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RESEARCH ARTICLE

ASSESSMENT OF CORAL BLEACHING DUE TO THERMAL STRESS OVER INDIAN OCEAN

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Abstract

Coral reef is an endangered species among the coastal ecosystems. It can act as a rainforest; forms an ecosystem; provide habitat; protect coast from waves; contribute in carbon sinking and attract tourists along the coast. The fragile coral reefs are highly sensitive to environm ental variations (temperature, salinity, turbidity, etc.) and anthropogenic activities. Among the above, temperature is the major factor that can affect corals to a large extent. Therefore, it is important to assess the coral bleaching due to an abnormal rise in Sea Surface Temperature (SST). Current study is an attempt to quantify the intensity of coral bleaching using Marine Heat Wave (MHW) based on persistent SST over 90 percentile in the Andaman environs during April to May, 2010. The contiguous degree of MHW is a dictator of thermal stress, which is non-conducive to corals can lead to bleaching. In this study the relationship was established between MHW and *In-Situ* observations to estimate the Percentage of Coral Bleaching (PCB) on a synoptic scale. Extent and PCB can be calculated only based on MHW by using the estimated slope value 1.36 and intercept value -13.957. Further, the relation between the ratio index value derived based on the ratio of Remote Sensing Reflectance (Rrs) values of bands 412 & 531 nm and PCB to estimate the coral bleaching threshold (2.5). Significant correlation between Rrsratio index and PCB recorded is 0.82. The extracted threshold limits 2.5 ratio index can be used to confirm bleaching and values above this can categorize the coral bleaching intensity. The approach used in the current study enhances the capabilities of the operational coral reef monitoring programs and researchers.

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Introduction:-

Corals are marine organisms belonging to invertebrate under the phylum *Coelenterata* or *Cnidaria* and are primitive animals occurring in tropical waters in the depth ranging from low tide to 200 metres of the oceans and seas. Coral reefs are mainly composed of reef-building colonial animals (polyps) that live symbiotically with the single celled microalgae (*zooxanthellae*) in their body tissue and secrete a calcium carbonate skeleton. Coral reefs form an important ecosystem in the shallow marine environment and provide habitat for many species. Healthy reefs contribute to local economies through tourism. Diving tours, fishing trips, hotels, restaurants and other business bases near reef system provide millions of jobs and contribute billions of dollars all over the world (Banks et al., 2005, NMFS/NOAA, 2001). Coral reefs also buffer adjacent shorelines form wave action and prevent erosion, property damage and loss of life. Coral reefs have been identified as an endangered ecosystem because they are subject to multiple natural and man-made stresses such as increase in extreme sea surface temperatures, heavy sedimentation, eutrophication, and thermal pollution (Glynn, 1996, Ixchel et al., 2012).

However, in the last couple of decades worldwide coral ecosystem have been degrading largely due to global warming with anomalous rising temperature which leads to coral bleaching (Reaser, Pomerance and Thomas, 2008, Sammarco, 2008, IPCC, 2001). Coral bleaching has been one of the significant contributors to the increased deterioration of reef health. Coral bleaching is a phenomenon that takes place when the symbiotic relationship between algae (zooxanthellae) and their host corals breaks down under certain environmental stresses. The overall shape of the spectral reflectance of coral reef at different spectrum is determining by pigment (zooxanthellae) inside the coral (Hochberg, Atkinson and Andréfouët, 2003, Call, Hardy and Wallin, 2003, Holden and Ledrew, 1999, Lubin et al., 2001). The low values at blue and green wavelengths are largely the result of absorption by photosynthetic and photo protective compounds. Similarly, higher values at red wavelengths indicate a lack of absorption or presence of active fluorescence (Hochberg, Atkinson and Andréfouët, 2003). Hence the bleaching signature can be easily identified by using satellite Remote sensing reflectance (Rrs) in synoptic level.

