Determining Thermal stress using indices: sea surface temperature anomalies, degree heating days and heating rate to allow for-casting of coral bleaching risk.

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A B S T R A C T

Sea temperatures in many tropical regions have increased by almost 1°C over the past 100 years and are currently increasing at 1 ~ 2°C per century. Satellite and compiled in situ observations of sea surface temperatures have greatly increased the ability to detect anomalous and persistent warm water and are being widely used to predict climate change, coral bleaching and mortality.
In my study I attempted to measure in situ sea surface temperature using vemco water prob loggers. I used three indices: sea surface anomalies, degree heating days and heating rate to determine thermal stress on a reef flat. I identified the indices sea surface temperature anomalies provide significant data to determine heating is accruing on a reef and just mean monthly temperature data of a reef is not sufficient enough to indicate that the reef is heating and result in bleaching. Accumulated heat stress represented by exposure time and temperature (DHD) allows for-casting of bleaching severity. The cumulative thermal stress graph in my study indicates that after 120 degree heating days the thermal stress kept increasing on the reef for at least 3 more weeks in cooler month hence its vital to note temperature even after summer months.

1. Introduction

Sea surface temperature (SST) is a critical physical attribute of coastal ecological systems. Water temperature directly affects process rates, water column stability, and the species of plants (such as algae, seagrasses, marsh plants, and mangroves) and animals (microscopic animals, larger invertebrates, fish, and mammals) that live in a particular region. Increases in temperature are thought to be associated with the degradation of coral reefs (bleaching) and may increase the frequency or extent of blooms of harmful algae. The phenomenon of coral bleaching related to the impact of increase sea surface temperatures was first described by Glynn in 1984, which affected the extensive reef areas across the pacific (Brown, 1996). Bleaching is defined as the loss of color arising from the partial or total elimination of the *Symbiodinium* population or degradation of algal pigment and is not restricted to corals but displayed by all animals in symbiosis with zooxanthellae (Douglas, 2003). Berkelman's findings in 2002 identified sea surface temperatures (SST) as the most important parameter for predicting coral bleaching from four possible environmental variables: temperature, wind speed, solar radiation and barometric pressure collected over 10-12yr from weather stations at 2 locations on the Great Barrier Reef. Light levels during these months approached the highest theoretical surface light intensities for these locations. However, while high light intensities (at various wavelengths, including PAR, UV-A and UV-B) may confound the interpretation of the bleaching state of corals in the field (especially over small spatial scales (<1 to 100s of m), the evidence remains that elevated temperature is the primary stress factor in widespread 'natural' bleaching events (Berkelmans, 2002).

Current increase in coral reef bleaching has created an initiative for mapping and monitoring coral reefs regionally and globally, which is essential to assess change, detect stress and prevent eventual coral destruction. Environmental and ecological properties are measured through various satellites around the world today. Sea surface temperature data products at global and regional scales are well established and regional data exist back 100 years and accurate satellite infrared data have been acquired for the last 20 years (Robinson et al., 2000). Predictions of bleaching for large geographic areas are primarily based on daily or monthly measurements of sea surface temperature (SST) recorded by satellite (Gleeson and Strong 1995; Strong et al., 1997; Winter et al., 1998; Aronson et al., 2002). However, there are problems in using exclusively satellite sea temperature data, the most significant being the lack of resolution (better than 0.5 ^{o}C cannot be achieved) and the difficulties to measure absolute accuracy. Satellite data only give values relating to the top few millimeters of surface waters which may relate more closely to changes in solar radiation than bulk sea temperature. In some cases, attempts have been made to collaborate these large-scale temperature patterns with in situ measurements of temperature (Wellington et al. 2001; Aronson et al. 2002). Direct measurements of water temperature complement satellite imagery by providing data that are higher spatial and temporal resolution. Interpreting bleaching risk based on direct measurements of sea temperature requires an understanding of the exposure likely to trigger bleaching response. Mass coral bleaching begins wit the build- up of climate conditions that warm the air and sea, followed by above average sea temperatures (Marshall et al 1996). Fiji has been experiencing mass bleaching events in 1998, 2000, and 2002, with variable bleaching in 2001 and 2006. Fiji's satellite data is only picked up from Beqa Island only. At national level this data is not sufficient enough to detect early warning bleaching for other reefs due to geographical area difference.

