Chapter

Climate Change Induced Thermal Stress Caused Recurrent Coral Bleaching over Gulf of Kachchh and Malvan Marine Sanctuary, West Coast of India

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Abstract

Coral reefs are one of the most sensitive, productive, and invaluable biological resources on the earth. However, coral reefs are facing unprecedented stress due to ongoing climate changes and intensified anthropogenic disturbances globally. Elevated Sea Surface Temperature (SST) has emerged as the most imminent threat to the thermos-sensitive reef-building corals. The 2010–2014-2016 El Niño Southern Oscillation (ENSO) caused prolonged marine heat waves (MHWs) that led to the most widespread coral bleaching and mortality in the tropical Indi-Pacific regions. Coral bleaching prediction is vital for the management of the reef biodiversity, ecosystem functioning, and services. Recent decades, satellite remote sensing has emerged as a convenient tool for large-scale coral reef monitoring programs. As thermal stress is a critical physical attribute for coral bleaching hence, the present study examines the effectiveness of the elevated SSTs as a proxy to predict coral bleaching in shallow water marginal reefs. Advanced Very High-Resolution Radiometer (AVHRR) satellite data from the NOAA Coral Reef Watch's (CRW) platform has been used for this study. Coral bleaching indices like Bleaching Threshold (BT), Positive SST Anomaly (PA), and Degree Heating Weeks (DHW) are computed to analyze the thermal stress on the coral reefs. The computed thermal stress from satellite-derived SST data over regions concurrence with the mass coral bleaching (MCB) events. This study concludes that in the last decades (2010 to 2019) the coral cover around these regions has dramatically declined due to higher SST, which indicates that the thermal stress induced recurrent bleaching events attributed to the coral loss.

Keywords: Sea Surface Temperature, Bleaching Threshold, Degree Heating Weeks, El Niño Southern Oscillation, thermal stress

1. Introduction

Coral reefs are one of the most ancient, dynamic, highly sensitive, complex, biologically diverse, highly productive ecosystems, found in the tropical coastal environment between 30° N and 30° S latitudes. Coral reefs provide an conducive environment where one-third of all marine fish species and many thousands of other species are found and offer substantial ecological and economic services to millions of people through fishery and tourism worldwide [1]. Coral reef ecosystems are degrading in rapid pace, and some facing extinction risk due to the synergistic impact of global climate change and chronic human activities including overfishing, pollution, eutrophication, sedimentation, coastal development [2–4]. Rapid decline of coral reef ecosystem health is now the most pressing challenge to the reef managers [1, 5]. Most of the tropical coral reefs are found only within a narrow range of environmental conditions, making them vulnerable to abrupt change in seawater physico-chemical parameters like temperature, and salinity [6–10]. Coral bleaching events are associated with thermal stress are acute disturbances recognized as the primary global challenge to the persistence of coral reefs, which disrupts the mutualistic relationship of corals with the thermo-sensitive endosymbiotic dinoflagellates of the family *Symbiodinaceae* by photoinhibition and their expulsion. Coral bleaching can be divided into two parts: (1) The initial response where corals expel *Symbiodinium*, and (2) The longer-term effect, which may be either coral tissue recovery or mortality [11]. Coral bleaching events occur when sea surface water becomes so warm and remains high for more than 28 days [6, 8, 12]. Coral mortality after bleaching depends on the extent of heat stress, its severity, and duration of bleaching [13, 14]. Coral bleaching prevalence and the extent of subsequent coral mortality patterns are commonly associated with natural and anthropogenic disturbances, which is highly venerable both within and across the region.

The ENSO event is one of the significant climatic events that trigger the rapid warming of the water column of the seas, altering biogeochemical processes and marine life. Thermal stresses associated with the El Niño Southern Oscillation (ENSO) are occurring with increasing frequency and severity [10]. The global SSTs have risen gradually since the 1980s, which have caused mass coral bleaching (MCB) and mortality in more than 90% of reefs since 1997–1998. Many researchers have reported four significant MCB events (i.e., 1982–1983, 1997–1998, 2010, 2015–2016) all over the world over the past four decades due to global warming-induced by the ENSO event [8, 15–17]. The 2015–2016 ENSO event emerged as the most extreme event in terms of ocean warming intensity and extent across the tropical oceans [18–21], which caused one of the most severe and widespread MCB events across the Indo-Pacific [15, 20]. The MHW caused by the 2015–2016 ENSO was unprecedented over the period of two centuries resulting in ecological and economic consequences worldwide [10]. More than 75% of global coral reefs have witnessed MCB and mortality back-to-back from 2014 to 2016 [19, 20]. Corals can re-establish themselves after mass bleaching in some cases; it takes one to two decades for the ecosystem to return to the pre-bleaching state [22]. However, the increasing thermal stress left no window of recovery for corals from the previous bleaching events, leading to mass mortality [19, 20, 23]. Mass coral bleaching events can cause long-term ecological, economic, and social impacts [1, 24]. As increase in the frequency and severity of MCB could overwhelm the ability of coral reefs to recover between events. Consecutive mass coral bleaching episodes and associated coral mortalities could shift coral reefs from coral dominated state to Cyanobacteria and algae dominated state [25, 26].

