RESPONSE OF INDIAN CORAL REEF REGIONS DURING MASS CORAL BLEACHING YEARS USING NOAA OISST DATA

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ABSTRACT: Coral reefs are the one of the most ancient, highly productive and marine bio-diverse ecosystem on the earth. Coral reefs are threatened to effective collapse under rapid climate change. ENSO (El Niño Southern Oscillation) event is one of the extreme climate change event which elevate Sea Surface Temperatures (SSTs) of tropical oceans. This elevated SST increases the level of thermal stress on coral reefs. Coral reefs are the most sensitive ecosystem of all ecosystems due to temperature change and exhibit bleaching when SST exceeds their normal summer maxima and remain high for more than 28 days. Bleaching Threshold (BT), Positive SST Anomaly (PA) and Degree Heating Week (DHW) are commonly used indices for calculating thermal stress on the coral reefs. The major coral reef formations in India are in Andaman, Nicobar, Lakshadweep, Gulf of Mannar and Gulf of Kachchh regions. SST data from National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature (OISST) v2 high resolution data set which is available daily at 0.25° global grids from 1982 to present was used for this study. This study focuses on the variations of SST experienced by Indian coral reef regions during known Mass Coral Bleaching (MCB) years. During MCB years: 1998, 2010 and 2016, year 2010 recorded the highest thermal stress for Andaman, Nicobar and Gulf of Kachchh region while year 2016 for Lakshadweep and Gulf of Mannar region. Nicobar region in 2010 observed to be the most vulnerable as per DHW index.

INTRODUCTION

Coral reef ecosystems provide habitat for over a million species and are important for the socio-economic well-being of approximately 500 million people (Wilkinson 2004). The reefs also act as barriers to wave action and storms by reducing the incident wave energy through wave reflection, dissipation and protecting the coast line. Reefs provides resource through tourism, fisheries etc. for an estimated half a billion people who live within 100 km of reefs (Crabbe 2008).

The growth and subsidence of coral reefs depend on many physical variables including Sea Surface Temperature (SST), Irradiance, Calcium Carbonate Saturation, Turbidity, Sedimentation, Salinity, pH and Nutrients. These variables influence the physiological processes of photosynthesis and calcification and as a result coral reefs occur in select areas of the world's oceans (Crabbe 2008). At present, reef building corals persist only within relatively narrow environmental conditions as well as for many other anthropogenic influence (Mumby *et al.*, 2007). The carbonate reef structures that result from their calcium carbonate skeletons commonly build up in the regions where seawater temperature exceed 18° C in winter and below 28° C in summer (Frieler *et al.*, 2013).

Coral reefs are the most sensitive of all coastal ecosystems to SST changes. During 1997-1998, 2010 and 2015-2016, El Niño Southern Oscillations (ENSO) events have occurred in tropical oceans (McField 2017). These ENSO events were the extreme climate change events which elevated SST in the Indian Seas. Elevated SST are considered a dominant cause of coral bleaching worldwide (Lesser 2011). Extremes in SST can impact stress on coral habitats (Brown 1997). Under stress, symbiotic zooxanthellae may get expel by coral polyps, leading to bleaching of the coral tissues. Coral bleaching is one of the major threat which is significantly affecting the reefs across the globe during different time periods (Hoegh-Guldberg 2011). Sea Surface Temperature (SST) is a critical physical attribute of coastal ecological systems and directly effects on process rates, water column stability and species of plants (such as algae, seagrass, marsh plants and mangroves), animals (microscopic animals, larger invertebrates, fish and mammals) which live in a particular coastal region.

Mass coral bleaching and mortality events have been observed worldwide since the early 1980s and affected reefs at regional scale (Eakin 2010). During 1997-1998, 2010 and 2015-2016 mass coral bleaching events affected coral reefs in almost every part of the world and caused mortality (McField 2017). The first mass coral bleaching was occurred in year 1998 whereas an approximately of 16% of reef-building corals were bleached worldwide (Wilkinson 2004). The second global coral bleaching event was declared in year 2010. The third global coral bleaching event in year

2016 was the longest event on record (McField 2017). During global bleaching event 2015-16, the Great Barrier Reef (GBR) in Australia experienced unprecedented levels of coral reef death on a large scale.

Corals in Indian regions have earlier experienced coral bleaching events during 1998, 2010 and 2016 (Arthur 2002; Kumar and Balasubramanian 2012; Mohanty *et al.*, 2017). Although corals can re-establish themselves after mass bleaching, in some cases it takes one to two decades for the entire ecosystem to return to the pre-bleaching state (Baker *et al.*, 2008). An increase in the frequency and severity of mass coral bleaching could overwhelm the ability of coral reefs to recover between events. If this happens, coral reef ecosystems would shift towards systems that are dominated by other organisms such as cyanobacteria and algae (Frieler *et al.*, 2013).

