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Annual summer bleaching of a multi-species coral community in backreef pools of American Samoa: a window on the future?

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Abstract. The prevalence of bleaching was recorded in staghorn thickets of two back reef pools on a biweekly basis during the October to June bleaching season, and monthly basis for the rest of the year at Tutuila, American Samoa. Recording began in late 2003 and has continued since, and used a rapid visual estimation procedure. Three species of staghorns (*Acropora spp.*) in both pools bleached every Austral summer for five years. Reports of reef slope bleaching events in 2002 and 2003 imply that they bleached in those years as well. Thus, these corals have bleached for at least five summers and likely seven summers or more in a row. Other, less common species of *Acropora* and *Millepora* were observed to bleach as well. The bleaching displayed patterns consistent with the view that both temperature and irradiance are involved in producing the bleaching. The term "photothermal bleaching" was applied to this type of bleaching. This appears to be the first annual multi-species summer bleaching event reported.

Key Words: bleaching, annual, coral, staghorn, American Samoa

Introduction

Mass coral bleaching events have been reported on many coral reefs around the world (Brown and Ogden 1993; Glynn 1996; Brown 1997, Hoegh-Guldber, 1999, 2000; Wilkinson and Souter 2008). Although most corals recover in some events, in other events, many corals die. The intensity of the 1997-98 mass bleaching event was such that about 16% of the world's corals were estimated to have died in that event alone (Wilkinson et al. 1999). Much evidence links mass bleaching events with increased temperatures, and bleaching is predicted well by sea surface temperatures (SST; Hoegh-Guldberg 1999; McWilliams et al. 2005; Liu et al. 2003). The frequency and severity of events has been increasing (Glynn 1993; Hoegh-Guldberg 1999; Bellwood et al. 2004; McWilliams et al. 2005; Marshall and Schuttenberg, 2006). Global warming has been implicated in the increasing frequency and severity of mass bleaching and mortality events, and events have been predicted to continue to increase in frequency and severity, becoming annual summer events sometime in the future (Williams and Bunkley-Williams 1990; Ware 1997) with most predicting that to occur by about 2020 to 2050 (Hoegh-Guldberg 1999; Done et al. 2003). More severe events such as that in 1998 could devastate reefs by that time even though they would not occur every year, because reefs would require several years to recover from each event (Sheppard 2003).

Coral bleaching events on reef slopes was reported in American Samoa in 1994 (Goreau and Hayes, 1994), 2002 and 2003 (Green 2002; Craig et al. 2005), and caused some coral mortality on reef slopes. SST's for American Samoa show an increasing trend over the last 25 years (US EPA 2007). The observation of bleached staghorn corals in back reef pools of Tutuila, American Samoa in late 2003 prompted the senior author to begin monitoring bleaching in those back reef pools (Craig et al. 2005; Whaylen and Fenner 2006; Fenner et al. 2008; Fenner and Carroll in prep). *Acropora* and *Millepora* are reported to be among the most sensitive genera to bleaching (Marshall and Baird 2000; Loya et al. 2001)

Materials and Methods

Tutuila, American Samoa has nearly continuous fringing reefs on the south shore, with shallow reef flats and steep reef slopes (Craig 2005; Craig et al. 2005; Birkeland et al. 2008; Brainard et al. 2008; Fenner et al, 2008). At a few locations, sections of the reef flat have been dredged to provide fill for the airport runway or village land. These pools reach about 7-10 m depth at their maximum. These back reef pools are now co-dominated by *Porites* *cylindrica* and the staghorn *Acropora muricata* (=*formosa*), with smaller amounts of the staghorns *A. pulchra* and *A. nobilis* (referred to as *A. intersepta* in some works). A few other species are scattered in these pools, including at least one stand of *Millepora dichotoma*, and individuals of a few other species of *Acropora*.

Staghorn thickets provide a particularly challenging subject for recording bleaching. Usually, the limits of colonies and clones are not clear. Further, bleaching commonly varies in intensity along the length of branches. In addition, what appear to be clones, and thickets, and different areas of the pools often bleach to different degrees. In most field studies of bleaching, bleaching is recorded by visual estimation. In this study, a rapid visual estimation method was used, in part because limited time was available for this study. A one hour swim over a fixed course was used, passing over two areas with different bleaching rates (Fig. 1), in each of two pools. A running estimate of bleaching was made during the swim, separately for each of the two different areas. At the airport pool, the area nearer to the runway typically was less bleached than the area farther from the runway. In the Alofau pool, the deeper eastern part of the pool always was more intensely bleached than the shallower western part. An area of staghorn was deemed bleached if at least part of branches were light or white on their upper surface only. The intensity of bleaching was not recorded. Bleaching was monitored biweekly when colonies were bleached, and approximately monthly when they were not bleached. Bleaching was also recorded on the reef flat and reef slope at Alofau beginning in January, 2007.