The objective of this study is to examine the thermal stress that causes coral bleaching over the coral reef regions on the Eastern Arabian Sea in the Indian Ocean using long-term NOAA CRW SST data. We computed the long-term climatologically mean and trend of SST for these coral reef regions and computed coral bleaching thermal indices: BT, PA, and DHW based on the SST analysis. Further, to ground-truth the accuracy of the computed coral bleaching indices, we visit at field sites for coral monitoring and analyzed the bleaching percentage.

2. Study areas

The coral reefs are geographically located at different latitudes on the Indian coast, and are highly important ecosystem for ecosystem service and economy. The climate over Indian coral reef regions is tropical, hot, and humid. Species diversity and reef structure in Indian coral reefs vary significantly between the areas due to differences in the reef extent and environmental conditions. This study was carried out at the Gulf of Kachchh and Malvan Marine Sanctuary, which lies in the Arabian Sea on the Indian coast and harbor some of the most northern reefs in the world [27]. The coral reefs in the Gulf of Kachchh is located between 22° 15' N to 23° 40' N Latitude and 68° 20′ E to 70° 40′ E Longitude to the north of Saurashtra Peninsula of Gujarat state (**Figure 1**). This region is very rich in terms of biodiversity value and supports varied coastal habitats, including coral reefs, mangroves, creeks, mudflats, islands, rocky shores, sandy beaches, etc. (Arora et al., 2018) and mostly consisting of dead coral boulders and rubbles. The coral species over the Gulf of Kachchh region belonging to the common genera of *Coscinaraea, Favia, Goniastrea, Gonipora, Leptastrea, Porities, Turbinaria*, etc.

It extends over 170 kilometers in length (NNE–SSW) and about 75 kilometers in width (NNW–SSE), covering an area of approximately 7350 km^2 with a mean depth of 30 meters. A total of 76 species of stony coral (Scleractinian) belonging to 30 genera and 12 families [28] and 12 species of soft corals are found in this region [29]. On the other hand, the Malvan Marine Sanctuary, a Marine Protected Area (MPA), is located in the Central West coast of India along the Eastern Arabian Sea, spreads over a 29.122 km^2 area. The marine wildlife sanctuary harbor near shore patch coral reefs mostly dominated by massive and encrusting *Porites* species and

Figure 1.
Study area of Gulf of Kachchh and Malvan Marine Sanctuary, which lies in the EAstern Arabian Sea on the Indian coast.

foliose *Turbinaria mesenterina;* other species includes *Porites lichen, Porites lutea, Porites compressa, Pseudosiderastrea tayami, Siderastrea savignyana, Coscinaraea monile, Favites melicerum, Favites halicora, Cyphastrea serailia, Plesiastrea versipora, Goniopora sp., Tubastraea coccinea* [25, 30]. Corals in the Gulf of Kachchh and Malvan regions are surviving through extreme environmental conditions such as high temperature, high solar radiation, turbidity, salinity changes, and high suspended sediment loads [28, 31]. Both the regions have been designated as a Marine Protected Area (MPA). However, in the Malvan Manrine Sanctuary, the absence of a robust management system and opposition of the MPA from the local population resulted severe local disturbances includes fishing, wastewater drainage, and unregulated recreational activities along with climate change disturbance [30, 32].