Satellite assessment of coral stress have focused primarily on SST (Strong *et al.* 2011). Mass coral bleaching and mortality is the accumulation of thermal stress in the form of Degree Heating Week (DHW) (Liu *et al.*, 2003). The National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW) program use Degree Heating Weeks (DHW) (Gleeson and Strong 1995) to assess thermal stress on coral reefs based on satellite derived daily SST. Weekly thermal anomalies greater than 1° C above a climatology mean SST (maximum monthly mean SST) are summed over a 12-weeks period resulting in the Degree Heating Weeks (Eakin *et al.*, 2009). *In situ* experiments on the other hand are difficult to conduct or interpret due to inadequate replication and lack of suitable control sites (Hughes and Connell 1999) for validation coral bleaching.

The objective of this study to carried out the response of Indian coral reef regions due to increased thermal stress during mass coral bleaching years and provide to increase our understanding on coral bleaching. NOAA Optimum Interpolated Sea Surface Temperature (OISST) version 2 data was analysed and coral bleaching indices have computed.

STUDY AREA

This study includes analysis of variations of SST for five Indian coral reef regions. India with its coastline extending over 7500 kilometres and these five coral reef regions: Andaman, Nicobar, Lakshadweep, Gulf of Mannar and Gulf of Kachchh regions lie at geographically different latitudes (Navalgund *et al.* 2010) (see Figure 1). The geographically constraints of Andaman and Nicobar Islands are 6° N to 14° N Latitudes and 92° E to 94° E Longitudes. The Andaman and Nicobar Islands are a low mountain chain of islands. Lakshadweep Islands are situated between 8° N to 12° N Latitude and 71° E to 74° E Longitudes consisting of 36 Islands, 12 atolls, 3 reefs and 5 submerged coral banks. The Gulf of Mannar is situated between Latitude 8° 47' N to 9° 15' N and Longitude 78° 12' E to 79° 14' E consisting of 21 Islands that lies between Rameswaram and Tuticorin in the state of Tamil Nadu. The Gulf of Kachchh is located between Latitude 22° 15' N to 23° 40' N and Longitude 68° 20' E to 70° 40' E.

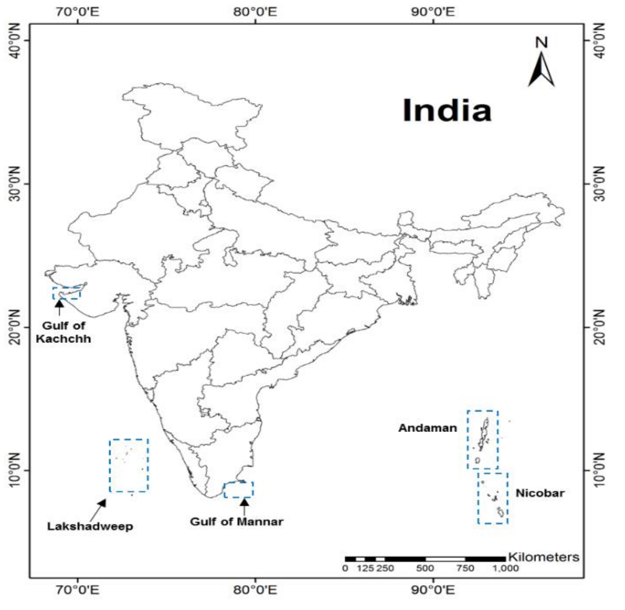

Figure 1: Study area of five Indian coral reef regions.

MATERIALS AND METHODOLOGY

The SST data for the present study was obtained from National Oceanic and Atmospheric Administration (NOAA) Optimal Interpolated Sea Surface Temperature (OISST) version 2 high-resolution data set available from the website at ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/NetCDF/2017/AVHRR/ has a spatial resolution of 0.25° x 0.25° and temporal resolution of one day (Reynolds *et al.*, 2007). NOAA OISST global data product provides daily SST data since 1982 to present. This SST product uses Advanced Very High Resolution Radiometer (AVHRR) satellite data from the Pathfinder AVHRR SST. Pathfinder AVHRR SST was chosen because of good agreement with the *in situ* data from ships and buoys. It also includes a large-scale adjustment of satellite biases with respect to the *in situ* data. This high resolution SST data product was developed using an optimum interpolation (OI) technique. SST data from NOAA OISST products for all five regions were analysed during Mass Coral Bleaching (MCB) years in order to monitor the patterns of SST and compute daily SST anomaly for warmest period. The computation of Maximum Monthly Mean Climatology (hereafter referred as Thermal Threshold) of warmest month SST was based on NOAA OISST data. The regional thermal thresholds were computed using the mean of warmest month SST for all five regions from 35 years' period. Bleaching Threshold (BT) for coral bleaching is based on the Thermal Threshold. For this study BT is defined as thermal threshold + 0.5° C as it was observed on the basis of an earlier exercise with long term HadISST 1 data (1950 - 2016) over Indian regions. Indian coral reef regions show an association with knowing MCB events with a range of Positive SST Anomaly. The range of Positive SST Anomaly was found 0.56° C to 1.60° C. The Warmest Month, Thermal Threshold and Bleaching Threshold for all five regions are found to be different (Table 1). Daily SST anomalies for warmest periods during MCB are constructed on the basis of Thermal Threshold. SST anomaly measures the magnitude of instantaneous thermal stress potentially conductive to coral bleaching (Liu *et al.*, 2003). SST anomaly is calculated as difference between the daily SST and the Thermal Threshold. Degree Heating Week (DHW) product measures the intensity and duration of thermal stress experienced by coral reefs (Strong *et al.*, 1997). DHW represent the accumulation of Positive SST Anomaly at that location over past 12-week period. The categories which are used to describe the severity of bleaching are Warning, Alert Level-1 and Alert Level-2 which are estimated based on DHW (Eladawy *et al.* 2015). The warning status is issued as "Warning" when the condition of $0 < DHW < 4°$ C weeks. The "Alert Level-1" is issued when the condition of $4 < DHW < 8°$ C weeks and "Alert Level-2" is issued when the condition of $8 < DHW < 12°$ C.

