

30 **Introduction**

31 Corals are marine organisms belonging to invertebrate under the phylum
32 *Coelenterata* or *Cnidaria* and are primitive animals occurring in tropical waters in
33 the depth ranging from low tide to 200 metres of the oceans and seas. Coral reefs are
34 mainly composed of reef-building colonial animals (polyps) that live symbiotically
35 with the single celled microalgae (*zooxanthellae*) in their body tissue and secrete a
36 calcium carbonate skeleton. Coral reefs form an important ecosystem in the shallow
37 marine environment and provide habitat for many species. Healthy reefs contribute
38 to local economies through tourism. Diving tours, fishing trips, hotels, restaurants
39 and other business bases near reef system provide millions of jobs and contribute
40 billions of dollars all over the world (Banks et al., 2005, NMFS/NOAA, 2001). Coral
41 reefs also buffer adjacent shorelines from wave action and prevent erosion, property
42 damage and loss of life. Coral reefs have been identified as an endangered ecosystem
43 because they are subject to multiple natural and man-made stresses such as increase
44 in extreme sea surface temperatures, heavy sedimentation, eutrophication, and
45 thermal pollution (Glynn, 1996, Ixchel et al., 2012). However, in the last couple of
46 decades worldwide coral ecosystem have been degrading largely due to global
47 warming with anomalous rising temperature which leads to coral bleaching (Reaser,
48 Pomerance and Thomas, 2008, Sammarco, 2008, IPCC, 2001). Coral bleaching has
49 been one of the significant contributors to the increased deterioration of reef health.
50 Coral bleaching is a phenomenon that takes place when the symbiotic relationship
51 between algae (*zooxanthellae*) and their host corals breaks down under certain
52 environmental stresses. The overall shape of the spectral reflectance of coral reef at
53 different spectrum is determining by pigment (*zooxanthellae*) inside the coral
54 (Hochberg, Atkinson and Andréfouët, 2003, Call, Hardy and Wallin, 2003, Holden
55 and Ledrew, 1999, Lubin et al., 2001). The low values at blue and green wavelengths
56 are largely the result of absorption by photosynthetic and photo protective
57 compounds. Similarly, higher values at red wavelengths indicate a lack of absorption
58 or presence of active fluorescence (Hochberg, Atkinson and Andréfouët, 2003).
59 Hence the bleaching signature can be easily identified by using satellite Remote
60 sensing reflectance (R_{rs}) in synoptic level.

61 The continuous rising in Sea Surface Temperature (SST) leads to generation
62 Marine Heat Wave (MHW). It is defined as discrete prolonged anomalously warm

63 water even in a particular region (Zhang et al., 2017). The relative baseline
64 climatology is defined using all data with a 11 day composed window centred on the
65 time of year with a period of more than 10 years and then a high percentile threshold
66 (90th percentile) (Zhang et al., 2017) is used to obtain the threshold value. A
67 percentile threshold rather than an absolute value above the climatology is used since
68 the magnitude of SST variability varies by different regions. The “Prolonged MHW
69 events” means a MHW must last more than 5 days and “discrete” means two events
70 with a gap of 2 days or less will be considered as a continuous event (Zhang et al.,
71 2017).

72 Therefore, it is necessary to study the impact of thermal stress on coral reef,
73 their monitoring and assessment of coral bleaching over global synoptic view by
74 using satellite SST observation (Soloviev et al., 1994). In addition to this, the
75 spectral characteristics of bleached (Lubin et al., 2001, Hochberg, Atkinson and
76 Andréfouët, 2003) coral at different level were also assessed for quantitative
77 calculation of coral bleaching percentage. Hence, the main objective of the present
78 study is to calculate the spatial distribution of Coral Bleaching Percentage (CBP)
79 around the Andaman region by using persistence of Marine Heat Wave (MHW) and
80 established a relationship between spectral reflectance with respective intensity of
81 coral bleaching percentage.

