Assessment of Bleaching Stress Vulnerability of Lakshadweep Islands using Google Earth Engine (GEE)

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Abstract: Coral reefs, among the Earth's most diverse and valuable ecosystems, face challenges due to climate change. Coral bleaching is a phenomenon wherein corals lose their symbiotic zooxanthellae owing to various stressors, leading to a whitening effect on the coral tissues. In recent decades, climate change has intensified coral bleaching events. Multiple stressors, including elevated Sea Surface Temperature (SST), extreme irradiance levels, and various biotic and abiotic factors trigger bleaching events. Coral bleaching is primarily driven by thermal stress caused by elevated SSTs. Global bleaching events are often linked to planetary ocean-atmospheric circulation processes such as El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). This study focused on assessing the vulnerability of coral reefs in the Lakshadweep region of India from 2016 to 2023 using the National Oceanic and Atmospheric Administration's Climate Data Record Optimum Interpolation Sea Surface Temperature (NOAA CDR OISST) daily data. GOOGLE EARTH ENGINE (GEE) is a cloud computing platform which is used to collect and generate the base data for this study. The vulnerability assessment utilized two bleaching indices: SST anomaly and Degree Heating Week (DHW). Analysis of DHW data reveals that 2020 experienced the highest SST anomaly residence time due to the IOD event of 2019, as compared to 2016 and 2023 which are known El Niño years. All Lakshadweep islands exhibited vulnerability, although in varying degrees across different areas. Based on the magnitude, intensity, and frequency of bleaching stress, the islands are categorized into different categories of vulnerability. This study identifies Baliyapaniyam, Cheriyam-Kalpeni and Suhelipar reefs as very highly vulnerable reefs in Lakshadweep.

Keywords: Coral bleaching, SSTA, DHW, GEE, Lakshadweep

1. Introduction

Coral reefs, among the Earth's most diverse and valuable ecosystems, face unprecedented challenges due to climate change. Coral bleaching refers to a physiological process where corals expel their endo-symbiont zooxanthellae due to various stressors, leading to a whitening effect of the coral tissues. These corals appear white like they are bleached. Coral bleaching is affected by many factors ranging from elevated sea surface temperature, high levels of irradiance, physiological thermal stress, and various biotic and abiotic factors (Plass-Johnson et al. 2015). Among the coastal ecosystems, coral reefs are sensitive to SST changes and are declining at a disturbing pace (Anthony 2016). Coral reefs around the world are impacted by the increase in sea surface temperature which in turn affects the livelihood of coastal populations (Hughes et al. 2017; Eakin et al. 2019). Global warming has considerably increased the stress on corals. Recurrence period of bleaching events has been reduced from 25 years to 6 years on average (Hughes et al., 2018).

Coral bleaching frequency has increased since 1980 due to increased SST caused by global warming (Hughes et al. 2017; Lough et al. 2018; Eakin et al.2019). It has been reported in various studies that even a slight increase in sea surface temperature by 1-2°C can cause widespread coral bleaching (Baker et al. 2008; Plass-Johnson et al. 2015). Coral bleaching has been reported to be correlated with SST anomalies and geographical position as well (Sully et al. 2019). Corals present at 15° north to 20° south of the equator are considered to be more vulnerable than others (Sully et al. 2019). Baker *et al* (2008), and Sully *et al* (2019) reported more stress on corals during the high SST anomaly period (Baker et al. 2008; Sully et al. 2019). Severe coral bleaching events are reported between 1980 to 2020, which correlates well with increased global sea temperature and particularly thermal anomalies (Baker et al. 2008; Sully et al. 2019). SST anomaly is highly variable and directly influenced by various planetary circulation processes like El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO) etc. (Houk et al. 2020). It has been reported most of the global-level mass bleaching coincided with such events (Baker et al. 2008; Plass-Johnson et al. 2015; Hughes et al. 2018). ENSO is an ocean-atmosphere coupled process, intrinsic to the tropical Pacific Ocean. It is characterised by anomalous warm SST over the eastern Pacific Ocean. During El Niño conditions, heavy rainfall is witnessed over the Peru upwelling region. Drought is more prevalent in Australia and Indonesia. Failure of the Indian summer monsoon and Indonesian monsoon are also observed. Even though ENSO is restricted to the Pacific Ocean, its effects are observed all over the world. Most of the warm years in the globe are associated with ENSO years (Kumar et al. 2024; https://www.pmel.noaa.gov/elnino/what-is-el-nino).

Warm SST over the tropics is also observed especially over the Pacific and the Indian Ocean (Claar et al. 2018; Porter et. al. 2021). In a study on coral mortality in the Thousand Islands, Indonesia, coral reefs have shown a considerable decline during 1982-83 El Niño (Brown 1990). A study in the Galapagos Islands located in Pacific Ocean showed a high positive correlation of 0.7 between positive SST anomaly and ENSO. 1983, 1987 and 1992 coral bleaching in Galapagos coincided with ENSO events. Persistent positive SST observed during that time was considered as the cause of bleaching (Podestá & Glynn 1997). Of all the El Niño's, the one of the years 2016 is considered to be the strongest as it surpassed the strength of 1997 and 1983 El Niño's (Claar et al. 2018). Major global coral bleaching was observed during this period (Claar et al. 2018). In the year 2016 severe coral bleaching was observed over the western tropical Pacific Ocean, Central Pacific and Western Indian Ocean (Barkley et al. 2018; Porter et al. 2021; Qiu et al. 2021). A study by Porter et al., on the corals of the Western Indian Ocean has revealed severe bleaching in 2016. A degree heating week (DHW) of 15 was reported. Cumulative DHW was considered the reason for coral bleaching (Porter et al. 2021). A study conducted between 1987 and 2020 showed a significant decrease in coral cover in the Andaman Sea. During 1997, 2010 and 2019 a reduction of 29.1%, 33.9% and 27.9% in coral cover was observed. Correspondingly DHW of 4.1°C, 11.51°C and 4.5 °C were recorded respectively (Dunne et al. 2021). The peculiarity of the 2016 El Niño was that, it coincided with the Negative IOD event which made this year the warmest year on Earth (Avia et al. 2018; Lu et al. 2018). IOD is another ocean-atmosphere coupled process. It is intrinsic to the Indian Ocean and has two modes namely positive mode and negative mode. During the positive mode western Indian Ocean experiences anomalous warming and anomalous cooling is observed over the east Indian Ocean. During the negative mode, an opposite situation is observed (Avia et al. 2018; Lu et al. 2018). Both El Niño and IOD have a significant impact on the Arabian Sea. During El Niño years, monsoon winds over the Arabian Sea weakens, resulting in the warming of Sea surface temperature. Poor rainfall is recorded over the Indian subcontinent (Kumar et al. 2024). During Positive IOD, warming of the West Indian Ocean is observed, resulting in strong monsoon winds, and more rainfall over the Indian subcontinent (Sarma 2006). All these processes have a considerable impact on the corals of the Indian coast in the Arabian Sea (Lakshadweep, Grande Island-Goa, Malvan-Maharashtra, Gulf of Kachchh).