RESULTS

The variation of SST during the known Mass Coral Bleaching (MCB) years: 1998, 2010 and 2016 for all five regions provide the information of magnitude, duration of thermal stress and intensity experienced by the regional coral. The variations in SST, daily SST anomalies and DHW during MCB years have been derived from NOAA OISST data set. The climatologically warmest month for Andaman, Nicobar, Lakshadweep region is May, for Gulf of Mannar region is April and for Gulf of Kachchh region is June (Table 1).

Table 1. Computed Warmest Month, Thermal Threshold and Bleaching Threshold for Indian coral reefs regions using NOAA OISST data from 1982 to 2016

Sr. No.	Indian Coral Reef Regions	Warmest Month	Thermal Threshold (° C)	Bleaching Threshold (° C)
1	Andaman	May	29.90 (± 0.58)	30.40
2	Nicobar	May	29.83 (± 0.63)	30.33
3	Lakshadweep	May	29.90 (± 0.49)	30.40
4	Gulf of Mannar	April	30.23 (± 0.39)	30.73
5	Gulf of Kachchh	June	29.35 (± 0.45)	29.85

The regional Thermal Threshold for Andaman region is 29.90° C (± 0.58), for Nicobar region is 29.83° C (± 0.63), for Lakshadweep region is 29.90° C (± 0.49), for Gulf of Mannar region is 30.23° C (± 0.39) and for Gulf of Kachchh region is 29.35° C (± 0.45). BT is computed as 0.5° C + Thermal Threshold. Our analysis reveals the highest BT 30.73° C found in Gulf of Mannar region and Lowest BT 29.85° C in Gulf of Kachchh region.

This study shows that year 2010 was the warmest year among the three well known MCB years for Andaman, Nicobar, and Gulf of Kachchh regions while year 2016 was warmest for Lakshadweep and Gulf of Mannar region (Figure 2-6). The warmest month SST, daily SST anomaly and DHW were computed for 1998, 2010 and 2016 for all five regions (Table 2). For Andaman region, 2010 recorded the highest warmest month SST and it is 0.40° C more than year 2016 and 0.77° C more than 1998. For Nicobar region, 2010 recorded highest warmest month SST which is 0.06° C more than 2016 and 0.57° C more than 1998. For Lakshadweep region, 2016 recorded the highest warmest month SST and it is 0.09° C more than 2010 and 0.15° C more than 1998. For Gulf of Mannar region, 2016 recorded highest warmest month SST which is 0.34° C more than 2010 and 0.37° C more than 1998. For Gulf of Kachchh region, the result shows that 2010 recorded the highest warmest month SST and it is 0.53° C more than 2016 and 0.86° C more than 1998. The daily SST anomalies derived for all five regions over the period from March to July during years 1998, 2010 and 2016 (Figure 2-6 (B)).

For Andaman region, the total duration of daily Positive SST anomalies for year 1998 recorded 61 days out of the 153 days and continuous SST anomalies was 43 days. The daily SST value crossed the thermal threshold during the first week of April and went below the thermal threshold was observed 2nd week of June with three intermittent breaks (Figure 2 (B)). The first break was observed for three days from 14th to 16th April, second break was observed for a single day on 20th April and the third break was observed for three days from 3rd to 5th June. The highest daily SST anomalies 1.87° C observed on 9th May. The cumulative stress or DHW for year 1998 was 4.91° C. In year 2010, the total duration of daily Positive SST anomalies recorded 87 days out of the 153 days and continuous was 75 days. The daily SST values crossed the thermal threshold during the fourth week of March and went below the thermal threshold by the 3rd week of June with one intermittent break on 3rd April. The highest daily SST anomalies 2.16° C observed

