MONITORING CORAL BLEACHING BY SATELLITE THERMAL PRODUCTS: A CASE STUDY IN THE SOUTHERN EAST SEA, VIETNAM

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ABSTRACT

Since thermal stress is marked as an essential cause of coral bleaching, monitoring thermal anomalies of seawater has become an imperative need. The U.S. National Oceanic and Atmospheric Administration (NOAA) developed methods to predict bleaching based on the sea surface temperature (SST) achieved from satellite images. However, the predictions usually underestimate at local and regional scales due to the low spatial resolution (50 km). As a contribution to improve prediction of coral bleaching in the southern East Sea, my research examined SST derived from higher spatial resolution products (4 km), including the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS). Two parameters, HotSpot and Degree Heating Week (DHW) were applied to describe thermal stress in historical bleaching years at two archipelagos in Vietnam, Con Dao and Phu Quoc. The major findings include: (1) SST climatology data revealed that SST in the southwest sea is approximately 1^0C higher than SST in the southeast sea. That difference explained the phenomenon of fewer bleaching events at Phu Quoc than at Con Dao because coral living in different temperature conditions can have different bleaching thresholds. (2) Coral reefs at the study area suffered a severe thermal stress in 2010 with longer duration and higher DHW value than in 1998 and 2005. (3) The application of 4 km spatial resolution data prevented underestimating thermal anomaly than with the 50 km resolution data.

1. INTRODUCTION

1.1. Coral bleaching and Monitoring coral bleaching by sea surface temperature

Coral reefs are underwater structures formed by colonies of thousands tiny stony corals called polyps, living in a symbiotic relationship with microscopic algae known as zooxanthellae. Healthy reefs are seen as yellow or brownish colour due to the photosynthetic pigments of their symbiotic algae. If corals lose their zooxanthellae, the concentration of photosynthetic pigments declines, the living coral tissues become pale and the white of the skeleton underneath becomes visible. This phenomenon is usually described as coral bleaching. Even though corals are able to catch prey and feed themselves, most of them will be starved and weaken without their zooxanthellae. Bleached corals often die if the stress persists and reefs suffering severe mortality following bleaching can take many years or decades to recover. Although causes of bleaching may be various and complicated, most scientists emphasized high sea temperature as the primary cause of mass bleaching events, particularly at regional and global scales (Glynn 1996, Brown 1997). Observations and experiments also recognized that corals begin to bleach when sea temperature exceeded one to two degrees Celsius above the highest summer temperature, called the Maximum Monthly Mean (MMM) (Berkelmans and Willis 1999, CRW 2011). Therefore, monitoring sea temperature is able to assess coral health. Since remote sensing is the most effective means of acquiring global and continuous surface temperature, the NOAA's Coral Reef Watch (CRW) program utilizes the near-real-time SST derived from the Advanced Very High Resolution Radiometer (AVHRR) at 50 km spatial resolution to monitor thermal conditions associate to coral bleaching around the globe. In commonly recognized products, the potential bleaching is identified by Degree Heating Week (DHW) and HotSpot value (Strong *et al.* 2006, CRW 2011). However, the CRW products were criticized as less successful in detecting severe bleaching conditions at local scales because of their use of a constant thermal threshold and low spatial resolution (Weeks *et al.* 2008). To improve the prediction of coral bleaching in the southern East Sea, my research explored the higher spatial resolution products (4km), including the AVHRR and the Moderate Resolution Imaging Spectroradiometer (MODIS) to examine thermal stress in historical bleaching years at Con Dao and Phu Quoc archipelagos of Vietnam.