The objective of this study is to examine the thermal stress which is responsible for coral bleaching over the 16 reefs of Lakshadweep using National Oceanic and Atmospheric Administration Climate Data Record Optimum Interpolation Sea Surface Temperature (NOAA CDR OISST) data for the period of eight years: 2016 to 2023. Two bleaching indices SST anomaly and Degree Heating Week were computed. Based on the two indices bleaching vulnerability map was prepared for the Lakshadweep Islands.

2. Study area

On the Indian coast, coral reefs are located at different latitudes. This study was carried out for the Lakshadweep reefs which are one of the most vulnerable and bleaching prone reefs as they occur in clear transparent water which makes them susceptible to photo-bleaching (Arthur 2000; Arora et al. 2019b). Lakshadweep reefs are located between 08° 00′ N and 12° 30′ N latitude and 71° 00′ E and 74° 00′ E longitude in the Arabian Sea. They are located in the northern part of the Laccadive-Chagos Ridge, approximately 200-300 kilometres away from the west coast of India (Mallik 2017). The ridge is grouped as Amindivi, Laccadive, and Minicoy with an area of 32 sq.km. There are sixteen reefs located in Lakshadweep: Baliyapaniyam, Cheriyapaniyam, Chetlat, Kiltan, Bitra, Perumalpar, Kadmat, Bangaram, Agatti, Amini, Pitti, Kavaratti, Andrott, Cheriyam-Kalpeni, Suhelipar, Minicoy (Figure 1).

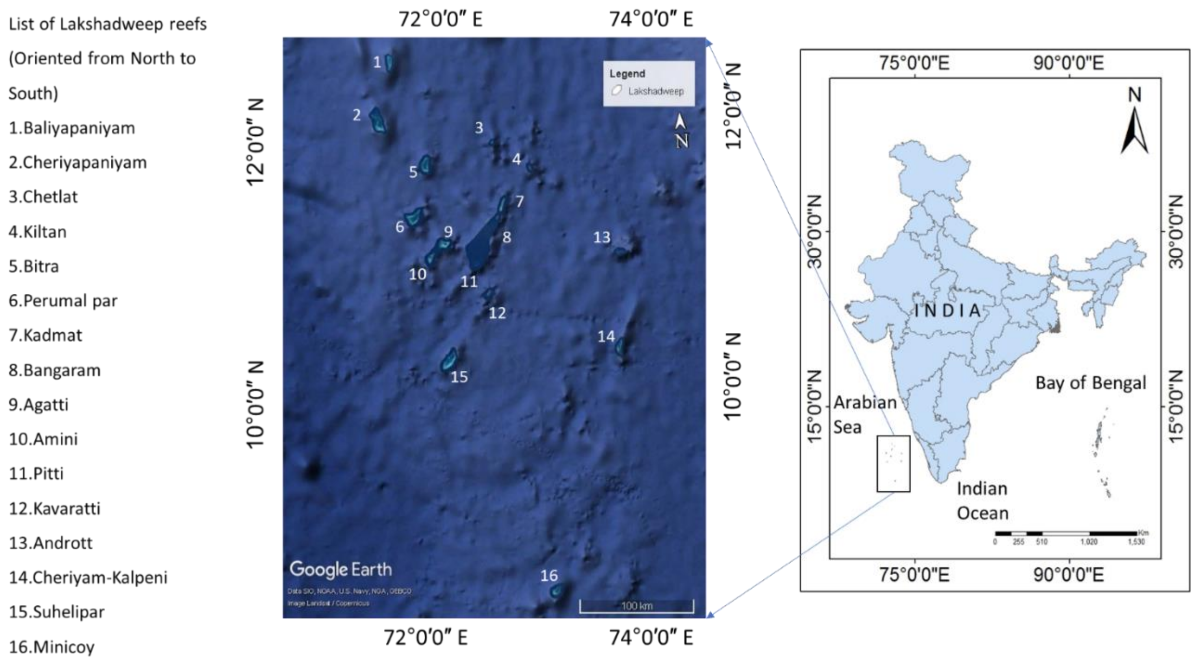

Figure 1. Study area map of Lakshadweep Reefs

3. Methodology

The SST anomaly data for the present study was obtained from NOAA CDR OISST version 2.1 using GEE (Figure 2). This dataset has a spatial resolution of 27830 meters and a temporal resolution of one day. This SST product uses Advanced Very High-Resolution Radiometer (AVHRR) sensor's data. The SST anomaly data product is available on Google Earth Engine as a derived product.

Sea Surface Temperature Anomaly

Sea Surface Temperature anomaly is the difference between the current sea surface temperature and the long-term sea surface temperature average of a particular location. Negative anomaly or temperature difference indicates that the ocean is cooler than average, while positive anomaly indicates that the ocean is warmer than average. SST anomaly measures the magnitude of thermal stress conductive to coral bleaching. The SST anomaly data used is NOAA CDR OISST daily data which was extracted for each island/reef by averaging the pixels occurring within reef polygon. The data was then classified as negative anomaly and positive anomaly. The positive anomaly was further categorized into five classes. The classes are Very Low, Low, Moderate, High, and Very High. The Very Low class includes the SST Anomaly values as 0°C-0.49°C. The Low class encompasses anomaly values of 0.5°C-0.99°C. Moderate class is assigned when values range from 1.0°C to 1.49°C. The High values include a range of 1.50°C to 1.99°C. Very High values include values above 2.0°C.

Degree Heating Week

Degree Heating Week index measures the intensity and duration of thermal stress experienced by coral reefs. DHW represents the accumulation of Positive SST Anomaly at a location over the twelve-week period. The categories that are used to describe the severity of bleaching based on our study for Lakshadweep region are No Stress, Bleach Watch, Bleach Warning, Alert Level-1 and Alert Level-2 based on DHW. The "No Stress" status is issued when the condition of 0°C -2°C weeks prevails. The "Bleach Watch" status is issued when the condition of 2°C -4°C weeks is met. The "Bleach Warning" status is satisfied when the condition of 4°C -6°C weeks is recorded. The "Alert Level-1" is issued when the condition of 6°C -8°C weeks and "Alert Level-2" is issued when the condition of above 8°C weeks are satisfied.

Bleaching Stress

The bleaching stress vulnerability map is made using the following criteria based on the DHW observations for the three anomalous years identified among the eight years as: 2016,2020 and 2023. When a reef qualifies into Bleach Alert Level 1 category for at least once out of the three years and records Bleach Warning for the remaining two years then the reef is considered to be in "Vulnerable" category. When a reef qualifies in to Bleach Alert Level 1 for two years and records Warning or Watch once then the reef is considered to be in "Moderately Vulnerable" category. When a reef qualifies in to Bleach Alert Level 2 for two years and/or Bleach Alert Level 2 once, Bleach Alert Level 1 once and Warning or Watch once then the reef is considered to be in "Highly Vulnerable" category. When a reef qualifies in to Bleach Alert Level 2 for two years and combinations of Bleach Alert Level 2 or Bleach Alert Level 1 for the third year then the reef is considered to be in "Very Highly Vulnerable" category.