3. Materials and methodology

The SST data analysis for the present study was obtained from National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch's (CRW) (known as 'CoralTemp') high-resolution time-series data product (available from NOAA Coral Reef Watch 2019 https://coralreefwatch.noaa.gov). This data set has a high spatial resolution of 5 km ($0.05 \times 0.05^{\circ}C$ exactly) and a temporal resolution of one day. NOAA CRW global data product provides near real-time SST data from 1985 to the present. This datasets product uses advanced very high-resolution radiometer (AVHRR) satellite data from NOAA Pathfinder SST and has been found in good agreement with *in situ* data from ships and buoys. It also includes a large-scale adjustment of satellite biases with respect to the *in situ*. Bleaching Threshold (BT), Positive SST Anomaly (PA), and Degree Heating Weeks (DHW) are commonly used indices for calculating thermal stress on coral reefs. BT is based on the concept of Thermal Threshold (also known as long-term climatological mean), and the thermal threshold for the Gulf of Kachch & Malvan region was computed using the mean of warmest month SST based on NOAA Optimum Interpolated Sea Surface Temperature (OISST) from 1982 to 2016 (35 years period). SST Anomaly was derived by subtracting the thermal threshold from daily SST values. SST Anomaly provided the information of magnitude of thermal stress and was computed for the 11 years during the warmest period (from 2010 to 2020). DHW provides information on the intensity and duration of thermal stress experienced by coral reefs. DHW product is a cumulative measure of thermal stress over an area over three months [33]. The DHW product indicates the reefs around the world which are at risk of bleaching. Coral bleaching generally begins for corals exposed to a DHW value of 0.5 or more [34]. The categories which are used to describe the severity of bleaching for Indian regions are no stress ($0^{\circ}C < DHW \leq 2^{\circ}C$), bleach watch ($2^{\circ}C < DHW \leq 4^{\circ}C$), warning ($4^{\circ}C < DHW \leq 6^{\circ}C$), alert level-1 ($6^{\circ}C < DHW \leq 8^{\circ}C$) and alert level-2 ($DHW > 8^{\circ}C$) based on DHW [8, 15].

4. Results and discussion

The SST variations during the warmest period from 2010 to 2020 for both regions provide information on magnitude, intensity, and duration of thermal stress. The warmest month, warmest quarter, thermal threshold, and bleaching threshold for both regions were computed from NOAA CRW datasets. Based on the maximum frequency of the warmest month recording the maximum monthly mean SST in the year, the climatologically warmest months were identified for both coral reef regions. The warmest month, warmest quarter, Thermal Threshold, and Bleaching

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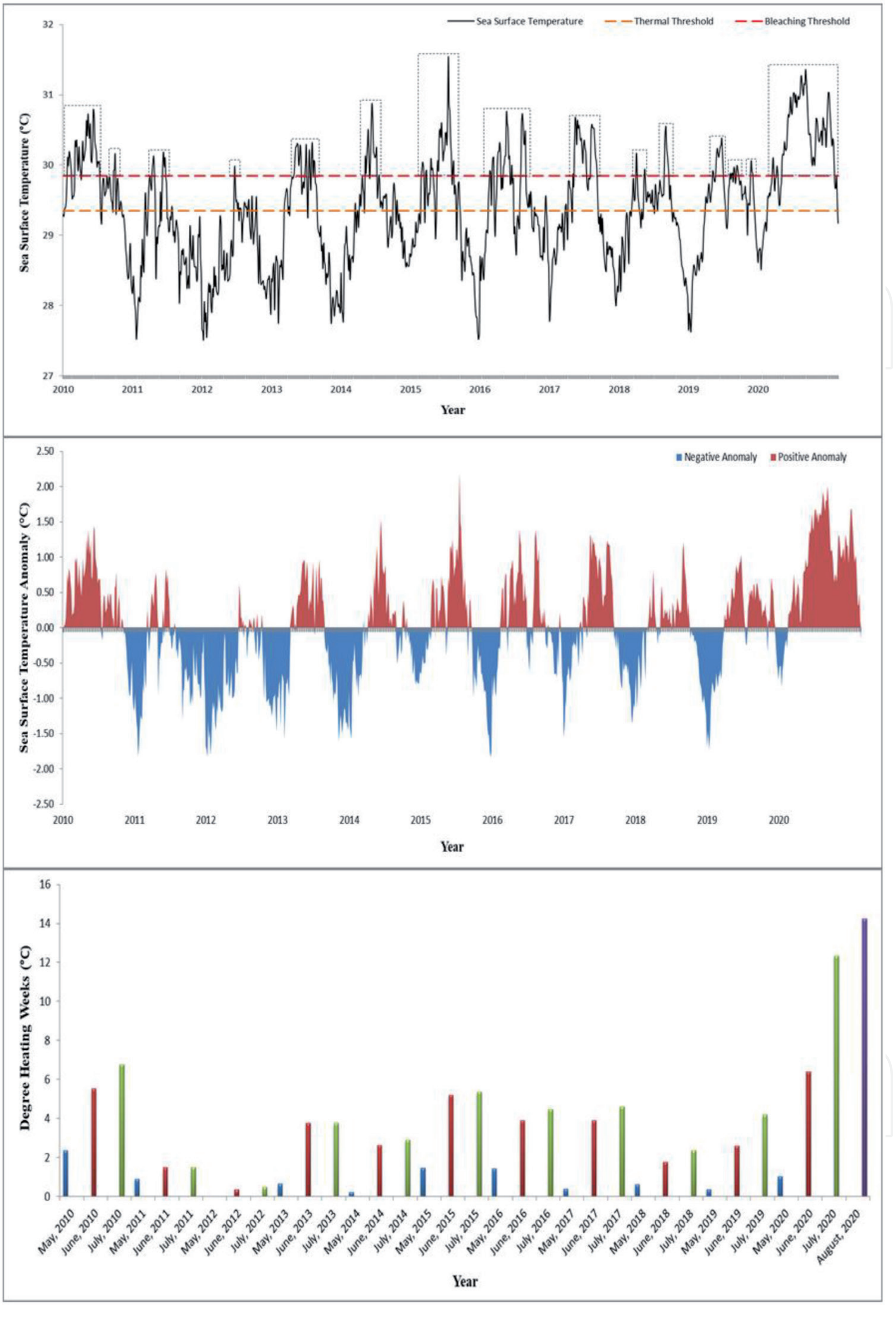