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

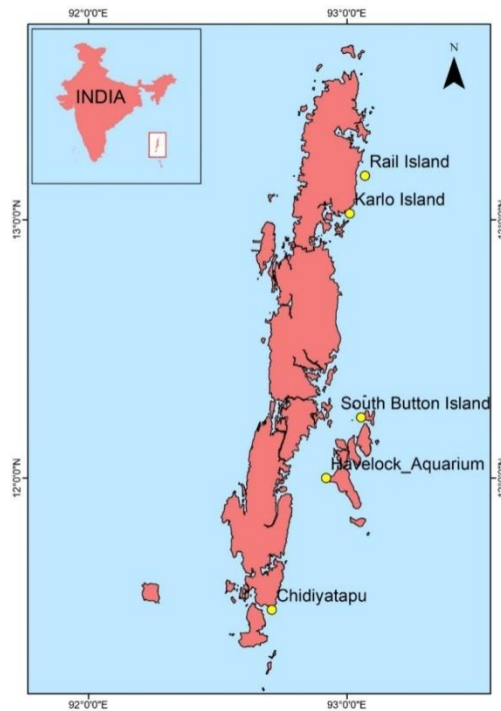


Figure 1: Location map of Study area overlaid with locations of Rrssampling points

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 [website https://incois.gov.in/site/services/coralwarning.jsp](https://incois.gov.in/site/services/coralwarning.jsp) and 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.

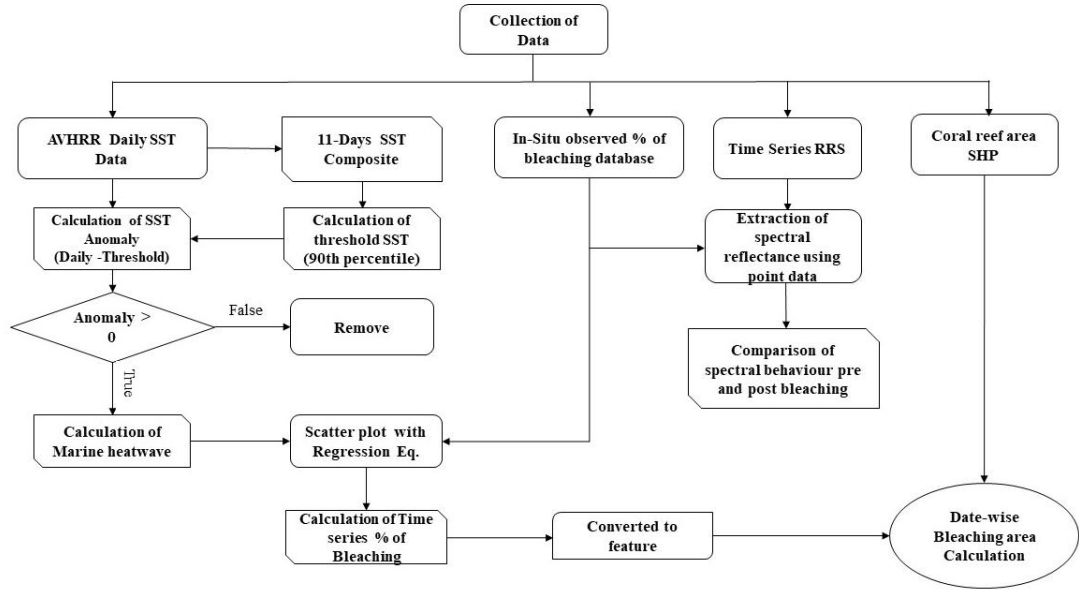


Figure 2: Methodology flow chart.

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

118 The persistence of MHW was calculated using cumulative sum of SST
119 anomaly with multiplicative time-series weightage factor. The maximum intensity of
120 MHW at the end of contiguous event was calculated to understand the spatial
121 distribution of MHW in percentage over the study period using Equation 1.