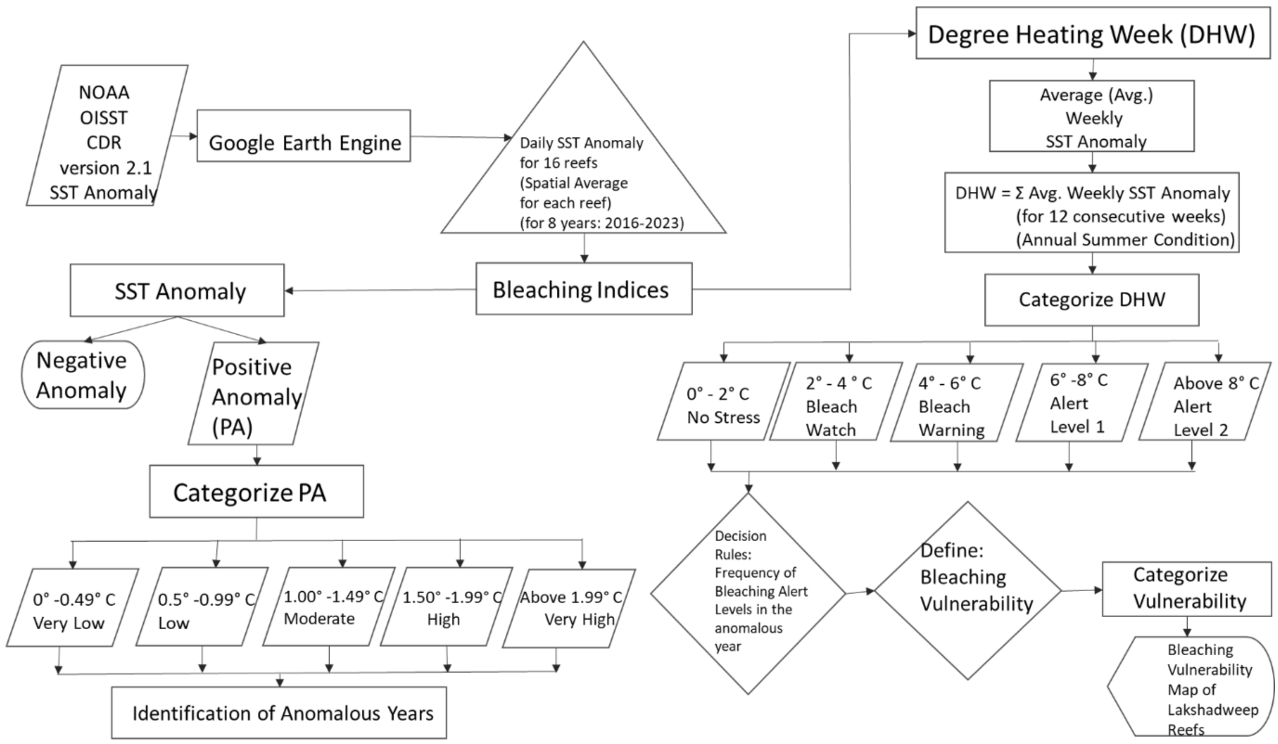

Figure 2. Flow chart depicting the methodology

4. Results

4.1 SST anomaly

SST anomaly patterns during the years 2016 to 2023 provides information on the magnitude of thermal stress experienced by these reefs (Figure 3). This study shows that 2016, 2020, and 2023 were warm years. The years 2017, 2018, 2019, 2021, and 2022 were observed as normal years. The year 2016 was observed as the hottest year. The SST Anomaly peak values were between 1.50°C and 1.99°C. Previously, 2016 was reported as an El Niño year, which was the reason for the warming. In 2016, Mass Coral Bleaching occurred worldwide (Mohanty 2017). The year 2017 was observed as the coolest year, as the lowest sea surface temperature anomaly was observed in this year. In the year 2018 highest SST anomaly range was observed between 1.0°C and 1.49°C. The year 2020 was also observed as an anomalous year, as it was an effect of the Indian Ocean Dipole event of 2019-2020 (Zhang & Du 2021). In 2020, all the islands showed a high SST anomaly, which was between 1.50°C and 1.99°C. In 2021, the two reefs, Baliyapaniyam and Perumalpar, showed high anomaly between 1.50°C to 1.99°C. In 2022, it was observed that Baliyapaniyam, Cheriyapaniyam, Bitra, Perumalpar, Agatti, Kavaratti, Andrott, Suhelipar, and Minicoy these nine reefs showed high SST anomaly between 1.50°C and 1.99°C. The year 2023 showed an unusual trend with a large anomaly that was greater than 2.0°C in magnitude. The reefs Cheriyapaniyam, Chetlat, Kiltan, Bitra, Kadmat, Pitti, Kavaratti, Andrott, Cheriyam-Kalpeni and Suhelipar showed anomalies more than 2.0°C for a shorter duration. The year 2023 was announced as an El Niño year, which might have caused an increase in SST anomalies (https://earthobservatory.nasa.gov/images/151481/el-nino-returns; https://www.weather.gov/mhx/ensowhat)

