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Coral bleaching due to increased sea surface temperature in Gulf of Kachchh Region, India, during June 2016

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The 2015-2016 E1 Niño Southern Oscillation event was one of the extreme climate events which elevated the sea surface temperature (SST) of tropical oceans, which in turn increased the level of thermal stress on corals. Coral bleaching event is mainly caused due to high positive SST anomaly, i.e., when SST exceeds its normal summer maxima. Corals in the Gulf of Kachchh region of Gujarat earlier experienced coral bleaching events during 1988, 2010 and 2014. For this study, SST was derived from NOAA OISST data set which is available daily at 0.25° global grids from 1982 to present. The climatologically warmest month for the Gulf of Kachchh region is June when the maximum monthly mean temperature is 29.31°C, as observed from NOAA OISST. The present study focuses on monitoring daily SST anomalies during summer 2016 for the Gulf of Kachchh reefs and field observations on early responses of coral bleaching from Laku Point reef, a site known for high coral diversity. It was found that in summer 2016, SST rose to 30.62 °C and recorded a maximum positive anomaly of 1.31°C in the month of June. A total of 72 days out of 122-day monitoring period showed positive SST anomaly, including 28 days of continuous positive thermal stress in June 2016.To validate coral bleaching forecast at the end of the regional warmest quarter, a field visit was carried out at Laku Point reef near Poshitra village in the southern coast of the Gulf of Kachchh. A total of 13 coral species and a sea anemone were found bleached in various proportions during the field sampling after two months of prolonged thermal stress. The field data showed an average of 3.9% bleaching of corals at colony scale. The maximum proportion of colony scale bleaching was observed in *Porites lutea* species.

[Keywords: Sea surface temperature, Coral reefs, Coral bleaching, Laku Point reef]

Introduction

Coral reefs are one of the most ancient, highly productive and biologically diverse ecosystems on earth. Coral reefs provide shelter for 25% of all known marine species[1] and plays a key role in coastal protection, fisheries and tourism[2]. Coral reefs are among the most sensitive of all coastal ecosystems to temperature change, exhibiting bleaching. Coral reefs, however, are threatened to effective collapse under rapid climate change. A variety of environmental stress are known to cause worldwide coral bleaching, including increased or decreased temperature, increased or decreased solar irradiation, reduced salinity, and sedimentation[3]. Elevated sea surface temperature (SST) caused by E1 Niño Southern Oscillation (ENSO) events is known to cause stress in corals and mortality through a phenomenon known as bleaching[1]. Coral bleaching is one of the major threat that has significantly affected the reefs across the globe during different time[2].

Coral bleaching is a stress response by coral organisms when symbiotic single-celled microscopic dinoflagellate algae known as zooxanthellae are expelled by coral polyps. Under this bleached condition coral loses its algal pigmentation and appears white in colour. SST is a critical factor for the well being of symbiotic association of zooxanthellae host animals like corals, sea anemones, giant clam, etc.[4]. Corals usually recover from bleaching when SST condition improves but they die in extreme cases[5]. Severe bleaching can lead to coral mortality. Accordingly, it is important to determine how SST affects the coral reefs. SST anomalies highlight potential perturbation to coral reef ecosystems and sometimes reveal possible shift in species richness and abundance that might be prioritized for marine conservation efforts[6].

The objective of this study was to monitor daily SST anomalies triggering coral bleaching in the Gulf of Kachchh region of India during summer 2016 using satellite data. A common feature of bleaching is the observation that corals bleach when SST exceeds its normal summer maximum[7]. Satellite-derived daily SST data were analysed to see the diurnal SST anomalies for the period of April to July 2016, the local summer in the Gulf of Kachchh coral reef region. Diurnal SST anomalies during May to June indicated a likelihood of possible coral bleaching in the region and a field survey was carried out within a month's time to validate the bleaching response of corals from a test reef in the region.

