J. Mar. Biol. Ass. India, **50** (2) : 209 - 214, July - December 2008

Thermal thresholds for coral bleaching in the Indian seas

*E. Vivekanandan, M. Hussain Ali, B. Jasper and M. Rajagopalan

Central Marine Fisheries Research Institute, Cochin - 682 018, India
**E-mail: evivekanandan@hotmail.com*

Abstract

To find out the thermal threshold for coral bleaching, sea surface temperature (SST) data prior to, during and after the 1998 coral bleaching events in the Andaman Sea, Nicobar Sea, Lakshadweep Sea, Gulf of Mannar and Gulf of Kachchh obtained from NOAA/NASA satellite were plotted. From these plots, the Degree Heating Month (DHM) accumulations of the SST hotspot anomalies were estimated. The warming during the years 1985-2005 was correlated with Multivariate El Nino/Southern Oscillation Index (MEI). The results show increase in SST and MEI in all the five regions during the years of strong El Nino events. Coral bleaching occurred when the summer SST maxima exceeded 31^{o}C and remained high for more than 30 days. The indices on thermal thresholds and DHMs estimated in this analysis can lead into projections on coral vulnerability to thermal stress in future in the Indian seas.

Keywords: Coral bleaching; thermal threshold; Degree Heating Months

Introduction

The atmosphere and oceans have warmed since the end of the 19th century and will continue to warm into the foreseeable future, largely as a result of greenhouse gas concentrations (IPCC, 2001). The hypothesis that corals and associated reef organisms might be the first to show adverse effects of global warming has been widely recognized (Gorean and Hayes, 1994). Although many factors such as acidification, outbreak of diseases, predators, sedimentation and nutrient inputs are responsible for coral bleaching (Wilkinson, 1999), rise in seawater temperature causes stress, which leads to the expulsion of symbiotic zooxanthellae by the corals (Jokiel and Coles, 1990).

Bleaching at small local scales has been reported for almost a century (Yonge and Nichols, 1931). Mass bleaching at larger geographical scales, however, is relatively a new phenomenon. A combination of elevated seawater temperature and exposure duration induces coral bleaching and can be used to predict coral bleaching with great certainty (Toscano *et al*., 2000). Indian reefs have experienced 29 widespread bleaching events since 1989 (*www.reefbase.org*). Among these, events in 1998 and 2002 were intense (Arthur, 2000; Rajasurya *et al*., 2002, 2004). There is no attempt so far to correlate the SST and bleaching and to find out the threshold sea surface temperature (SST) in the coral regions in the Indian seas. In this analysis, the bleaching events of 1998 in the coral reef regions of the Indian seas have been correlated with the elevated SST. This analysis is expected to be useful to project future mass bleaching events as a consequence of warming of the Indian seas.

Material and methods

In the absence of continuous real time data, the NOAA/NESDIS images are the most useful and accurate means of gaining a comprehensive data on the SST anomaly in the India seas (Arthur, 2000). Monthly SST data for the years 1985-2005 obtained from NOAA/NASA satellite on 9 km resolution was used (*http://podaac.jpl.nasa.gov*) to illustrate the water heating around the reefs. The warming estimated for the years 1985-2005 was correlated with Multivariate ENSO (El Nino/ Southern Oscillation) Index (MEI). The MEI is a composite index using a number of variables to measure ENSO events and uses sea surface temperatures, surface air temperatures, sea level pressure, zonal (east-west) and meridional (north-south) surface winds and total amount of cloudiness. The MEI values estimated by Wolter and Timlin (1993, 1998) have been applied for the present analysis.

Subsequently, the SST prior to, during and after the coral bleaching events in the Andaman Sea, Nicobar Sea, Lakshadweep Sea, Gulf of Mannar and Gulf of Kachchh was plotted to find out the threshold SST for bleaching. From these plots, Degree Heating Month (DHM) accumulations of these SST hotspot anomalies, which usually commence at the 1°C threshold and provide an estimate of the residence time of anomalously warm water in the region, were estimated. One DHM is equivalent to 1 month of SST 1°C greater than the expected summer maximum value. Two DHMs are equivalent to 2 months of SST 1°C or 1 month of SST 2°C greater than the expected summer maximum value. Bleaching begins for corals exposed to DHM value of 0.5 or more (Done *et al.*, 2003).

