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Sea Surface Temperature Analysis for Predicting Coral Bleaching Induced by Thermal Stress for Hurghada Region Using AVHRR Satellite Imagery

S. Zakaria[1], B. Salem[2], K. El-Din[3], M. Selim[1]*

[1] Department of Marine Science, College of Science, Suez Canal University
[2] Department of Environmental Science, College of Science, Alexandria University
[3] Department of Oceanography, College of Science, Alexandria University

ABSTRACT

Coral reefs are vital ecosystems which are incredibly diverse and have a very important role in the marine life ecosystem. They are very sensitive to environmental change; one of the most threats to the coral reefs is thermal stress that could lead to coral bleaching and affects the coral ability to recover. The satellite approach solution is one of the important monitoring systems to predict thermal stress and possible coral bleaching alerts. The remote sensing approach uses Sea Surface Temperature (SST) derived from infrared observations collected by the Advanced Very High Resolution Radiometer (AVHRR) sensors from the NOAA polar orbiting satellites using the Multi-Channel Sea-Surface temperature (MCSST) algorithm. SST was computed for the study area on a daily basis along the year 2009 from 9km resolution AVHRR night images after scaling the byte digital number or DN values into the appropriate sea surface temperature and convert Pixel Coordinate to Latitude and Longitude positions. The Sea Surface Temperature Anomaly and Coral Bleaching Hot Spot and Coral Bleaching Degree Heating Week (DHW) were calculated to define regions of unusual elevated SST and the occurrence and magnitude of thermal stress as well as the accumulation of thermal stress over time in order to monitor the cumulative effect as a thermal stress index. Applying the remote sensing approach on Hurghada region showed a good primary indicator to be used for monitoring coral stress and predicting possible coral bleaching and coral resilience ability. The aim of the study was to introduce the satellite approach as an assessment process and a prediction tool of the thermal stress on the coral that could perform bleaching and that is an important key factor for providing accurate, economical and useful results for the preservation of the coral reef ecosystem

Keywords: Bleaching, Coral reef, Hurghada, Remote Sensing, Sea Surface Temperature.

INTRODUCTION

Coral reefs are vital ecosystems, providing a source of income, food and coastal protection for millions of people, and recent studies have shown that coral reef goods and services provide an annual net benefit of US$30 billion to economies worldwide (Cesar *et al.*, 2003). They are composed mainly of reef building corals "colonial animals" (polyps) that live symbiotically with the single celled microalgae (zooxanthellae) in their body tissue and secrete a calcium carbonate skeleton. Coral reefs are formed by hundreds of thousands of these polyps and are found in warm, shallow, clear and low-nutrient tropical and sub-tropical waters, with optimum temperatures of 25-29ºC, although they exist in ranges from 18ºC (Florida) to 33ºC (Persian Gulf) (Buddemeier and Wilkinson, 1994). They are incredibly diverse, covering only 0.2% of the ocean's floor but containing 25% of its species and they are often named the "tropical rainforests of the oceans" (Roberts, 2003).

Corals and coral reef ecosystems occur under a rather well defined set of environmental conditions which are mostly associated with shallow, continental shelf areas and island setting in tropical and subtropical regions. Maximum coral development requires clear transparent water, warm water temperature, full strength seawater, continual water circulation, absence of excessive suspended sediments and a suitable hard substrate (Borhan, 2000). As a result reefs and coral reef organisms are extremely sensitive to salinity change due to water inflow, waterborne sediments, pollutants, breakage caused by storms or boat anchoring, excessive nutrient loading and temperature extremes beyond the thermal limits of the coral (Borhan, 2000). Unfortunately, coral reefs are also among the most vulnerable ecosystems in the world. Disturbances such as bleaching, fishing, pollution, waste disposal, coastal development, sedimentation, SCUBA diving, anchor damage, predator outbreaks, invasive species and epidemic diseases have all acted synergistically to degrade coral reef health and resilience. Today, an estimated 20% of coral reefs worldwide have been destroyed, while 24% are in imminent danger and a further 26% are under longer term danger of collapse (Wilkinson, 2004 and 2008).