The Gulf of Kachchh (22° 15' N to 23° 40' N Latitude and 68° 20' E to 70° 40' E Longitudes) is very rich in terms of biodiversity value and supports varied coastal habitats, including coral reefs, mangroves, creeks, mud flats, islands, rocky shores, and sandy beaches (Fig. 1). It is situated at the northern boundary of Saurashtra Peninsula of Gujarat state of India. The coral reef region of the Gulf of Kachchh represents the northern most limit of coral reefs in India. One third of Indian hard (Scleractinian) coral genera is found in this region[8]. The test reef or Laku Point reef in Poshitra was chosen for field observations, as this site is known to harbour good coral diversity and high rate of recruitment. Laku Point is located in the coastal village of Poshitra situated in the Okhamandal region of the Gulf of Kachchh in Dwarka district. This reef lies between from 22°23'58'' to 22°24'21'' N latitudes and 69°12'02'' E to 69°12'36'' E longitudes, comprising rocky shores, coral reefs and mangrove patches as its adjacent coastal habitats. Laku Point is a narrow fringing reef where coral colonies grow in shallow, rock-pools. Laku Point has nearly 40% coral cover with coral formations spreading over 100 m^2 area[9-10]. This reef is characterized by diverse coral species hence it is often referred as *'Crown of the Gulf of Kachchh*[11].

Materials and Methods

The SST data analysis for the present study was carried out using two types of SST data products having different spatial and temporal resolutions. A reference SST climatology was set up based on Hadley Sea Ice and Sea Surface Temperature Sea Surface Temperature (HadISST1) version 1 data available from the UK Met Office Hadley Centre for Climate Prediction and Research (*www.metoffice.gov.uk*). The HadISST1 is a set of quality controlled global long-term *in situ* SST data collected from ships and buoys[12] and is provided as monthly means for 1° latitudes by 1° longitudes grids. The HadISST1 SST data is available since 1870 to present and the SST values are accurate to within ~ 0.3 K (*www.metoffice.gov.uk*). For this study, HadISST1 monthly SST data was analysed for the 67-year period (1950 to 2016) for establishing monthly SST climatology for the Gulf of Kachchh. This analysis revealed June as the climatologically warmest month for the Gulf of Kachchh while the climatologically warmest quarter was April to June.

The second data source was National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature (OISST) version 2 high-resolution data set[13] available from *www.ncdc.noaa.gov/oisst*, which has been primarily used for monitoring of diurnal SST anomalies. NOAA OISST global data product provides daily SST data on 0.25° latitude x 0.25° longitude grids since 1982 to

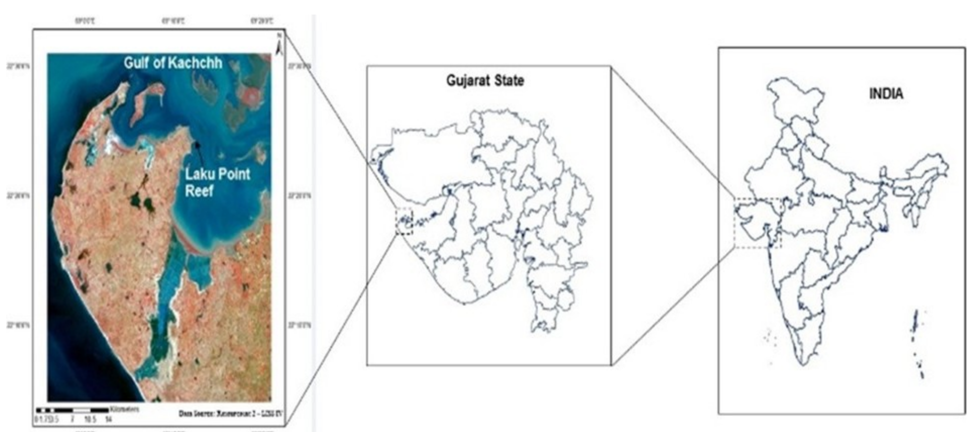

Fig. 1 — The study area: Laku Point reef, Poshitra in Gulf of Kachchh region, India.

present. NOAA OISST data comes from Advanced Very High-Resolution Radiometer (AVHRR) and Advanced Microwave Scanning Radiometer (AMSR) on board the National Aeronautics and Space Administration (NASA) earth observing system satellite SST data and incorporates ship and buoy based *in situ* SST observations. Daily SST from NOAA OISST data products for the Gulf of Kachchh were analysed for the warmest quarter (April to June) of 2016 to monitor the trend of daily SST (Fig. 2) and to compute daily SST anomaly.

