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Photosynthetically active radiation, a critical parameter for mass coral bleaching in the North Indian Ocean

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The Gulf of Mannar (GOM) and Kadamat Island (KI) are two major coral reefs that were severely bleached en masse in the North Indian Ocean (NIO) during 1998. Mass coral bleaching took place once again in NIO during 2002, which severely affected the GOM corals but not the KI corals. This contrasting phenomenon prompted us to re-examine parameters such as surface sea temperature (SST), photosynthetically active radiation (PAR), hotspots, heat content, sea-surface height anomaly (SSHA) and North Indian Ocean Dipole (NIOD) events. The analysis indicates that the above mass bleaching events are associated with high PAR (47 Einstein/m^2/day) with minimum SST of 30°C, which was probably critical for mass bleaching in NIO during 1998 and 2002. However, the above bleaching events do not show any direct link with SSHA, hotspots and NIOD.

Keywords: Coral reefs, hotspots, mass bleaching, photosynthetically active radiation.

CORAL bleaching is the whitening of corals caused by expulsion of zooxanthellae, the photosynthetic pigments in corals. Regardless of the geographic location, mass bleaching occurs worldwide due to elevated temperature[1] and thermal stress[2,3] under changing climatic scenarios such as greenhouse warming, El Niño and El Niño Southern Oscillation (ENSO). Earlier studies have shown that tolerance of corals to thermal stress varies regionally[4–6] and high photosynthetically active radiation (PAR) causes stress to the corals[7]. Thermal stress reduces reproductive capacity, growth and resistance to diseases of corals[7,8]. Sporadically, local fluctuations in critical parameters such as temperature, salinity, excessive sedimentation and diseases also affect the coral communities[9]. In general, a temperature of 29°C and salinity range 34–39 PSU are set as threshold for healthy corals[10]. High sediment attenuates light needed for the symbiotic algae growth[11] and sustained sedimentation of > 0.2 kg/m^2/day causes stress to the corals[12].

The Gulf of Mannar (GOM) and Kadamat Island (KI) are two major coral reefs in the North Indian Ocean (NIO). Both GOM and KI corals had severely bleached en masse in 1998, causing extensive deaths up to 60% in GOM and 90% in KI[8]. These mass bleaching events are attributed to elevated temperatures[13–16]. During 2002,

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Table 1. Water quality parameters for the study areas

	Location			
Water quality parameter	Kadamat Island		Gulf of Mannar	
Period	1998	2002	1998	2002
Temperature (°C)	29.5	29.2	30	27.8
Suspended solids (mg/l)	3.17	9.20	3.2	10.00
pH	8.2	8.2	8.06	8.0
Salinity (ppt)	34.61	34.46	35.0	31.70
Dissolved oxygen (mg/l)	3.63	4.72	4.7	5.6
Inorganic phosphate (mmol/l)	0.63	1.61	0.58	0.74
Silicate (μmol/l)	0.70	2.36	6.06	0.53
Total phosphorus (μmol/l)	2.01	3.62	1.12	1.16
Ammonia–nitrogen (μmol/l)	0.027	0.03	5.40	0.61
Nitrite–nitrogen (μmol/l)	BDL	0.92	1.52	0.29
Nitrate–nitrogen (μmol/l)	0.35	3.10	NA	5.47
Total nitrogen (μmol/l)	2.14	8.38	52.5	12.7
BOD (mg/l)	1.23	1.46	NA	2.23
Cadmium (ppb)	0.31	0.16	0.2	BDL
Lead (ppb)	1.18	1.91	6.0	BDL
Mercury Hg (ppb)	0.35	0.04	0.31	BDL

BDL, Below detectable limit; NA, Not available.

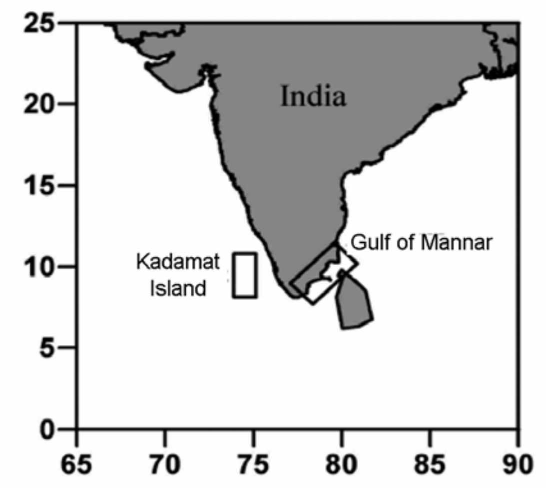

Figure 1. Geographical representation of the study areas.

mass coral bleaching took place in GOM but corals in KI did not bleach. This contrasting phenomenon prompted us to re-examine parameters such as sea-surface temperature (SST), heat content, sea-surface height anomaly (SSHA) and PAR on the mass bleaching to understand their impact on the selective coral bleaching.

