Assessment of the coral bleaching during 2005 to decipher the thermal stress in the coral environs of the Andaman Islands using Remote Sensing

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Abstract
Sea Surface Temperature (SST) derived from the NOAA AVHRR satellite data were used to generate the Degree of Heating Weeks (DHW) and Hot Spot (HS) products. Combination of the cumulative temperature anomalies and the thermal stress studies were yielded to synoptically identify the probable areas of bleaching. The bleaching status of the Andaman region was assessed based on the DHW and HS for the bleaching event occurred in the Andaman region in April/May 2005. The bleaching status up to Alert Level-1 was recorded with the maximum HS of 3°C and DHW 6°C-week. Simultaneous in-situ reef observations conducted in the Andaman Sea confirmed the coral bleaching event. The maximum mortality in the region due to coral bleaching was shown by the Acropora species (43%) followed by Montipora species (22%) and Porites species (14%). This study focused on detection of coral bleaching warning based on the SST in compliment with the in-situ observations.
Keywords: Andaman Island, Hot Spot, degree of heating weeks, thermal stress, sea surface temperature.

Introduction
The coral reefs are massive biological set up in the coastal seas and have taken several millenniums to attain current form. However, during the last decade, worldwide coral reef ecosystems have been degrading at an alarming rate threatening the survival of these vital organisms. 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. This result in the host corals expelling their *zooxanthellae*. In the absence of symbiotic algae, the corals expose their white underlying calcium carbonate coral skeleton

and the affected coral colony becomes pale in color. Coral bleaching can be activated and persisted during varied environmental stresses. It was observed that massive coral bleaching occurred worldwide due to increased anomalous warm waters during recent years [Berkelmans and Willis, 1999; Andrews and Sankaran, 2002; Celliers and Schleyer, 2002; Bahuguna et al., 2008]. Coral bleaching takes place even at 1-2°C increase in ambient water temperature during summer months [Berkelmans and Willis, 1999; Reaser et al., 2000]. Prolonged partial/total bleaching events on coral environment can cause reef degradation and mortality. Stern bleaching events have striking long-term ecological and social impacts, which include extinction of reef-building corals, changes in benthic habitat, and changes in reef associated flora and fauna. It may take several years for severely bleached reefs to recover even favorable conditions prevail after the event. The importance of study of coral reef is the one of the well-known proxies of climate records providing indirect measurements of the physical and chemical characteristics of past environmental conditions and climate change [Wang et al., 2010].

There is a strong need for improved understanding, monitoring, and prediction of coral bleaching. The application of satellite remote sensing is an important tool to provide synoptic views of the global oceans in near-real-time for monitoring the global reef areas [Liu et al., 2003; Bahuguna et al., 2008; Mahendra et al., 2010]. Nocturnal Sea Surface Temperature (SST) is an important parameter to assess the thermal conditions and intensity of the bleaching. Globally, several remote sensing satellites have the ability to provide SST information during day and night routinely. This facilitates in the development of the coral reef bleaching warning system to generate early warning advisories/bulletins in near real-time. Earlier studies [Goreau and Hayes, 1994; Montgomery and Strong, 1995; Strong et al., 2004; Liu et al., 2005] were reflecting the impact of thermal stress on coral reef, their monitoring and assessment over global synoptic view.

The motivation of current study is to demonstrate and validate coral bleaching warning/prediction methodology based on the thermal stress. The parameters SST climatology, bleaching Hot Spot (HS) and Degree of Heating Week (DHW) were used for the study. These parameters generated using SST data with 5X5 km grid resolution retrieved from Advanced Very High Resolution Radiometer (AVHRR) sensor on-board National Oceanic and Atmospheric Administration (NOAA) satellites. In order to validate this approach, *in-situ* observations were carried out at Havelock Island, Andaman for the bleaching event occurred during April-May 2005.