The continuous rising in Sea Surface Temperature (SST) leads to generation Marine Heat Wave (MHW). It is defined as discrete prolonged anomalously warm water even in a particular region (Zhang et al., 2017). The relative baseline climatology is defined using all data with a 11 day composed window centred on the time of year with a period of more than 10 years and then a high percentile threshold (90th percentile) (Zhang et al., 2017) is used to obtain the threshold value. A percentile threshold rather than an absolute value above the climatology is used since the magnitude of SST variability varies by different regions. The “Prolonged MHW events” means a MHW must last more than 5 days and “discrete” means two events with a gap of 2 days or less will be considered as a continuous event (Zhang et al., 2017).Therefore, it is necessary to study the impact of thermal stress on coral reef, their monitoring and assessment of coral bleaching over global synoptic view by using satellite SST observation (Soloviev et al., 1994). In addition to this, the spectral characteristics of bleached (Lubin et al., 2001, Hochberg, Atkinson and Andréfouët, 2003) coral at different level were also assessed for quantitative calculation of coral bleaching percentage. Hence, the main objective of the present study is to calculate the spatial distribution of Coral Bleaching Percentage (CBP) around the Andaman region by using persistence of Marine Heat Wave (MHW) and established a relationship between spectral reflectance with respective intensity of coral bleaching percentage.

The present study was carried out around the Andaman coral environ is located in the SE of the Bay of Bengal, between 6°-14° N latitude and 91°-94° E longitude. Andaman reefs contain about 83% of the maximum coral diversity found anywhere in the world, equal to the “Coral Triangle” of Indonesia, and about 400 species could emerge after further surveys (Roy, Sreeraj and George, 2009). Andaman falls under a tropical climatic condition prevailing moderate temperature within the range of 23°C to 31°C. Figure1 shows the map of study area.

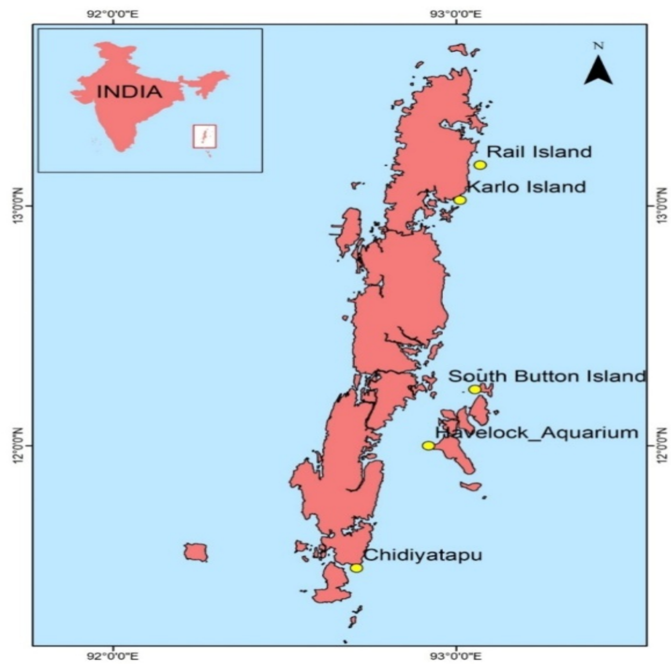

Figure 1: Location map of Study area overlaid with locations of Rrssampling points

Data and Methodology:-

The systematic procedure for proposed in the current study depicted in flow-chart as Figure 2. The daily NOAA AVHRR SST data pertaining to the period 1998 to 2010 were downloaded for present study. The main aim of the current study is to understand the consequence of MHW on the intensity of coral bleaching and their spectral characteristics. In this regard, in-situ observation on percentage of coral bleaching was obtained from the websitehttps://incois.gov.in/site/services/coralwarning.jspand other published literature was used in the present study. In addition to this, the time series Remote Sensing Reflectance (Rrs) data at 412, 443, 469, 488, 531, 555, 645, 667 and 678 nm were downloaded from MODIS Aqua to assess the spectral characteristics of corals bleached at different intensity. This enables to set a coral bleaching threshold limit based on the band ratio index.