The two major reefs in NIO namely GOM (9°N, 78°30′E) and KI (11°13′N and 72°48′E; Figure 1) were selected for the present study. It has been reported that about 96 species of corals belongs to 36 genera in these reefs[17,18].

For time-series analysis of SST, a 2° × 2° box area was selected in both GOM and KI. Since the area is large and continuous time series (December 1997–December 2002) analysis is required, we have used Tropical Rainfall Monitoring Mission, Microwave Imager (TMI) SST data. For site-specific comparison of SST among these areas on finer resolution, we used Advanced Very High Resolution Radiometer (AVHRR) data for the same period. The severities of bleaching were visually observed using remotely operated under-water camera and by scuba divers during these events. Goreau and Hayes[19] have defined a SST hotspot as an area where monthly average temperature is 1° above the historical baseline average for the warmest month of the year. Following this definition, we have computed hotspots for the same period at both the places. PAR was taken from SeaWiFS and SSHA from exiting altimeter observations (http://www.aoml.noaa.gov). The heat content of the ocean was obtained from the temperature profile (R. Murtugudde, pers. commun.).

The visual observations of corals in GOM indicated mass bleaching during May 1998 and 2002, but only during May 1998 in KI. Therefore, the selective bleaching phenomenon was studied by analysing *in situ* water qualify (Table 1), SST, hotspots, SSHA, heat content and PAR data. As the *in situ* water quality in both these locations during the study periods was similar, impact of this parameter on the selective bleaching was ruled out.

The time series analysis of SST at both the locations along with deviations from climatology from December 1997 to December 2002 are shown in Figure 2. In the GOM reef, SSTs are 30.48°C in April 1998 and 31.28°C in April 2002. In the KI reef, SSTs are 30.8°C in April 1998 and 30.8°C May 2002. Since mass bleaching occurred in 1998 and 2002 in GOM and only in 1998 in KI, we may consider that a SST of > 30°C remained as a

