Available online at www.sciencedirect.com
ScienceDirect
Marine Pollution Bulletin 54 (2007) 1923–1931
MARINE POLLUTION BULLETIN
www.elsevier.com/locate/marpolbul

Coral bleaching indices and thresholds for the Florida Reef Tract, Bahamas, and St. Croix, US Virgin Islands

Derek P. Manzello [a,*], Ray Berkelmans [b], James C. Hendee [c]

[a] *Cooperative Institute of Marine and Atmospheric Studies, Rosenstiel School, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA*
[b] *Australian Institute of Marine Science, PMB 3 Townsville, Qld. 4810, Australia*
[c] *National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149-1026, USA*

Abstract

It is well established that elevated sea temperatures cause widespread coral bleaching, yet confusion lingers as to what facet of extreme temperatures is most important. Utilizing long-term in situ datasets, we calculated nine thermal stress indices and tested their effectiveness at segregating bleaching years *a posteriori* for multiple reefs on the Florida Reef Tract. The indices examined represent three aspects of thermal stress: (1) short-term, acute temperature stress; (2) cumulative temperature stress; and (3) temperature variability. Maximum monthly sea surface temperature (SST) and the number of days >30.5 °C were the most significant; indicating that cumulative exposure to temperature extremes characterized bleaching years. Bleaching thresholds were warmer for Florida than the Bahamas and St. Croix, US Virgin Islands reflecting differences in seasonal maximum SST. Hind-casts showed that monthly mean SST above a local threshold explained all bleaching years in Florida, the Bahamas, and US Virgin Islands.

Keywords: Coral bleaching threshold; Thermal stress indices; SST; Florida Reef Tract; Lee Stocking Island, Bahamas; St. Croix, US Virgin Islands

1. Introduction

Coral bleaching (loss of symbiotic zooxanthellae and/or their pigments) is a stress response that can be caused by many adverse environmental conditions; however, high sea temperature has been repeatedly identified as the most important causal factor at large spatial scales (Glynn, 1993; Brown, 1997; Hoegh-Guldberg, 1999; Berkelmans, 2002a). Coral bleaching events have been reported with increasing frequency on the Florida Reef Tract over the past 25 years. Isolated bleaching events occurred in 1911, 1961, 1973, and 1983 (Mayer, 1914; Shinn, 1966; Jaap, 1979, 1985), whereas the first event spanning the entire reef tract occurred in 1987 (Causey, 2001). Bleaching events in the 1980s were limited to the offshore reef tract, but in 1990 hydrocorals (*Millepora* spp.) on inshore patch reefs and the outer reef tract bleached (Causey, 2001). The most widespread and severe bleaching events have occurred during the past 10 years in 1997, 1998, and 2005, punctuated by mild and more localized bleaching events in the interim.

The variability in severity of bleaching both within and between sites is understandable given the complexity of the bleaching response. There is a broad continuum of pigment state (color) in zooxanthellate corals that is a function of temperature, light, and exposure time (Fitt et al., 2001), as corals naturally go through seasonal changes in zooxanthellae densities (Fitt et al., 2000). Although normal seasonal changes do occur in zooxanthellae densities, Warner et al. (2002) found that corals in the *Montastraea* species complex can lose up to 90% of their zooxanthellae without showing obvious signs of bleaching. Thus, visibly discernable paling in corals is a considerable metabolic stress to the coral host and should not be misinterpreted as normal just because zooxanthellae densities vary

* Corresponding author.
E-mail address: dmanzello@rsmas.miami.edu (D.P. Manzello).

0025-326X/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2007.08.009

seasonally. Furthermore, inter- and intra-specific variability exists in the susceptibility of the coral host (Knowlton et al., 1992; Edmunds, 1994) and zooxanthellae (Rowan et al., 1997) to temperature stress.

Although the response of corals to elevated temperatures is highly complex, a number of indicators have been generated with temperature data to hind-cast and forecast bleaching episodes. Monthly mean sea temperatures above a local threshold (Goreau et al., 1993; Brown et al., 1996) as well as cumulative heat stress have been used to explain bleaching events (Gleeson and Strong, 1995; Podesta and Glynn, 1997). Berkelmans et al. (2004) found that 3-day maximum temperatures best correlated with spatial patterns of bleaching on the Great Barrier Reef, whereas a log–log linear relationship existed between temperature and number of days above that temperature at which bleaching occurred in Puerto Rico (Winter et al., 1998). Sammarco et al. (2006) re-evaluated the Puerto Rico dataset and showed warm, bleaching years were characterized by high variance in bi-weekly sea temperature whereas a lower variance in temperature occurred during warm, non-bleaching years.

