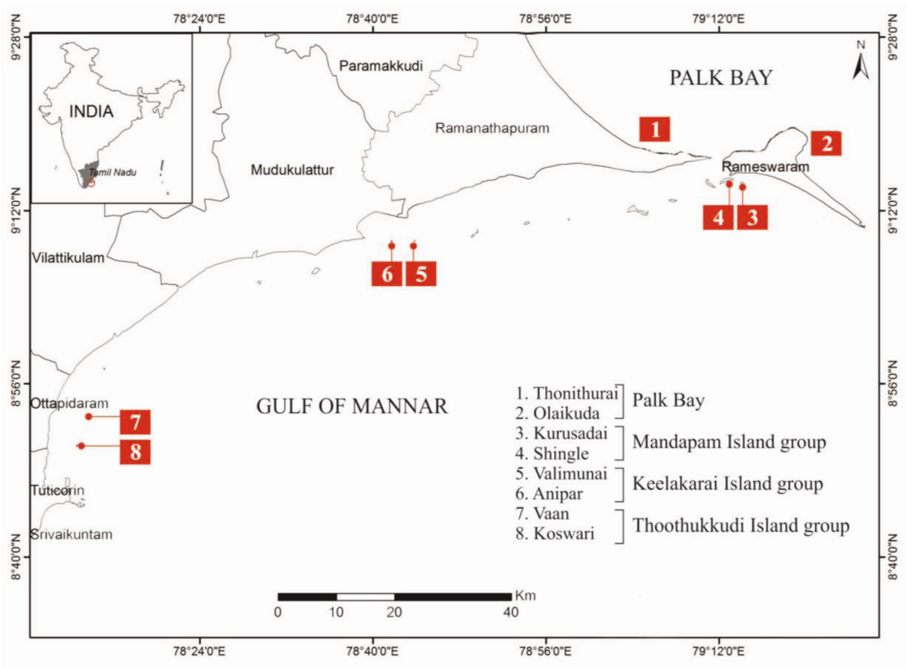

Figure 1. Study sites from Palk Bay and the Gulf of Mannar.

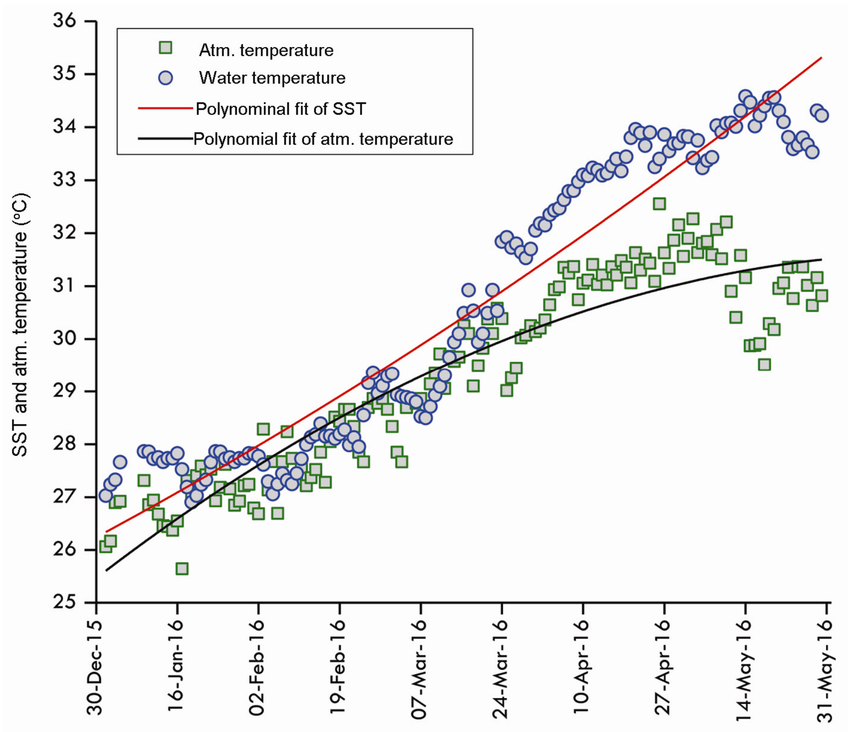

Figure 2. Temporal variation in sea surface temperature (SST) and atmospheric (atm.) temperature in GoM (recorded from data buoy at Krusadai Island and Automatic Weather Station at Mandapam).