Coral bleaching is the whitening of corals, due to stress-induced expulsion or death of their symbiotic zooxanthellae (Dove and Hoegh-Guldberg, 2006). Abnormal levels of UV radiations, salinity, or concentrations of chemicals can all contribute to coral bleaching; however, the dominant causes for large scale bleaching is increased water temperature (Hoegh-Guldberg, 1999). Coral reef bleaching is a major scientific and environmental issue (Brown, 1997 and Glynn, 1993). Bleaching frequency has increased since the early 1980s, and a severe global bleaching event took place in 1997 and 1998 (Wilkinson, 2000). One possible reason for the increased frequency of bleaching might be related to high sea-surface temperatures (SST) caused by global warming (Hoegh-Guldberg, 1999).

* Corresponding Author*: mohamedbedir@hotmail.com*

Any coral bleaching prediction requires locating potential stressors, such as warm water as well as approximating the coral's reaction to that stressor. Present prediction models are based at least in part on SST which can be obtained remotely by satellite. This technique presumes that the stress caused by high temperature dominates any stress from irradiation and water speed. At the same time, the coral's reaction to the water temperature is assumed to be related to the upper range of water temperature observed in the sea (Bird, 2005). Since the late 1990s, large scale coral bleaching predictions have been possible through remote sensing. Areas of elevated temperatures identified from satellite images are used as a proxy for thermal stress of coral reefs. These patches of hot waters can be tracked in near real-time, and are generally referred to as "hot spots" (Goreau and Hayes, 1994). Warm water is only considered a spot when the mean-monthly summer temperature has been surpassed. Hot spots are limited to identifying the possible location and degree of thermal stress; however, they do not give an indication of the coral's reaction to the stress. The length of time that the coral is exposed to the water anomaly is crucial in determining the likely outcome. Corals can survive a brief period of hot temperature, but may bleach after a longer period of moderately elevated water temperature (Bird, 2005).

The aim of the study is to introduce the satellite approach as an assessment process and a prediction tool of the thermal stress on the coral that could perform bleaching.

MATERIALS AND METHODS

Study Area

The study was performed in Hurghada, a city in the Red Sea Governorate of Egypt which is a main tourist center in Egypt located on the Red Sea coast at latitude 27°15′28″N and longitude 33°48′42″E (Fig. 1). The overall risk assessment done in 2005 by Vanderstraete *et al.* (2005) shows the presence of a relatively broad, medium risk zone along the entire coastline north and south of Hurghada. In consequence, 86% of the coral reefs are under medium to high risk of being damaged by the negative impacts of human coastal activities. This is exceptionally high when compared to global or regional percentages.

SST Data Images

The Sea Surface Temperature (SST) was derived from infrared observations collected by the Advanced Very High Resolution Radiometer (AVHRR) sensors from the NOAA polar orbiting satellites. The AVHRR images resolution was 9km, and the timing of the images was night SST images to avoid the diurnal variations (Nardelli *et al.*, 2005). The SST images were downloaded and authorized from the PODAAC AVHRR Pathfinder homepage (http:// podaac. Jpl.nasa. gov/sst/). SST was computed using the Multi-Channel Sea Surface temperature (MCSST) algorithm developed

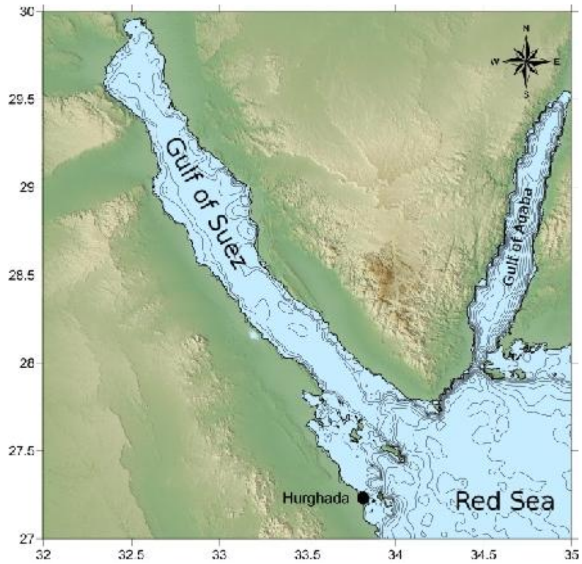

Figure (1): Map showing the North Red Sea and the Hurghada region.

by (McClain et al., 1985), the approximate root-mean square error of the AVHRR SST retrievals were of the order of 0.5°C (McClain *et al.*, 1983; Strong and McClain, 1984; Walton, 1988; Wick *et al.*, 1992). SST was computed for the study area along the year 2009 (from day 1to day 365 in the year of 2009).