Study Area

The study area Andaman Islands consist of very fragile Island ecosystems and some of the most pristine in the world. These ecosystems are very diverse and support very unique flora and fauna. These Island groups are a distinct eco region and are classified as one of the 12 bio-geographical zones of India [Rodgers and Panwar, 1988]. Andaman reefs consist of about 83% of maximum coral diversity found anywhere in the world and is equal to the "Coral Triangle" of Indonesia, and about 400 species could emerge after further surveys [Kulkarni, 2000; Vousden, 2000; Turner et al., 2001; Andrews and Sankaran, 2002; David and Olof, 2005; Roy et al., 2006]. Andaman falls under tropical climatic condition prevailing moderate temperature within the range of 23°C to 31°C. The geographical constraints of the study area are 11.0° to 13.6° N latitudes and 92.0° to 93.5° E longitudes as shown in Figure 1.
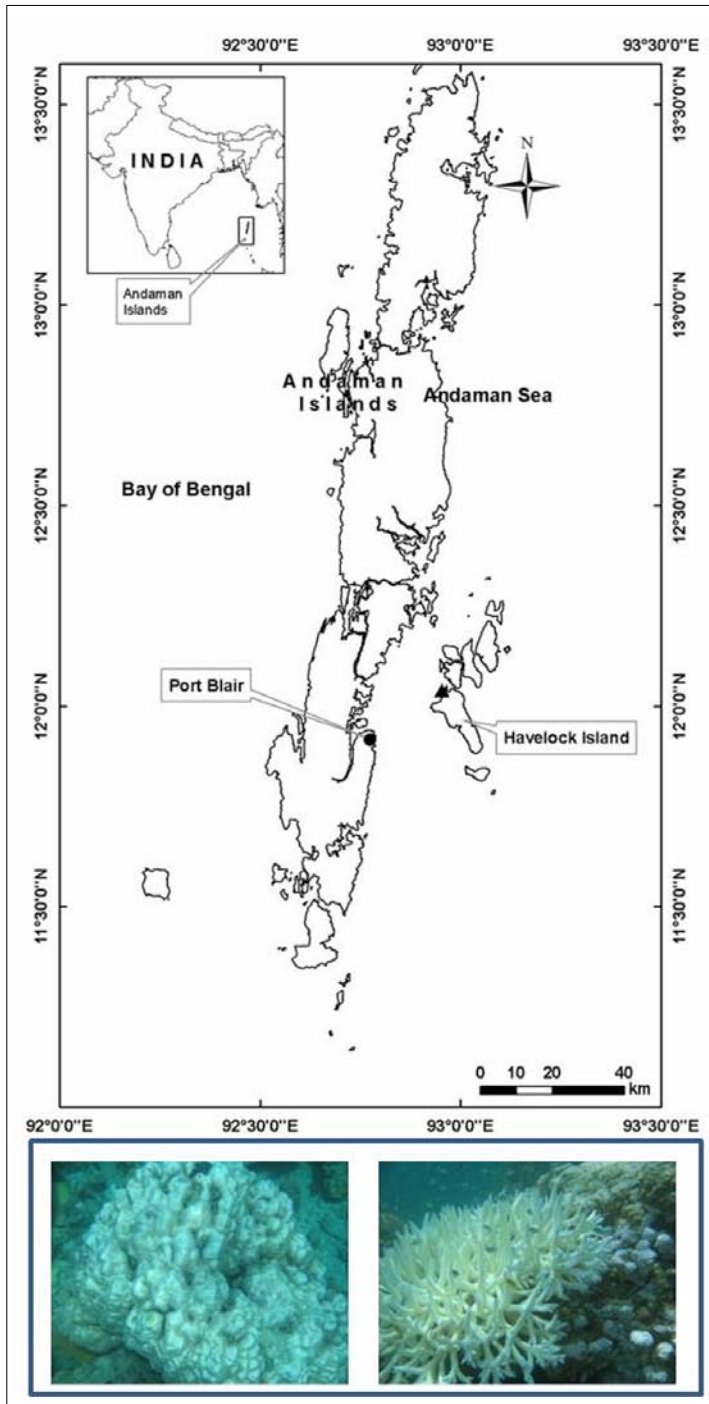
Figure 1 - Map showing the study area and the location of the in-situ sampling (triangle dot) in the Havelock Island (top). The field photos of the Havelock coast depicting the coral bleaching (bottom).

Data Used

Multi-channel Sea Surface Temperature (MCSST) data from NOAA, AVHRR Pathfinder version 5 was used in the current study. Daily nighttime SST data were used to assess the coral bleaching event occurred during April/May 2005 at Andaman area.