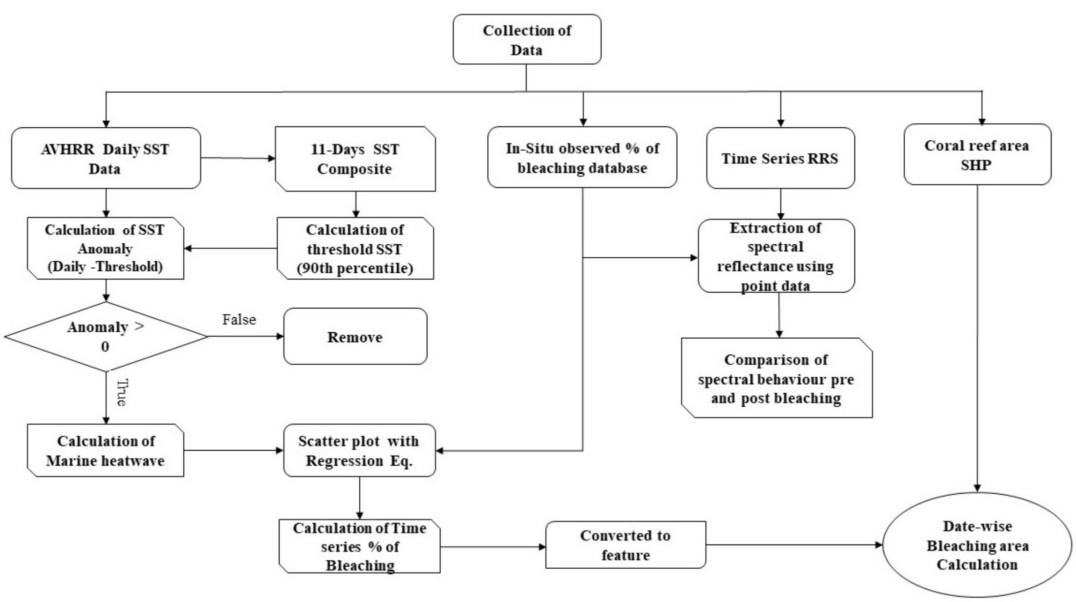

Figure 2: Methodology flow chart.

The threshold SST was calculated based on the 90th percentile of 11-day composite SST data. Daily SST anomaly was calculated by subtracting the daily SST with threshold SST. This daily SST anomaly is used as criteria to assess the thermal stress on coral environ depending on the period of persistence of such condition. The continuous time series (should not gap of 2 days) of positive SST anomaly was considered as one Marine Heat Wave (MHW) event or else it's said to be desecrated events.

MHW%=$n \times \Delta T$ref$\sum i$=1n($Ti - T$thresh,i)×100

Where:

- TiTi = daily SST on day ii
- Tthresh,iTthresh,i = 90th percentile SST for that calendar day (calculated from 1998–2009 baseline)
- nn = number of consecutive days with positive anomaly (MHW duration)
- ΔTrefΔTref = reference anomaly (set to 1°C for normalization)
- The sum is over the entire contiguous MHW event (gap ≤2 days)

The persistence of MHW was calculated using cumulative sum of SST anomaly with multiplicative time-series weightage factor. The maximum intensity of MHW at the end of contiguous event was calculated to understand the spatial distribution of MHW in percentage over the study period using Equation1.

$$MHW(\%) = (weightage * \Sigma precedingAnomalies)/100 \quad (1)$$

The relationship between MHW with in-situ observation at different intensity (% of Bleaching) of coral bleaching has been established by least square method. The coefficient value of resulted regression fitted equation-2 is used to calculate percentage of coral bleaching as dependent parameter with MHW as an independent parameter.

$$PCB(\%) = 1.36 * MHW - 13.957(2)$$

The spectral characteristics of coral reef during pre/post-bleaching period also assessed to quantify the intensity of coral bleaching and there threshold limits of contrasting band ratio analysis. The daily Rrs412and Rrs531 nm band data at the different magnitude of PCB location were extracted and calculated ratio of both the band (Rrs412/Rrs53 1). These two bands can explain the contrasting spectral behaviour at pre/post coral bleaching period. Finally, established a relation between band ratio with PCB time series scattered plot to extract the particular threshold limits indicating the beginning of coral bleaching. The threshold of 2.5 for the Rrs412/Rrs531 ratio was derived from 12 spectral samples collected at locations with known bleaching percentages. Bootstrapping (1000 iterations) gave a 95% confidence interval of 2.3–2.7. Independent testing on a 2016 bleaching event in Lakshadweep showed that areas with ratio >2.5 coincided with reported bleaching, while areas with ratio <2.3 showed no bleaching. Users should recalibrate the threshold for other regions.