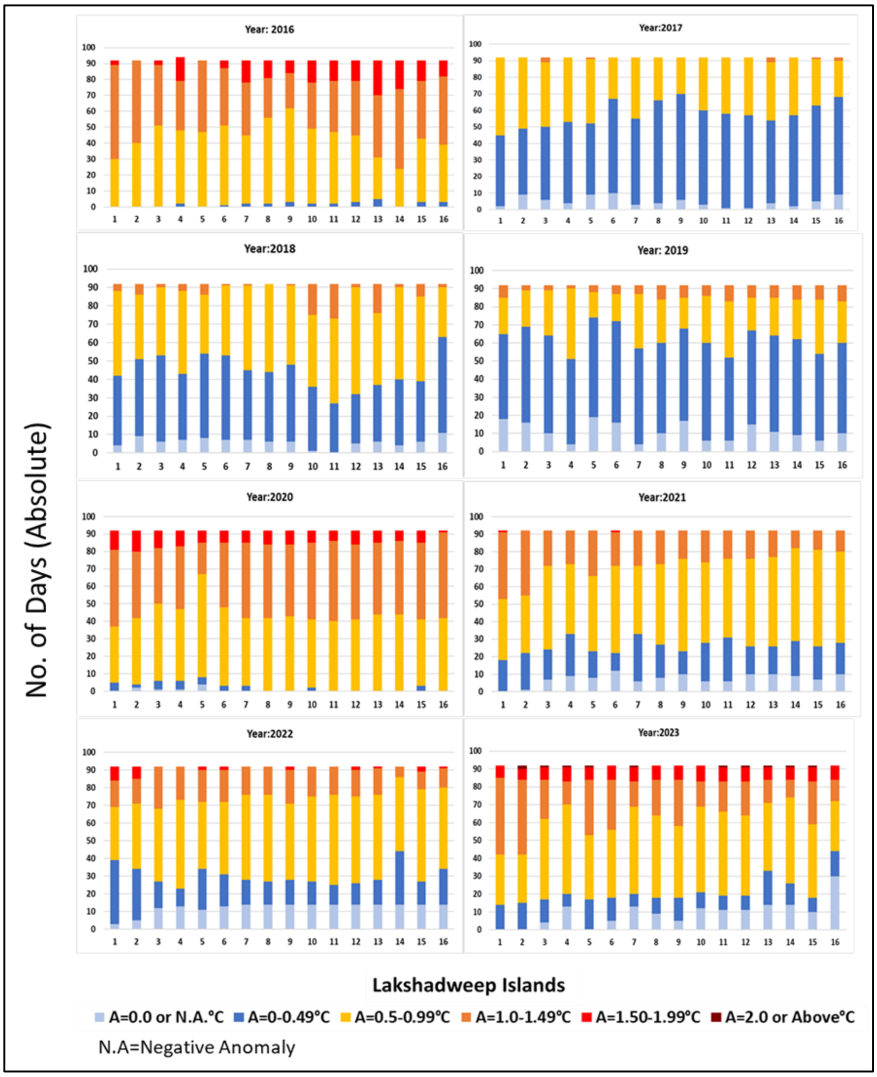

Figure 3. SST anomalies experienced by the Lakshadweep reefs in the summer quarter during 2016 to 2023 (X axis shows the islands 1 to 16 as numbered in Figure.1)

4.2 Degree Heating Week

These eight years, were also analysed for DHW index (Figure 4a and 4b), which showed the heating in terms of twelve heating week period for all 16 reefs. In 2016, it was observed that all the reefs recorded a 12-heating week period, but the two islands Baliyapaniyam and Cheriyam-Kalpeni recorded higher values. The year 2017, is the year in which DHW wasn't recorded greater than 1°C per week for any of the reef. In 2018, the central islands Perumalpar, Bangaram, Agatti, Amini, Pitti, Kavaratti, Cheriyam-Kalpeni, and Suhelipar showed a higher residence time of SST anomalies. Baliyapaniyam and Cheriyapaniyam the two northernmost reefs show highest average DHW for the year 2020, 2021, 2022 and 2023.

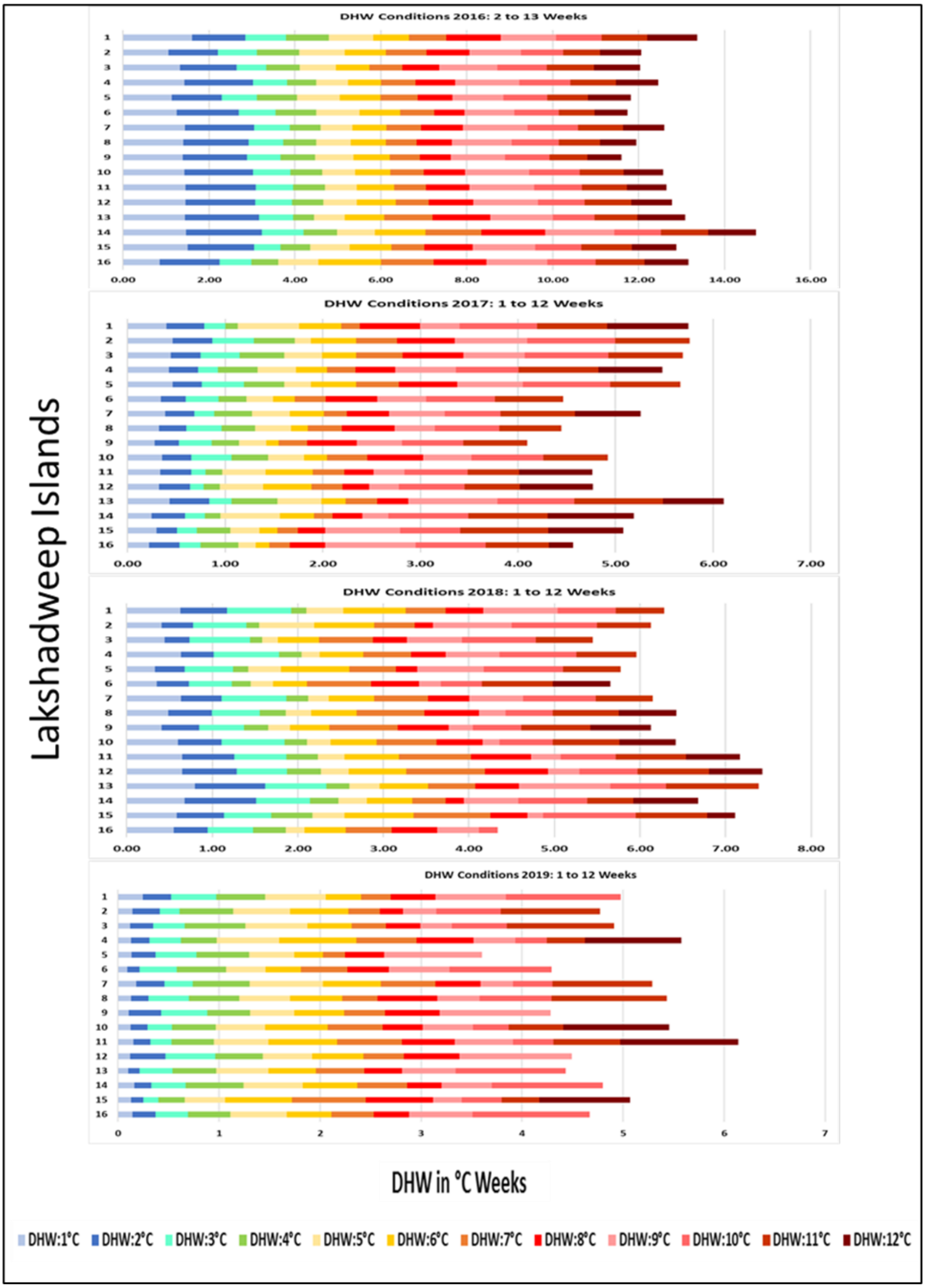

Figure 4a. DHW conditions during 2016 to 2019 (Y axis shows the islands 1 to 16 as numbered in Figure.1)