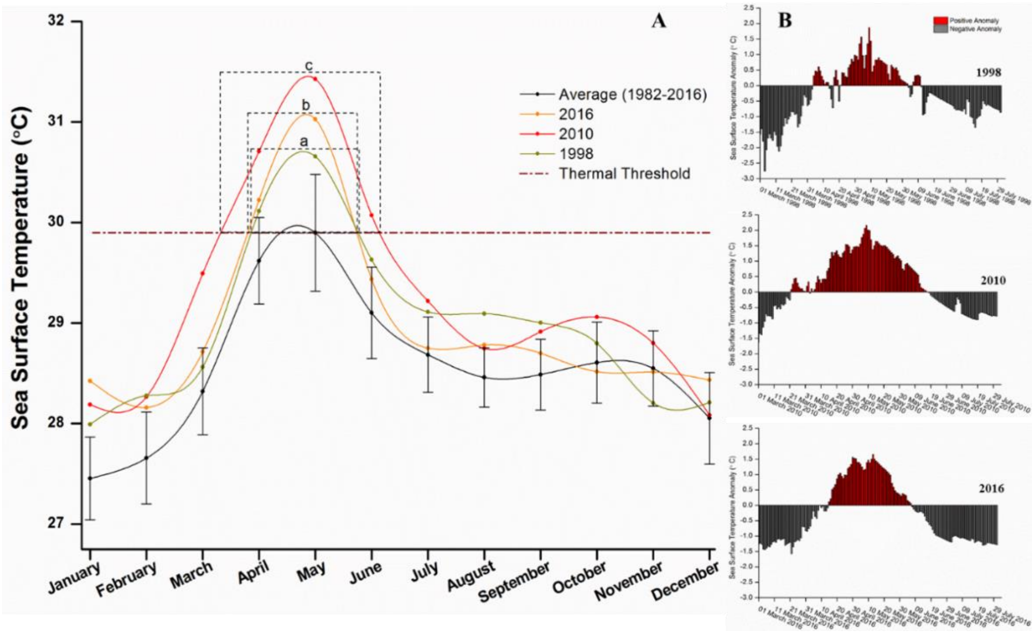

Figure 2. (A) SST variations during Mass Coral Bleaching years: 1998, 2010 and 2016 for Andaman region (Data source: NOAA OISST v2 high-resolution data). Black line shows the climatological mean SST (1982 -2016) and dark red dash dot line shows the thermal threshold of region; (B) Daily SST anomalies for Andaman region of MCB years. Red bar shows Positive Anomaly and grey bar shows negative anomaly.

on 9th May. The cumulative stress for year 2010 was 11.72° C. In year 2016, the continuous total duration of daily Positive SST anomalies recorded 53 days out of the 154 (leap year) days. The daily SST values crossed the thermal threshold as observed during third week of April and went below the thermal threshold as observed in 1st week of June without any intermittent breaks. The highest daily SST anomalies 1.65° C observed on 13th May. The cumulative stress for year 2016 was 7.21° C. The highest magnitude, duration of thermal stress and intensity during MCB years have been recorded in 2010.

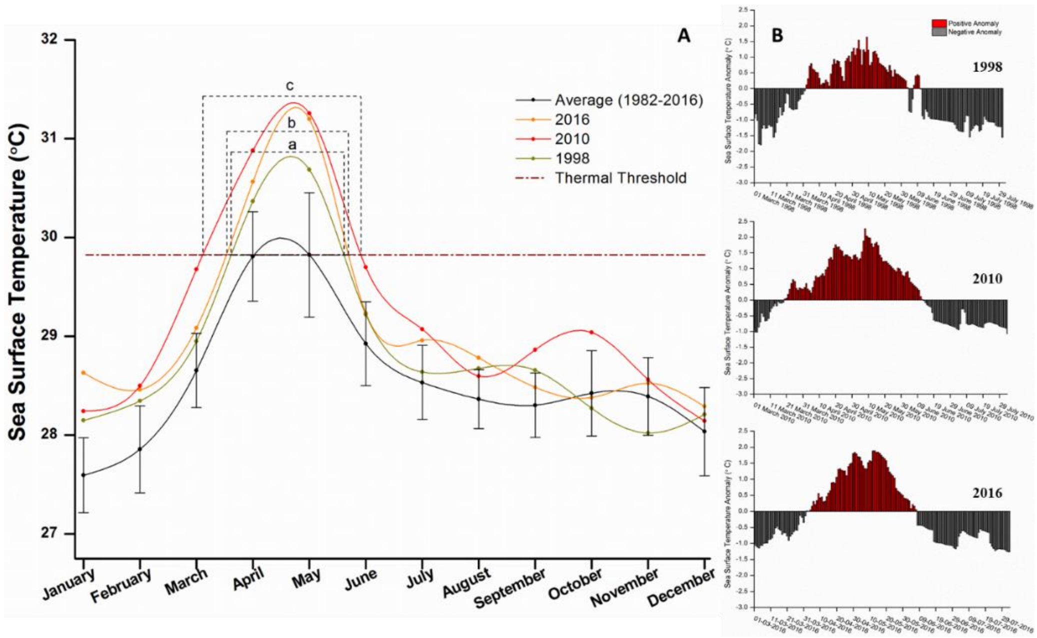

Figure 3. (A) SST variations during Mass Coral Bleaching years: 1998, 2010 and 2016 for Nicobar region (Data source: NOAA OISST v2 high-resolution data). Black line shows the climatological mean SST (1982 -2016) and dark red dash dot line shows the thermal threshold of region; (B) Daily SST anomalies for Nicobar region of MCB years. Red bar shows Positive Anomaly and grey bar shows negative anomaly.