Result and Discussion:-

Marine Heatwave (MHW):-

The figure 3 is showing the spatial distribution of weekly time series of MHW over the study region. In this study the anomaly of more than 90 percentiles data were considered and multiplied with cumulative time period as per proposed methodology. This reveals the persistence of thermal stress over the time period. Further, the persistence of MHW is converted to percentage of MHW for better interpretation and analysis. It was recorded that the MHW was only 20% till first week of May and its gradually increases in subsequent weeks and peak MHW with greater than 60 % was observed during 1st week of Jun, 2010 in the northern parts of Andaman region.

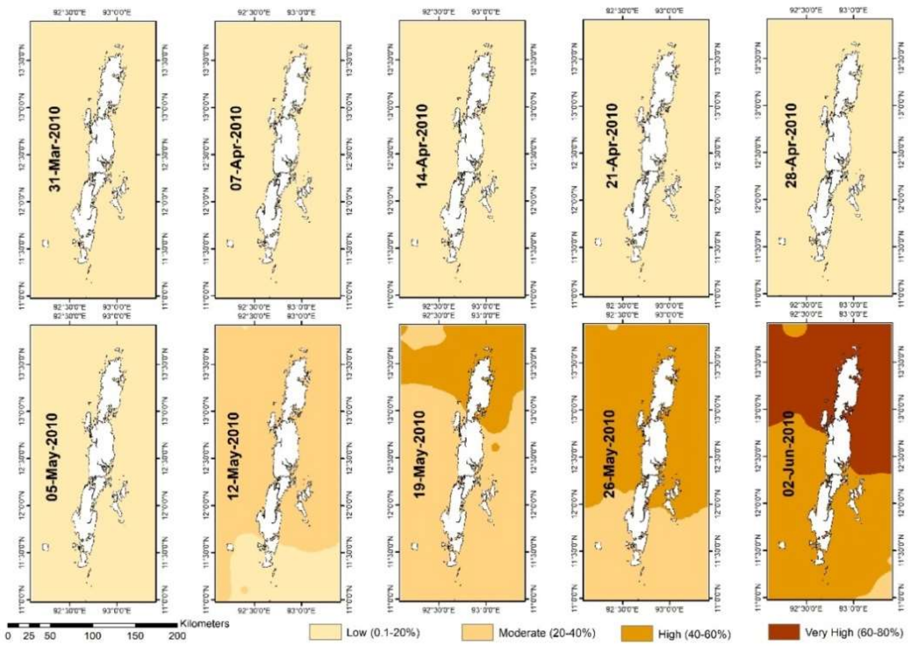

Figure 3: Showing the weekly variation of MHWs in (%) during Mar-June 2010

The following figure 4 showing the scatter plot of MHW against in-situ observed PCB. This plot was drawn in order to establish a linear relation between MHW and PCB. It is observed that the both parameters were significantly correlated with each other with R^2 =0.95 as shown in the figure 4.4, the dependent variables such as PCB can be calculate using coefficient and intercept of the equation with independent variable of MHW for understanding the spatial and temporal variability of PCB during Apr-June, 2010.