Results

Andaman Sea: The mean SST trend shows that the reef area has warmed from 28.40 °C in 1985 to 28.78 °C in 2005 (Fig.1A) *i.e.*, at the rate of 0.19°C per decade. The annual average maximum SST increased from 30.08°C to 30.54°C, *i.e.*, at a rate of 0.23°C per decade. The minimum SST increased at a faster rate of 0.35°C per decade (from 27.1° to 27.8°C). The vertical bars in Fig. 1A marks the strong El Nino events that occurred during this period and its effect on increase in the SST. The effect of El Nino was not experienced during the El Nino events of 1987 and 1992, but the increase in temperature was instantaneous in the 1998 event. Fig. 1B shows the monthly SST values, with 0.5 DHM as the horizontal threshold for corals to bleach; marked behind are the MEI values. The SST and MEI values were very high in April and May 1998.

In 1998, the SST increased above the monthly mean of 30.9°C on 25th March, and remained high for nearly two months until 23rd May except for one week in April (Fig. 1C). High coral bleaching occurred in May 1998 as the DHM exceeded 0.5.

Andaman region

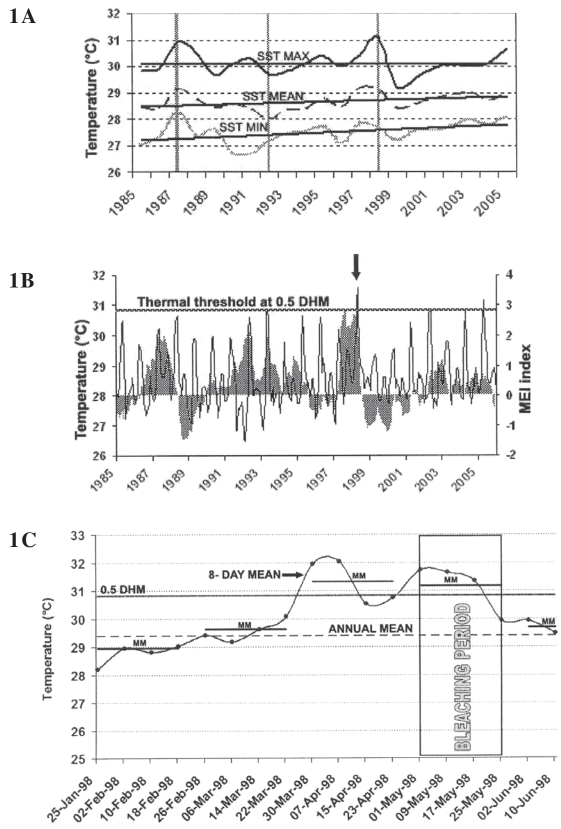
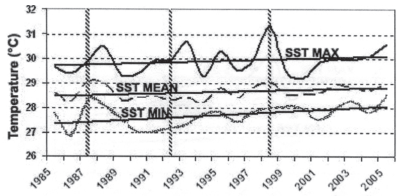


Fig. 1A. Maximum, mean and minimum SST values and trendlines from 1985 to 2005 in the Andaman region; Fig. 1B. Monthly mean SST and MEI Index; the shaded area indicates MEI Index; arrow indicates the reported period of bleaching; Fig. 1C. Rise in SST (8-day mean) during 1998 bleaching event; annual mean during 1998 and monthly mean (MM) during January-June 1998 are indicated

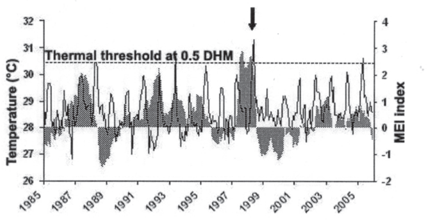
Nicobar Sea: The annual mean SST trend shows that the reef area has warmed from 28.54°C in 1985 to 28.88°C in 2005 (Fig. 2A), at the rate of 0.17°C per decade. The annual average maximum SST increased from 29.80°C to 30.10°C. The annual average minimum SST increased at a faster rate of 0.28°C per decade (from 27.45°C to 28.01°C). The effect of El Nino on SST was evident in 1998 when the maximum SST exceeded 31°C. Figure 2B shows that the SST exceeded the thermal threshold for 0.5 DHM in 1998, which caused the corals to bleach. The SST increased above the monthly mean of 30.45°C for 45 days from 11th April 1998 to 25th May 1998 (Fig. 2C). High coral bleaching event occurred in May 1998 as the DHM exceeded 0.5.