1.2. Coral bleaching at Con Dao and Phu Quoc, Vietnam

Con Dao archipelago, located in the south-eastern waters of Vietnam was the best protected reefs in Vietnam with the average reef cover higher than 50%. However, the typhoon *Linda* in November 1997 and the bleaching event in summer 1998 destroyed a large area of coral reefs at Con Dao (Vo *et al.* 2005). After those events, coral reefs recovered very slowly. In October 2005, bleaching was observed in the North-East of the archipelago while there was no bleaching observed in the South-East (Hoang *et al.* 2008). In 2010, thermal observation for Con Dao, published by the NOAA CRW, predicted that a severe bleaching would occur in July 2010 due to the prolonged thermal stress. However, the ground data regarding the bleaching in 2010 at this archipelago have not been reported. Similarly, Phu Quoc, located in the gulf of Thailand, is recognized as significant biodiversity and fisheries areas of Vietnam. In Phu Quoc, reefs occupy in the shallow waters of the South (An Thoi) and the North-West (Ghenh Dau, Cua Can) (Vo *et al.* 2005). Status of reefs at those sites ranges from good to severe impact by destructive and over fishing. The newest observation (unpublished) conducted by the Oceanography Institute of Vietnam in May and August, 2010 reported that coral bleaching was observed at most reefs of Phu Quoc due to the thermal anomalies in 2010.

2. MATERIALS AND METHODS

In this research, the monthly SST "climatology" data which represent the stable thermal characteristic of the southern East Sea were produced from the AVHRR Pathfinder (PF) Level 3 Monthly Night-time SST Version 5, available from 1985 to 2009. The night-time SST data were used to prevent the non-representative noise caused by intense day-time solar heating of the upper sea surface ''skin'' (Haines *et al.* 2007, Weeks *et al.* 2008). Since the AVHRR data are available until 2009, the AVHRR PF Level 3 8 Day Night-time SST Version 5 products were used to examine the thermal stress occurring in 1998 and 2005, and the MODIS Aqua Level 3 SST Thermal 8 Days Night-time were used for 2010. The raw data derived from AVHRR and MODIS validated with the CRW SST. Besides, the location of observed reefs at Con Dao and Phu Quoc (Vo *et al.* 2008) and the country boundary map layer (World Resource Institute 2012) were used to determine which pixel in the remote sensing products would be used to extract SST values (Figure 1).

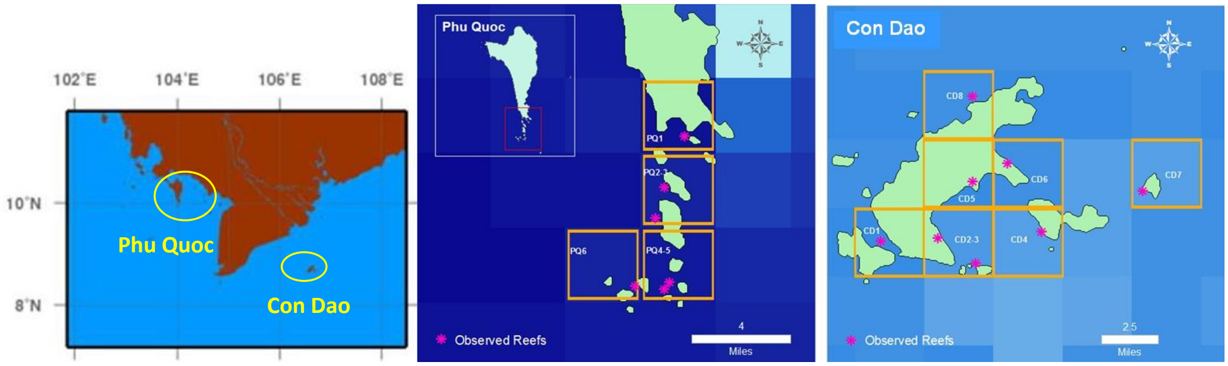

Figure 1: Location of reefs and relative SST pixels at Phu Quoc and Con Dao

All pixel values in the studied area, extending from 7^0 14’ North to 11^0 97’ North and 101^0 61’East to 108^0 83’ East, were converted to degrees Celsius. Then, the time series SST data were excluded the cloud contaminated values and were smoothed by the Savitzky-Golay filter method (Savitzky and Golay 1964). Examining the monthly SST climatology cure of each pixel, May was found as the hottest month and SST climatology value of May was defined as the MMM in this research. Using the MMM as a common baseline, monthly and weekly HotSpot was generated (Equation 1). Only positive HotSpot values were derived and the value of 1^0C was set as the threshold for thermal stress leading to coral bleaching.