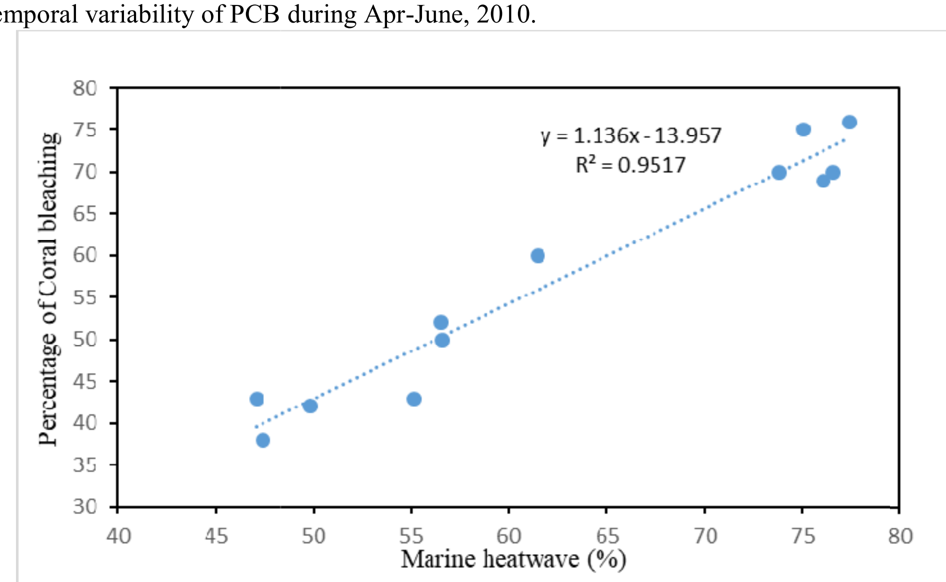

Figure 4: Scatter plot showing the Marine Heat Wave (MHW) plotted against observed percentage of Coral Bleaching (PCB).

Percentage of Coral Bleaching (PCB):-

The following figure 5 is showing the spatial distribution of PCB on a weekly average. It was observed that coral bleaching occurs along the entire coast of Andaman and its started from first week of May 2010 as much as 40-70% corals are found to have been bleached in the entire Andaman due to persisted very high SST during Apr-May 2010. The coral species found in middle and north region of Andaman *Acropora, Menulina, Pacillopora, Porites* and

*Pachyseris*are badly affected by this bleaching event (Sadhukhan and Raghunathan, 2012). The SST in Andaman coast was varied from 30-32.2°C during the study period with a peak temperature observed in May, 2010. This was led to widespread coral bleaching maximum up to 70% in the region (Krishnan et al. 2011)