For Nicobar region, the total duration of daily Positive SST anomalies for year 1998 recorded 67 days out of the 153 days and continuous SST anomalies was 63 days. The daily SST values crossed the thermal threshold during first week of April and went below the thermal threshold in 2nd week of June with one intermittent break (Figure 3 (B)). This break was observed for three days from 4th to 6th June. The highest daily SST anomalies 1.64° C observed on 9th May. The cumulative stress for year 1998 was 6.43° C. In year 2010, the continuous total duration of daily Positive SST anomalies recorded 85 days out of the 153 days. The daily SST values crossed the thermal threshold during third week of March and went below the thermal threshold in 2nd week of June without any intermittent breaks. The highest daily SST anomalies 2.27° C observed on 8th May. The cumulative stress for year 2010 was 12.24° C. In year 2016, the continuous total duration of daily Positive SST anomalies recorded 67 days out of the 154 (leap year) days. The daily SST values crossed the thermal threshold by the first week of April and went below the thermal threshold in 1st week of June without any intermittent breaks. The highest daily SST anomalies 1.89° C observed on 13th May. The cumulative stress for year 2016 was 9.51° C. The highest magnitude, duration of thermal stress and intensity during MCB years also have been recorded in 2010. The monitoring period of thermal stress for year 1998 and 2016 was same but DHW was computed different (Table 2).

For Lakshadweep region, the total duration of daily Positive SST anomalies for year 1998 recorded 68 days out of the 153 days and continuous SST anomalies was 65 days. The daily

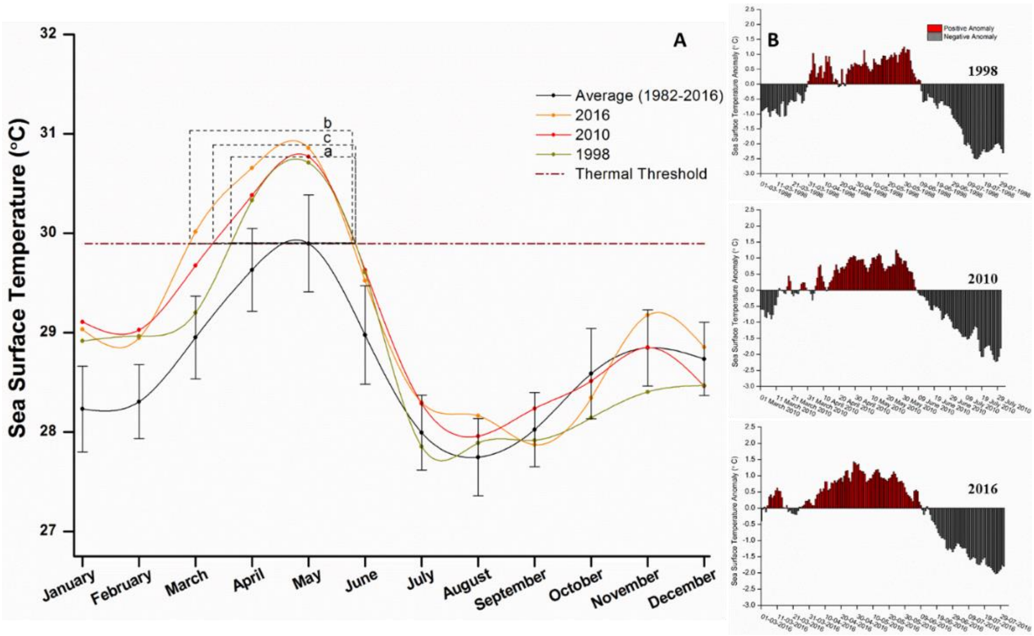

Figure 4. (A) SST variations during Mass Coral Bleaching years: 1998, 2010 and 2016 for Lakshadweep region (Data source: NOAA OISST v2 high-resolution data). Black line shows the climatological mean SST (1982 -2016) and dark red dash dot line shows the thermal threshold of region; (B) Daily SST anomalies for Lakshadweep region of MCB years. Red bar shows Positive Anomaly and grey bar shows negative anomaly.

SST values in year 1998 crossed the thermal threshold during last week of March and went below the thermal threshold in 2nd week of June with two intermittent breaks (Figure 4 (B)). The first break was observed for two days from 19th to 20th April and second break was observed for one day on 23rd April. The highest daily SST anomalies 1.24° C observed on 30th May. The cumulative stress for year 1998 was 6.17° C. The total duration of daily Positive SST anomalies for year 2010 recorded 73 days out of the 153 days and continuous SST anomalies was 56 days. The daily SST values crossed the thermal threshold during 2nd week of March and went below the thermal threshold in 1st week of June with four intermittent breaks. The first break was observed for three days from 15th to 17th March, second break was observed for five days from 21st to 25th March, the third break was observed for again five days from 31st March to 04th April and fourth break was observed for one day on 12th April. The highest daily SST anomalies 1.14° C observed on 27th May. The cumulative stress for year 2010 was 6.80° C. In the year 2016, the total duration of daily Positive SST anomalies recorded 91 days out of the 154 days and continuous SST anomalies was 77 days. The daily SST values crossed the thermal threshold during first week of March and went below the thermal threshold in 2nd week of June with four intermittent breaks. The first break was observed for one day on 4th March, second break was observed for another single day on 16th March, the third break was observed for seven days from 18th March to 24th April and fourth break was observed for three days from 10th to 12th June. The highest daily SST anomalies 1.43° C observed on 28th April. The cumulative stress for year 2016 was 8.71° C. The highest magnitude, duration of thermal stress and intensity during MCB years have been recorded in 2016 (Table 2).