Nicobar region

2A



2B



2C

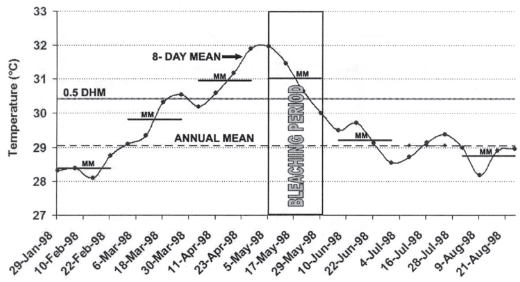
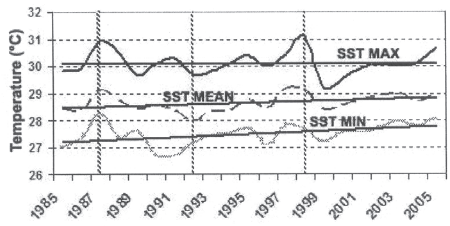


Fig. 2A. Maximum, mean and minimum SST values and trendlines from 1985 to 2005 in the Nicobar region; Fig. 2B. Monthly mean SST and MEI Index; the shaded area indicates MEI Index; arrow indicates the reported period of bleaching; Fig. 2C. Rise in SST (8-day mean) during 1998 bleaching event; annual mean during 1998 and monthly mean (MM) during January-June 1998 are indicated

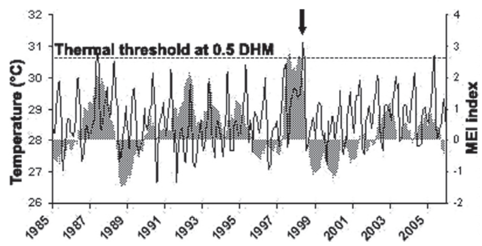
Lakshadweep Sea: The annual mean SST trend shows that the reef area has warmed from 28.50°C in 1985 to 28.92°C in 2005 (Fig. 3A), at the rate of 0.21°C per decade. The annual average maximum SST did not increase, but the annual average minimum temperature increased from 27.2°C to 27.8°C, at the rate of 0.30°C per decade. The effect of El Nino on SST was evident in 1987 and 1998 when the SST reached 31°C. Fig. 3B shows that the SST exceeded the thermal threshold for 0.5 DHM in 1987, 1998 and 2005, and bleaching occurred in 1998. The SST increased above the monthly mean of 30.8°C for 38 days from 27th March 1998 to 3rd June 1998 (Fig. 3C). High coral bleaching event occurred in May.

Lakshadweep region

3A



3B



3C

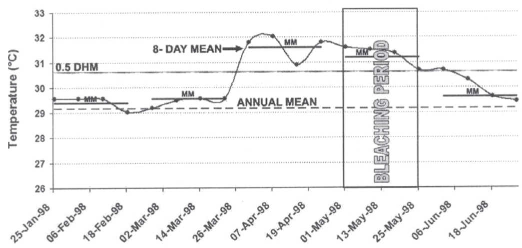


Fig. 3A. Maximum, mean and minimum SST values and trendlines from 1985 to 2005 in the Lakshadweep region; Fig. 3B. Monthly mean SST and MEI Index; the shaded area indicates MEI Index; arrow indicates the reported period of bleaching; Fig. 3C. Rise in SST (8-day mean) during 1998 bleaching event; annual mean during 1998 and monthly mean (MM) during January-June 1998 are indicated

Gulf of Mannar: The annual mean SST trend showed that the reef area has warmed from 28.07°C in 1985 to 28.45°C in 2005 (Fig. 4A), at the rate of 0.19°C per decade. The annual average maximum and minimum SST increased from 30.10°C to 30.45°C and 26.65°C to 26.98°C, respectively *i.e*., at the rate of 0.17°C per decade. The effect of El Nino on SST was evident in 1998 and 2002 when the maximum SST exceeded 31°C. Fig. 4B shows that the SST exceeded the thermal threshold for 0.5 DHM in 1998 and 2002, which caused the corals to bleach. The SST increased above the monthly mean of 30.9°C for 80 days from 22nd March 1998 to 10th June 1998 (Fig. 4C). High coral bleaching occurred in May 1998 as the DHM exceeded 0.5.