SST data were observed from shallow waters (~4 m) of Kurusadai Island by deploying a data buoy capable of real-time measurement and subsequent transmission of nine physico-chemical variables (water temperature, pH, salinity, dissolved oxygen, oxygen saturation, coloured dissolved organic matter, turbidity, total dissolved solids and chlorophyll) to the NCSCM database. Continuous measurement at every 15 min time interval ($n = 14,688$) was carried out from 1 January to 31 May 2016. Similarly, simultaneous measurements of seven meteorological variables, including atmospheric temperature at every 3 min interval ($n = 75,429$) were made using an automatic

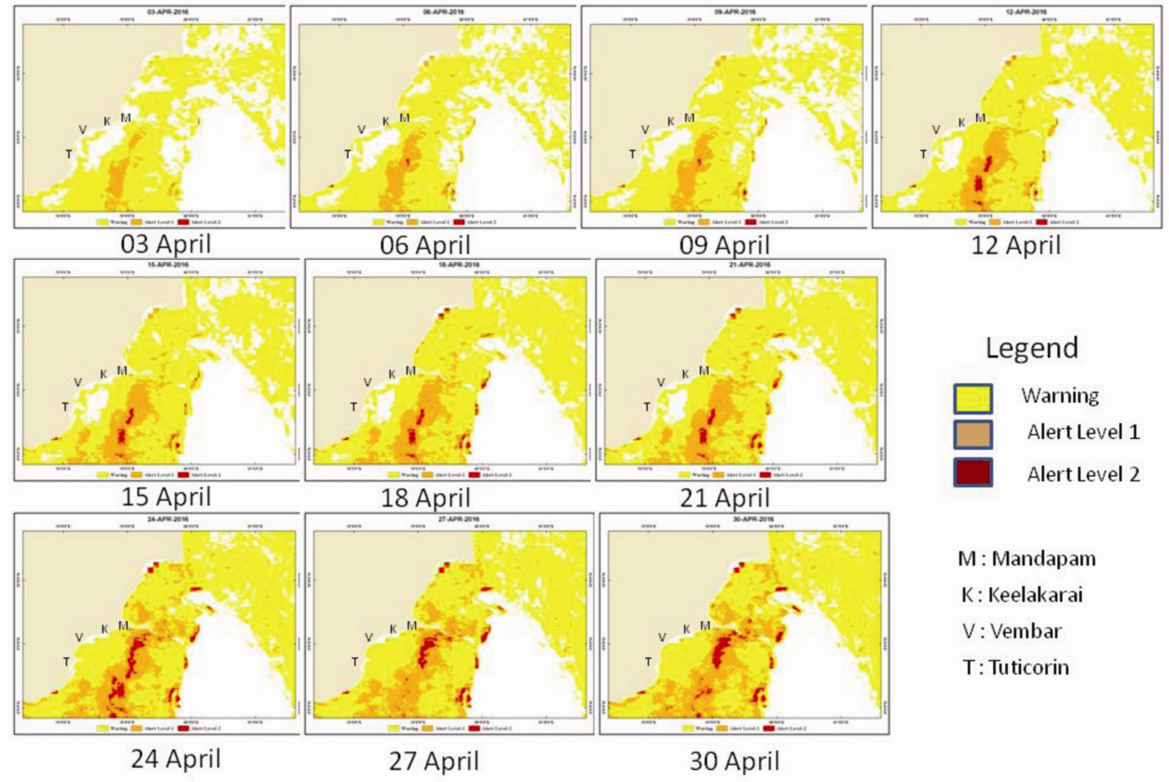

Figure 3. Spatial distribution of Degree Heating Week around GoM and Palk Bay showing the alert status during April 2016.

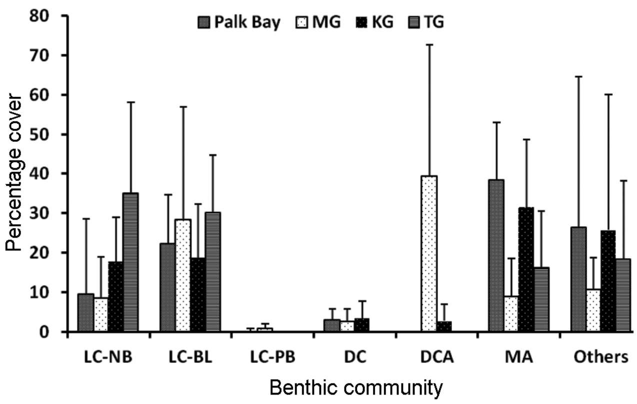

Figure 4. Percentage cover of major benthic components in Palk Bay and the GoM (LC-NB, Live coral, non-bleached; LC-BL, Live coral, bleached; LC-PB, Live coral, partially bleached; DC, Dead coral; DCA, Dead coral with algae; MA, Macro algae and others, sand, rock, rubbles.)