For Gulf of Mannar region, the total duration of daily Positive SST anomalies for year 1998 recorded 67 days out of the 153 days and continuous SST anomalies was 50 days. The daily SST values in year 1998 crossed the thermal

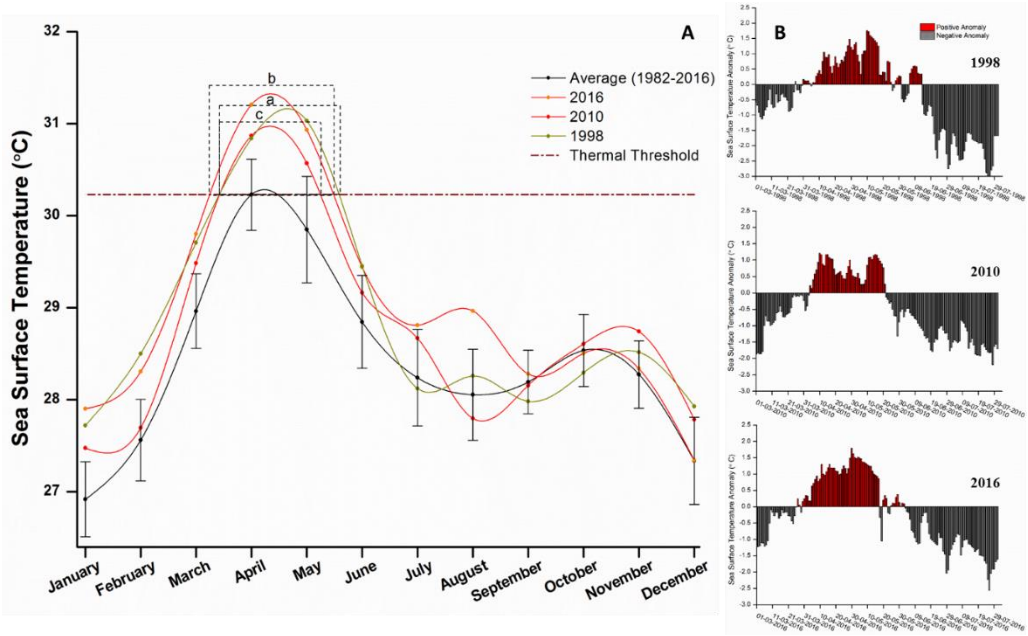

Figure 5. (A) SST variations during Mass Coral Bleaching years: 1998, 2010 and 2016 for Gulf of Mannar region (Data source: NOAA OISST v2 high-resolution data). Black line shows the climatological mean SST (1982 -2016) and dark red dash dot line shows the thermal threshold of region; (B) Daily SST anomalies for Gulf of Mannar region of MCB years. Red bar shows Positive Anomaly and grey bar shows negative anomaly.

threshold during last week of March and went below the thermal threshold in 2nd week of June with three intermittent breaks (Figure 5 (B)). The first break was observed for one day on 5th April, the second break was observed for two days on 26th and 27th May and third break was observed for five days from 1st June to 5th June. The highest daily SST anomalies 1.75° C observed on 10th May. The cumulative stress for year 1998 was 6.77° C. The continuous total duration of daily Positive SST anomalies for year 2010 recorded 48 days out of the 153 days. The daily SST values crossed the thermal threshold as observed during 1st week of April and went below the thermal threshold in 3rd week of May without any intermittent breaks. The highest daily SST anomalies 1.23° C observed on 10th April. The cumulative stress for year 2010 was 5.06° C. In the year 2016, the total duration of daily Positive SST anomalies recorded 63 days out of the 154 days and continuous SST anomalies was 49 days. The daily SST values crossed the thermal threshold by the fourth week of March and went below the thermal threshold in 1st week of June with three intermittent breaks. The first break was observed for one day on 29th March, second break was observed for two days on 18th and 19th May, the third break was observed for another two days on 23rd and 24th May. The highest daily SST anomalies 1.79° C observed on 30th April. The cumulative stress for year 2016 was 7.69° C. During MCB years, the highest duration of thermal stress has been recorded in 1998 while magnitude, intensity in 2016 (Table 2).