In-situ observations

The concurrent *in-situ* observations over the reefs at Havelock Island were carried out following the Line Intercept Transects (LIT) during 5th and 6th June 2005 [English et al., 1997]. *In-situ* observation was done in order to assess the percentage distribution of the eco-morphological classes of the coral reefs including the bleached corals. The length of transect was measured using the measuring tape and the different eco-morphological classes along these transects were recorded. The percentages of the species distribution as well as the bleaching status in different species were noted down.

The thermal stress on coral reefs around Andaman has been studied. The calculation of thermal stress based on NOAA coral reef watch [URL: coralreefwatch.nooa.gov]. According to Coral Reef Watch (CRW) the scheme of the coral reef bleaching warning levels is presented in the flow-chart (Fig. 2). The status of coral bleaching has been assessed in and around the coral reefs of Andaman using SST and *in-situ* parameters.

Methodology

Estimation of monthly maximum mean of SST climatology

The estimation of MMM of SST climatology was carried out using night time SST data retrieved from NOAA, AVHRR. Advanced Very High Resolution Radiometer (AVHRR) products are being generated by NOAA/NODC, the University of Miami and the NASA Jet Propulsion Laboratory at the California Institute of Technology. The Pathfinder processing uses a modified version of the non-linear sea surface temperature (NLSST) algorithm [Walton et al., 1998; Kilpatrick et al., 2001]. This include an improved atmospheric correction, superior cloud masking, and monthly recalculation of algorithm coefficients based on a match-up database of in situ SST measured from moored buoys and drifting buoys with an accuracy within 0.3 degrees Celsius. However, several previous validation studies of AVHRR SST with in-situ observation and TMI data were carried out [Shenoi, 1999; Qiu et al., 2009]. The Statistical analysis of AVHRR SST and match-up TMI (which is unbiased cloud radiance) was carried out in order to compare the data [Antoine et al., 2008]. The analysis shows that average absolute percent difference (RPD) and unbiased percent difference (UPD) are 5.311 % and 5.01% respectively.

The night time images are used to eliminate the effect of solar glare and reduce the variation in SST caused by the heating during day time. The daily night time SST data were used to generate monthly mean composites. Monthly SST climatology was calculated from 20 years of data during 1985-2004. Then a Maximum Monthly Mean is defined as the warmest monthly mean value for each pixel around the area.

HotSpot analysis

Corals are vulnerable to bleaching when the SST exceeds the temperatures they would normally experience in the hottest month. This reveal in the coral bleaching HS product, which highlights regions where the SST is currently warmer than the highest MMM of SST. The HS values lesser than or equal to zero were categorized as "No Stress" condition, the

HS value within the range of 0 to 1°C is categorized as "watch" and values above 1°C was a threshold for thermal stress leading to coral bleaching updated twice-weekly (Fig. 2). Coral bleaching HS is a measure of the occurrence of thermal stress above threshold limits leading to coral bleaching at a location. The HS anomaly is based on the climatological mean SST of the hottest month [Liu et al., 2003; Liu et al., 2005; Skirving, 2006]. The calculation of MMM SST climatology is the highest of the monthly mean SST climatology showing temperatures exceeding 1°C above the usual summertime maximum sufficient enough to cause stress on corals. Based on this study, MMM SST climatology was derived as a threshold for monitoring coral bleaching. The value of HS gives the difference between the measured near-real time SST and the MMM SST climatology as given in [1].

$$\text{Hot Spot}\ (°C) = \text{SST} - (\text{MMM SST Climatology})\ \ [1]$$

Only positive values derived as the HS are designed to depict the incidence and distribution of thermal stress responsible for coral bleaching.

Calculation of degree of heating week

Prolonged thermal stress resulted in coral bleaching. Therefore, it is assumed that the DHW product that sums up Hot Spots greater than 1°C recorded for 12 weeks will result in a stressful condition for coral reefs leading to bleaching. Thus, it is a cumulative measurement of the intensity and duration of thermal stress expressed in °C-weeks. The areas recorded DHWs up to 4°C-weeks depicts "Warning" status which will cause stress on corals. DHWs 4-8°C-weeks depicts the "Alert Level-1" and these have been shown to cause significant coral bleaching. The DHWs above 8°C-weeks depict the "Alert Level-2" and this can cause widespread bleaching (Fig. 2). While the coral bleaching Hot Spot provides an instantaneous measure of the thermal stress conducive to coral bleaching, there is evidence that corals are sensitive to an accumulation of thermal stress over time. In order to monitor this cumulative effect, a thermal stress index termed as Coral Bleaching Degree Heating Week (DHW) was developed [Liu et al., 2003; Liu et al., 2005]. Temperatures exceeding 1°C above the usual summer time maximum are sufficient to cause stress on corals [Glynn and D'Croz, 1990]. This is commonly known as the temperature threshold for coral bleaching.