The NOAA/NESDIS operational SSTs are provided twice a week in near real-time and use both day and night retrievals. Degree heating weeks (DHW) are indicated on the chart which indicates the accumulation of thermal stress that coral reefs have experienced over the past 12 weeks. The charts are produced twice a week at 50km resolution and are being used to depict the duration and strength of thermal stress that results in bleaching is critical (McClanahan et al., 2006). Studies on influence of thermal history on the response *M.annularies* to short term temperature exposure through measurements of photosynthesis and respiratory ratio versus temperature of coral colony in outer reef and inner lagoon indicated a significant difference between the elevations of the regression lines suggesting that *M.annularies* from the outer barrier reefs may have been more physiologically stressed than those from the inner lagoon reefs when exposed to acute temperature changes which indicate that thermal stress must be considered with in the context of acclimation temperatures and that short – term exposures may have physiologically important effects on this species (Castillo et al 2004).To measure thermal stress there is a need for a reliable way to continuously monitor water temperatures so a better and true impact of SST on the health of coral reefs can be assessed. Both the intensity and duration of heat stress are important factors in predicating the onset severity of mass bleaching events (Marshall et al., 1996). Multiple temperature variables or indices of cumulative heat stress allow for a better estimate of bleaching risk than any single one (Maynard et al., 2007)

In this study I examined summer month temperature from January to May to determine the thermal stress on a reef flat. I investigated three indices , sea surface temperature anomaly , degree heating rates and heating rate.

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2. Materials and methods.

Sampling was conducted at Votua Reef Front, Coral Coast Viti levu Fiji lands.

2.1 ***Seawater temperature measurements***

In January 2007 a Vemco Water temperature Pro logger (standard range -5 to 35^0C, resolution 0.2 ^{0}C and accuracy ± 0.3^0C) was installed at 1m depth on a reef base to record temperature at every 2hrs from Jan to June using cable ties and dive weights.

2.2 ***Temperature logger retrieval***

The logger was picked up on June and temperature data was downloaded using the vemco minlog software program. Raw data was downloaded in the excel program from the minlog vemco program to conduct further analysis.

2.2 ***Temperature logger data analysis***

For analysis three indices were selected based on research a) Sea Surface Temperature anomaly, b) Degree Heating Days (DHD) and the c) Heating rate. Daily average temperature was calculated from day temperature 2hr interval recordings followed by calculation of daily average temperature monthly average. For SST calculation maximum temperature over any 3-day period ($3d_{Max}$SST) was subtracted from the long-term mean summer temperature (LMST) of Fiji over ten year period from 1987 – 1997) prior major bleaching period in Fiji. This data was obtained from Hadley climate center UK. The Degree heating days value was summed positive deviations of daily average sea surface temperatures ($T_{Heating}$) from historical summer mean temperatures (*LMST*). The heating rate (HR) was calculated by dividing DHD value by the number of days that temperature exceeded the LMST – mathematically the average rate that DHDs have been accumulating through the summer. A heating rate was calculated each month and over the total summer period (Maynard et al., 2007). *(Note due to technical problems with logger downloading 2006 summer raw data was used.*

3. Results

The monthly average sea surface temperature from January to April 2006 showed drastic increase when compared with long term historical sea surface temperature. Monthly sea surface temperature average for January was 28.91 ^{o}C, February 29.4 ^{o}C , March 28.64, April 30.0 ^{o}C , May 28.6 ^{o}C. SST Anomalies for January was 1.26 ^{o}C , February 1.28 ^{o}C , March 1.81 ^{o}C, April 2.44 ^{o}C and May 3.00 ^{o}C.The Sea surface anomalies was above 1^oC through out the summer month from Jan to May.

Table 1 -Long term historical average data, maximum temperature over any 3-day period , SST anomalies , the degree heating days , summed positive deviations of daily average sea surface temperatures ($T_{Heating}$) from historical summer mean temperatures (*LMST*) and Heating rate for month of January to May 2006

	Jan (^{0}C)	Feb (^{0}C)	March(^{0}C)	April (^{0}C)	May (^{0}C)
Long-term Mean ST	28.27	28.82	28.64	28.26	27.10
3 day max ST	29.53	30.10	30.45	30.70	30.10
SST (+)	1.26	1.28	1.81	2.44	3.00
DHD	20.2	16.8	39.5	52.7	46.7
T(h)>T(historical)	28	24	31	30	21
HR	0.72	0.70	1.27	1.76	2.22

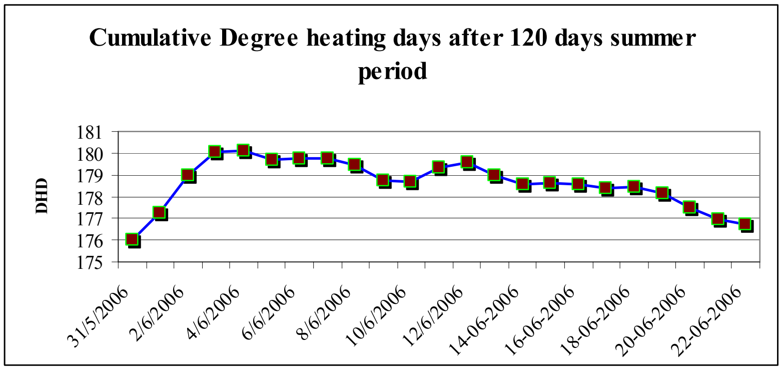

Fig 1.0 – Cumulative heat stress after the summer period (Jan- May).