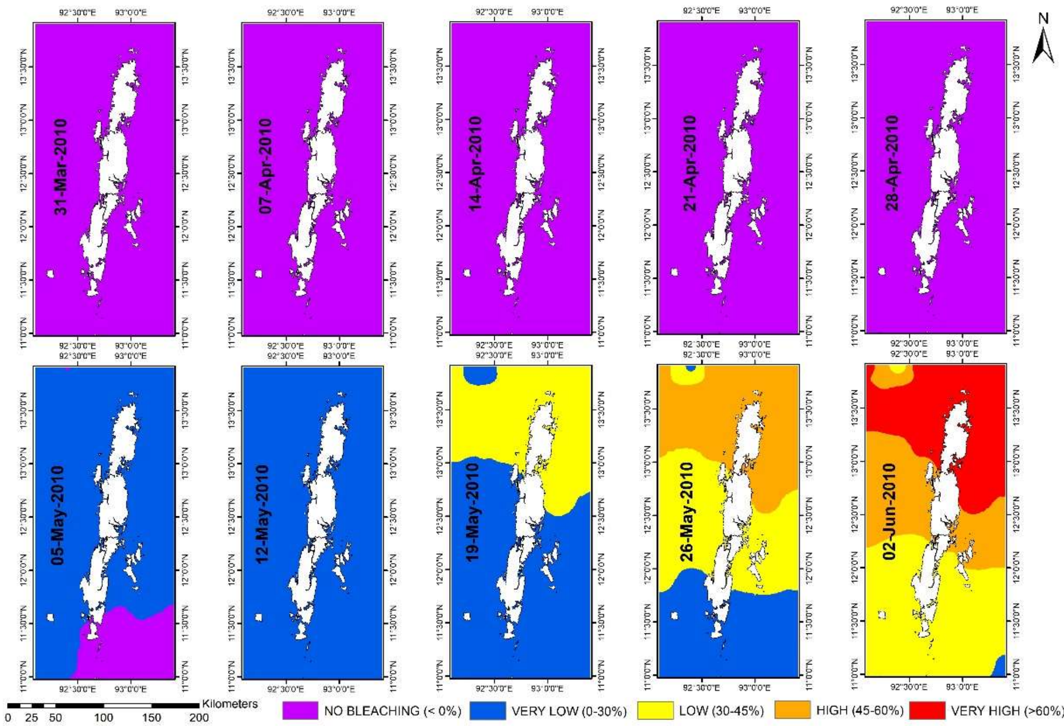

Figure 5: Showing the spatial distribution of Percentage of coral bleaching.

As per the PCB results, in the 1st weeks of May, bleaching was intensified and gradually increased. Therefore, the area of coral bleaching at multi-temporal period were extracted and plotted in the figure 6 it is observed that, the area of PCB increase with rising MHW. The results depicted that, at 1stweek of May 2010 more than 350 Sq.km. area was under (0-10%) bleaching and about 170 Sq.km area was unbleached. Subsequently, area PCB was increased and peak was observed on 29th may with more than 60% of bleaching around 150 Sq.km. and about 170 Sq.km of coral area was under 40-50% out of total 520 Sq.km.

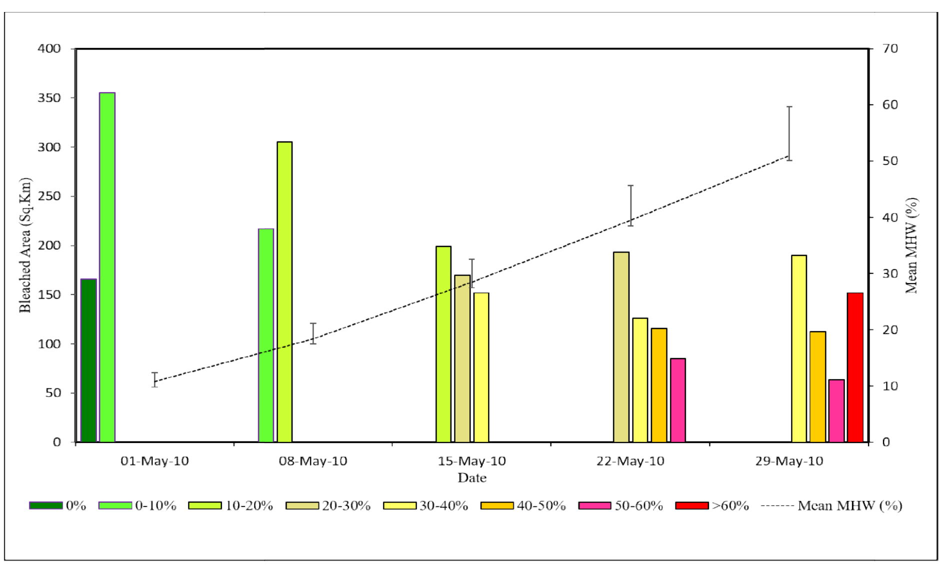

Figure 6: The line graph showing the Mean Marine Heat wave (%) overlay on percentage of coral bleach area (Sq.km) bar plot during study period

Spectral variations of different levels of PCB:-

The following figure 7(a)-(e) showing the spectral characteristics of different level of PCB for some selected points shows that the spectral signature varies for high, medium and low level of PCB. The spectral reflectance increases at Rrs412& 443 nm with increasing degree of MHW which leads to increase PCB. Whereas, it was recorded that reflectance inRrs531 relatively decrease with high PCB. The increased reflectance (Rrs) at 412 & 443 nm and absorption at 531nm might be due to the mortality of zooxanthellae by which chlorophyll decrease during bleaching period. Bleaching is characterized by a reduction in symbiotic algal density and photosynthetic pigments, leading to decreased absorption efficiency and enhanced reflectance due to increased light scattering from the underlying coral skeleton (Hill et al., 2004; Zhou et al., 2014; Terán et al., 2010). The current study observed that, the bleaching episode stated after 1st week of May 2010. Based on the spectral characteristics of Rrsduring bleaching period, ratio index of two contrasting spectral band i.e. 412 and 531 nm was used for further study to find out the threshold limits of coral bleaching.