A half-week approach is used in this study because near-real-time coral bleaching monitoring products are updated twice-weekly. With this approach, the DHWs are accumulated based on twice-weekly Hot Spots using [2].

$$\text{DHWs}\ (°C - week) = 0.5\ *\ \sum \text{preceding 24 bi - weekly Hot Spots}\ \ [2]$$

HS values more than or equal to 1°C-week required to be accumulated for the calculation of the DHW.

Assessment of thermal stress levels

The coral bleaching warning status was estimated based on the thermal stress levels using the threshold Hot Spot and DHW values (Fig. 2). The warning status categories "No Stress" and "Watch" were estimated using only Hot Spot values zero or less and more than zero

respectively. The categories Warning, Alert Level-1 and Alert Level-2 were estimated based on both Hot Spot and DHW. The warning status will be assessed as "Warning" when the conditions of Hot Spot => 1°C and 0<DHW<4°C-week were satisfied. The "Alert Level-1" was assessed when the conditions of Hot Spot => 1°C and 4<=DHW<8°C-week were satisfied. Whereas "Alert Level-2" was assessed when conditions of Hot Spot => 1°C and DHW >=8°C-week was satisfied. A DHW accumulation of 4°C-weeks triggers a significant bleaching which is Alert Level-1 and bleaching is expected at the site within a few weeks. An accumulation of 8°C-weeks triggers a strong bleaching with warning status Alert Level-2 causes widespread bleaching with severe coral mortality.
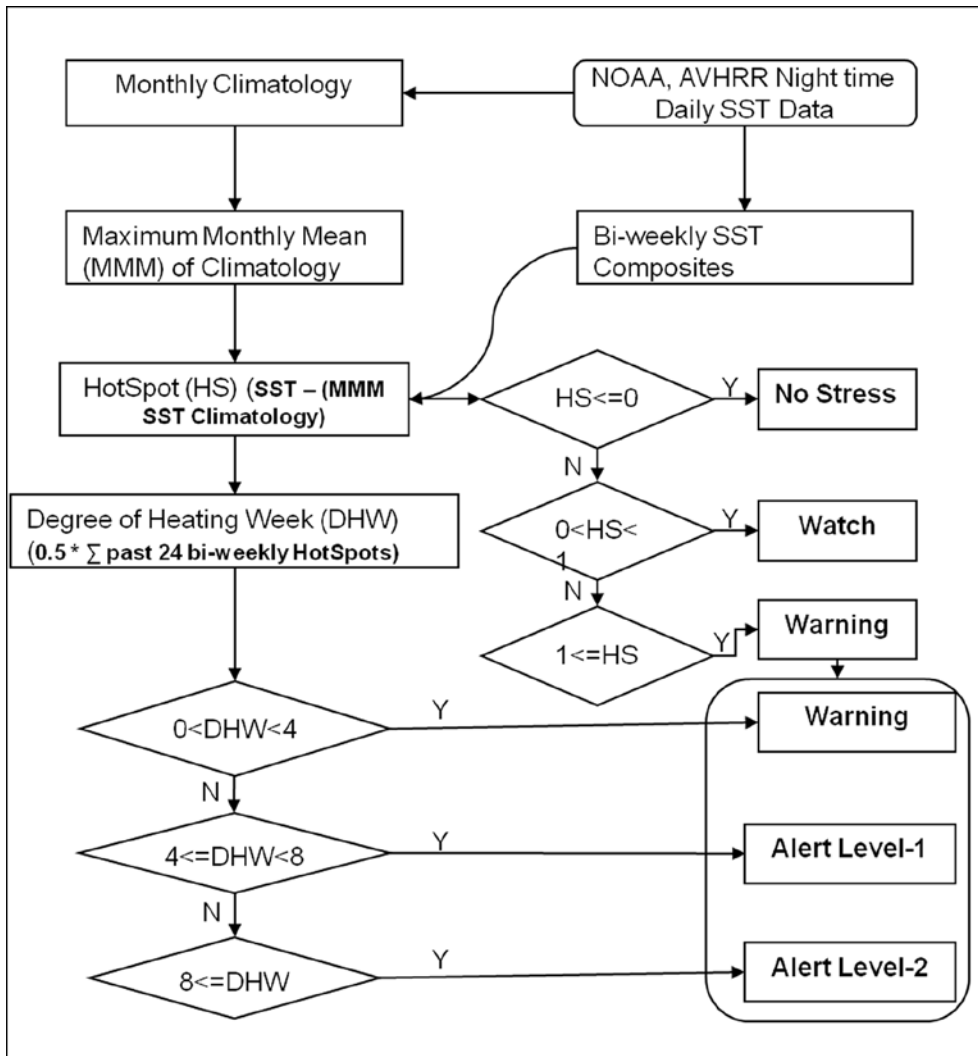