$$122 \quad MHW(\%) = (weightage * \Sigma preceding Anomalies) / 100 \quad (1)$$

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

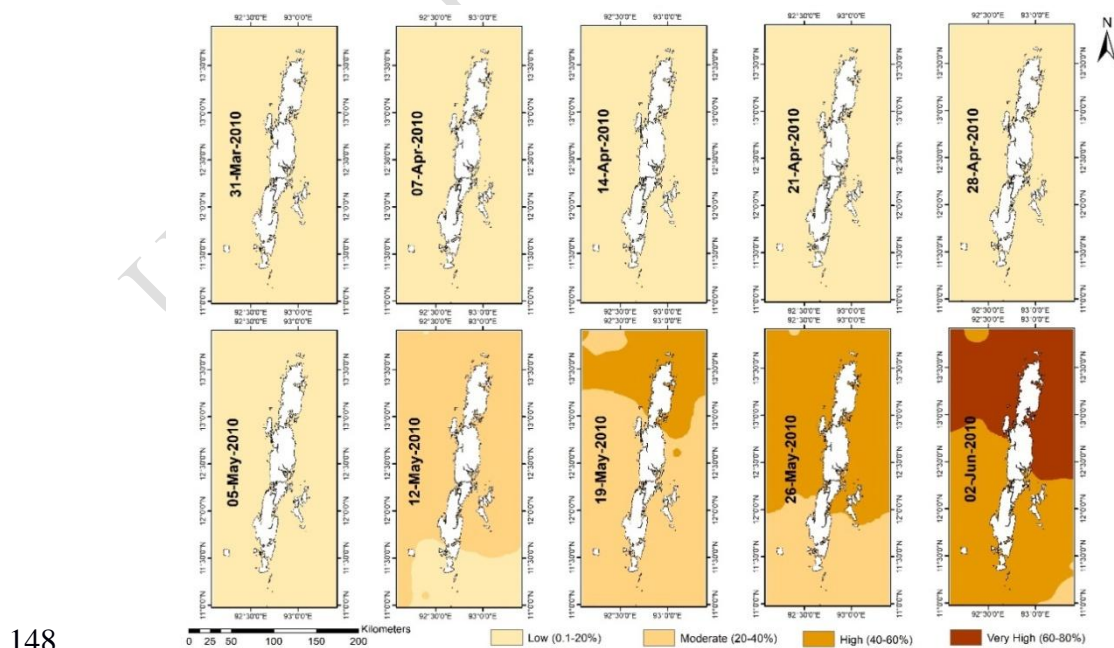
$$128 \quad PCB(\%) = 1.36 * MHW - 13.957 \quad (2)$$

129 The spectral characteristics of coral reef during pre/post-bleaching period also
 130 assessed to quantify the intensity of coral bleaching and there threshold limits of
 131 contrasting band ratio analysis. The daily Rrs412and Rrs531 nm band data at the
 132 different magnitude of PCB location were extracted and calculated ratio of both the
 133 band (Rrs412/Rrs531). These two bands can explain the contrasting spectral
 134 behaviour at pre/post coral bleaching period. Finally, established a relation between
 135 band ratio with PCB time series scattered plot to extract the particular threshold
 136 limits indicating the beginning of coral bleaching.

137 **Result and Discussion**

138 **Marine Heatwave (MHW)**

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



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

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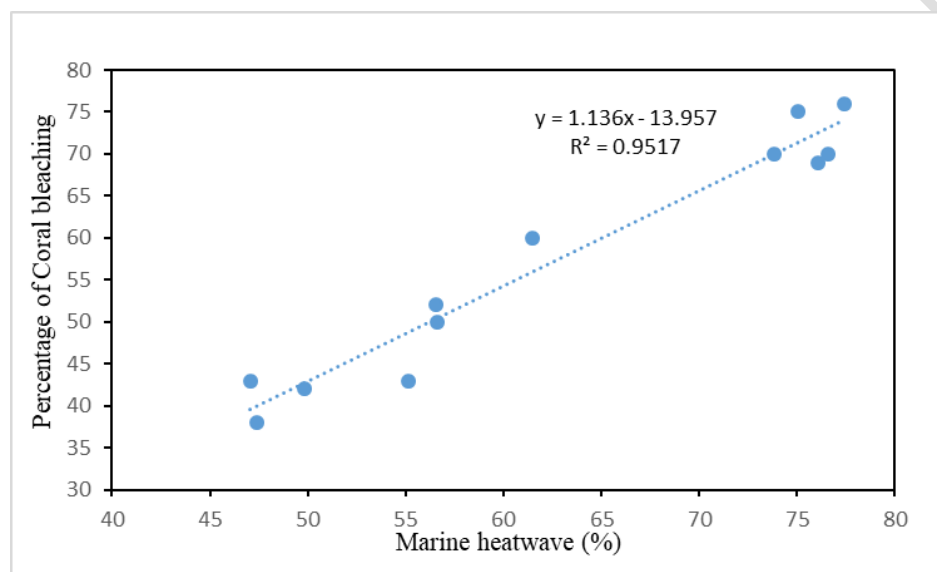
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The following figure 4 showing the scatter plot of MHW against in-situ observed PCB. This plot was drawn in order to establish a linear relation between MHW and PCB. It is observed that the both parameters were significantly correlated with each other 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.