Algorithms and Data Processing

Current retrieval algorithms for sea surface temperature from AVHRR are based largely upon the multi-channel sea-surface temperature (MCSST) algorithm (McClain *et al.*, 1985) which may be written as:

$$SST= \alpha_1 + \alpha_2 T_4 + \gamma (T_4 - T_5)$$

Where, "α_1" and "α_2" are constants determined through least-squares fit to in-situ data, T_4 and T_5, are brightness temperatures as derived from channels 4 and 5.

The term "γ" is a weighting factor based on the knowledge of known absorption coefficients (Emery *et al.*, 1994). In this form, the linear model has no correction for water vapour attenuation. A nonlinear SST algorithm (NLSST) was introduced that incorporates an initial estimate of the SST field, where the coefficients are calculated for different water vapour regimes as defined by ($T_4 - T_5$) differences. The form of the NLSST algorithm used to derive the SST becomes:

$$SST= \alpha_1 + \alpha_2 T_4 + \alpha_3 (T_4 - T_5) .T_{surf} + \alpha_4 (\sec(\theta)-1) (T_4 - T_5)$$

Where, the "α" are still coefficients based on a least squares fit to in-situ data and T4 and T5 are the brightness temperatures in channels 4 and5.

"θ" is the satellite scan angle or the incidence angle of the incoming radiation based on the horizontal plane of the satellite, and T_{surf} is a first guess sea surface temperature field; in this case the Reynolds optimally interpolated (OI) sea surface temperature data. A non-linearity in the algorithm arises because of the T_{surf} term and the 4 coefficients being calculated over two different (T_4 - T_5) differences. This form of algorithm was approved for reprocessing of the MCSST data by the AVHRR Oceans Science Working group because it tended to lower the overall bias over the widest possible environmental conditions (Podesta,. 1995). Nonlinearity arises from the coefficients being calculated over different water vapour regimes corresponding to (T_4 - T_5); the V1 algorithm calibration coefficients were calculated yearly for three different water vapour regimes or T_4-T_5 channel differences.

Sec (θ) is the secant of the satellite zenith angle which is the angle at the earth that connects between two points one on the earth and the other one at the satellite or the sun in degrees. The satellite zenith angle is computed using the following relation according to *Li et al.* (2001):

$$\text{Sin } \theta = (1+H/R) .\text{Sin } \alpha$$

Where H is the height of the satellite in km; R is the radius of the earth in km and α is the scan angle, which is also called the nadir angle is defined as the angle between the line connecting the satellite with the sub satellite point and a line connecting the satellite to a viewed spot on the earth in degrees. For AVHRR scans, the angle ranges from 0° to 55.4° (Li *et al.*, 2001). The scan angle α is computed using the following relation:

$$\sim = \frac{55.4}{N}\left|M - N\right|$$

Where M is any given spot number and N is the spot number of nadir.

All the algorithms used the non-linear SST algorithm (NLSST), developed and used operationally by NOAA/NESDIS.
(http://www.rsmas.miami.edu/groups/rrsl/pathfinder/Processing/proc_index.html) (Kilpatrick *et al.*, 1998).

Conversion of DN to SST and Pixel Coordinate to Latitude and Longitude

The files were daily images of sea surface temperature data. The HDF data were in the form of raster images, therefore the data were contained in byte arrays. Values ranged from 0 to a possible maximum of 255. Values of 0 referred to missing data or cloud cover. The format of the file of the study area consisted of a byte array of dimension 183 x 160 for a nominal 9 km spatial resolution data set. The byte digital number or DN values could then be scaled into the appropriate sea surface temperature by using the following y-intercept and slope values.

$$SST=0.15*DN-3.0$$

Where, SST is the degree in Celsius.

To convert from pixel coordinate to latitude and longitude, the conversion factor degree/pixel. Data was used gridded with respect to an origin at (180°West, 90°North).

The number of degrees per pixel was 360/4096. Using these values then dx=0.0878906 for the 9km data sets. The value of dx was then used in the equation to convert from pixel coordinate. The conversion then became:

$$\text{longitude} = (i-1)*dx.+x_1$$
$$\text{latitude} = y_1-(j-1)*dx$$

Where, i and j are the centered pixel locations in the x and y direction and (x_1, y_1) are the latitude, longitude of the first pixel. For 9m, x1=-179.956 and y1=89.956.