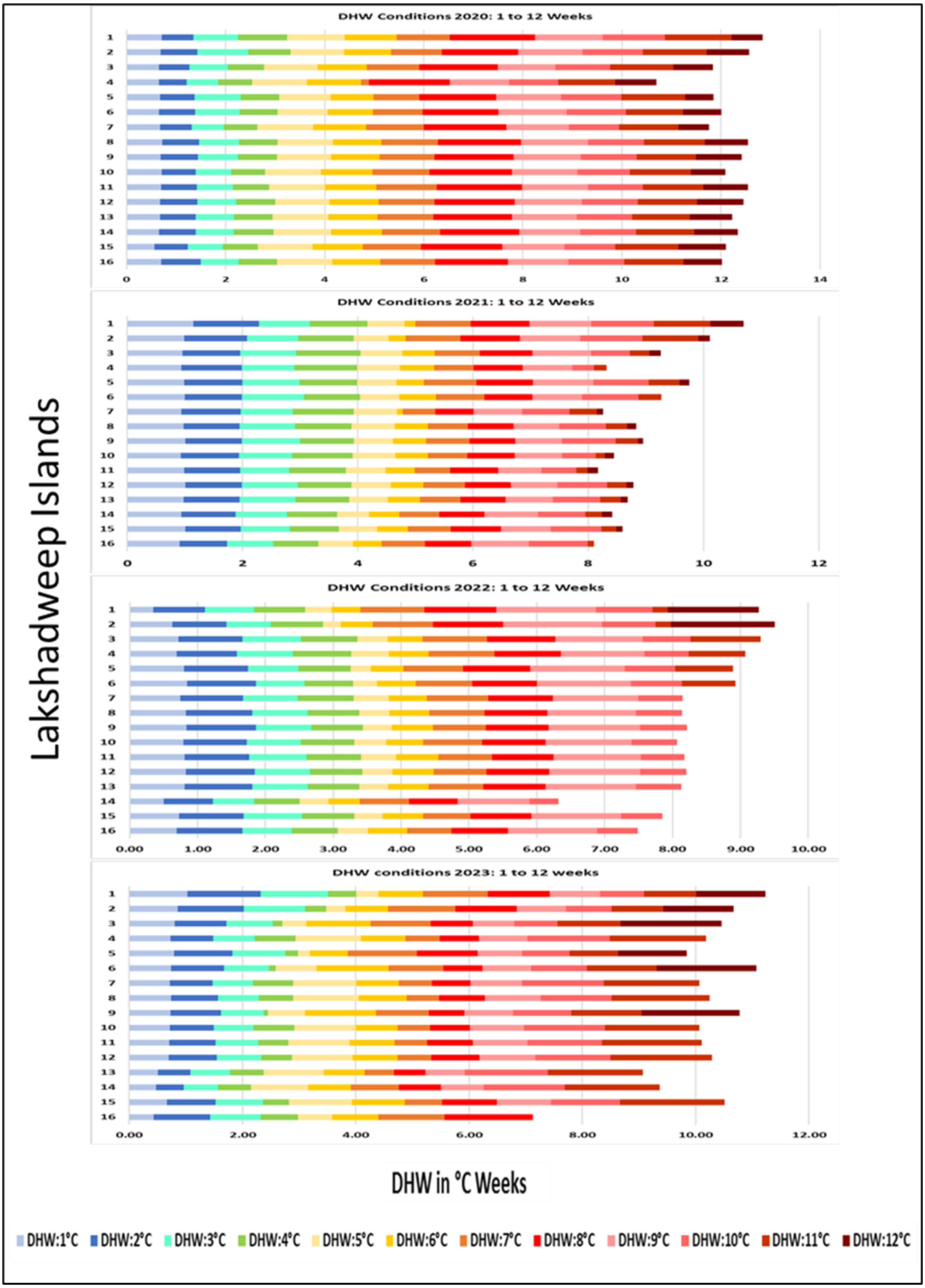

Figure 4b. DHW conditions during 2020 to 2023 (Y axis shows the islands 1 to 16 as numbered in Figure.1)

4.3 Maximum SST anomaly and Degree Heating Week

For the warmest years 2016, 2020 and 2023 the maximum SST anomaly was compared for all the sixteen islands of Lakshadweep (Figure 5a; Figure 6). It was found that 2023 shows the Maximum SST, but if this graph is compared with the SST anomaly graph of three months (Figure.3,), it is observed that even though 2023 shows the maximum SST anomaly, the maximum anomaly value in 2023 did not last longer, the values were seen for 1-2 days only, while 2020 recorded a higher residence time of higher SST anomaly values. The maximum SST anomaly map (Figure 6) was created for the Lakshadweep islands for the years: 2016, 2020 and 2023 which indicated that the maximum SST anomaly observed in 2016 was between moderate and high category, similarly year 2020 indicates that all the reefs recorded high value of maximum SST anomaly. Meanwhile 2023 showed maximum values between high and very high for all the islands. The DHW graph of the same year indicates that 2020 is the warmest as compared to 2016 and 2023(Figure 5b). DHW graph indicates that seven out of sixteen reefs show higher DHW value in 2020, and three reefs show overlap. The maps indicate that in the year 2020 all the reefs show bleach alert level 1 (Figure 7) and bleach alert level 2 while in 2016 there was a bleaching warning for four reefs, bleach alert level 1 for seven reefs and bleach alert level 2 for five reefs which makes year 2016 relatively less warm as compared to 2020. In 2023 it was observed that one reef showed bleach alert level 1, and one reef was at bleach watch. It indicates that even though SST anomaly was higher in 2023, the residence time was less, making it less impactful than 2020.

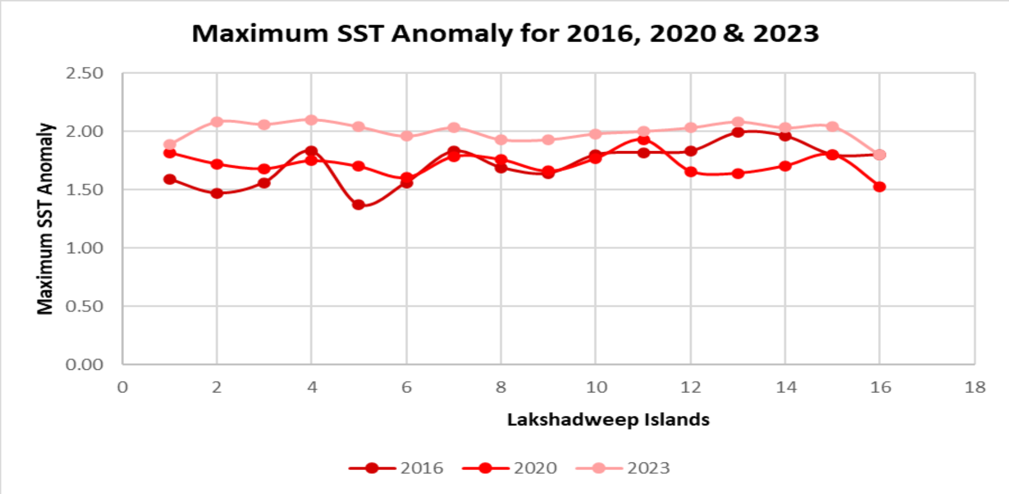

Figure 5a. Graph representing maximum SST anomaly for anomalous years (X axis shows the islands 1 to 16 as numbered in Figure.1)