Figure 2 - Flow Chart depicting the methodology and the decision criteria for the coral bleaching status.

Results and Discussions

The climatology of MMM SST during the period of 1985 to 2004 is shown in Figure 3. It is depicting that the peak MMM was 29.78°C during April 2005 near the *in-situ* sampled location at Havelock Island. Therefore 29.78°C temperature can act as a threshold limit for coral reef at the current study point. Beyond this threshold temperature the corals will be under stress and get bleached if the higher temperature regime prolonged.
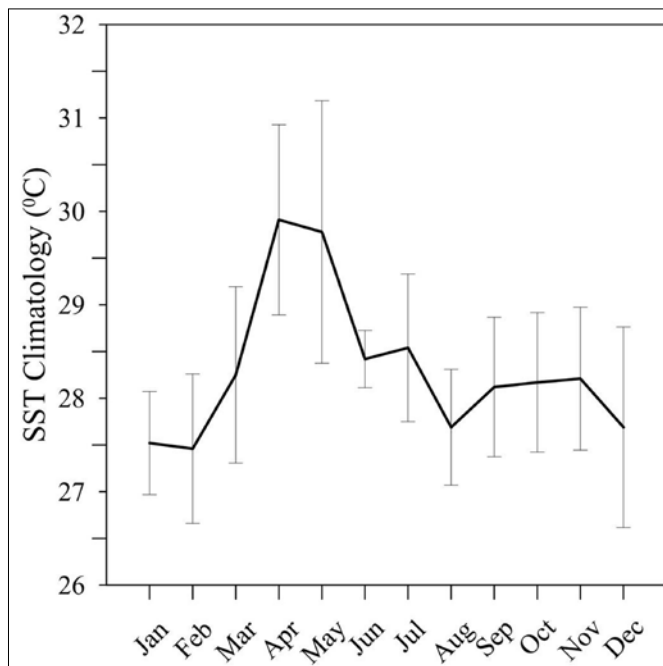

Figure 3 - Plot showing the maximum monthly mean SST climatology.

The Figure 4 is showing time-series measurements of HS, which shows the temperature above MMM SST climatology. It indicates that the temporal variation of HS trend during 28 January 2005 to 28 April 2005. Till April 4, 2005 the HS has shown values less than threshold limit, hence there was no thermal stress on corals. The watch status was recorded during 4-7th April, after 7th April the thermal stress reaches up to Hot Spot condition which indicates bleaching warning on coral reef. Earlier researchers observed that the bleaching stress occurs when the water temperatures exceed 1°C above the maximum mean summertime temperature [Glynn and D'Croz, 1990]. Therefore the Hot Spot starts from 7th April to 28 April.