To assess which aspects of temperature best explained bleaching years on the Florida Reef Tract, we calculated nine separate indices representing three facets of thermal stress: (1) short-term, acute temperature stress; (2) cumulative temperature stress; and (3) temperature variability. In addition, daily and monthly anomalies were calculated from derived seasonal cycles for Florida reef sites. Lastly, estimated bleaching thresholds for Florida were compared with those for the Bahamas and St. Croix, US Virgin Islands.

2. Methods

2.1. SEAKEYS data

The SEAKEYS (sustained ecological research related to management of the florida keys seascape) program began in 1989 to complement the National Data Buoy Center's (NDBC) Coastal-Marine Automated Network (C-MAN) (Ogden et al., 1994). The SEAKEYS network was implemented for long-term monitoring of meteorological and oceanographic conditions along the 220-mile Florida Reef Tract and Florida Bay encompassing the Florida Keys National Marine Sanctuary (FKNMS). For the purpose of this study only those SEAKEYS stations that are situated on the Florida Reef Tract were of interest. These are Fowey Rocks (25.59 °N, 80.1 °W, at the northern terminus of the Florida Reef Tract), Molasses Reef (25.01 °N, 80.38 °W, east of Key Largo), Sombrero Reef (24.63 °N, 81.11 °W, south of Marathon), Sand Key (24.46 °N, 81.88 °W, south of Key West), and the Dry Tortugas (24.64 °N, 82.86 °W, at the western end of the Florida Reef Tract). From these stations hourly averages of bulk in situ sea surface temperature (SST) were obtained. Daily average SST was calculated from the beginning of data acquisition at each site through to 2005. The Molasses Reef site provided the most complete data set beginning in 1988 (Table 1). Data collection began at Sombrero Reef in 1988 as well, but data are limited at this site for some years. Data from the station at the Dry Tortugas is the least complete with large gaps during critical warm summer periods in 1997, 2004, and 2005. The remoteness of this station and the frequent impact of hurricanes in 2004 and 2005 explain why this site recorded only 82.7% of hourly data from 1992 to 2005 (Table 1). Nevertheless, all sites except the Dry Tortugas provide a record that is >90% complete for hourly, in situ SST from the time of their installation through 2005.

2.2. Thermal stress indices and anomalies

The annual maximum daily average and hourly SSTs were calculated to assess if short-term extreme temperatures were related to bleaching. Maximum monthly mean SST and degree-days were used as indices of cumulative heat stress per year. Degree-days were calculated according to Podesta and Glynn (1997). This index is similar to the degree-heating weeks of Gleeson (1994) and Gleeson and Strong (1995). The number of days per year that daily SSTs were >29.5, 30, 30.5, and 31 °C were calculated to assess their value as simple bleaching indices. These annual temperature variables were then logistically regressed with the presence–absence of bleaching. Only those years without missing data were used in the logistic regressions totaling 58 non-bleaching years and 12 bleaching years for Florida sites. The role of temperature variability was assessed by computing the coefficient of variation (CV) in bi-weekly mean SST from 1 July to 31 October and then comparing the CVs of warm, non-bleaching (WNB) and warm, bleaching (WB) years by site (Sammarco et al., 2006). WNB and WB compared by site were: Fowey Rocks, WNB (1993, 1999, 2004), WB (1997, 1998, 2005); Molasses Reef, WNB (1993, 1995, 2002), WB (1997, 1998, 2005); Sombrero Reef, WNB (2000, 2001, 2002), WB (1997, 1998, 2005); Sand Key, WNB (1995, 2001,

Table 1
Description and completeness of data by site

	Fowey Rocks	Molasses Reef	Sombrero Reef	Sand Key	Dry Tortugas
Start date	8/1/1991	1/1/1988	2/10/1988	5/19/1991	12/9/1992
N	5155	6460	5960	4994	4224
% Complete	94.2	98.3	90.7	91.2	82.7

N is number of days.