Figure 2.
(Top) Sea surface temperature; (middle) sea surface temperature anomaly; (lower) degree heating weeks variations over Gulf of Kachchh region during warmest quarter (May to July) period from 2010 to 2020.

Threshold for both regions were found to be different. The climatologically warmest month for the Gulf of Kachchh region was June, and the warmest quarter was May to July. Similarly, the climatologically warmest month for the Malvan region was May, and the warmest quarter was April to June. The Gulf of Kachchh region recorded a maximum thermal threshold of 29.35° C(±0.45° C), and the Malvan region recorded

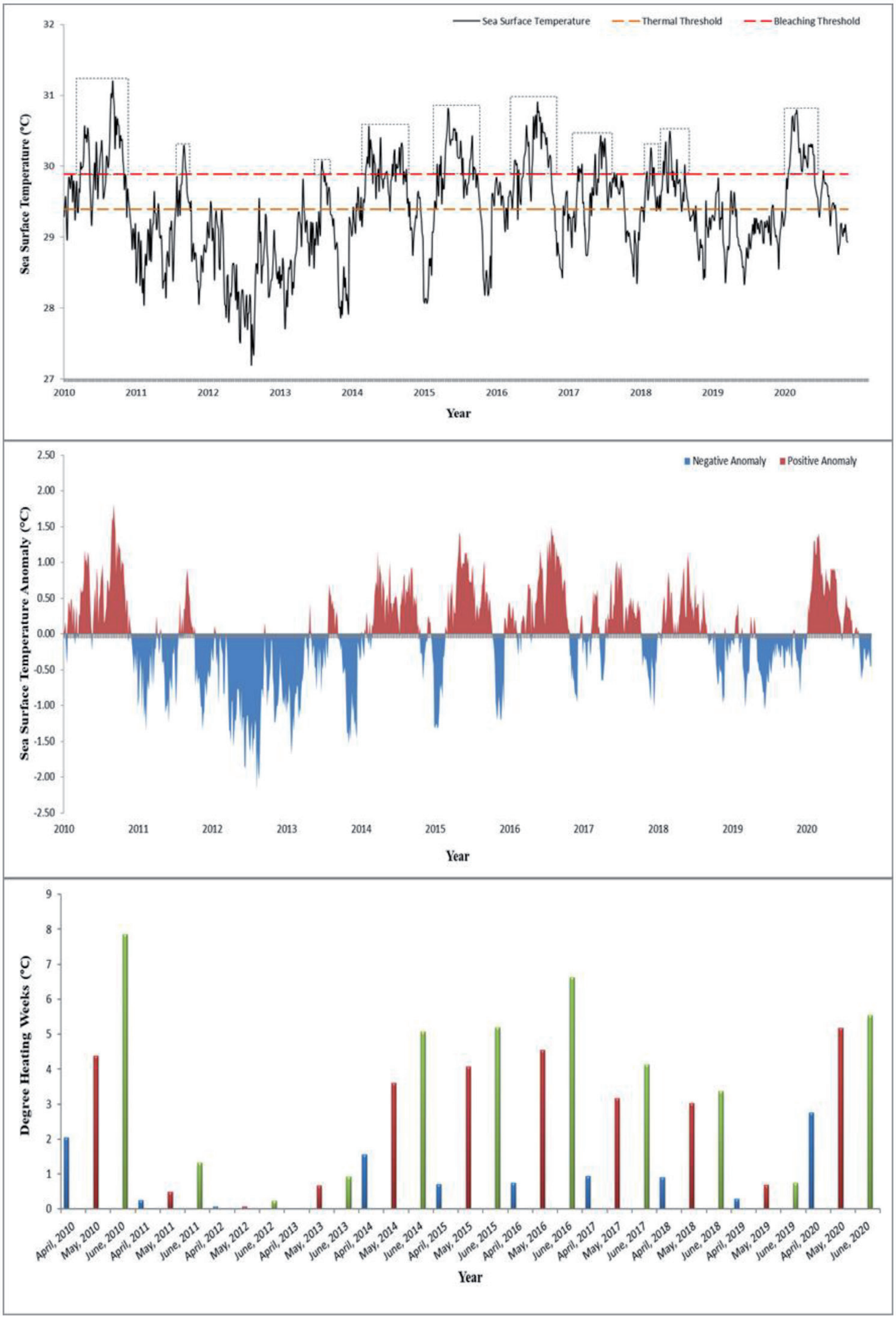

Figure 3.
(Top) Sea surface temperature; (middle) sea surface temperature anomaly; (lower) degree heating weeks variations over Malvan region during warmest quarter (April to June) period from 2010 to 2020.

maximum threshold of 29.39° C(±0.49° C) (**Figures 2** and **3**). In both figures, the orange dotted line shows the thermal threshold, and the red dotted line shows the bleaching threshold for the corals become stressed when SSTs crossed thermal threshold and get bleached if the elevated SST regime is prolonged. BT and daily SST anomalies have been computed on the basis of thermal threshold (sometimes referred as climatologically mean warmest month). Once the climatologically warmest month was identified, the climatologically warmest quarters were identified comparing SST values averaged over three summer months period from a combination of the warmest month and two adjacent months (i.e., the pre and post month). SST anomalies for the warmest quarter were calculated as the absolute difference between the daily SST and the thermal threshold. The warmest quarter anomalies were plotted from 2010 to 2020 for both regions, and positive anomalies were represented