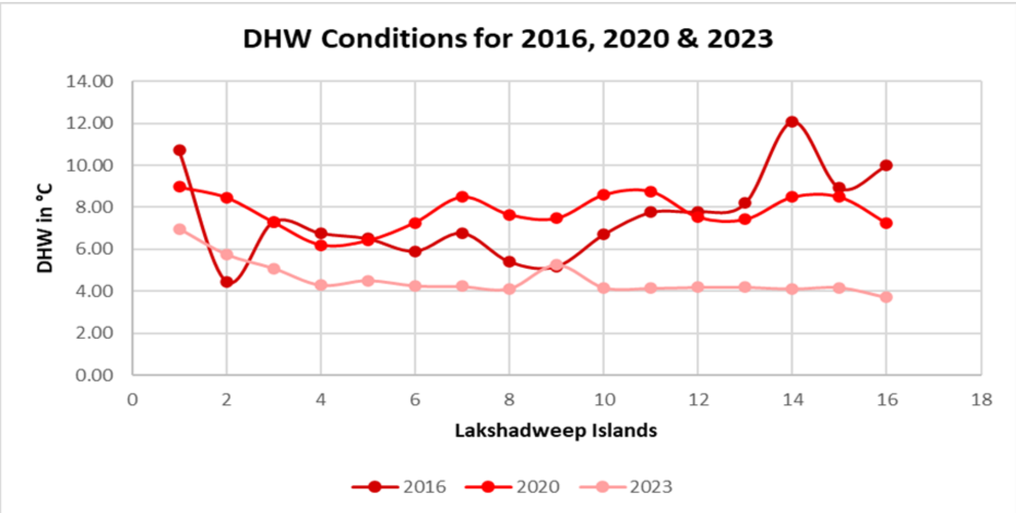

Figure 5b. Graph representing DHW conditions for anomalous years (X axis shows the islands 1 to 16 as numbered in Figure.1)