Gulf of Mannar region

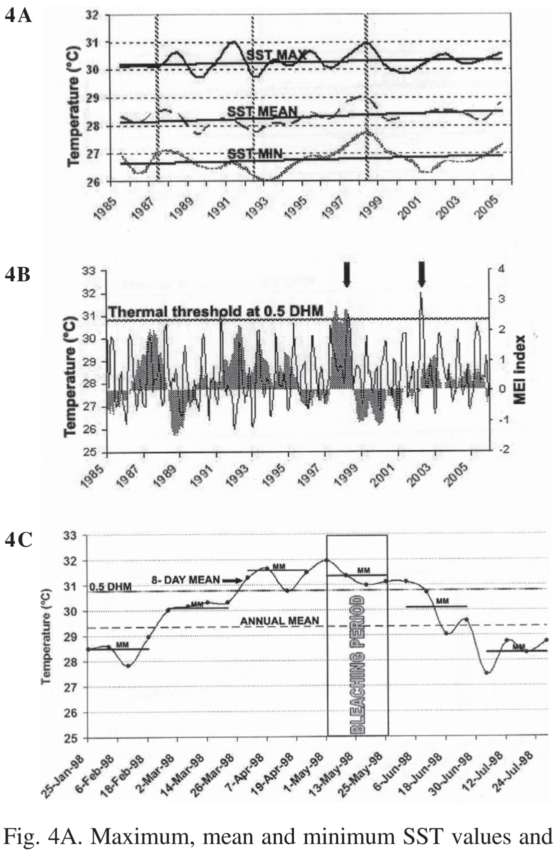


Fig. 4A. Maximum, mean and minimum SST values and trendlines from 1985 to 2005 in the Gulf of Mannar; Fig. 4B. Monthly mean SST and MEI Index; the shaded area indicates MEI Index; arrows indicate the reported period of bleaching; Fig. 4C. Rise in SST (8-day mean) during 1998 bleaching event; annual mean during 1998 and monthly mean (MM) during January-June 1998 are indicated

Gulf of Kachchh: The annual mean SST trend shows that the reef area has warmed marginally from 26.04°C in 1985 to 26.10°C in 2005 (Fig. 5A) at the rate of 0.06°C per decade. The annual average maximum and minimum SSTs were around 28.9°C and 23°C, respectively through the decades, and did not increase. The effect of El Nino on SST was evident in 1987 and 1998. Fig. 5B shows that the SST exceeded the thermal threshold for 0.5 DHM (29.2°C) in 1987 and 1998, and bleaching occurred in 1998. The SST increased above the monthly mean of 29.25°C for one month from 10th June 1998 to 12th July 1998 (Fig. 5C). Medium bleaching event occurred in June 1998.

Discussion

During 1985-2005, the minimum SST in the coral reef regions in the Indian seas increased by 0.116°C per decade (Gulf of Kachchh) and 0.205°C per decade (Lakshadweep Sea) (Table 1). The rate of increase of minimum SST was 1.5 to 2.0 times faster than the maximum SST, as has been reported for other regions (Walther *et al*., 2002).

The ENSO warm water ocean current system of 1998 created a nearly pan-tropical band of global climatic condition and brought in its wake a spate of global climatic condition and ecological changes (World Wildlife Fund, 2004). The magnitude of the ENSO event is implicated as the primary cause of mortality of coral in reef ecosystems in the Indian Ocean (Wilkinson *et al*., 1999). In the Indian seas too, the ENSO elevated the SST as evidenced from the significant correlation between the MEI and SST in the coral regions (except in the Gulf of Kachchh; Table 1). Elevated temperature accurately predicts the development of mass bleaching (World Wildlife Fund, 2004). Elevated temperatures generally preceded mass bleaching by about 4 weeks in the coral regions. The thermal threshold for 0.5 DHM was found to be 31.0 – 31.4°C for Andaman Sea,