The satellite sea surface temperature (SST) is produced operationally by NOAA Coral Reef Watch in near real-time (http://coralreefwatch.noaa.gov). The SST values are produced globally twice each week and are ~9-km sub-sample averages presented on a 0.5-degree (approximately 50-km) grid (for detail see Skirving et al, 2006). The data used are from the pixel nearest the Airport Lagoon, just to the south, centered at [170.5W, 15.0S]. The warmest month climatology value used by Coral Reef Watch is representative of the expected summertime maximum temperature (and therefore a threshold for bleaching conditions) at this location. While not precisely co-located with the observation site, periods when the SST value exceeds the climatology at the offshore location are representative of when thermal stress is experienced near the coast.

Results

Porites cylindrica was not observed to bleach except at one small area in early 2007 (a patch on the reef flat in Faga'alu Bay). All three of the staghorn species were observed to bleach during the Austral summer at the Airport, Alofau, Nu'uuli, and Faga'itua pools. The Faga'itua pool is a maximum of 2 m deep and may be natural, while the other pools were produced by dredging. Bleaching typically involved lightening of color on the upper surface of horizontal branches, and when intense the entire upper surface was white. Lower surfaces always retained some color, except when a colony died. Polyps on the upper surfaces of a few branches died, while surviving on all of the rest of their surfaces and retaining color on their undersurface. Even during the Austral winter when very few staghorns were bleached, overturned colonies were observed bleached on what was previously their undersurface. Most years there was little if any colony death, but in 2007 in particular, some colonies died all except for branch tips, and a couple of thickets died completely. Thus, this is not just annual summer lightening of color (Fitt et al. 2000). Two of the staghorn species (*A. muricata* and *A. pulchra*) were found only in the back reef pools, but one (*A. nobilis*) was found also on reef slopes. *A. nobilis* was never observed to bleach on reef slopes at the same time it was intensely bleached in the back reef pools. On the reef slope at Alofau, *A. nobilis* on the reef slope at the same depth (about 4-5 m) as in the back reef pool of Alofau, was not bleached in 2007 when the colonies in the pool bleached sufficiently severely that only a few branch tips survived. *M. dichotoma* and some of the *Acropora* species other than the three staghorns were observed to bleach at the same time as the staghorns. A second, much less common bleaching pattern was for several centimeters of branch tips to bleach completely on all surfaces.

Water in the pools was typically warmer than the ocean, and at times could be felt to be warmer near the surface than deeper (the stratification likely due to low-wind conditions). Logger temperature records were obtained from 0.5 and 6 m at the airport pool, which reached maximum temperatures of about 32 °C for short periods midday. In Fagaitua, the logger at 2 m depth recorded a maximum of 34.9 °C for one half hour. That is a temperature similar to the maximum recorded in the back reef pools at Ofu Island in American Samoa, where a high diversity of corals lives (Craig et al. 2001). Staghorns there were moderately bleached at that time.

Staghorns in the Alofau pool bleached every summer (Fig. 1). Data for the deeper eastern area and shallower western area are plotted separately. As can be seen, the deeper area bleached more intensely and for a longer period than the shallow area. Bleaching began each year in October, and ended around the end of May or early June. For the deep pool, the onset and end of bleaching was rapid, and bleaching was near 100% for most of the Austral summer. Staghorns in the deep pool spent most of the year bleached with only a short respite between years; despite this, corals manage to survive. Bleaching was much less intense on the reef flat, and near zero on the slope.

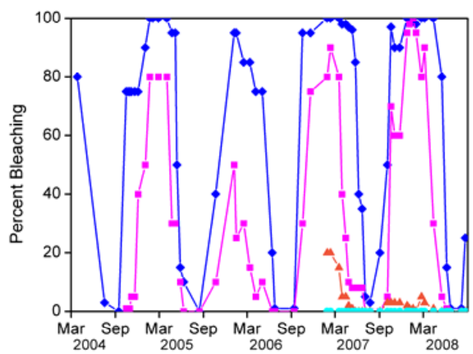

Figure 1 Staghorn bleaching observed at four sites at Alofau – left pool (blue diamond), right shallow (pink square), reef flat (orange triangle), reef slope (cyan circle).