Bleaching Threshold for coral bleaching is based on Maximum Monthly Mean climatology (MMM_Climatology; http://coralreefwatch.noaa.gov). The computation of maximum monthly mean or the long-term mean (hereafter referred as thermal threshold) of climatologically warmest month was based on NOAA OISST data. The spatial mean of monthly SSTs computed for the Gulf of Kachchh region for a 35-year period was used to construct the regional thermal threshold. For this study, Bleaching Threshold (BT) was defined as thermal threshold + 0.5 °C, as it has been observed that the historical global coral bleaching events for Indian regions are associated with positive SST anomalies equivalent to 0.5 °C or more based on an earlier study using HadISST1 data as referenced climatology. The regional thermal threshold and BT as represented in Figure 2 are based on climatologically warmest month (June) analyses. After a month's observation (by May end) of diurnal SST anomalies almost reaching the regional BT, a likelihood of bleaching was expected in the region provided the same SST anomaly trend continued in the coming months.

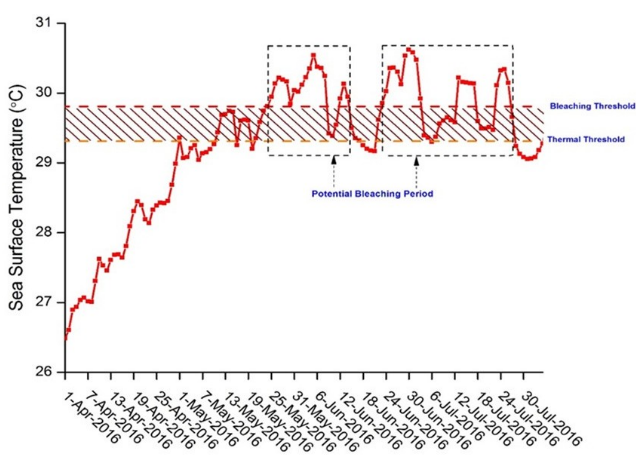

Fig. 2 — Daily SST experienced for summer 2016 in Gulf of Kachchh region. Thermal Threshold and Bleaching Threshold are indicated by dashed lines in orange and red colour respectively.

Diurnal SST anomalies were routinely monitored for June and July and accordingly a field survey was carried out in July 2016 to confirm bleaching responses in coral species at Laku Point reef of Poshitra.

Results

This study showed the diurnal trend of SST and daily SST anomalies derived from NOAA OISST data for the warmest quarter: April to June 2016 and for an extended monitoring period of July (Figure 2) for the Gulf of Kachchh region. The regional Thermal Threshold and BT for the Gulf of Kachchh are 29.31 °C and 29.81 °C respectively as computed from NOAA OISST climatology. In April, 2016 the daily SST values ranged from 26.48 °C to 28.99 °C, well below the regional thermal threshold. It was observed that during the first week of May, the SST values crossed the thermal threshold and persisted for two weeks. In the second half of May, the SST rose further and even crossed the BT. During this period (24^{th} May – 8^{th} June), the daily SSTs ranged from 29.81 °C to 30.54 °C. This fortnight recorded an average of 0.85 °C rise of daily SSTs above the thermal threshold, sufficient to trigger bleaching responses in zooxanthellate corals considering the bleaching responses of Indian coral reef regions above 0.5 °C SST anomalies. The month of June recorded the maximum SST of 30.62 °C, which was also the maximum for summer 2016. In the second half of June, the SSTs came down from the BT and even went below the thermal threshold during 18^{th} to 21^{st} June. However, the SST condition worsened after 23^{rd} June when again SSTs crossed the thermal threshold and subsequently the BT and stayed above for a continued spell of 11 days. This spell recorded an average SST rise of 0.98 °C above the thermal threshold. This close to 1°C rise above thermal threshold at the start of July called for an extended monitoring of the daily SSTs even beyond the climatologically warmest quarter of the region. In between 7^{th} and 28^{th} July, there were two less-than-a-week spells when the SSTs remained above thermal threshold. The first spell continued for six days from 13^{th} to 18^{th} July with an average rise 0.76 °C above thermal threshold while the second spell lasted for five days from 23^{rd} to 27^{th} July with an average of 0.81 °C rise above thermal threshold. Out of a total 122 days, 72 days the daily SST values remained above the thermal threshold, while for 39 days out of 72, the SST remained above the BT. These 39 days were recorded in five discrete spells of 16, 3, 11, 5, and 4 days. The monitoring period of April to July, 2016 for the Gulf of Kachchh region recorded 72 days of positive SST anomaly (Figure 3) out of a total of 122 days. The first spell of SST anomaly started on 11th May and continued up to 19th May with an intermittent break of one day on 16th May. During these eight days, the maximum SST anomaly was 0.43 °C. The next spell of continuous SST anomaly lasted for 28 days (4 weeks) from 21st May to 17th June with a maximum anomaly of 1.23 °C and an average daily anomaly of 0.61°C. The third continuous spell started in the second half of June and remained for 35 days. This spell, starting from 22nd June ended on 27th July with an intermittent break for one day on 6th July. This period recorded the maximum anomaly of 1.31°C, which is also the maximum for summer 2016. Comparing the monthly maximum anomalies, the month of June recorded the maximum of 1.31 °C followed by July (1.26 °C) and May (0.91 °C).