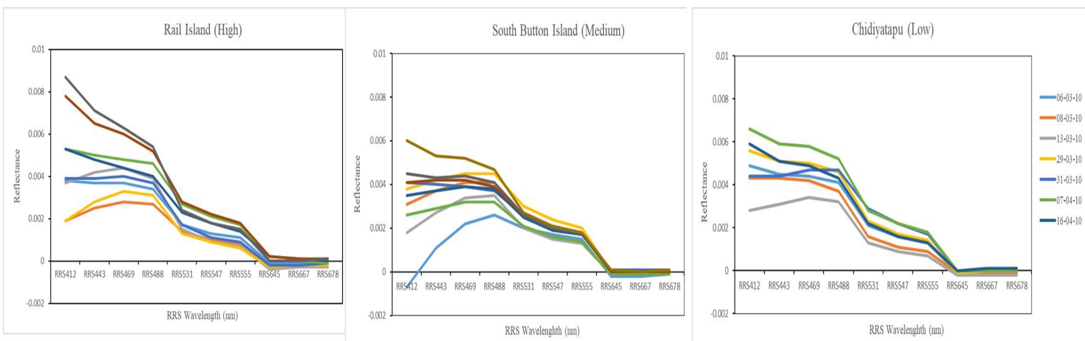

Figure7 (a), (b), (c), (d) and (e) showing the variation in spectral signature of different level of Coral Bleaching.

Our derived threshold of 2.5 for Rrs412/Rrs531 is higher than the 2.2 reported for Caribbean reefs (Andréfouët et al., 2002) but comparable to values from the central Pacific. This may reflect differences in coral pigmentation, water optical properties, or the severity of the 2010 bleaching event. Future intercalibration exercises across regions would improve global coral bleaching monitoring.The regression model (PCB = 1.36×MHW – 13.96) was derived from nine in-situ observations during a single bleaching event in 2010. Leave-one-out cross-validation gave an average R^2 of 0.89, suggesting moderate predictive skill. However, the small sample size limits generalizability. Additional in-situ data from multiple bleaching events and regions are needed to confirm the slope and intercept.

Conclusion:-

In the present study, we have concluded that the quantitative estimation of PCB using In-situ observations based on two approaches by establishing significant relation between (a) Marine Heat wave and Percentage of Bleaching, (b) Remote sensing Reflectance and Percentage of Coral bleaching. In prior approach, the PCB was calculated using linear fit relationship of coefficients 1.136 and intercept of -13.957 with 0.95 R^2 value, MHW as an independent parameter. In the case of later approach, spectral characteristic of PCB at different bands were assessed. The relatively amplitude of spectra at Rrs412 is showing high during the bleaching period. In contrast, lower spectral amplitude was observed at Rrs531. Hence ratio analysis was employed and threshold limit of ratio index (Rrs412/Rrs531) value is 2.5 for onset of coral bleaching.These two independent approaches are feasible to confirm the possible coral bleaching intensity and distribution. Hence these approaches can be operationally used for the coral bleaching alerts. This information is also useful for the coastal managers, researcher/climatologist and tourism. The continuous time series of intensively bleaching in-situ data and near ground spectral observation data during pre-post bleaching period can further improve the accuracy of PCB results. In summary, we present two independent approaches for quantifying coral bleaching percentage using MHW and spectral ratios. The regression model (R^2 = 0.95, LOOCV R^2 = 0.89) and the spectral threshold (2.5 ± 0.2) are promising but not yet operationally ready. We provide all code and data for reproducibility. Future work should focus on multi-event validation, uncertainty quantification, and regional calibration to support robust operational coral bleaching monitoring.

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