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

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Percentage of Coral Bleaching (PCB)

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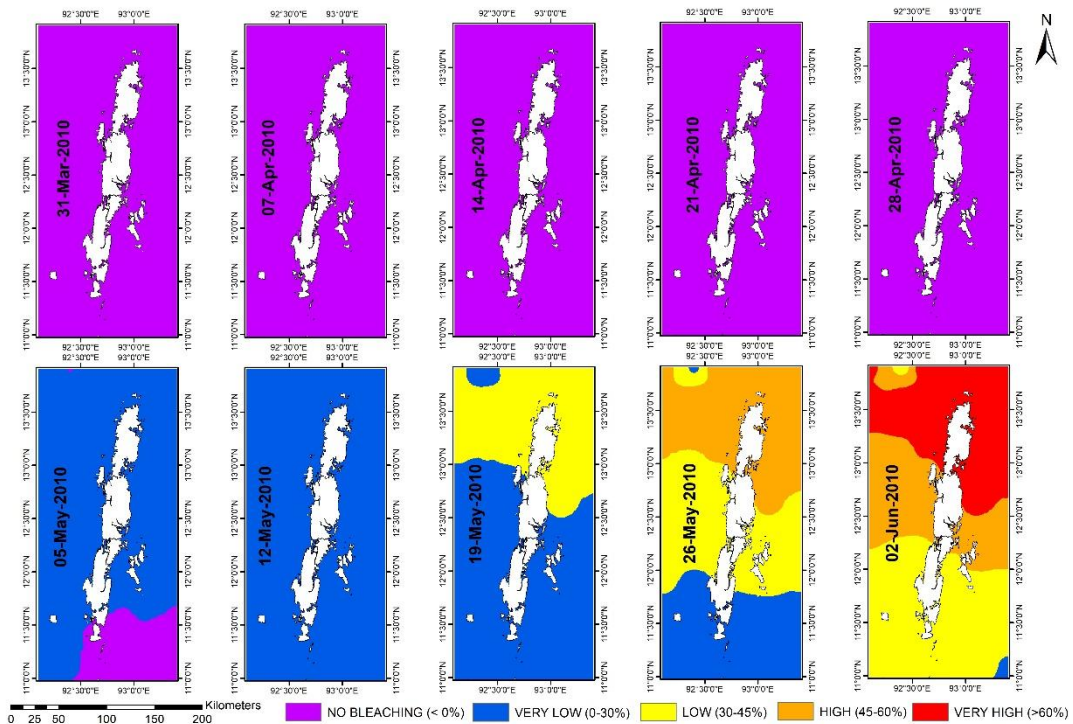
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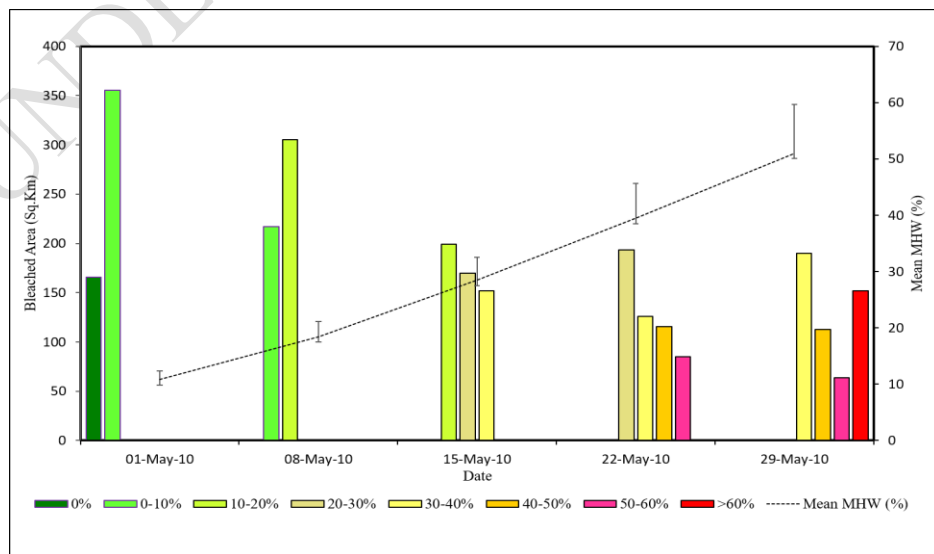
The following figure 5 is showing the spatial distribution of PCB on a weekly average. It was observed that coral bleaching occurs along the entire coast of Andaman and its started from first week of May 2010 as much as 40-70% corals are found to have been bleached in the entire Andaman due to persisted 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)