The average daily anomaly was 0.63 °C for this spell, which superseded both number of days and magnitude of SST anomaly of the previous spell. After 27th July, negative SST anomalies were observed.

To confirm the likelihood of coral bleaching on field, a field visit was planned and carried out at the sample location of Laku Point reef, near Poshitra village in The Gulf of Kachchh. This field visit was planned within a fortnight after continuous monitoring of the diurnal SSTs and SST anomalies up to 7th July, as two major continuous spells of SST anomalies had passed by this date. For a rapid

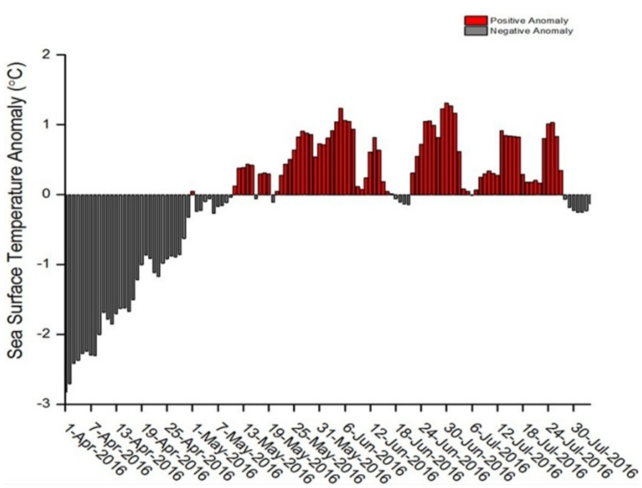

Fig. 3 — Daily SST anomaly during April-July 2016 in Gulf of Kachchh region.

reconnaissance of the bleaching responses among the hard corals, a point sampling strategy was followed and field data were collected from a total of 30 GPS-tagged 1m x 1m quadrats. These quadrats were laid on coral species in Poshitra reef during low tide exposure (0.38 m) of 22nd July, 2016 at 07:51 am[14]. The field data revealed an average of 3.9% of bleaching at colony scale from a total of 13 sampled coral species belonging to the common genera of Coscinaraea, Favia, Goniastrea, Goniopora, Leptastrea, Porites, and Turbinaria. At colony scale, the bleaching responses ranged from 2% to 6.7%. The magnitude of coral bleaching was assessed using coral health chart available from www.coralwatch.org. The coral health chart is marked with four different colours, each graded to six successive shades of brightness like shade code: B1 to B6 shades of green; C1 to C6 shades of dark brown; D1 to D6 shades of light brown, and E1 to E6 shades of yellowish green. The higher the number of shades, visibly the healthier the coral and vice-versa. The maximum colony scale bleaching was found in the ubiquitous species, *Porites lutea*. As per the field observations, the bleaching responses in summer 2016 were not only confined to the reef-building corals, but was also observed among other zooxanthellate reef invertebrates like sea anemone Figure 4.

Discussion

Coral bleaching in The Gulf of Kachchh was observed during summer 2016 in two spells. The first spell of SST anomaly started on 21st May and continued up to 17th June, and as discussed earlier, during these 28 days, the maximum SST anomaly was 1.23 °C. The second spell of SST anomaly started from 22nd June and ended on 27th July with one-day intermittent break. This period recorded the maximum anomaly of 1.31°C for 35 days. The thermal stress started increasing in the third week of May 2016. However, the maximum SST for summer 2016 was recorded in June as 30.62 °C. To confirm the likelihood of coral bleaching, a field visit was carried out at Laku Point reef, near Poshitra village in Gulf of Kachchh. This field visit confirmed an average of 3.9% of bleaching at colony scale from a total of 13 sampled coral species after a prolonged period of two months since when the SSTs crossed the regional Thermal Threshold of 29.31°C. Coral bleaching was also reported in the Andaman region during April, 2016 attributed to thermal stress[15]. Bleaching has been reported from many coral reef locations of the world,