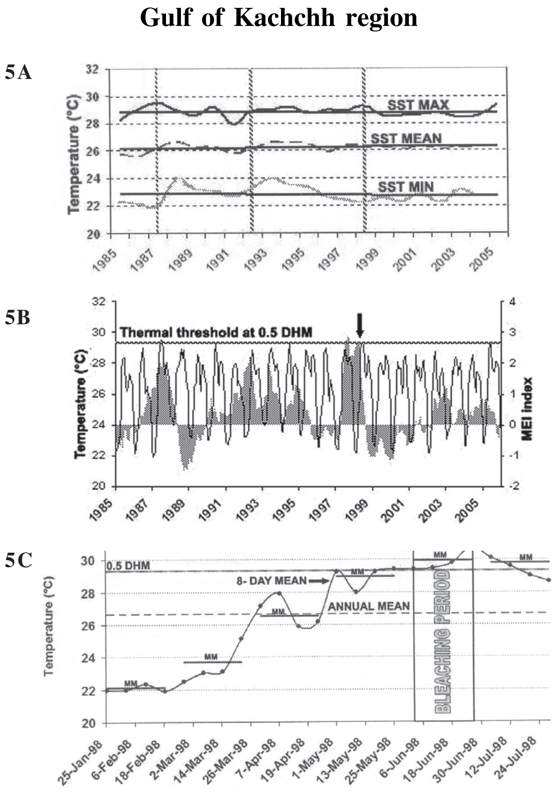


Fig. 5A. Maximum, mean and minimum SST values and trendlines from 1985 to 2005 in the Gulf of Kachchh; Fig. 5B. Monthly mean SST and MEI Index; the shaded area indicates MEI Index; arrow indicates the reported period of bleaching; Fig. 5C. Rise in SST (8-day mean) during 1998 bleaching event; annual mean during 1998 and monthly mean (MM) during January-June 1998 are indicated

Nicobar Sea, Lakshadweep Sea and Gulf of Mannar and 30.0°C for Gulf of Kachchh. The DHM value was the highest for Lakshadweep coral region (1.57) and lowest for Gulf of Kachchh (0.75). Arthur (2000) reported coral bleaching in the Lakshadweep Sea, Gulf of Mannar and Gulf of Kachchh when abnormal SST had begun to affect the Indian reef areas. Between 30% and 40% of coral cover were severely bleached in the Lakshadweep and Gulf of Mannar reefs respectively and more than 20% died in both the areas because of bleaching-related stress. The reefs in the Gulf of Kachchh, in contrast, were less severely affected; only 2% of the coral was bleached severely and no bleaching-related death was observed. The present analysis confirms that the warming was centered between 07°N and 12°N latitudes and the intensity reduced towards the northern latitudes (23.5°N; Gulf of Kachchh). This is reflected in the greatest exposures to stress in the 07°-12°N latitudes, which is indicated by high DHM values. The highest decadal increase in SST and DHM occurred in the Lakshadweep Sea.

Considering the scale of impacts on coral reefs in 1998, there is substantial scientific evidence that the reefs in the Indian seas are under severe threat from climate change. It is likely that with increasing warming of the seas, the thermal threshold of corals will exceed with rapid rise in DHM values. The indices on thermal thresholds and DHMs estimated in this analysis can lead into projection of the outcome of exposure of corals to thermal stress in the future. There are also threats from human exploitation such as fishing, usage for

Table 1. Thermal threshold and Degree Heating Months estimated for five coral reef regions in the Indian seas; the estimates are based on 1998 bleaching events

Region	Position	Mean SST (°C)	SST rise(°C/ decade)	Correla - tion with MEI	Max SST (°C)	Duration of high SST (days)	Thermal threshold (°C)[a]	DHM
Andaman	11°.21'N;92°.59'E	28.60	0.192	0.186**	32.15	52	31.4	1.07
Nicobar	07°.50'N;93°.50'E	28.70	0.172	0.143*	32.00	45	31.0	1.18
Lakshadweep	10°.57'N;72°.63'E	28.71	0.205	0.201**	32.05	38	31.4	1.57
Gulf of Mannar	09°.38'N;79°.31'E	28.28	0.203	0.144*	31.00	80	31.4	1.14
Gulf of Kachchh	22°.5'N;69°.33'E	26.10	0.116	0.086	30.85	33	30.0	0.75

**Significant at 0.01 level; *significant at 0.05 level; [a]for 0.5 DHM building construction, erosion and coastal land use, which will exacerbate the effects of warming. Field research on coral reefs has started only recently in India. As mass mortality of corals will have serious ecological implications, there is need for continuous monitoring of the health of the reefs for their conservation.