$$\text{HotSpot} = \text{Weekly/ monthly SST - MMM\_SST} \qquad (1)$$

The DHW (^{0}C-weeks) is the accumulation of HotSpot values which are equal or higher than 1^0C that coral reefs have experienced over the past 12 weeks. In order to compare DHW between the three bleaching years, my research generated DHW for the first 12 weeks of summer (May-July) and the last 12 weeks of summer (August-October). After HotSpot at Phu Quoc and Con Dao were examined, some reefs were recognized suffering early thermal stress in April and the stress prolonged more than 12 weeks. Therefore, in this research, DHW based on the actual stress duration also were calculated. Finally, bleaching levels were identified, following the method developed by the CRW (Table 1).

Table 1: The flexible global tool for monitoring of coral bleaching (CRW 2011)

Level	Definition	Description
No Stress	HotSpot ≤ 0	Corals are not currently experiencing any thermal stress
Bleaching Watch	$0<$ HotSpot < 1	Temperatures are above normal summer maximum, but corals are not yet stressed
Bleaching Warning	$1 \leq$ HotSpot and $0 <$ DHW < 4	Corals are experiencing a low-level buildup of thermal stress
Bleaching Alert Level 1	$1 \leq$ HotSpot and $4 \leq$ DHW < 8	Corals are currently stressed, accumulating to a level where bleaching is expected
Bleaching Alert Level 2	$1 \leq$ HotSpot and DHW ≥ 8	Corals are currently stressed, accumulating to a level where widespread bleaching and some coral mortality is expected

3. RESULTS

3.1. SST in the south-western and south-eastern areas of the East Sea

As a product of the long-term mean SST (1985-2009), the SST climatology derived in this study revealed that the thermal base of the south-western area where Phu Quoc is located appears higher than that of the south-eastern area where Con Dao is located. Generally, temperature in the south-western area varies from 26^{0}C to 31^{0}C while that range in the south-eastern area is from 24^{0}C to 30^{0}C. In each month, SST in the West is usually on average of 1^{0}C warmer than SST in the East. This distinction is particularly remarkable from November to May. After reaching its peak in May, SST in the south-western area decreases gradually while SST in the south-eastern area remains high for one more month. This phenomenon is described on the map of June where most of the study area was covered by a temperature of 30^{0}C and there is no thermal difference between the West and the East (Figure 2).