Table 1. Percentage of live and bleached corals in Palk Bay and the Gulf of Mannar

Regions	Percentage of live coral cover in the transect	Percentage of bleached coral in the live coral
Palk Bay	31.10 ± 4.56	71.48 ± 8.9
Mandapam group	37.75 ± 3.87	67.55 ± 12.32
Keelakarai group	36.50 ± 6.8	51.37 ± 4.75
Thoothukudi group	65.53 ± 6.78	46.04 ± 3.78

weather station (AWS), installed at a height of 10 m from the surface at an adjacent location. The daily average temperature was extracted from 24 h observational data (between 00 h and 24 h) to understand the temporal changes in SST ($n = 148$) and atmospheric temperature ($n = 148$) patterns, and their subsequent impact on coral health.

Analysis of daily average SST and atmospheric temperature data indicates that at any given point in time during January to May 2016, SST was warmer than atmospheric temperature, which is unusual under normal climatic conditions (Figure 2). SST varied from a minimum of 26.9°C in January 2016 to a maximum of 34.6°C in May 2016, rising at a consistent rate of 0.03°C/month from January to March 2016. However, SST accelerated to 0.07°C/month during the period between April and May 2016, which was threefold higher than the preceding months. Sudden increase in SST was consistent with the increase in DHW during first week of April 2016, followed by sustained increase in the average and maximum DHW plots, till the end of April 2016. Although the atmosphere temperature showed steady increase over the same period of time, the exponential rate of increase was not on par with the SST, possibly due to the impact of other met-oceanic variables, that change on shorter time-scales[11].

Elevated SST causes thermal stress leading to the expulsion of symbiotic zooxanthellae by corals. In

Table 2. List of species identified from Palk Bay and the GoM

Morphology code	Coral species	Palk Bay	MG	KG	TG
ACB	*Acropora abrolhosensis*				●○
	Acropora brueggemanni				●
	Acropora chesterfieldensis				○
	Acropora copiosa				○
	Acropora formosa		●○		○
	Acropora forskali			●	
	Acropora schimitii		●		
ACC	*Acropora polystoma*	●			
ACD	*Acropora digitifera*	●		●	
	Acropora gemmifera	●			
ACT	*Acropora hyacynthus*				○
	Acropora lamarcki				●
CB	*Montipora digitata*			○	●
	Montipora samarensis		○		
CE	*Montipora peltiformis*			●	
CMP	*Symphyllia radians*				○
	Symphyllia recta				●
CM	*Cyphastrea microphthalma*			●	
	Diploria clivosa				○
	Favia favus	●○			
	Favia lizardensis		○		
	Favia mathaii	○			
	Favia rosaria	○			○
	Favia speciosa	○			●○
	Favia veroni			○	
	Favites chinensis				○
	Favites flexuosa				○
	Favites russelli				○
	Goniastrea minuta		●	●○	○
	Goniastrea peresi				○
	Goniastrea retiformis	●			○
	Leptastrea purpurea		●	○	●
	Leptastrea transversa	●○		●	
	Leptoria phrygia				●
	Montastrea annularis			●	
	Montastrea colemani	○			
	Montastrea valencinensis	○			
	Oulophyllia crispa	○			
	Platygyra sinensis	○			
	Platygyra verweyi	●			
	Porites lobata	●○	○		
	Porites lutea	●○	○	○	○
	Porites solida	●○			
CF	*Turbinaria mesenterina*				○
	Turbinaria peltata				○
CT	*Montipora florida*			○	●
CSM	*Favites halicora*	●			●
	Favites spinosa				○
	Hydnophora microconus				○
	Pavona variance		○		
	Pocillopora damicornis		●○		●
Total no. of species		18	10	12	29
Non-bleached, bleached		11, 12	5, 7	7, 6	11, 20

●, Non-bleached; ○, Bleached. MG, Mandapam Group; KG, Keelakarai Group; TG, Thoothukkudi Group.

tropical conditions, an increase in SST by >1°C during summer for 3–4 weeks triggers corals bleaching[12,13]. The real-time SST recorded from NCSCM data buoy showed an increase in temperature by ~2°C from the end of March till the first week of April, which could be attributed to the expulsion of zooxanthellae and resultant bleaching event in the study sites.