Sea Surface Temperature Anomaly

Sea Surface Temperature Anomaly was produced by subtracting the long-term mean SST calculated from several satellite images for a location in that time of year from the current value. A positive anomaly means that the current sea surface temperature is warmer than average, and a negative anomaly means it is cooler than average.

SST Anomaly = SST - (Daily SST climatology)

Sea Surface Temperature Anomaly makes it possible to quickly define regions of unusual elevated SST.

Coral Bleaching Hot Spot

Coral Bleaching Hot Spot is a measure of the occurrence and magnitude of thermal stress potentially conducive to coral bleaching for a location. It is an anomaly product, but not a typical climatological SST anomaly which is based on the average of all SSTs. The Hot Spot anomaly is based on the climatological mean SST of the hottest month (the maximum monthly mean (MMM SST climatology) (Liu *et al.*, 2003; Liu *et al.*, 2005 and Skirving*et al.*, 2006). This MMM SST climatology is simply the highest of the monthly mean SST climatology.

The Coral Bleaching Hot Spot became available in 1997 (Strong *et al.*, 1997) and the technique was developed based on the earlier work by Goreau and Hayes (1994). Glynn and D'Croz (1990) showed that temperatures exceeding 1°C above the usual summer time maximum are sufficient to cause stress on corals. Based on this study, MMM SST climatology was derived as a threshold for monitoring coral bleaching.

The value of Hotspot gives the difference between the measured global 0.5°C (50-km) near-real-time nighttime satellite SST analysis field and the MMM SST climatology:

Hotspot = SST - (MMM SST climatology)

Only positive values are derived, since the Hot Spot is designed to show the occurrence and distribution of thermal stress conducive to coral bleaching. The range of Hotspots is 0.0°C to +5.0°C, bleaching stress occurs when the water temperatures exceed 1.0°C above the maximum mean summer time temperature (Glynn and D'Croz, 1990).

Coral Bleaching Degree Heating Week (DHW)

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 the accumulation of thermal stress over time.

In order to monitor this cumulative effect, a thermal stress index called Coral Bleaching Degree Heating Week (DHW) was developed by Coral Reef Watch (CRW) in 2000 (Liu *et al.*, 2003 and Liu *et al.*, 2005).

Coral Bleaching DHW measures the accumulation of thermal stress that coral reefs have experienced over the past 12 weeks (3 months) and since the DHW is a 12 week accumulated Hot Spot, it is possible for a location to have a non-zero DHW value when the Hot Spot value is already less than 1°C and even 0°C. This condition simply means that there has been thermal stress at that location sometime over the last 3 months, but the local conditions are not currently stressful for corals. The exposure to the thermal stress previously may still have adverse impact on the corals, although recovery may be underway.

Liu (2003) determined that field observations indicated that there was a correlation with bleached corals when DHW values of 4°C-weeks have been reached. By the time DHW values reached 8°C-weeks, widespread bleaching was likely with some mortality (Liu *et al.*, 2003).

RESULTS

The SST images were processed for the North Red Sea with no effect of the cloud cover over the Hurghada region. After testing the image body temple, the image was found suitable to be included in the process and the SST was extracted for the study area along the year (Fig. 2).

By applying the coral bleaching thermal stress detection on the Hurghada area for the year 2009, SST was determined weekly from the SST images then the SST anomaly; coral bleaching hot spot and the bleaching degree heating week (DHW) were calculated.

The SST image showed that the SST of Hurghada ranged from 22°C to 29.9°C. The SST of highest range of temperature [29.5°C to 29.9°C] occurred between the last third of July (23/7/2009) to the last third of August (19/8/2009) (Fig. 3).

When the SST anomaly was computed along the year, two significant anomalies were discernible. The first was during the last week of July with an SST anomaly of 1.52°C and SST of 29.8°C and the second during the second week of November with an SST anomaly of 1.68°C and SST of 27.9°C (Fig. 4).

When the coral bleaching hot spot data was computed along the year, the results indicated a warning of coral bleaching possibility from the period of the end of the July to the end of August with a 1°C hot spot value (Fig. 5). Results of the bleaching degree heating weeks (DHW) along the year showed that there was a value equals to 1.5°C that appeared during August, September and October (Fig. 6). The current pattern showed that there was a continuous southward current flow of speed of 0.6 m/sec around the coral area.

The in-situ survey photos show the impact of thermal stress in some of coral colonies at El-Gouna site; it was noticeable that bleaching process started at the tips of the branches (Fig. 7).