in red color while negative anomalies were represented in blue color. It was found that a stark rise in the number of days recording the positive anomalies. Another thermal stress index termed as coral bleaching DHW was calculated in order to assess the accumulative thermal stress. The DHW was generated using the warmest quarter daily SST data. The DHW was also represented in color from blue to green based on their intensity and duration of thermal stress.

5. Gulf of Kachchh region

The diurnal trends of SST in the warmest quarter over a period from 2010 to 2020 provided information on the direction of changes in SST. The BT value for the Gulf of Kachchh region was observed 29.85° C (± 0.45° C) means 0.5° C above the thermal threshold value (**Figure 2**). Over a period from 2010 to 2020, it was observed that the SST value during the warmest quarter had crossed the BT in each year. The maximum SST 31.54° C has been recorded in the year 2015, while the minimum SST 29.97° C has been recorded in the year 2012. During the year 2020, the SST values crossed the thermal as well as BT values and persisted for more than three months. In the same year, the monitoring period was extended up to mid-August. This study also computed and showed variations of daily SST anomaly. The absolute range of positive anomaly for the Gulf of Kachchh region varied between 0.01° C to 2.2° C, and a maximum of 2.2° C was recorded in 2015. The frequency and intensity of positive anomaly have increased continuously over the region. The range of DHW was found to be 0.5° C to 14.26° C, and the maximum was recorded in the year 2020, whereas the minimum was recorded in the year 2012. The "Alert Level-2" status was recorded in 2020, while the "Alert Level-1" status was recorded in 2010. The year 2015, 2016, 2017, and 2019 were recorded "Warning" status.