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4. Discussion

The present data analysis showed that 2006 summer month was a warmer year then normal summer month experience on the reef. Only day temperature was used for data analysis, considering that high solar irradiance may alter attributed coral bleaching as a secondary effect. Light levels are almost high at the time of bleaching events as solar radiation drives sea temperatures increase (Berkelmans 2002). The historical temperature data used was standard data for Fiji islands from 1987 – 1997, prior any major recorded bleaching period. The sea surface temperature anomalies results indicate that May 2006 was hottest month on the reef through the summer period. SST anomaly is the amount of sea surface temperature difference from normal temperature (long term average) for and it provides a useful reference point that shows the extend to which current temperatures vary from those that the corals are accustomed on that reef on that time of the year. Monthly sea surface average analysis just shows a trend of temperature increase or decrease with in the summer months, however the increase or decrease trend does not indicate whether the heat is having any impact on the reef since it does not take in account the temperature the reef is already accustomed to experiencing during its normal summer months and because of the geographical locations there will be variations in the average water temperature. In the result the anomalies over the summer period was above 1^0C through out the summer period and was 2.55^0C in April and 3.0^0C in May, this indicated that bleaching was experience on this reef as the data shows the temperature exceeded the seasonal maximum . Elevated temperatures, of as little as $1\text{-}2^o$C above mean monthly summer values, are a major cause of bleaching (Glynn 1993; Brown 1996.). The summed of anomalies provide a measure of the accumulated exposure to temperature above the normal maximum. Accumulated heat stress has been represented by a single number (eg degree heating days) where by exposure time and temperature are integrated by adding cumulative time above a given temperature (Gleeson & Strong 1995).The degree heating days (*DHD*) and heating rate hence are indices that describe the accumulation of thermal stress. Accumulation of thermal stress indicates how long the impact of heating on coral ecosystem was after the heating period or summer months and the lag of accumulation of heat to get to the point of off stress will also indicate the severity of bleaching (minor, moderate or server) the reef experiences. The results indicate that out of 120 days, 56 days had temperature 2^0C above the long term average giving a total of 176 Degree heating Days over the 120 Days. One DHD is calculated as one degree above the local long term average temperature for one day (Maynard et al., 2007).DHDs are defined as the cumulative degrees of temperature for one day where the temperature is $\geq 1°$C above the mean temperature of the climatologically warmest month or period for a specific site; it is often used to predict bleaching (Robinson et al, 2000).

In June the mean average sea surface temperature decreased to 27.7 ^{O}C from 28.6 ^{O}C but the cumulative stress after the 120 days (summer period) kept accumulating for the next 22 days shown in Fig 1.0, indicating the impact of heating stays in the water column for at least 2 or 3 weeks and this post heating stress lags to bleaching period.The cumulative heat is indicator which indicates severity of bleaching. Degree-Heating Days can represent a broad range of heat stress in that three weeks at 1°C above the local long-term average results in the same number of DHDs as one week at 3°C, the latter representing more severe stress to corals. For this reason, *ReefTemp* also displays the Heating Rate, calculated as the number of Degree Heating Days divided by the number of days in which temperatures have exceeded the long-term average. This index is initiated after temperatures have been above the long-term average for a minimum of five days (Maynard et al., 2007).Monthly heating rate for April was 1.76 and 2.22 for May. This rate when compared with NOAA satellite color code chart indicated moderate bleaching occurred during the summer period. NOAA bleaching HotSpots and degree heating weeks (DHW), provide rapid synoptic reporting of temperature data and their anomalies (http://www.coralreefwatch.noaa.gov/satellite). It's been pointed out that satellite observe the skin sea surface temperature where as in situ measurements record bulk temperature (Robinson 2000).

The rate gives the level of thermal stress experienced on the reef and recovery from the heat stress is dependent by the cumulative stress. Both the intensity and duration of heat stress are important factors in predicating the onset and severity of mass bleaching events. Logger Temperature data source produce a moderate predictive ability to detect bleaching on a reef, the remaining variability: local historical environmental effects and infield biological surveys will better assist to determine severity of bleaching. The limitation of this study was, no test was done against a control site without high temperature anomalies and no biological surveys were conducted. Intensity of temperature anomalies combined with the duration of exposure provides a composition picture of accumulated temperature stress over the period. While SST data provides a invaluable means of estimating the exposure of corals to elevated temperatures over large spatial scales and long term periods , our understanding of how frequency spatial and temporal variability temperature affect the physiological performance of corals at a national scale is still very limited. There is a need to develop a more précised study to determine cumulative stress by measuring temperature over both summer and cooler months. This is will better indicate the severity of bleaching on a reef and sub- lethal range of corals and recovery from bleaching.

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