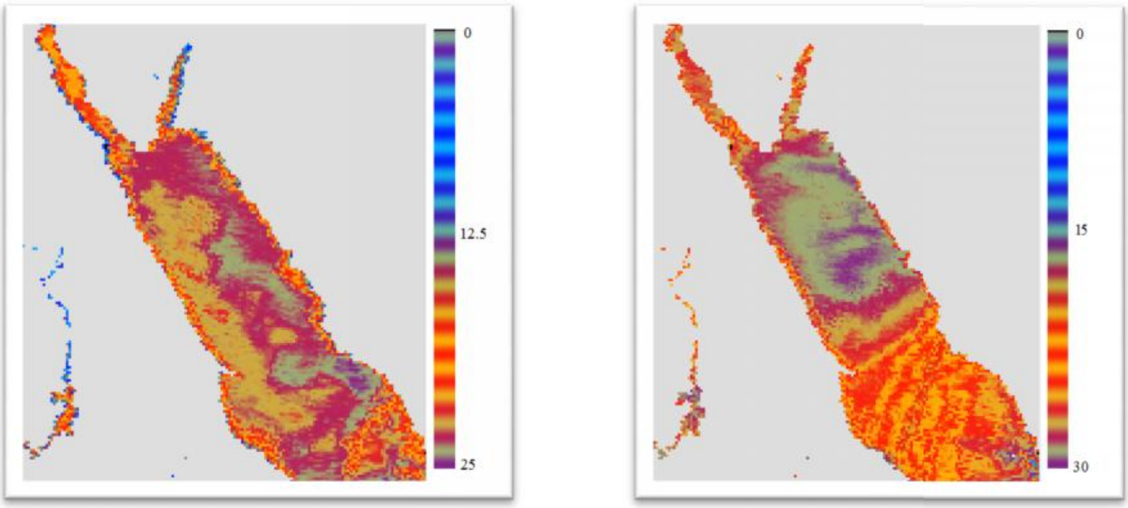

Figure (2): Example of the Distribution of Sea Surface Temperature (SST) extracted from AVHRR night images on day 4 “4/1/2009” (Left) and day 185 “4/7/2009” (Right).

Figure (3): Weekly mean sea surface temperature (SST) in degree centigrade extracted from AVHRR night images during 2009 for Hurghada.

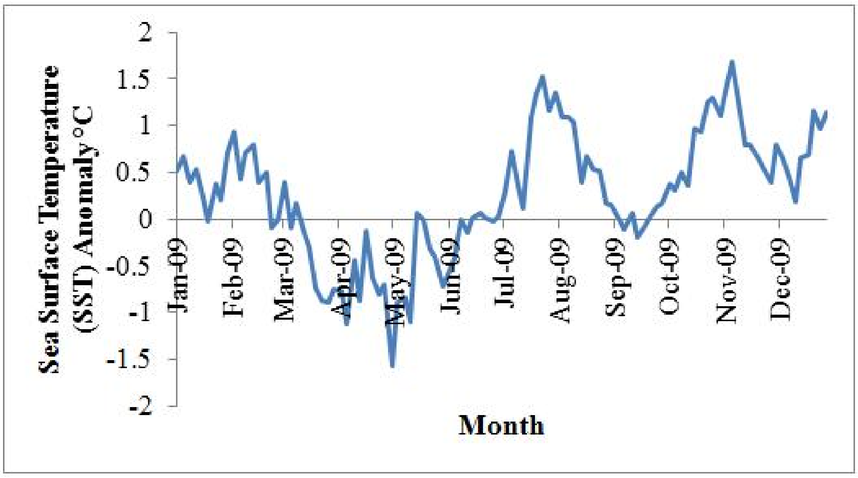

Figure (4): SST anomaly in degree centigrade calculated during 2009 for Hurghada.