6. Malvan region

The diurnal trends of SST in the warmest quarter over a period from 2010 to 2020 provided information on the direction of changes in SST. The BT value for Malvan was observed 29.89° C (± 0.49° C) means 0.5° C above the thermal threshold value (**Figure 3**). Over a period from 2010 to 2020, it was observed that the SST value during the warmest quarter had crossed the BT in each year except two years: 2012 and 2019. Year: 2012 and 2019 have experienced significantly less SST as compared with other years. The maximum SST 31.21° C has been recorded in the year 2010. During the year 2020, the SST values crossed the BT values and persisted for three months with two intermittent breaks. This study also computed variations of daily SST anomaly. The absolute range of positive anomaly for the Malvan region varied between 0.01° C to 1.8° C, and a maximum of 1.8° C was recorded in 2010. The frequency and intensity of positive anomaly have increased continuously over the region. The range of DHW was found to be 0.2° C to 7.84° C, and the maximum was recorded in 2010, whereas the minimum was recorded in 2012. The "Alert Level-1" status was recorded in the year 2010 and 2016, while "Warning" status was recorded in the year 2015, 2017, and 2020. The DHW under "Alert Level-2" status was absent over the Malvan region. The year 2019 has shown the least coral bleaching thermal stress indices because of the long period cyclone '*Vayu*' was formed in the Arabian Sea, which triggered heavy to extreme rainfall.

Field observations data were collected over both locations during the period from 2010 to 2020. The recorded satellite-derived SST and field observations data indicated that corals in both regions experienced prolonged heat stress, which is the primary cause of back-to-back coral bleaching events. Field survey at Gulf of Kachchh region revealed bleaching of *Coscinaraea, Favia, Goniastrea, Goniopora, Leptastrea, Porites, and Turbinaria* (**Figure 4**). Field surveys at the Malvan region were revealed partial and whole colony bleaching of *Porites* spp., *Favites spp., Turbinaria mesenterina, Pseudosiderastrea tayami, Cyphastrea serailia, Plesiastrea versipora, Goniopora* spp., *Siderastrea savignyana* (**Figure 5**). Gulf of Kachchh region recorded ~4% and ~ 10% bleaching during 2016 and 2019 temperature peaks. During field survey at Malvan region in 2014, the bleaching prevalence was observed 14.58%; in the year 2015, the bleaching prevalence was observed 54.20%; in 2016, the bleaching prevalence was observed 46.76%; in 2017, the bleaching prevalence was observed 20.22%; in 2018, the bleaching prevalence was observed 5.07%, and in 2019, the bleaching prevalence was observed 8.37% (**Figure 6**) [25, 30]. The effects of increasing thermal stress on corals were correlated with field observations data. We found that the DHW derived from SST and field observations were positively correlated with a correlation coefficient of 0.71 (**Figure 7**). The significant correlations indicate the SST peaks during the warmest quarter were the predominant cause of mass coral bleaching and mortality.

SST-driven impacts trigger cascading effects at the ecosystem level by reducing coral species heterogeneity, weakening the reef carbonate framework, loss of reef functionality, and negatively impacting the reef-associated biodiversity [9, 24]. This heat shock-mediated bleaching mortality of corals has emerged as the greatest threat to

Figure 4.
Coral bleaching observed at Laku Point reef, Gulf of Kachchh region during 2016 and 2019. (a-b) Healthy and bleached Turbinaria sp.; *(c) bleached* Gonipora sp.*; (d) partially bleached* Favites sp.*; (e) partially bleached* Porites sp.*; (f) bleached sea anemone* Heteractis sp.; *(g) bleached colonies of* Dipsastraea sp.*; (h) bleached colonies of* Favites sp. *and* Porites sp.*; (I & j) bleached colonies* Dipsastraea sp.