The characteristics of the intraseasonal latent-heat flux variations in summer are highly vary when compared to winter [Zeng and Wang, 2009]. Comparison of the running average latent heat flux with HotSpot (Fig. 5) reveals decreased latent heat with increased HotSpot. This obvious tendency, however the transfer of the heat to atmosphere could be low. This leads to the increase of the water heat content along with the increased SST during the study period. This non-conducive condition of the overlaying heat content of the water column in the coral environ led to the coral bleaching.
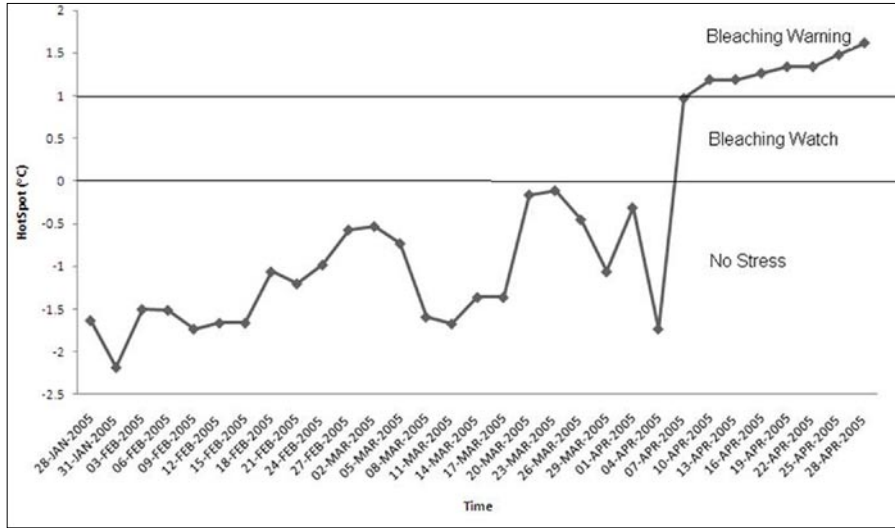
Figure 4 - Plot depicting the time-series bi-weekly HotSpot at Havelock Island (where *in-situ* sampling was done and bleaching recorded at 12.02 N Latitude and 92.96 E longitudes) shows the area was accumulated thermal stress with bleaching warning status after April 7, 2005.

Figure 5 - Trend line showing the running overage of HotSpot and Latent heat flux during the study period.

The Figure 6 is showing the spatial distribution of bi-weekly HS over study area during 7-28 April, 2005 where SST was warmer than the highest monthly mean SST climatology. The HS value of 1°C is set as threshold for thermal stress leading to coral bleaching. The values HS>=1 are significant enough to cause thermal stress on the coral reefs. But, some areas in the southern and northwestern parts recorded no stress with HS value less than 1°C. It depicted that the maximum areas attained HS condition during 25-28 April 2005 except some patches. However, the northeastern parts depicted very high values on 28th April with HS more than 2°C resulted in a warning that lead to bleaching. The time series HS measurement carried out near Havelock Island (star mark on Fig. 7) also depicted this condition.
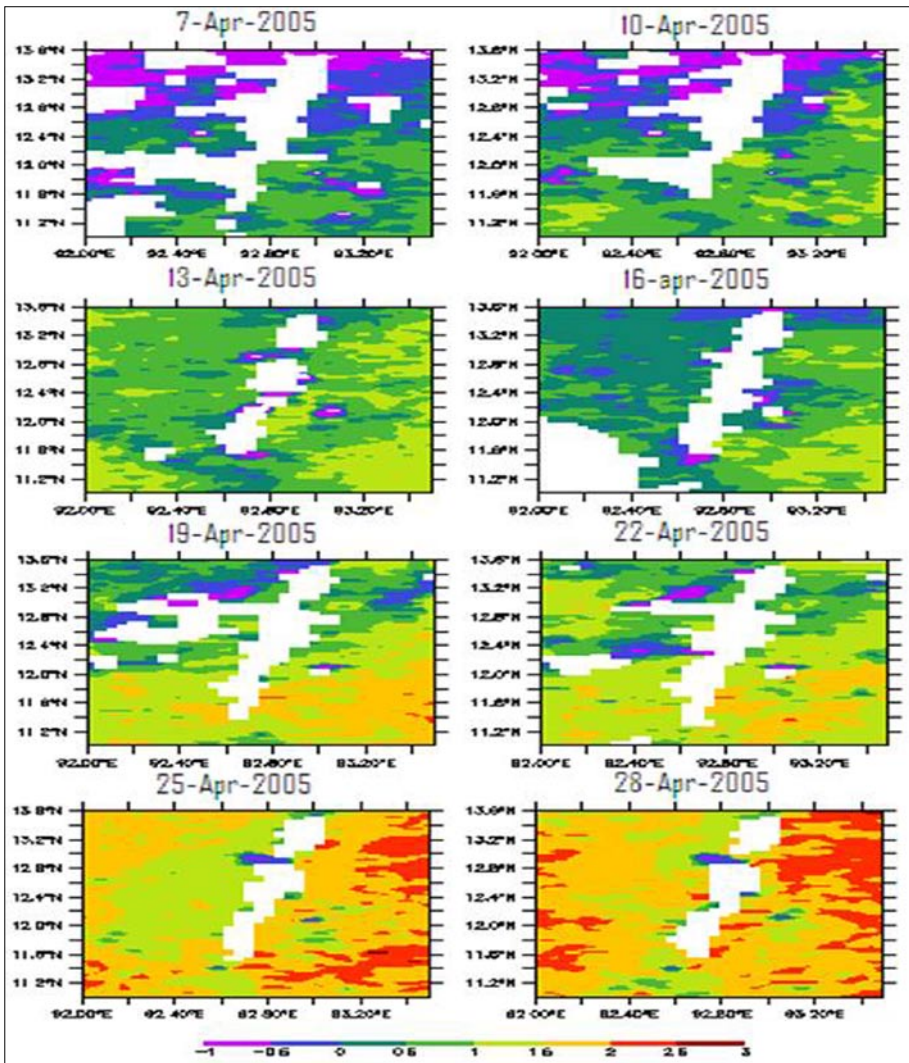