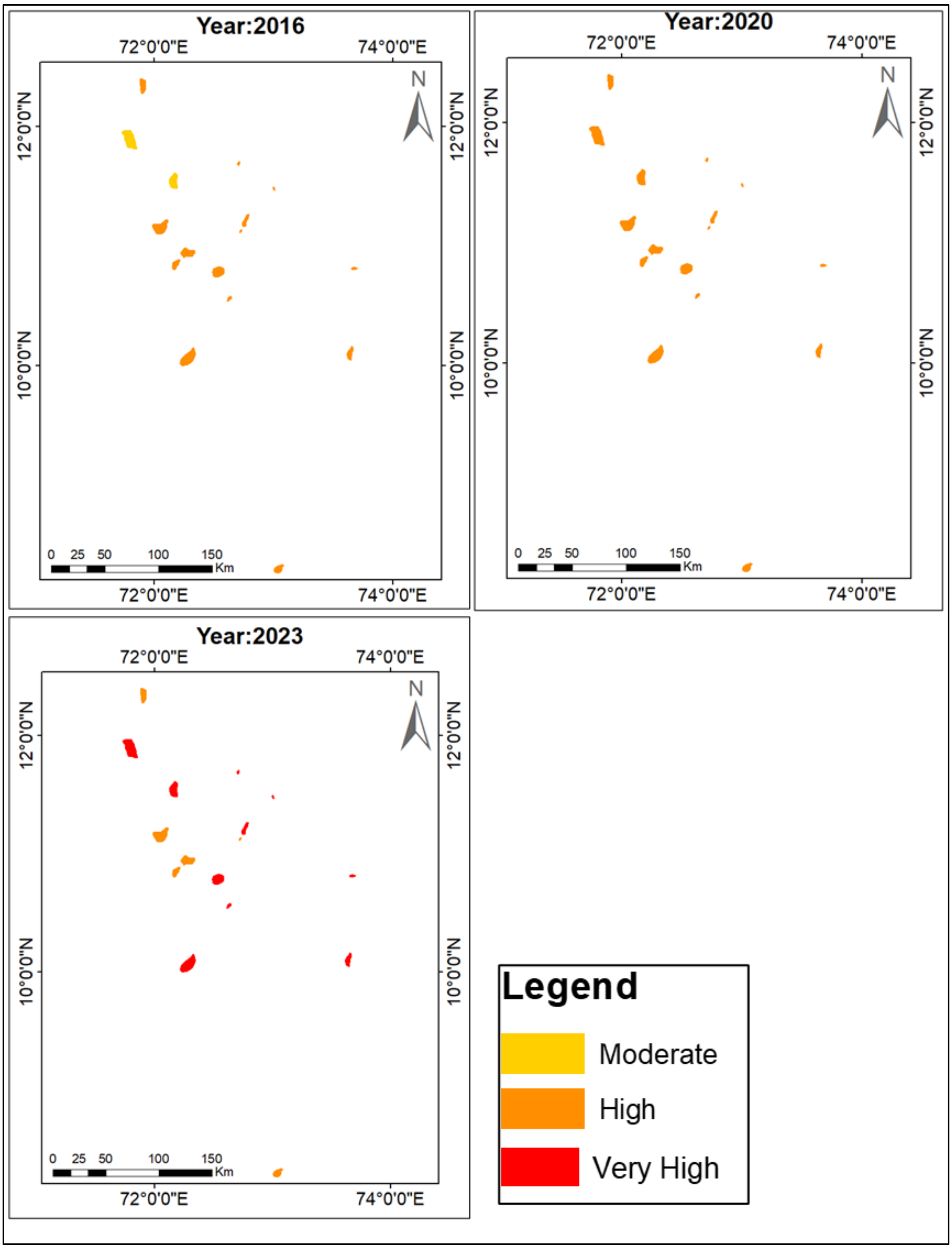

Figure 6. Maximum SST anomaly map of Lakshadweep reefs for the anomalous years

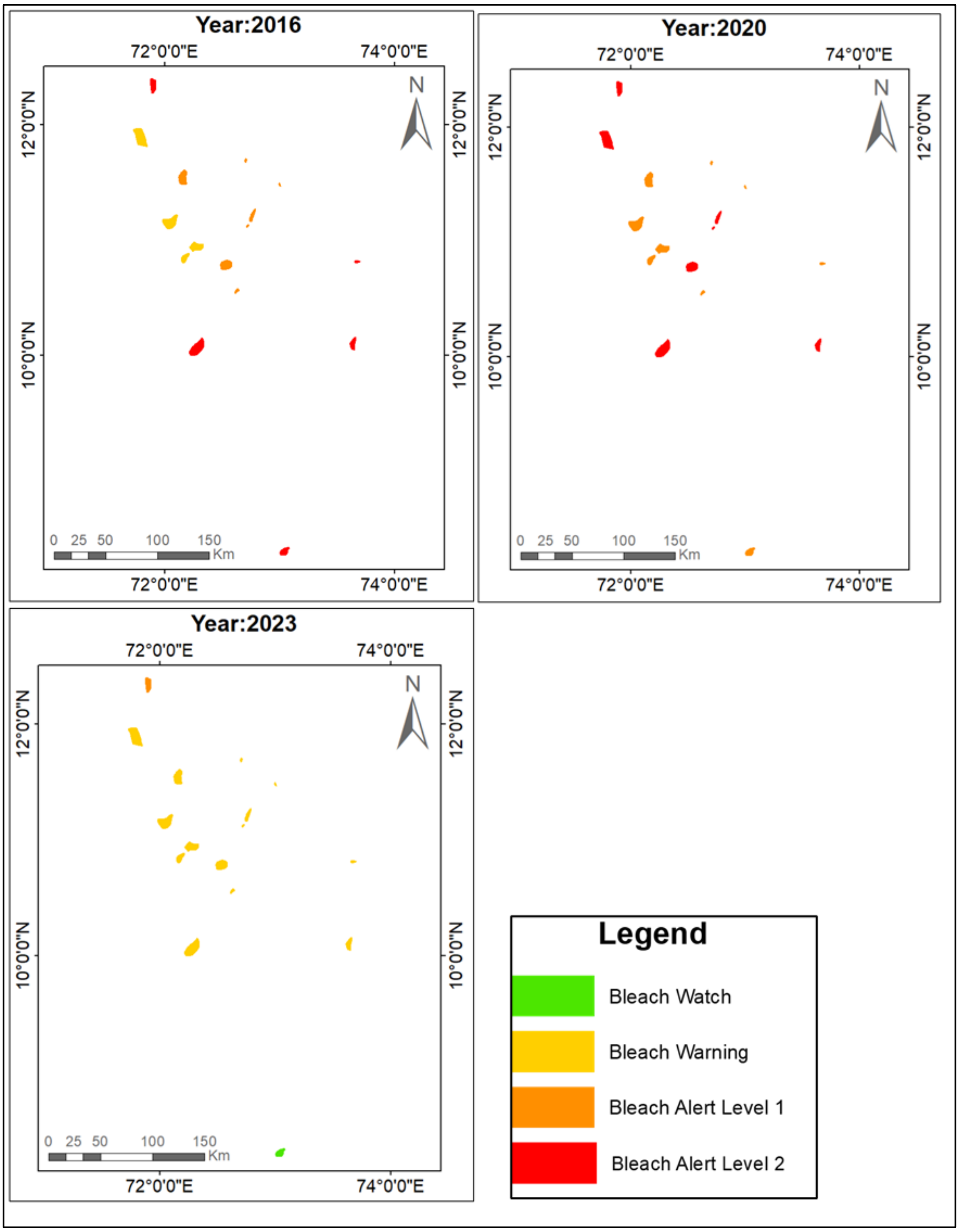

Figure 7. Bleach Alert Status map for Lakshadweep reefs for anomalous years

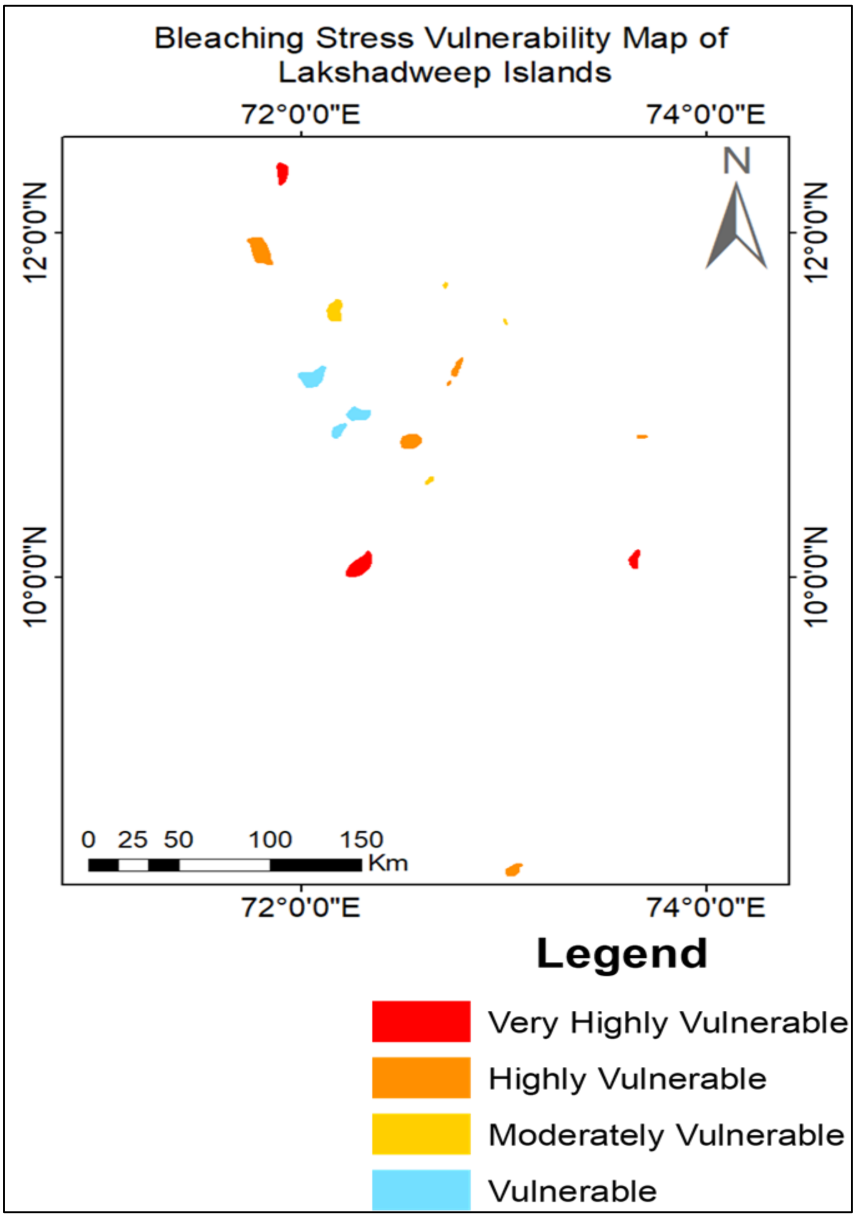

Figure 8. Bleaching stress vulnerability map of Lakshadweep Reefs

5. Discussion

Climate change and the resultant warming of oceans affect coral reefs worldwide and endanger the fragile ecosystem. Anomalous SST is a well-known cause of coral bleaching, worldwide. This study was carried out to assess the bleaching stress vulnerability for past eight years 2016 to 2023 for sixteen reefs of Lakshadweep. Here we tried to estimate the bleaching stress caused to coral reefs and categorize them on their vulnerability. Two indices were considered for this: the SST anomaly and DHW. For this purpose, NOAA CDR OISST daily SST anomaly data were used. The SST anomalies during the summer quarter of March, April, and May were computed. SST anomaly measures the magnitude of stress. Using the SST anomaly, the DHW was calculated to understand the intensity of the stress. Based on magnitude, intensity, and frequency, islands were categorized into very highly vulnerable, highly vulnerable, moderately vulnerable, and vulnerable for the study period of three anomalous years.