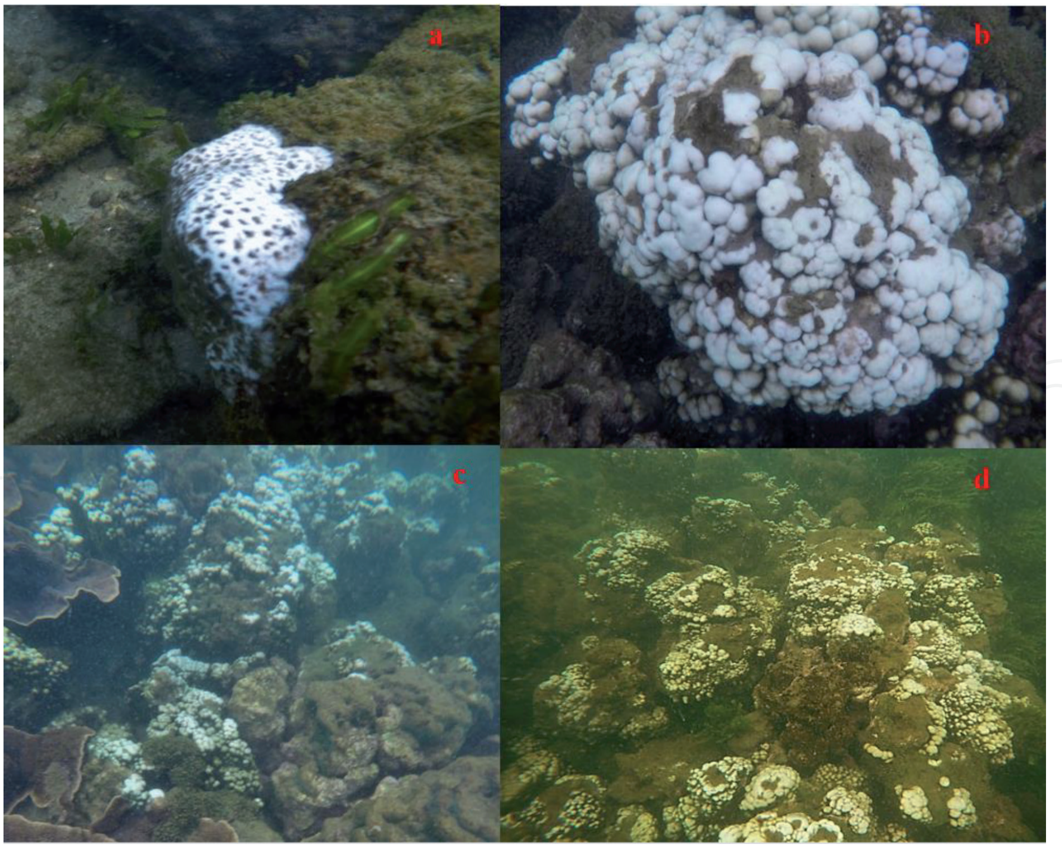

Figure 5.
Coral bleaching observed at Malvan region from 2014 to 2019. (a-b) Bleached Favites sp.*; (c) bleached massive* Porites sp.*; (c & d) bleached and dead coral colonies covered by turf algae and sediments.*

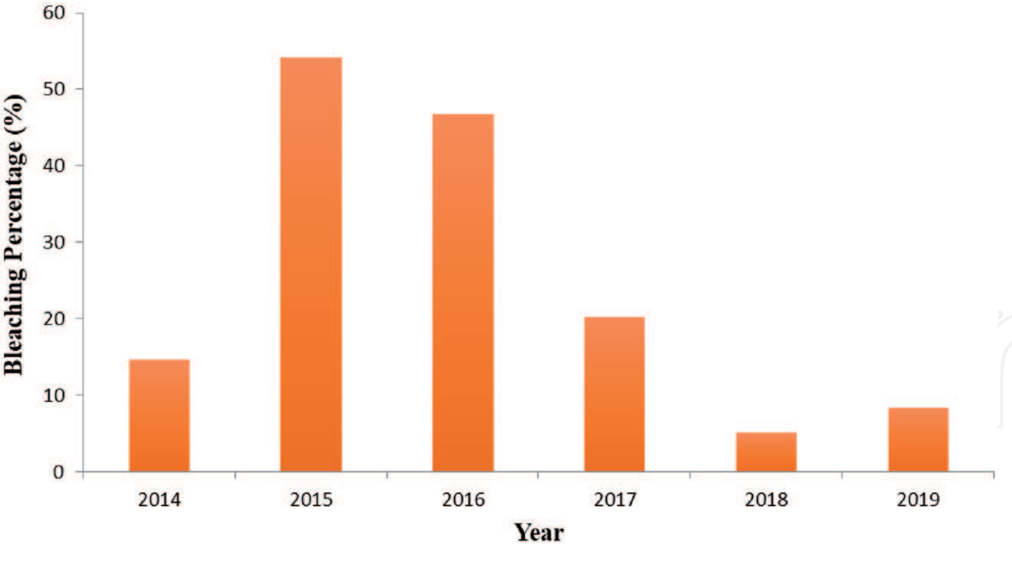

Figure 6.
Coral bleaching prevalence at Malvan Marine Sanctuary, Central West coast of India.

the existence of reefs globally as these habitats fail to recover [10, 16, 19, 35]. The present study highlights that the satellite-derived SST data may be used as a convenient tool for thermal stress-driven coral bleaching events, which will improve reef management practices in the thermal stress-impacted coral reef environment. Climate change poses a threat to the persistence of the coral reefs in tropical seas. The mass coral bleaching estimated during 2010 and 2016 was correlated with a multivariate ENSO index. The year 2010 and 2015–2016 were a strong ENSO years.