Figure 6 - Plate depicting the spatial distribution of the bi-weekly HotSpot images showing the HotSpot areas during 07-28 April, 2005 around the Andaman Island.

The degree of Heating Week (DHW) shown in Figure 7 reveal the status on the level of thermal stress on coral reefs in the study region, estimated based on the cumulative sum of bi-weekly HS values for preceding 3 months from April 28, 2005. It reflects that DHW values ranging from 0 to 4°C-Weeks depicts the areas under bleaching Warning. The DHW values in the range of 4-8°C-Weeks shows bleaching Alert Level-1 resulting in significant coral bleaching. The maximum DHW recorded here was up to 6.5°C-Week in the southeastern parts. However, DHW values were recorded up to 5°C-Week near the Havelock Island (Star mark in Fig. 7) where *in-situ* observations also reported bleaching.
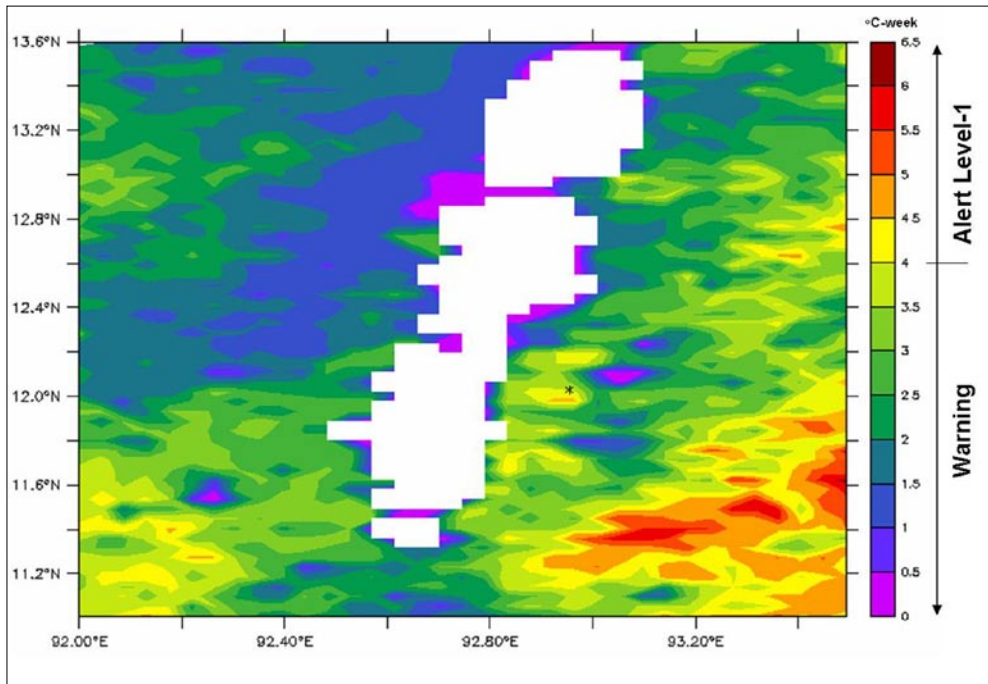

Figure 7 - Distribution of the DHWs around the Andaman Island depicted the warning and alert level-1 bleaching status. Star mark in the east of Andaman depicting the location of the Havelock Island.