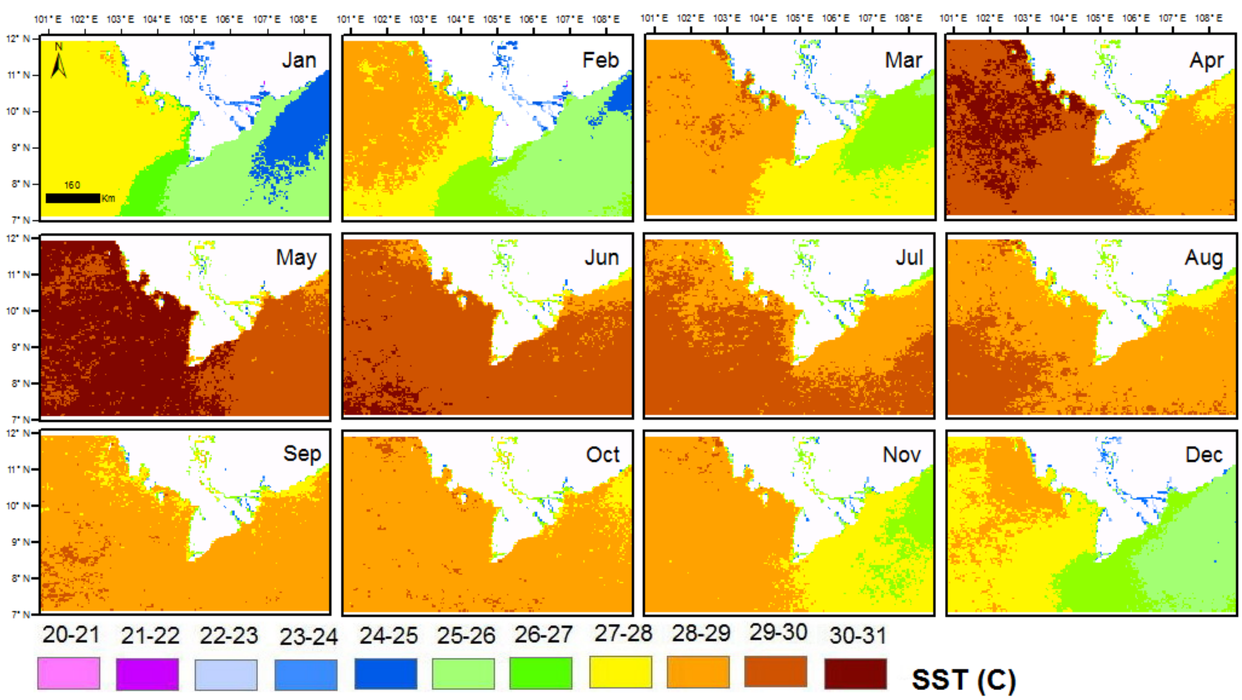

Figure 2: Sea surface temperature climatology from January to December

The average of Minimum Monthly Mean SST at the six observed sites of Phu Quoc is 27.38^{0}C whereas that number at the eight sites of Con Dao is 24.88^{0}C. The average of Maximum Monthly Mean at Phu Quoc is 30.4^{0}C and that at Con Dao is 29.19^{0}C (Figure 3). As results, coral reefs at Phu Quoc have a bleaching threshold at 31.4^{0}C in average while thermal limit of reefs at Con Dao is 30.19^{0}C. Since most corals have the ability to acclimate to changes in temperature (Wilmer *et al.* 2000), coral reefs at Phu Quoc are able to resist higher SST than reefs at Con Dao, which reasonably explains the fewer frequent observations of bleaching at Phu Quoc.