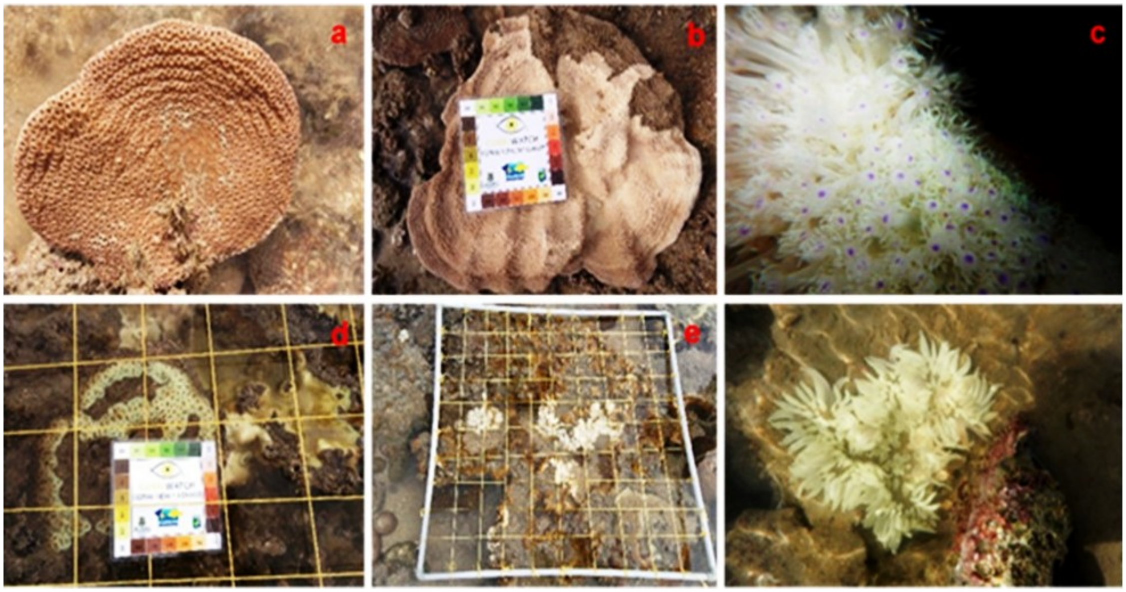

Fig. 4 — Healthy and bleached corals and sea anemone as observed at Laku Point reef in July 2016. (a) Healthy coral: *Turbinaria sp.* (b) Bleached coral: *Turbinaria sp.* (c) Bleached coral: *Goniopora sp.* (d) Partially bleached coral: *Favia sp.* (e) Partially bleached coral: *Porites sp*. (f) Bleached sea anemone: *Heteractis sp,*

including The Great Barrier Reef (GBR) which has experienced the worst mass coral bleaching event in its history[16] in 2016. Since March 2016, the SST over the northern GBR had remained around 1 °C to 1.5 °C above the recent long-term average (2002-2011) for this time of the year[17]. This resulted in coral bleaching across large areas of the GBR, particularly the most pristine and isolated reefs in the far north[17]. Worldwide, bleaching responses to rising temperature reflect the underlying trend of global ocean warming caused by climate change. GBR water have warmed by approximately 0.67 °C since 1871, with most of the warmest years occurring in the past two decades[18]. According to the Bureau of Meteorology (Australia), in 2016 the GBR recorded its hottest-ever average SST for February, March, April, May and June since the historical SST records of 1900. Current warming anomalies indicate that the global extent of coral bleaching during 2015-2016 was a good "global coral reef bleaching event"[19].

Conclusion

This study demonstrates the potential of continuous monitoring of daily SST anomaly above the regional summer Thermal Threshold in accurate prediction of the likelihood of coral bleaching. In case of The Gulf of Kachchh region, which is otherwise a climatologically adapted coral reef region of India, summer 2016 were thus warm enough to cause bleaching in hard corals as well as in other zooxanthellate invertebrates like sea anemones. Synergistic use of geophysical parameters like SST retrieved from remote sensing satellite along with early field/*in-situ* monitoring of bleaching responses can help in timely prediction/forewarning of bleaching. Monitoring daily SST anomalies supported with real-time field monitoring of bleaching responses can help to develop and adopt suitable management strategies to alleviate the environmental stress on coral reef ecosystems.

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