The pie-chart (Fig. 8) shows the average transect distribution of percentage of average length observed along the coral reefs of the Havelock island (location Marked on Fig. 1) as different eco-morphological categories. The *in-situ* observations carried out on the coral reefs during 5-6 June 2005 was recorded dominantly with 25% of bleached coral categories, 25% sand and 24% reef flat. The completely bleached coral category contributes 19% of the recorded corals distributed along the reef flat (16%) and reef slope (3%) areas.

The analysis of the parameters estimated using SST derived from the NOAA AVHRR reveals the coral bleaching. Combined analysis of HS and DHWs indicate that the coral bleaching observed can be categorized as Alert Level-1. This was the condition potentially causing the partial to total coral bleaching which was confirmed from the *in-situ* observations in the study site at Havelock Island in Andaman. The corals in southeastern parts of the Andaman

Islands have experienced severe thermal stress resulted in the partial to total coral bleaching. The southwestern and northeastern parts of the Andaman also depicted the warning condition with "Warning" resulting in the partial bleaching and full bleaching. However the *in-situ* observations have shown that the individual species respond differently to this change in the thermal environment. The maximum mortality due to coral bleaching was shown by the *Acropora* species with 43%, *Montipora* species recorded 22% and *Porites* species 14% in the region. It was reported that the coral bleaching also took place in areas around Sri Lanka during March-May 2005 affecting the many *Acropora* species colonies [David and Olof, 2005]. Corals of this area were already suffering large degradation due to the tectonic effect of Sumathra Earthquake [Bahuguna et al., 2008] just before this bleaching event. The consecutive events within a short time span would have adverse effect on the coral eco-system to a great extent.
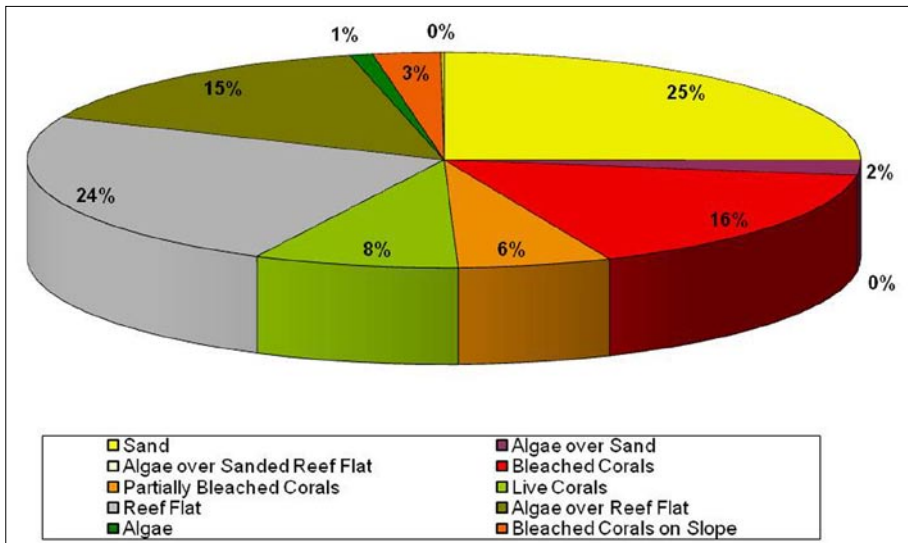

Figure 8 - Phi-chart presenting the distribution percentage of Eco-morphological classes and bleached corals observed along transects in the Havelock Island.

The status of the coral bleaching carried out in this study using HS, DHW and the *in-situ* observation give the accurate insight on the degradation of the spatial extent of corals. The methodology used here is capable of giving accurate warning at higher resolution on the probable areas of coral bleaching as well as the status of the bleaching level. Confirmation of *in-situ* observations on the mortality caused due to coral bleaching in the warning zones enhances the capability of the technique. The techniques and methods used for the study area Andaman Islands are capable of proving the accurate early warnings on the coral bleaching as well as the assessment of the damage.

The study further can be enhanced to access the spatial extent of damage by using the spectral signatures derived from high resolution optical remote sensing data. Further the study can be enhanced by using the high resolution SST data for improved results.

Acknowledgements

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