Spatial distribution of DHW images indicated that the Mandapam region was at 'alert level 1' during the latter part of April 2016 (Figure 3). The Keelakarai, Vembar and Tuticorin regions consistently indicated 'warning levels' of DHW during the same period. The spatial distribution of DHW indicated that the level of threat to the reefs in Mandapam region was high and it decreased towards the south of GoM.

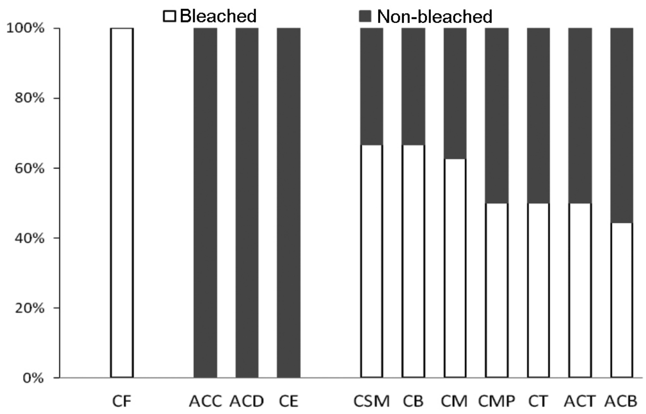

Figure 5. Percentage cover of bleached and non-bleached coral life-forms in Palk Bay and the GoM. (ACB, Acropora, branching; ACC, Acropora, corymbose; ACD, Acropora, digitate; ACT, Acropora, tabular; CB, branching coral (non-Acropora); CE, encrusting coral; CMP, massive-platy coral; CM, massive coral; CF, foliose coral; CT, tabular coral (non-Acropora); CSM, sub-massive coral.)

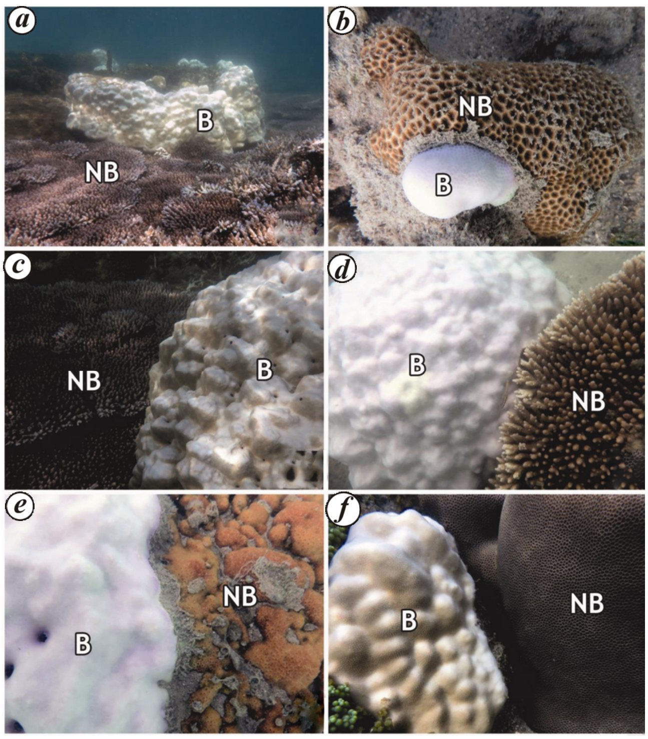

Figure 6. Differential bleaching patterns among the hard corals of different genera. ***a***, *Porites lobata* (B) and *Acropora digitifera* (NB); ***b***, *Porites solida* (B) and *Leptastrea transversa* (NB); ***c***, *Acropora digitifera* (NB) and *Porites lutea* (B); ***d***, *Porites solida* (B) and *Acropora digitifera* (NB); ***e***, *Porites lutea* (B) and *Cyphastrea microphthalma* (NB); ***f***, *Porties lobata* (B) and *Goniastrea minuta* (NB). B, Bleached; NB, non bleached.

Figure 4 shows the per cent cover of different components of reef substrates in the study sites. The per cent cover of live corals in the transects (including bleached, partially bleached and non-bleached) of the Thoothukkudi Island group (65.53% ± 6.78%) was significantly ($P < 0.01$) higher than that in other island groups. The per cent cover of dead coral with turf algae was maximum in Mandapam Island group (39.5 ± 32.6) and minimum in Keelakarai Island group (2.75 ± 3.24). The per cent cover of partially bleached coral was not significant ($P > 0.01$) in all the study sites.