For Gulf of Kachchh region, the total duration of daily Positive SST anomalies for year 1998 recorded 37 days out of the 153 days and continuous SST anomalies was 10 days. The daily SST values in year 1998 crossed the thermal threshold as observed during first week of May and went below the thermal threshold in 1st week of July with five intermittent breaks (see Figure 6 (B)). The first break was observed for twelve days from 08th to 19th May, second break was observed for one day on 28th May, third break was observed for two days on 2nd and 3rd June, fourth break was observed for three days from 11th to 13th June and fifth break was observed for five days from 20th to 24th June. The highest daily SST anomalies 0.80° C observed on 9th June. The cumulative stress for year 1998 was 2.16° C. The continuous total duration of daily Positive SST anomalies for year 2010 recorded 91 days out of the 153 days. The daily SST values crossed the thermal threshold as observed during fourth week of April and went below the thermal threshold as observed in 4th week of July without any intermittent breaks. The highest daily SST anomalies 1.97° C observed on 11th June. The cumulative stress for year 2010 was 10.98° C. In the year 2016, the total duration of daily Positive SST anomalies recorded 70 days out of the 154 days and continuous SST anomalies was 62 days. The daily SST values crossed the thermal threshold as observed during 2nd week of May and went below the thermal threshold as observed in 4th week of July with four intermittent breaks. The first break was observed for one day on 16th May, second break was observed for another single day on 20th May, third break was observed for five days from 17th June to 21st June and fourth break was observed for one day on 6th July. The highest daily SST anomalies 1.27° C observed on 30th June. The cumulative stress for year 2016 was 5.57° C. The highest magnitude, duration of thermal stress and intensity during MCB years have been recorded in 2010 (Table 2).

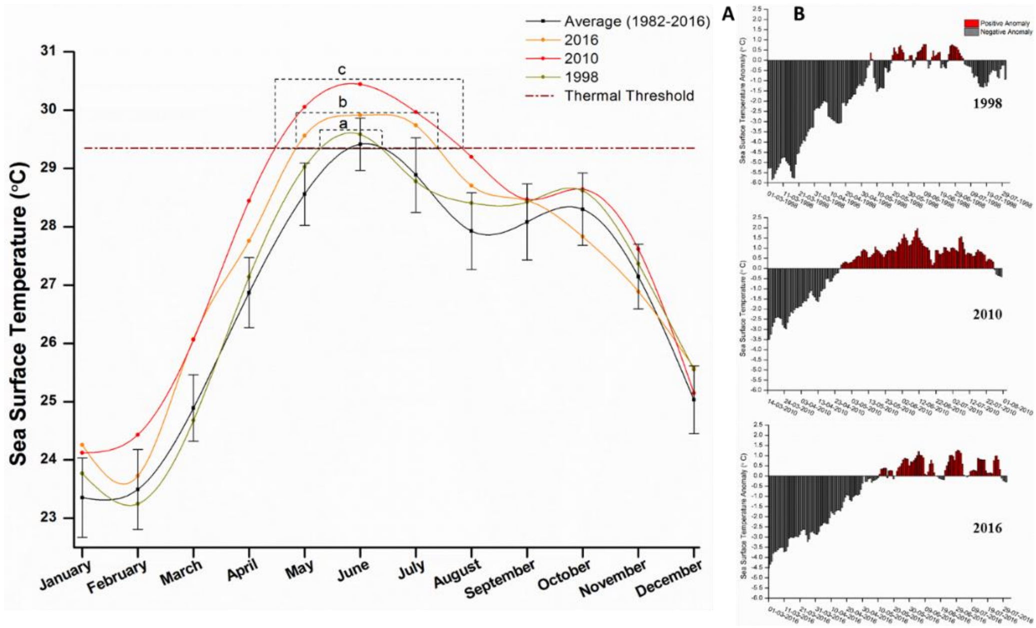

Figure 6. (A) SST variations during Mass Coral Bleaching years: 1998, 2010 and 2016 for Gulf of Kachchh region (Data source: NOAA OISST v2 high-resolution data). Black line shows the climatological mean SST (1982 -2016) and dark red dash dot line shows the thermal threshold of region; (B) Daily SST anomalies for Gulf of Kachchh region of MCB years. Red bar shows Positive Anomaly and grey bar shows negative anomaly.

The result also shows that, during MCB years: 1998, 2010 and 2016, The highest thermal stress for Andaman, Nicobar and Gulf of Kachchh region recorded in 2010 while for Lakshadweep and Gulf of Mannar region in 2016.

Table 2. Maximum Sea Surface Temperature, Maximum Sea Surface Temperature Anomaly, Duration of Thermal Stress and Degree Heating Weeks for Mass Coral Bleaching (MCB) years

Year	**Coral Bleaching Indices**		**Indian Coral Reef Regions**				
			Andaman	**Nicobar**	**Lakshadweep**	**Gulf of Mannar**	**Gulf of Kachchh**
1998	Warmest month SST		30.66° C	30.69° C	30.71° C	30.84° C	29.58° C
	Warmest month SST Anomaly		0.76° C	0.87° C	0.81° C	0.61° C	0.23° C
	Duration of Thermal Stress	No. of Days	61	67	68	67	37
		% of total days	39.87	43.79	44.44	43.79	24.18
	DHW		4.91° C	6.43° C	6.17° C	6.77° C	2.16° C