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

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

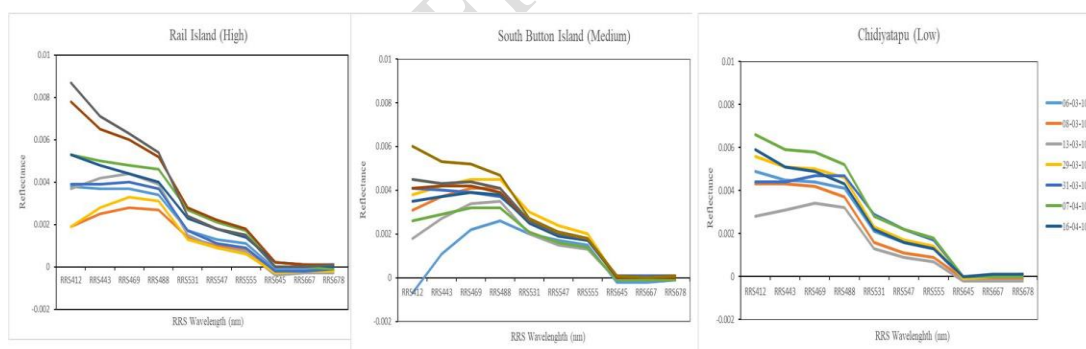


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183 *Figure 6: The line graph showing the Mean Marine Heat wave (%) overlay on percentage of coral*
184 *bleach area (Sq.km) bar plot during study period*

185 **Spectral variations of different levels of PCB**

186 The following figure 7(a)-(e) showing the spectral characteristics of different
187 level of PCB for some selected points shows that the spectral signature varies for
188 high, medium and low level of PCB. The spectral reflectance increases at Rrs412&
189 443 nm with increasing degree of MHW which leads to increase PCB. Whereas, it
190 was recorded that reflectance inRrs531 relatively decrease with high PCB. The
191 increased reflectance (Rrs) at 412 & 443 nm and absorption at 531nm might be due
192 to the mortality of zooxanthellae by which chlorophyll decrease during bleaching
193 period. Bleaching is characterized by a reduction in symbiotic algal density and
194 photosynthetic pigments, leading to decreased absorption efficiency and enhanced
195 reflectance due to increased light scattering from the underlying coral skeleton (Hill
196 et al., 2004; Zhou et al., 2014; Terán et al., 2010). The current study observed that,
197 the bleaching episode stated after 1st week of May 2010. Based on the spectral
198 characteristics of Rrsduring bleaching period, ratio index of two contrasting spectral
199 band i.e. 412 and 531 nm was used for further study to find out the threshold limits
200 of coral bleaching.



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

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206 **Conclusion**

207 In the present study, we have concluded that the quantitative estimation of
208 PCB using In-situ observations based on two approaches by establishing significant
209 relation between (a) Marine Heat wave and Percentage of Bleaching, (b) Remote

210 sensing Reflectance and Percentage of Coral bleaching. In prior approach, the PCB
211 was calculated using linear fit relationship of coefficients 1.136 and intercept of -
212 13.957 with 0.95 R^2 value, MHW as an independent parameter. In the case of later
213 approach, spectral characteristic of PCB at different bands were assessed. The
214 relatively amplitude of spectra at Rrs412 is showing high during the bleaching
215 period. In contrast, lower spectral amplitude was observed at Rrs531. Hence ratio
216 analysis was employed and threshold limit of ratio index (Rrs412/Rrs531) value is
217 2.5 for onset of coral bleaching.

218 These two independent approaches are feasible to confirm the possible coral
219 bleaching intensity and distribution. Hence these approaches can be operationally
220 used for the coral bleaching alerts. This information is also useful for the coastal
221 managers, researcher/climatologist and tourism. The continuous time series of
222 intensively bleaching in-situ data and near ground spectral observation data during
223 pre-post bleaching period can further improve the accuracy of PCB results.

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