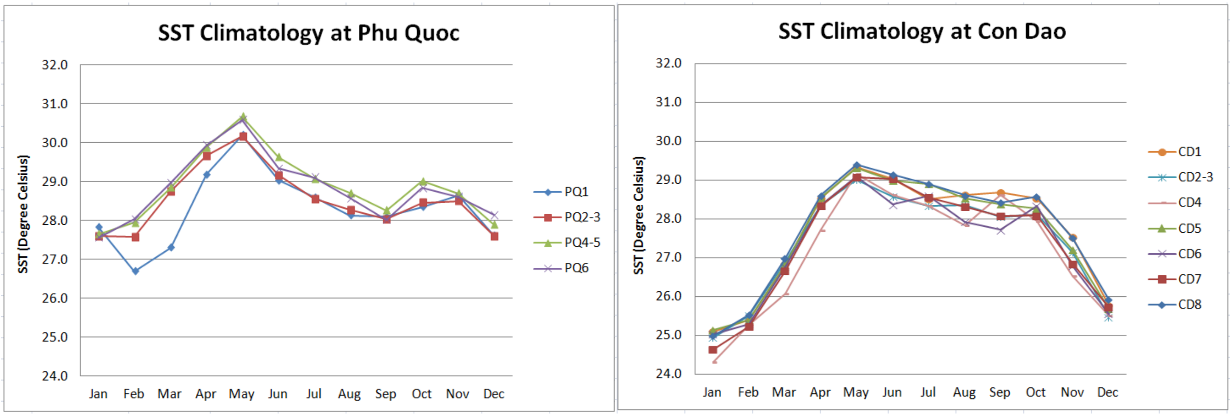

Figure 3: 12-month sea surface climatology at Phu Quoc and Con Dao

3.2. Thermal stress in bleaching years

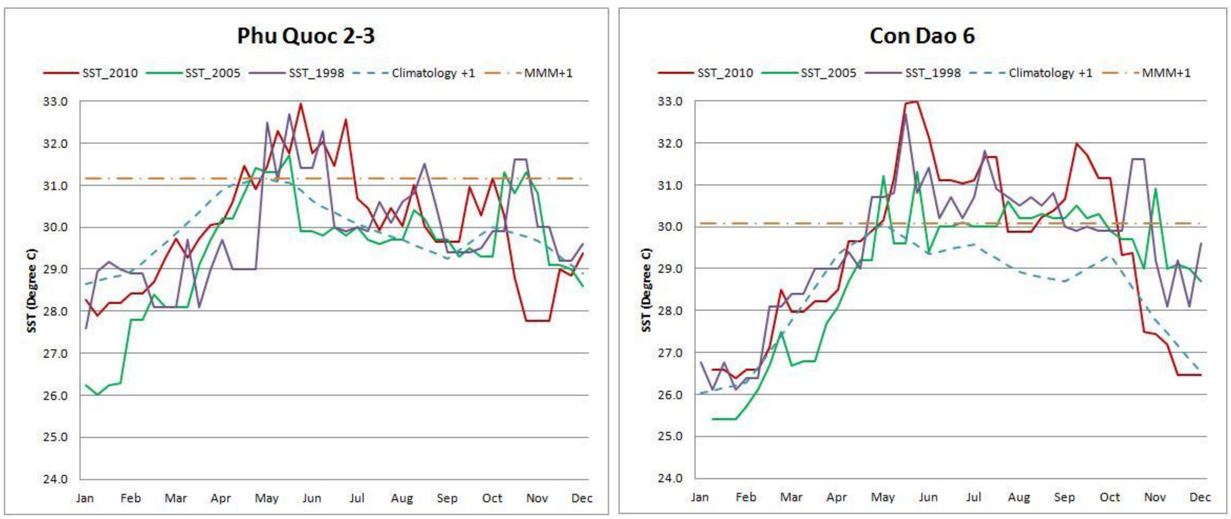

Figure 4: Thermal stress at Phu Quoc and Con Dao in 1998, 2005 and 2010

Thermal stresses in 1998, 2005 and 2010 are revealed through the weekly SST graphs (Figure 4) and DHW tables (Table 2 and 3). Starting in April 1998, SST at Con Dao and Phu Quoc increased quickly and exceeded the bleaching threshold during the first 12 weeks of summer, indicating a widespread of bleaching. Moreover, coral reefs at Con Dao suffered a more dramatic stress in levels and time than reefs at Phu Quoc. For instances, thermal stress at Phu Quoc occurred from April to Mid-July (12 weeks) and DHW ranged from 9.5^{0}C to 13.5^{0}C whereas DHW at Con Dao from Mid-April to the End of August (18 weeks) ranged from 17^{0}C weeks to 35^{0}C weeks. In 2005, coral reefs at Con Dao suffered a nearly 24-week thermal stress, from May to October while stress duration at Phu Quoc was shorter, in four weeks of May and in two weeks of October. Even though HotSpot values at Con Dao were not very high, the accumulation of continuous anomalies in 24 weeks placed coral reefs under level 2 of bleaching, meaning a significant mortality could occur. In April 2010, the SST at Phu Quoc exceeded the summer maximum value and prolonged during the first 12 weeks of summer. Meanwhile, at Con Dao, accelerative temperature occurred in nearly 24 weeks. Particularly, DHW values at several sites at Con Dao were higher than 30^{0}C weeks in three months and the six months accumulation indicated a remarkable range, the lowest DHW was 29.55^{0}C weeks and the highest was 55.23^{0}C weeks. In brief, thermal stress associated to bleaching at Con Dao and Phu Quoc in 2010 was more severe than the previous in 1998, with longer duration and higher DHW values.