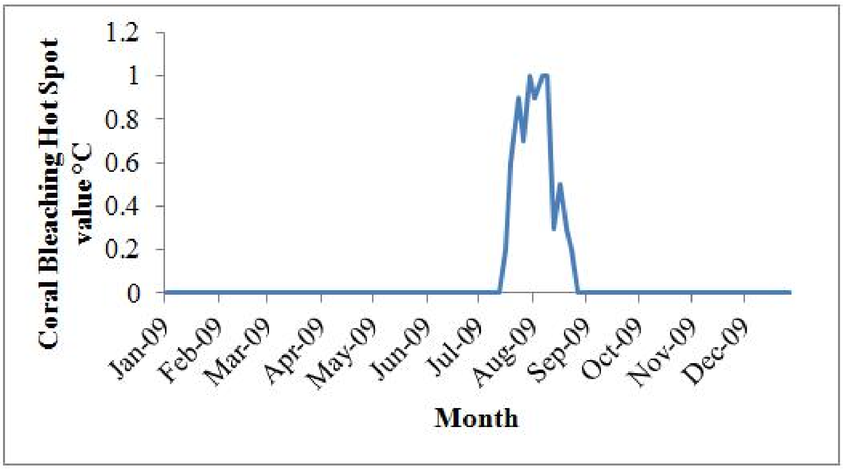

Figure (5): Coral bleaching hot spot in degree centigrade calculated for Hurghada during 2009.

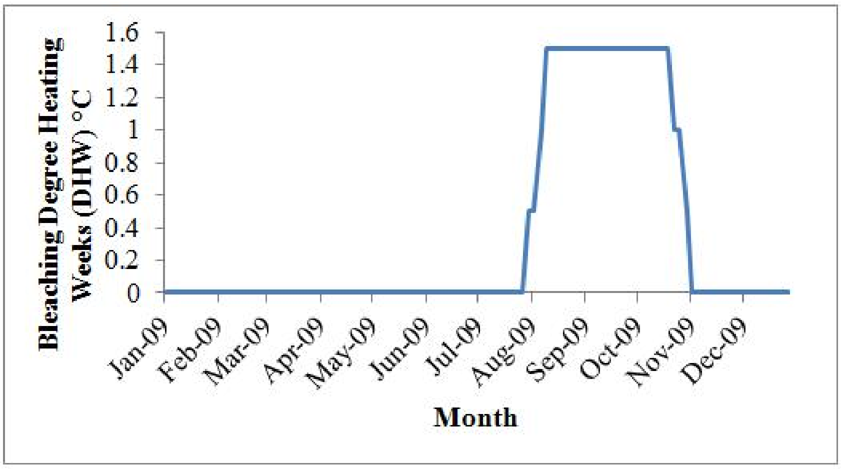

Figure (6): Bleaching degree heating weeks (DHW) in degree centigrade calculated for Hurghada during 2009.

(April, 2009) (August, 2009)

Figure (7): Bleaching in a coral colony at El-Gouna site (Hurghada) in 2009.

DISCUSSION

Corals live at the upper-limits of their thermal environment such as water temperature elevated by only one degree Celsius above the maximum monthly average in summer is considered to have reached a bleaching threshold (Goreau and Hayes, 1994). Prolonged exposure to "bleaching temperatures" will eventually kill the coral; however, if temperatures quickly return to normal levels, the coral have a chance to re-absorb the zooxanthellae and recover (Fitt *et al.*, 2001). Many studies have also emphasized the effect of solar radiation on coral bleaching (e.g. Coles and Brown, 2003; Lesser, 1996 and Mumby *et al.*, 2001), although it is unclear whether high irradiance acts independently of water temperature (Fitt *et al.*, 2001) or merely "aggravates the effect of temperature" (Hoegh-Guldberg, 1999). The idea that some patches of corals may be less susceptible to bleaching than other nearby patches is based on the considerable spatial variability observed in bleaching and bleaching-induced mortality.

Spatial variability in coral bleaching is well documented (Berkelmans*et al.*, 2004) and is observed between reefs, within reefs and even within single coral colonies. The processes that cause this variability can be broken into two groups, biological and physical.

Corals differ in their reaction to the stress causing the bleaching, branching corals such as *Acropora* are more prone to bleaching and temperature-induced mortality than the massive corals, such as *Porites* (Marshall and Baird, 2000).

In addition, mortality varies within the taxa. The most typical reaction to warm water is a combination of bleaching and mortality (McClanahan, 2004). Corals living in warmer, tropical water have a greater tolerance to high temperatures than the same species living in cooler, subtropical regions (Berkelmans, 2002).

Furthermore, corals that have survived a bleaching episode tend to be more resilient when faced with a subsequent thermal stress (Coles and Brown, 2003). An accurate bleaching prediction requires information regarding its location, species composition, bleaching history as well as the location and intensity of the stress itself. Unlike the biological approach which focuses on the coral's reaction to stress, the physical approach investigates where stress is located. The main stressors associated with mass coral bleaching are elevated temperature, increased irradiance and slow water movement (Bird, 2005). Temperatures can vary significantly over small distances. Solar radiation increases water temperatures; therefore, any spatial patterns of irradiance may also lead to similar spatial patterns of elevated temperatures.