The extent of bleached corals as a percentage of live coral cover in the transects was highest in Palk Bay (71.48% ± 8.9%) and showed a decreasing trend towards the southern islands with Thoothukkudi Island group recording the lowest value (46.04 ± 3.78%; Table 1). This trend was consistent with the levels of threat predicted in the DHW map of this region. The reefs in Thoothukkudi were deeper (6–10 m) than those in Palk Bay (2–3 m), which also would have contributed to the difference in the extent of bleaching in these island groups.

Analysis of the extent of bleaching among the life-forms indicated that out of 26 species of massive corals, bleaching was dominant in 22 species. *Acropora* corymbose, digitate and encrusting coral forms remained intact in all the study sites. It was observed that 50%–70% of the species representing other life-form categories, viz. *Acropora* tabular, branching coral (non-*Acropora*), platy massive corals, massive corals, foliose corals, tabular corals (non-*Acropora*) and sub-massive corals were bleached (Figure 5). In Thoothukkudi Island group, 100% of foliose corals were bleached.

A total of 51 scleractinian species were recorded along the transects laid in the study sites, of which massive

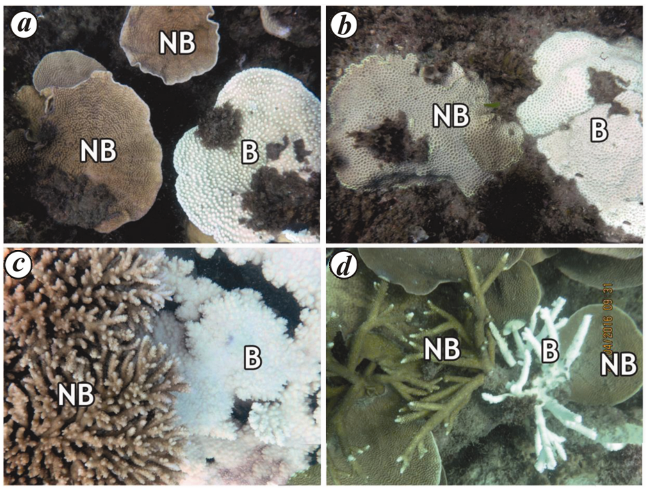

Figure 7. Differential bleaching patterns among the same genera/species of hard corals in Palk Bay and the GoM. ***a***, *Turbinaria mesenterina* (NB) and *Turbinaria peltata* (B); ***b***, *Goniastrea retiformis* (B) and (NB); ***c***, *Acropora forskali* (NB) and *Acropora hyacinthus* (B); ***d***, *Acropora abrolhosensis* (NB and B). B, Bleached; NB, non bleached.

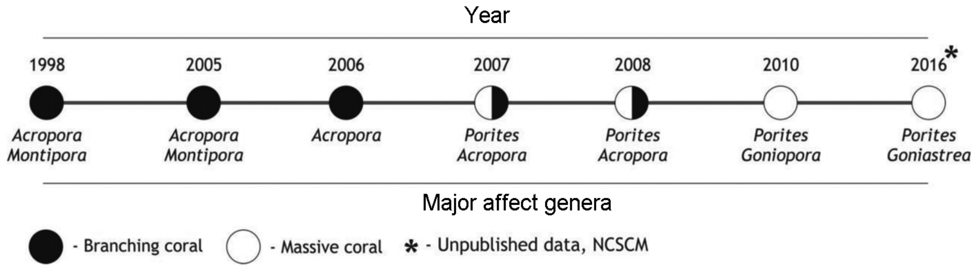

Figure 8. Bleaching trend recorded from previous events.