Much work has been done on the reefs of the Arabian Sea in order to understand their vulnerability to changing climate based on Bleaching threshold (BT), Positive SST anomaly (PA) and DHW. The year: 2016 was reported as the warmest year for Lakshadweep and the Gulf of Mannar region (Arora et al. 2019a; Arora et al. 2022). A study carried out in 2019 for the years 1998, 2010 and 2016 showed Lakshadweep had high thermal stress during 2016 with a DHW around 8.71 °C week. During the same year highest PA was observed to be 1.43 °C. The years: 1998 and 2010 had less thermal stress as compared to 2016, with a value of 6.17 and 6.80 respectively for Lakshadweep region. All the years considered for the study were El Niño years (Arora, et al. 2019a). A similar study for the same region based on DHW and WMSST produced the same results (Arora et al. 2019b). In this, high PA was observed during 1987, 2005 and 2017. A DHW of 0.19 °C to 9.96 °C was observed. The highest DHW of 9.96 °C was observed during El Niño and positive IOD year 2016. Throughout the study period, only El Niño years showed high thermal stress (Arora et al. 2019b). A study on the Malvan marine sanctuary, located in the central Arabian Sea, reported thermal stress of 6.92 °C week in 2016 during the course of the study, between 2014-2019, the thermal stress increased from 2014 and reached its peak in 2015 and 2016, El Niño years, and subsided later. During the El Niño period high PA was observed. In the same region, observation from 2010 to 2015 revealed a PA range of 0.01°C to 1.8 °C and DHW of 0.2 °C week to 7.84 °C week. The maximum value in PA and DHW was recorded during 2010 another El Niño year (Arora et al. 2022; De et al. 2022). During 2016 ~50% loss in the corals was reported from Grande Islands (Babu, et al. 2019) located in the eastern Arabian Sea which was a direct consequence of El Niño of 2015-2016 (Hussain & Ingole 2020). A study by Arora et al. (2019b) reported multiple bleaching events in the Lakshadweep Islands all of which coincided with major El Niño events.

In this study, we have observed three anomalous SST years 2016,2020 and 2023 out of the eight years of study period for the Lakshadweep Islands. Among these years, 2020 was observed as a warmest year which was due to an effect of IOD event of 2019. Other years which were observed to be anomalous years: 2016 and 2023 were El Niño years. Using SST anomaly and DHW indices as a base information followed with bleach alert status, bleaching vulnerability map (Figure 8) was prepared for Lakshadweep reefs. Based on the three anomalous years observation, it is found that all islands are vulnerable. Based on this study, Baliyapaniyam, Cheriyam-Kalpeni and Suhelipar reefs appear as very highly vulnerable. Cheriyapaniyam, Kadmat, Amini, Pitti, Andrott, and Minicoy are found as highly vulnerable. Figure 9 indicates the severity of coral and coral reef associate-bleaching at these highly vulnerable reefs in the summer of 2020. Chetlat, Kiltan, Bitra, and Kavaratti are found as moderately vulnerable, While Perumalpar, Bangaram, and Agatti are vulnerable reefs in Lakshadweep.

6. Conclusion

This study concludes that there is increased thermal stress over the Lakshadweep region. This thermal stress is due to increased frequency of occurrence of planetary circulation processes like El Niño, and IOD due to changing climate. This study highlights that out of the three anomalous years, 2020 was the warmest year based on the residence time of the high-magnitude SST anomalies. The anomalous years 2016 and 2023 were El Niño years, and the year 2020 was observed due to the IOD of 2019. Based on the recurrence of the mass coral bleaching events in the wake of El Niño and/or IOD events, it is found that all reefs in Lakshadweep appear vulnerable, but this study identifies Baliyapaniyam, Cheriyam-Kalpeni and Suhelipar reefs as very highly vulnerable, Cheriyapaniyam, Kadmat, Amini, Pitti, Andrott, and Minicoy as highly vulnerable reefs, Chetlat, Kiltan, Bitra, and Kavaratti are found as moderately vulnerable, while Perumalpar, Bangaram, and Agatti appears vulnerable reefs in Lakshadweep. This study highlights the need for monitoring and management measures to mitigate the impact of climate change on coral reef ecosystems for Lakshadweep reefs. An understanding of spatial vulnerability patterns can inform targeted conservation strategies to safeguard these delicate ecosystems.

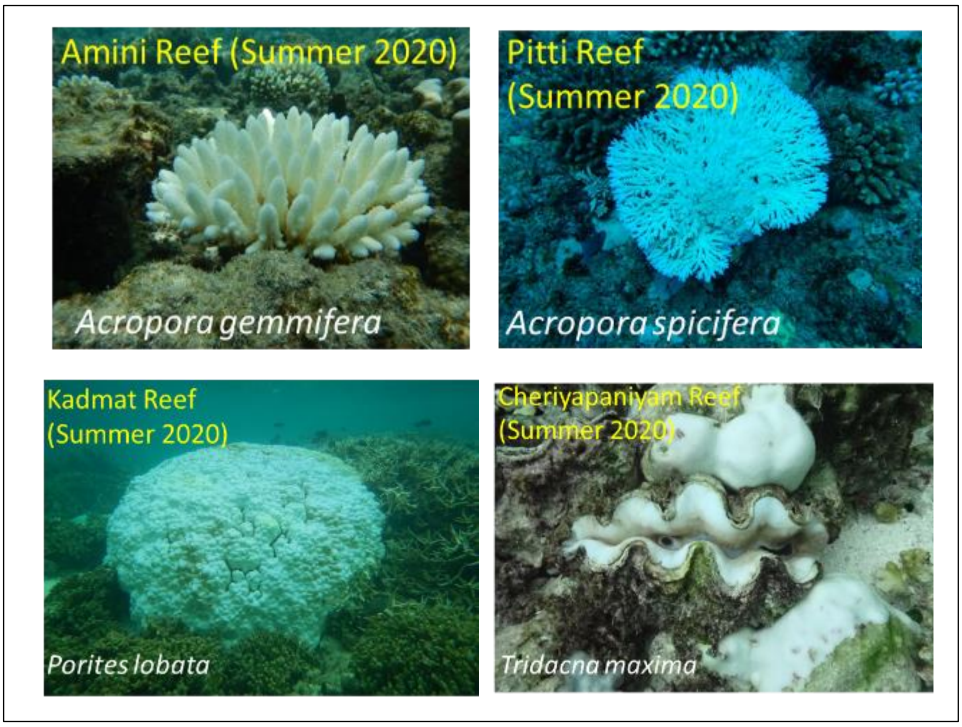

Figure 9: Coral and coral associate- bleaching observed at highly vulnerable reefs of Lakshadweep during 2020

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