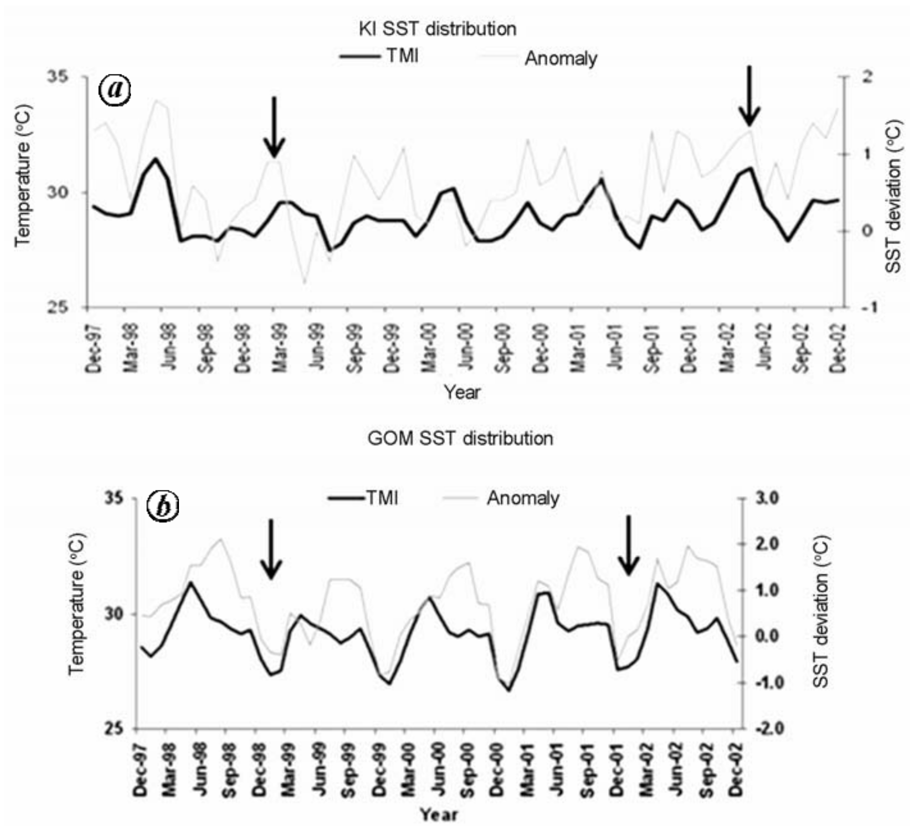

Figure 2. Sea-surface temperature (SST) distribution for (***a***) Kadamat Island and (***b***) Gulf of Mannar.

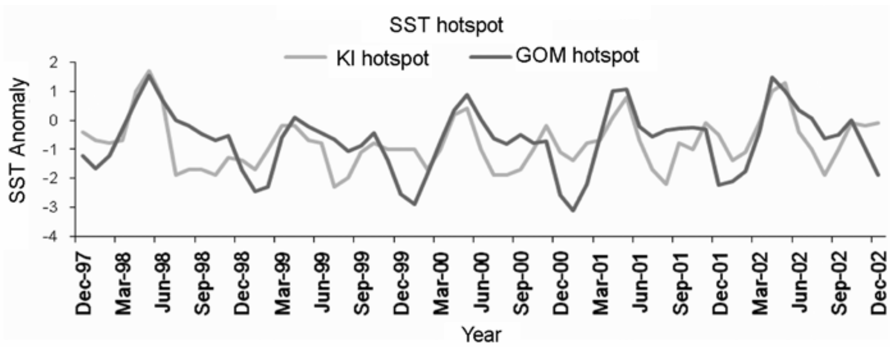

Figure 3. Time series analysis of SST hotpot for the study areas.

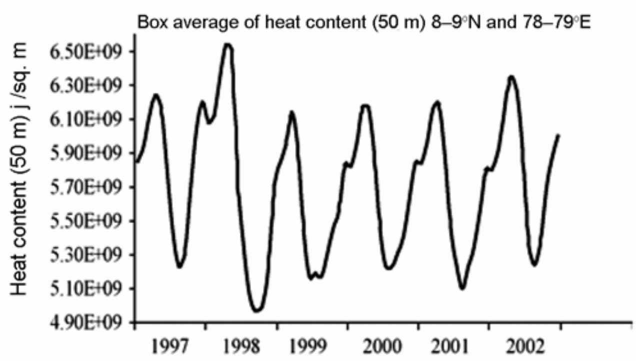

Figure 4. Heat content for the study areas.

threshold for bleaching, assuming that the temperature in March/April causes stress on the corals, resulting in peak bleaching in May. The elevated temperature of 1°C (29°C is the reported threshold for healthy corals) could only stain corals, because a highest deviation of 1.9°C in August 2001 (1.3°C during May 2002 in KI) did not bleach the corals in GOM. Hence, the role of other parameters was analysed to understand the mass bleaching in NIO.

Goreau and Hayes[20] concluded that ocean hotspots of more than 1°C deviation would lead to coral bleaching. The temporal variation of hotspot in both GOM and KI showed almost similar trend, particularly during the two bleaching periods. Further, non-bleaching in KI during

Table 2. Sea-surface temperature (SST) anomalies and photosynthetically active radiation (PAR)

Year	Kadamat Island				Gulf of Mannar			
Parameter	SST	Div	HS	PAR^{mean}	SST	Div	HS	PAR^{mean}
March 1998	29.1	0.4	–0.7	46	29.5	0.8	–0.3	45
April 1998	30.8	1.2	1.0	47	30.5	0.9	0.7	47
May 1998	31.5	1.7	1.7	42	31.4	1.6	1.6	43
Summer average	30.5	1.1	1.87	45	30.5	1.1	1.2	45
June 1998	30.6	1.6	0.8	32	30.5	1.5	0.7	41
March 2002	29.7	1.0	–0.1	46	29.4	0.7	–0.4	46
April 2002	30.8	1.2	1.0	46	31.3	1.7	1.5	47
May 2002	31.1	1.3	1.3	37	30.8	1.0	1.0	43
Summer average	30.5	1.17	0.73	43	30.5	1.13	0.7	45
June 2002	29.4	0.4	–0.4	36	30.2	1.2	0.4	42