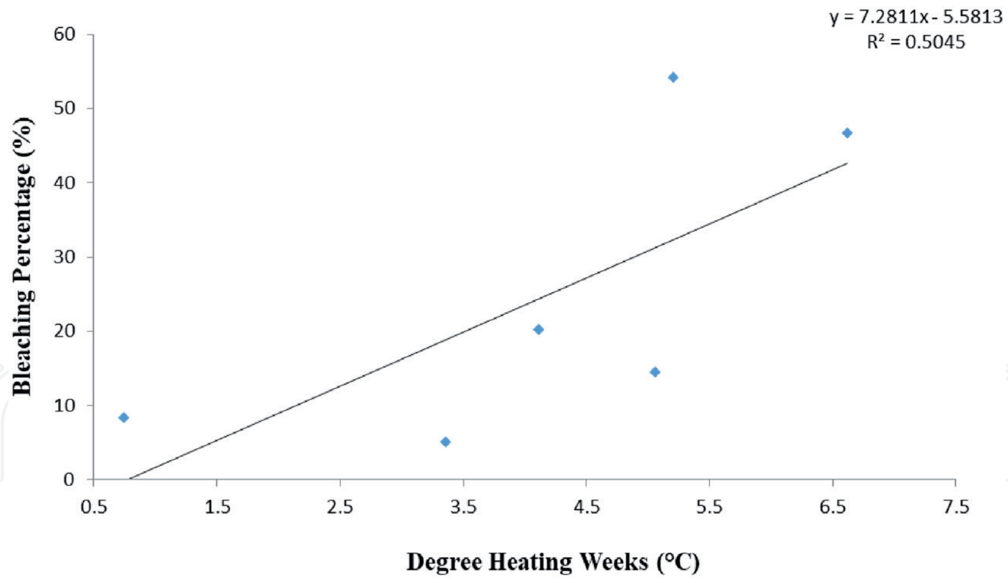

Figure 7.
Correlation of duration of thermal stress (i.e., DHW) and bleaching percentage during the period from 2014 to 2019.

The tropical Indian Ocean is warming rapidly compared to rest of the tropical oceans [36], and warming of the Arabian Sea has increased significantly since the 1990s [37, 38]. In recent years, rapid warming event caused severe negative ecosystem impact in the Indian Ocean. For instances, 2015–2016 ENSO caused a significant decline in oil sardines fishery in South-West India [39], and phyto-plankton community shift in the North-eastern Arabian Sea [40], as well as coral bleaching and mortality in Lakshadweep archipelago [41]. Understanding how the Indian Ocean suffered severe coral bleaching and mortality in 2015 following a 7.5 maximum degree heating weeks (DHWs), which caused a 60% coral cover decrease from 30% cover in 2012 to 12% in April 2016 [11]. Therefore, ENSO induced heat stress driven coral bleaching, coral mortality and ecosystem level impact of recur-rent mass bleaching events require global scale quantification of the magnitude, intensity, and duration of thermal stress for each reef location for formulation of improved and timely management policies.

7. Conclusion

This study concludes that the increased thermal stress and back-to-back coral bleaching are the particular concern over Indian coral reef regions due to pressure from long-term climate change and anthropogenic activities. This study highlights that the satellite-derived SST data could serve as a useful coral reef monitoring tool along with the field data confirmation. Corals in the Gulf of Kachchh and Malvan regions show distinct regional sensitivity towards BT, SST anomalies, and DHW. NOAA CRW data proves its potential towards a long-term SST. The year 2020 was the warmest in the Gulf of Kachchh region, and 2010 was in the Malvan region during the period from 2010 to 2020, which recorded a high duration of thermal stress over the region. But the highest temperature and highest anomaly was recorded in the year 2015 over the Gulf of Kachchh region, while the Malvan region was received in 2010. In the Gulf of Kachchh region, the year 2020 was recorded high DHW compared to other years, which was under "Alert Level-2" status, and the Malvan region recorded high DHW in 2010 with "Alert Level-1" status. The year 2012 recorded minimum thermal stress over both regions. This study revealed that the high intensity and long duration thermal stress led to bleaching and mortality, which indicates the dire situation of coral reef health degradation. Therefore, the persistence of fragile coral reefs in the Gulf of Kachhh and Malvan Marine Sanctuary are in need of urgent science-informed active conservation, restoration and management intervention.

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Disclosure statement

The authors declare no conflict of interest.

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