Staghorns in the airport pool bleached each summer as well, and the staghorns spent about as much time bleached as unbleached (Fig. 2). In 2006 and 2008, a period of several weeks of cloudy, rainy, cool weather was followed by a sharp drop in bleaching, and the resumption of normal weather was followed by a resumption of bleaching. Changes in the percentage of corals bleached corresponded closely with nearby ocean SSTs (Fig. 2), appearing to show a rapid, proportional response to warming.

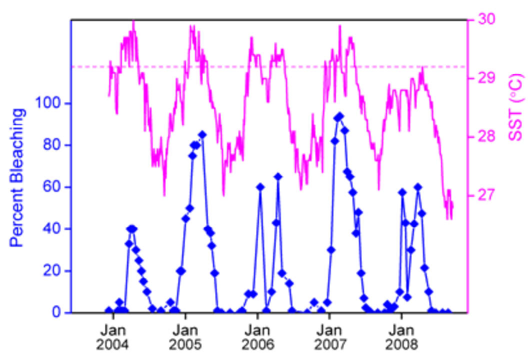

Figure 2 Staghorn bleaching at airport lagoon, Tutuila, and satellite SST. The dashed pink line indicates the temperature of the climatologically warmest month.

Maximum bleaching at the two locations during the five-year period was most often in February with four maximums observed in that month, two in January, two in March, and one in April.

Discussion

Normally, healthy corals show a seasonal variation in the density of their zooxanthellae, with fewer zooxanthellae during the summer and autumn (Fitt et al. 2000). However, healthy corals normally do not loose so many zooxanthellae that they turn white and/or die, so the present observations are beyond the normal range of variation. The pools reached temperatures of about 32 ^{o}C while Fig 2 shows peak temperatures of about 30 ^{o}C for nearby ocean SST's. The fact that *A. nobilis* colonies bleached and partly died in the Alofau pool while the same species at the same depth on the slope about 100 m away did not bleach, indicates that water temperature played an important role in this bleaching, though water motion may well have been a factor as well. The fact that the upper surfaces of staghorns bleached and even died while lower surfaces retained color and survived, is similar to previous reports that upper surfaces of corals bleach more than lower surfaces (Hoegh-Guldberg 1999) and indicates that solar irradiation played an important role in the bleaching as well. This is consistent with the bleaching of the undersurfaces of overturned colonies when other colonies were not bleached, and in addition suggests that upper branch surfaces may have greater resistance to bleaching from irradiation than lower branch surfaces. This pattern is consistent with evidence that bleaching involves the effects of high temperature and irradiation on the photosynthetic system in the zooxanthellae (Coles and Jokiel 1978; Gleason and Wellington 1993; LeTissier and Brown 1996; Hoegh-Guldberg 1999). It is also consistent with reports that previous exposure of coral to bleaching-inducing irradiation can increase resistance to subsequent thermal bleaching (Brown et al. 2000, 2002). The dual roles of irradiation and temperature in bleaching can be captured in the phrase "photothermal bleaching." This also distinguishes this type of bleaching from bleaching produced by other factors, such as darkness, fresh water, or disease. The coral bleaching responded rapidly and proportionately to temperature changes. Maximum bleaching occurred in February, two months after the austral summer solstice, compared to three months after the northern summer solstice in the Caribbean (McWilliams et al. 2005). Thus, bleaching follows peak irradiance and corresponds better to peak SST's in both data sets, indicating that the influence of light is regulated by temperature. Further, there is no sign of the corals developing increasing resistance to bleaching, even though some in Alofau spend most of the year bleached. However, the low levels of mortality suggest that the corals in these pools may be better equipped to tolerate the effects of bleaching.

Annual summer or autumnal bleaching has been reported in single coral species for *Oculina patagonica* in the eastern Mediterranean (Ainsworth et al. 2007) and *Meandrina meandrites* in Florida (Tichenor 2004). Seven species of intertidal corals have been reported to bleach in Thailand, at least one of which (*Goniastrea aspera*) was documented to bleach annually from solar irradiation (Brown et al. 1994). However, the bleaching of a multi-species coral community in the back reef pools of American Samoa appears to be the first subtidal multi-species bleaching event that appears regularly every summer due to temperature and irradiation. Although this project began at the end of 2003, the fact that bleaching events were reported in 2002 and 2003 indicates that staghorns in the pools very likely have bleached for at least seven years in a row. Such annual bleaching events have been predicted to appear in the future due to global warming (Williams and Bunkley-Williams 1990; Ware 1997; Hoegh-Guldberg, 1999, 2000; Done et al. 2003; Sheppard 2003). These events in the back reef pools of Tutuila may provide insights into the future for coral reefs, and may provide a predictable opportunity to study annual bleaching events and test possible mitigation strategies long before annual summer bleaching becomes common on coral reefs around the world.

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