2010	Warmest month SST		31.43° C	31.26° C	30.77° C	30.87° C	30.44° C
	Warmest month SST Anomaly		1.53° C	1.44° C	0.87° C	0.64° C	1.09° C
	Duration of Thermal Stress	No. of Days	87	85	73	48	91
		% of total days	56.86	55.55	47.71	31.37	59.48
	DHW		11.72° C	12.24° C	6.80° C	5.06° C	10.98° C
2016	Warmest month SST		31.03° C	31.20° C	30.86° C	31.21° C	29.91° C
	Warmest month SST Anomaly		1.13° C	1.38° C	0.96° C	0.98° C	0.56° C
	Duration of Thermal Stress	No. of Days	53	67	91	63	70
		% of total days	34.42	43.51	59.09	40.91	45.45
	DHW		7.21° C	9.51° C	8.71° C	7.69° C	5.57° C

Discussion

Global coral bleaching events on routine recurrence are a relatively new phenomenon (Hoegh-Guldberg 1999). The first global coral bleaching event was declared in 1998 in connection with a strong El Niño event (McField, 2017). During 1997-98, Mass Coral Bleaching was reported from many of the world coral reefs (Lough, 2000) and about 16% of corals reefs died worldwide (Wilkinson 2004). The second global coral bleaching event was declared in 2010 and is known to be caused by ENSO events (McField, 2017). The third global coral bleaching event was the longest event on record and it was declared in 2016. Coral bleaching is the most visible and wide-spread climate change event experienced by reefs. The Great Barrier Reef (GBR) in Australia experienced unprecedented levels of coral death on a large scale during third global bleaching event 2015-16 (McField, 2017). The 2015-16 El Niño has impacted Indonesian shallow coral reefs. The 2016 El Niño in Maldives was considered to be one of the strongest El Niño since 1950 and the overall percentage of bleached corals recorded is 73% across 71 sites.

This study shows that, during year 1998, 2010 and 2016, the duration of thermal stress for Andaman region recorded 61 days, 87 days and 53 days while DHW calculated comes to 4.91° C, 11.72° C and 7.21° C respectively. During year 1998, the duration of thermal stress was observed 61 days but DHW was 4.91° C and for year 2016, the duration of thermal stress was observed 53 days but DHW 7.21° C. We also observed similar type of results for other regions. The duration of thermal stress and DHW was monitored maximum for Andaman, Nicobar, Gulf of Kachchh region in the year 2010 which recorded under "Alert Level-2" warning status as per NASA NOAA standards protocol, for Lakshadweep region in the year 2016 which also recorded under "Alert Level-2" warning status but for Gulf of Mannar regions, the maximum duration of thermal stress was found in the year 1998 and maximum DHW was recorded in 2016. The warning status for Gulf of Mannar regions was in "Alert Level-1".

The 2015-16 El Niño and related ocean warming has generated significant coral bleaching and mortality worldwide (Ampou *et al.*, 2017). Coral bleaching reported in Andaman Islands during the April last week of 2016 due to thermal stress (Mohanty et al., 2017). Coral reefs in most of the Andaman and Nicobar Islands are at resilient stage after the major bleaching events of 1998, 2005 and 2010 (De *et al.*, 2017). Climate change influence coral bleaching was observed for year 2014 over Pirotan Island, Gulf of Kachchh region (Adhavan *et al.*, 2014). Coral bleaching was observed in Andaman region from April to July 2010 and about 74% of live corals was appeared in bleaching condition (Marimuthu *et al.* 2011). Due to climate change, SST observed in 2010 has been reported to be a combination of El Niño followed by La Niña (Marimuthu *et al.* 2011). The coral bleaching events also took place at the Agatti Island, Lakshadweep during 2010 and its impact on associated organisms like sea anemones and giant clams was observed (Kumar *et al.*, 2012). The average coral bleaching appears about 76.5% during May-June, 2010 (De *et al.*, 2017). Coral reefs in Gulf of Mannar region were found bleached condition during April to May, 2010 and bleaching was recorded about 85.1%. The region of Kavaratti atoll, Lakshadweep region during April to May, 2002 recorded high SST beyond the bleaching threshold and consequent coral bleaching occurred (Harithsa *et al.*, 2005). During1998, the coral reef areas of the Lakshadweep, Gulf of Mannar and Gulf of Kachchh region observed bleaching. The reported coral bleaching in Lakshadweep region was recorded about 82%, in Gulf of Mannar region was 89% and in Gulf of Kachchh region was 11% during April to July 1998 (Arthur, 2002).

CONCLUSION

We conclude that coral are sensitive to the accumulation of thermal stress during warmest period. Degree Heating Week (DHW) index is used to describe the severity of bleaching and is more powerful coral bleaching index as compared to only Positive Anomaly. The warmest MCB years for Andaman, Nicobar and Gulf of Kachchh region is 2010 while for Lakshadweep and Gulf of Mannar region, it is 2016. The response of Indian coral reef regions during MCB years are not same and uniform. 2010 and 2016 have surpassed the coral bleaching of 1998. So there is a likelihood that high intensity coral bleaching events may occur in future also. During events of the Mass Coral Bleaching, Nicobar region in 2010 observed to be the most vulnerable among the Indian coral reef regions as per DHW index.

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