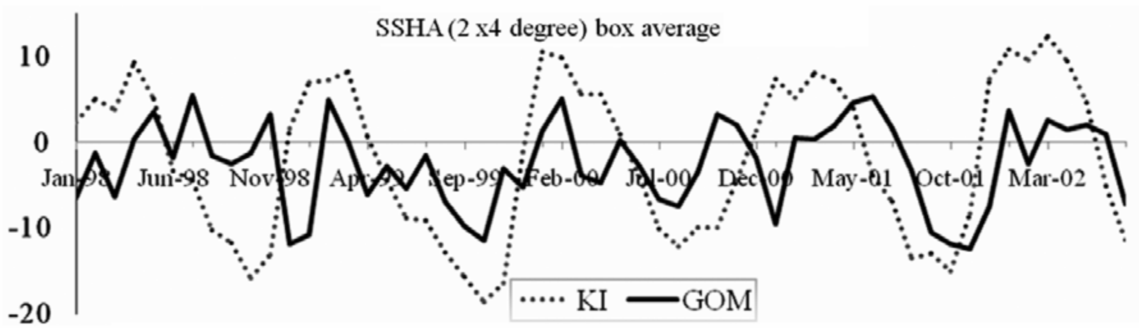

Figure 5. Time series analysis of sea-surface height anomaly (SSHA) for the study areas.

2002 by this phenomenon has not been clarified. In our study, 15 events of more than 1°C deviation were observed (Figure 3). Out of these, bleaching was observed only during three events. Correspondingly, high heat content was observed (Figure 4) in these waters. A high subsurface temperature can also cause thermal stress on the corals. The subsurface temperatures are better reflected in SSHA than surface SST alone[5,21,22]. We analysed SSHA from the existing altimeters during this period[23]. The temporal variations of SSHA in a 2° × 4° grid over KI and GOM are shown in Figure 5. The SSHA at KI is significantly more in 2002 (January–June) than in GOM, in spite of the fact that mass bleaching occurred during this period in GOM only, and not in KI. Therefore, the high SSHA cannot be considered as a factor for mass bleaching.

Abram *et al.*[24] have attributed the death of corals and fish in Menatawai reef ecosystem during 1997 to the highly unusual blooming of phytoplankton that coincided with the near peak of the Indian Ocean Dipole (IOD) event. Hence, we analysed recent IOD events of 1994, 1997, 2006, 2007 and 2008 (ref. 25). None of these years coincided with mass bleaching of KI and GOM (which occurred during 1998 and 2002). Hence, the impact of IOD on mass bleaching could be ruled out. A high PAR of 47 Einstein/m^2/day with SST of 30°C during April 1998 and 2002 in GOM, and a high PAR of 46 Einstein/m^2/day with SST of 30°C in the summer of 1998 in KI were observed during mass bleaching. Besides, the summer PAR of 46 Einstein/m^2/day during April 2002 and 37 Einstein/m^2/day during May 2002 at 31°C SST (Table 2) did not show bleaching in KI during summer 2002. From these observations, it may be concluded that a high PAR (47 Einstein/m^2/day) with minimum SST of 30°C is probably critical for mass bleaching of corals that occurred in NIO during 1998 and 2002. This observation is also supported by Lewis[26], who concluded that high level of visible light (400–700 nm) causes stress on symbiotic algae leading to coral bleaching. Brown and Dunne[27], and Fitt *et al.*[28] concluded that high PAR along with high SST affects the photochemical pathway known as photoinhibition. Understanding the actual cause for elevated SST and high PAR requires a detailed study of the climatological parameters. The seasonal and long-term variability of PAR and its cause and effects on mass coral bleaching need to be studied further, with the availability of historical data for better understanding of mass coral bleaching.

In the present study the basic and major parameters/factors that generally affect mass coral bleaching such as SST, SSHA, hotspots, PAR, heat content and water quality in terms of salinity were analysed to find out the reason for the mass coral bleaching that occurred only in GOM during 2002, but not in KI. The results reveal that a PAR of 47 Einstein/m^2/day with a minimum SST of 30°C is significant for mass coral bleaching in the tropical regions.

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