Coral bleaching is a serious threat to the health of reefs around the world. The link between global warming and mass-coral bleaching is now considered (Hughes *et al.*, 2003). While ocean heating is a global problem, using the remote sensing approach by using the SST and calculating hot spot value and DHW are presently a primary tool to detect where and when reef bleaching events are likely to occur as a first step to solving the problem.

The research data indicated a possible threat of bleaching that could occur at the end of July and the month of August. On the other hand, the DHW values showed a continuous increase of temperature by 1.5°C in three months (August, September and October). The temperature increased by 1°C in August, 0.25°C in September and 0.25°C in October and the occurrence of a continuous current with a 0.6m/sec speed in the area in that season may be reduced the chance of the bleaching danger.

By comparing this result to the Coral Reef Watch station data in Hurghada and the in-situ survey images, it was evident that the station gave a bleaching warning in 25/7/2009 and in 10/8/2009 and the in-situ images showed a noticeable bleaching process started at the tips of the branches in August, which was compatible with the result of the SST coral bleaching prediction.

Results from Hurghada applied example showed a compatibility with the results of the coral reef watch Hurghada station and the in-situ images, and thisdemonstrated that using the satellite approach in predicting the bleaching is a key factor for providing accurate, economical and useful results for the efficient preservation of the coral reef environment.

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تحليل درجة حرارة المياه السطحية لتوقع إبيضاض الشعاب المرجانية نتيجة الإجهاد الحراري عن طريق صور الأقمار الصناعية لمنطقة الغردقة AVHRR

سعد زكريا[١]، بشرى سالم[٢]، خالد علم الدين[٣]، محمد سليم[١]

[١] قسم علوم البحار، كلية العلوم، جامعة قناة السويس
[٢] قسم علوم البيئة، كلية العلوم، جامعة الأسكندرية
[٣] قسم علوم البحار، كلية العلوم، جامعة الأسكندرية

الملخـــص العربـــي

تعتبر الشعاب المرجانية من النظم البيئية الهامة لتنوعها ولأهميتها لباقي النظم البحرية البيئية الأخرى. كما تعد حساسة جداً للتغييرات البيئية خاصة تأثير إجهاد إزدياد الحرارة الذى يمكن أن يؤدى إلى إبيضاض الشعاب ويؤثر على كفاءة تجددها. تقدم تقنية الإستشعار عن بعد واحد من أهم الحلول لمراقبة وتوقع إجهاد الإزدياد الحرارى ويعطى إنذار مبكر للأماكن والأوقات التي يمكن حدوث فيها إبيضاض للشعاب. يعتمد نهج الإستشعار عن بعد في هذه الدراسة على إستخدم صور الأقمار الصناعية مختارة يومية ليلية (SST, NOAA-AVHRR) تحتوي على منطقة الدراسة و يتم حساب درجة الحرارة السطحية لمياه البحر(SST) بإستخدام نهج درجة الحرارة السطحية في القنوات الرقمية المختلفة (Multi-Channel Sea-Surface Temperature "MCSST").

تم حساب درجة الحرارة السطحية لمياه البحر عند منطقة الدراسة من الصور اليومية الليلية لسنة ٢٠٠٩ بدقة ٩ كم بعد تحويليها من البايت الرقمي (Digital Number "DN") لقيم درجات حرارة تمثل حرارة سطح المياه و تحويل أماكن النقط الرقمية إلى إحداثيات طول وعرض، بعد ذلك يتم حساب الشذوذ الحرارى لدرجات حرارة سطح المياه (Sea-Surface Anomaly) والنقاط الساخنة (Hot Spot)، ودليل درجة الإحترارالمؤدى للإبيضاض (DHW) لمنطقة الدراسة طول العام لتعريف الأماكن الأكثر عرضة لإرتفاع درجة الحرارة والإجهاد الحرارى و التي يمكن أن تتعرض لإبيضاض الشعب المرجانية. وأظهر تطبيق تنبؤ إبيضاض للشعب المرجانية في منطقة الغردقة توافق مع نتيجة محطة رصد (Coral Reef Watch) بالمنطقة.