Table 2: Degree Heating Week (^{0}C weeks) at Phu Quoc in 1998, 2005 and 2010

Year	Actual stress duration	PQ1	PQ2-3	PQ4-5	PQ6
1998	April to Mid-July (12 weeks)	13.51	9.53	9.47	11.08
	Last 2 weeks of October (2 weeks)	2.76	2.82	0	0
2005	May (4 weeks)	4.63	4.97	1.14	1.05
	October (2 weeks)	2.16	2.22	0	0
2010	Feb to Jul (19 weeks)	34.89	16.31	7.96	7.59
	Apr to Jul (12 weeks)	32.33	16.31	7.96	7.59

Table 3: Degree Heating Week (^{0}C weeks) at Con Dao in 1998, 2005 and 2010

Year	Actual stress duration	CD1	CD2-3	CD5	CD6	CD7
1998	Mid April to the End of August (18weeks)	19.9	25.14	18.1	35.78	30.07
	Last 2 weeks of October (2 weeks)	4.5	5.14	0	5.02	4.98
2005	May to July (12 weeks)	3.31	10.5	11.9	4.8	4.69
	August to October (12 weeks)	5.12	14	12.5	8.2	13.4
2010	May to October (24 weeks)	8.43	24.5	24.3	13	18.1
	Apr to Jul (12 weeks)	14.91	35.68	21.23	19.3	22.35
	Apr to Oct (24 weeks)	29.55	55.23	34.88	30.32	34.39

3.3. Comparison of the 50 km and 4 km thermal monitoring

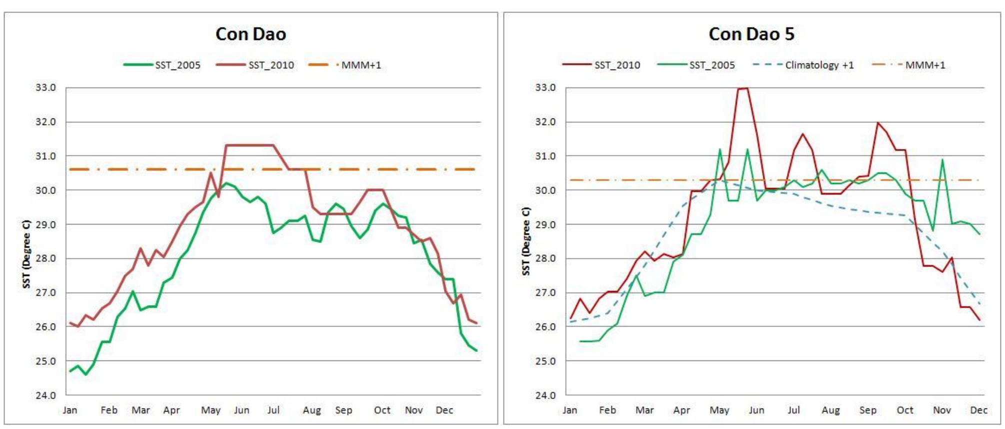

Figure 5: SST and bleaching threshold from the 50km (left) and the 4km (right) product

The bleaching threshold and the weekly SST in 2005 and 2010 was plotted to compare the data derived from the 50 km and 4 km products (Figure 5). The 50 km MMM is slightly higher than the 4 km MMM, around 0.2^{0}C, thus the bleaching thresholds of the two products are similar. However, the 4 km weekly SST plot showed a higher thermal stress than did the 50 km plot. According to the CRW data, coral reefs at Con Dao did not suffer any thermal stress in 2005 while this study and direct observation found that bleaching had occurred Additionally, the 4 km result also presented a more prolonged thermal stress with many 20C HotSpot values in 2010 than did the 50 km result. Thus, the application of 4 km spatial resolution data prevented underestimating thermal anomaly than with the 50 km resolution data.

4. CONCLUSIONS

Although corals can be bleached due to a variety of stressors, this research only focused on the major cause, thermal stress and examined the effectiveness of the most up-to-date high spatial resolution SST satellite-based products in monitoring bleaching in the southern East Sea. The results provided an adequate understanding, in both spatial and temporal dimensions, of SST and thermal stress in the study area, which are able to contribute to coral bleaching studies in Vietnam. For instance, the 4 km HotSpot and DHW maps are very useful in detecting locations and estimating levels of thermal stress. Those products can help scientists determine where and when to conduct a coral reef check. Moreover, the SST analysis based on satellite products also advantage in quickly assessing the role of elevated sea temperature in each bleaching event.

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