Table 3. Details of past bleaching events reported from India

Location, year	Bleaching %	Temperature (°C)	Most affected species/group	Reference
Lakshadweep (2010)	73	34	Scleractinian corals, sea anemone, giant clam	30
Andaman (2010)	36–69	31–33	*Acropora* spp., *Echinopora*, *Porites*, *Diplostrea*, and *Sinularis* (soft coral)	31
Car Nicobar (2010)	46.3	Not reported	Not reported	32
Palk Bay (2010)	41.3	31.5	*Porites*, *Goniopora* and *Favia*	18
Gulf of Mannar (2008)	10.5	32.5	*Porites* and *Acropora*	20
Gulf of Mannar (2007)	12.9	32.9	*Porites* and *Acropora*	20
Gulf of Mannar (2006)	15.6	33.5	*Acropora*	20
Gulf of Mannar (2005)	14.6	32.6	*Acropora* and *Montipora*	20
Palk Bay (2002)	50–60	29.5–32.6	*Acropora, Montipora* and *Pocillopora*	16
Gulf of Mannar (1998)	75.04 (dead coral)	Not reported	Not reported	15
Gulf of Kachchh (1998)	11	3°C above seasonal averages	Not reported	14
Gulf of Mannar (1998)	82		*Acropora, Montipora* and Tabular corals	14
Lakshadweep (1998)	89		Encrusting corals	14

corals and acroporid corals accounted for 51% (26 species) and 13% (13 species) respectively. The number of species was maximum in Thoothukkudi Island group (29), followed by Palk Bay (18), Keelakarai Island group (12) and Mandapam Island group (10). Among the corals observed along the transects, 14 species were not bleached in any of the study sites, whereas 23 species were observed to be completely bleached. The number of bleached coral species was higher than the non-bleached corals in all the study sites, except in Keelakarai Island group. Table 2 shows species-wise variation in the status of bleaching in Palk Bay and GoM.

The bleaching pattern observed in the reefs of GoM and Palk Bay was unique and uneven, that in some sites *Porites* colonies were bleached but adjacent colonies of *Acropora* were not affected (Figure 6 *a*, *c* and *d*). Other massive corals such as *Leptastrea*, *Cyphastrea* and *Goniastrea* were also not bleached in the same reef area (Figure 6 *b*, *e* and *f*). Such differential bleaching pattern was recorded within the genus and species, i.e. same species of two adjacent colonies showed uneven bleaching responses (Figure 7).

So far, five mass coral bleaching events have been recorded in GoM and two in Palk Bay[14–18] (Table 3). In all these cases, the pattern was more or less uniform where the branching *Acropora* corals were more susceptible to thermal stress than the massive corals such as Porites[19]. During the 1998, 2005 and 2006 bleaching, (ACB) and *Montipora* (CE) were severely bleached[14,16,17], whereas in the present study, none of the ACC, ACD and CE colonies was bleached and the percentage of bleached ACB was significantly ($P < 0.01$) less than that of massive corals (Figure 5). In this study, though the extent of bleaching of hard corals was relatively less (25.17%), distinct variation was seen in the pattern, i.e. 68% of the bleached corals were of massive form. The reversal in the hierarchy of taxa susceptible to thermal stress can be seen in this bleaching event.

A detailed look into the pattern and species of corals reported to have been bleached during the earlier events[13–16,18] indicates that since 2007, the branching corals in GoM and Palk Bay have shown greater resilience to fluctuating temperature than the massive corals (Figure 8). The increase in live coral cover in the reefs of GoM from 36.98% ± 13.12% (2005) to 42.85% ± 10.74% (2009), may perhaps be attributed to increasing resilience and adaptation to thermal stress since 2005 (ref. 20).

Corals are presumed to be capable of adapting to thermal stress by shifting to symbioses with more temperature-tolerant species (or clade) of Symbiodinium[20–23]. The possibility of algal switching or shuffling, however, relies on the assumption that a coral species can host multiple algal genotypes[24], either sequentially or simultaneously[25].

Our observations on *Acropora abrolhosensis* ($n = 27$), which had few bleached branches and healthy branches in a single colony (Figure 7 *d*) lead us to hypothesize that the branching corals (*Acropora* sp.) in GoM have possibly acquired the thermal tolerant algal symbionts following the previous bleaching events. While in all earlier bleaching events reported in different reef systems in India, acroporids (branching corals) were severely affected (Table 3 and Figure 8), in the present study, 7 out of 12 species of *Acropora* were not bleached. This could be attributed to adaptive bleaching[26,27], the basic principle of which is that shifting combinations of hosts and symbiotic algae have the ability to create new ecospecies that differ in environmental tolerance.

It is propounded that the recent bleaching events may have provided an opportunity for change of the dominant photo-symbionts in the susceptible life-forms of corals[28]. Notwithstanding the above, an adaptive response in certain taxa at a few locations does not indicate that the global threat to reefs from climate change has lessened[29]. Understanding the molecular mechanism of the association between corals and symbiotic algae would aid in implementing appropriate measures for conserving these sensitive ecosystems.

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