Acknowledgements

The authors are thankful to the Director, CMFRI, Kochi for providing facilities, and to Dr. P. K. Aggarwal, Head, Environmental Sciences Division, IARI, New Delhi for valuable suggestions. We are grateful to the ICAR, New Delhi for extending financial support under the Network Project "Impact, Adaptation and Vulnerability of Indian Agriculture to Climate Change".

References

Arthur, R. 2000. Coral bleaching and mortality in three Indian reef regions during an El Nino southern oscillation event. *Curr. Sci.*, 79 (12): 1723 -1729.

Done, T. J., E. I. Turak, M. Wakeford, S. Kininmorith, S. Wooldridge, R. Berkelman, M. J. H. van Oppen, and M. Mahonly. 2003. Testing bleaching resistance hypothesis for the 2002 Great Barrier Reef Bleaching event. *G.C.R.M.N. Report*, *Aust. Inst. Mar. Sci.*, p. 95.

Gorean, T. J. and R. L. Hayes. 1994. Coral bleaching and ocean hotspots. *Ambio*, Stockholm, 23 (3): 176 - 180.

IPCC 2001. Climate change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, Third Assessment Report, 520 pp.

Jokiel, P. L. and S. L.Coles. 1990. Response of Hawaiian and other Indopacific reef corals to elevated temperature. *Coral Reefs*, 8 (4): 155-162.

Rajasurya, A., K. Venkataraman, E. V. Muley, H. Zahir and B. Cattermonl. 2002. Status of coral reefs in south Asia: Bangladesh, India, Maldives, Sri Lanka. *G.C.R.M.N. Report*, *Aust. Inst. Mar. Sci.*, 101-121.

Rajasurya, A., H. Zahir, K. Venkataraman, Z. Islam and T. Tamelander. 2004. Status of coral reefs of south Asia: Bangladesh, Chagos, India, Maldives and Sri Lanka. *G.C.R.M.N. Report*, *Aust. Inst. Mar. Sci.*, 213-234.

Toscano, M. A., G. Liu, I. C. Guch, K. S. Casey, A. E. Strong and J. E. Meyer. 2000. Improved prediction of coral bleaching using high resolution hot spot anomaly mapping. *Proc. IX International Coral Reef Symp., Bali*, 2: 1143-1148.

Walther, R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J. Fromentin, Hoegh-Guldberg and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature*, 416: 389-395.

Wilkinson, C. 1999. Global and local threats to coral reef functioning and existence. *Mar. Freshwat. Res.*, 50: 867-878.

Wilkinson, C., O. Linden, H. Cesar, G. Hodgson, J. Rubens, and A. E. Strong. 1999. Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: an ENSO impact and a warning of future change? *AMBIO*, 26: 188-196.

Wolter, K. and M. S. Timlin. 1993. Monitoring ENSO in COADS with a seasonally adjusted principal component index. *Proc. of the 17th Climate Diagnostics Workshop,* Norman, 52-57.

Wolter, K. and M. S. Timlin. 1998. Measuring the strength of ENSO events – how does 1997/98 rank? *Weather*, 53: 315-324.

World Wildlife Fund. 2004. Great Barrier Reef 2050. Implications of climate change for the Australia's Great Barrier Reef. *WWF Report*, *Australia*, 345 pp.

Yonge, C. M. and A. G. Nichols. 1931. Studies on the physiology of corals: V. The effect of starvation in light and darkness on the relationship between corals and zooxanthellae. *Scientific Report of the Great Barrier Reef Expedition*, 1: 177-211.

Received: 30 January 2009
Accepted: 13 March 2009