Ecology Letters, (1999) **2**: 325–330

REPORT

Mass Coral Reef Bleaching: A Recent Outcome of Increased El Niño Activity?

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Abstract

Coral reefs are generally considered to be the most biologically productive of all marine ecosystems, but in recent times these vulnerable aquatic resources have been subject to unusual degradation. The general decline in reefs has been greatly accelerated by mass bleaching in which corals whiten *en masse* and often fail to recover. Empirical evidence indicates a coral reef bleaching cycle in which major bleaching episodes are synchronized with El Niño events that occur every 3–4 years on average. By heating vast areas of the Pacific Ocean, and affecting the Indian and Atlantic Oceans as well, El Niño causes widespread damage to reefs largely because corals are very sensitive to temperature changes. However, mass bleaching events were rarely observed before the 1970s and their abrupt appearance two decades ago remains an enigma. Here we propose a new explanation for the sudden occurrence of mass bleaching and show that it may be a response to the relative increase in El Niño experienced over the last two decades.

Keywords

Bleaching, climate change, coral reef, El Niño, hot spots, Southern Oscillation, time series analysis

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INTRODUCTION

Coral reefs are the most diverse ecosystems in the marine environment, comparable in richness to the tropical rainforests of terrestrial habitats (Connell 1978; Jackson 1991). These valuable aquatic resources have undergone significant degradation and decline in recent years (Brown 1987; Wilkinson 1992; Sebens 1994; Stone 1995). Damage to reefs has been exacerbated by the bleaching phenomenon whereby corals lose a significant portion of their pigmented algal symbionts (zooxanthellae), so that their normal colourful appearance becomes white or pale (Glynn 1993; Meehan & Ostrander 1997). Mass bleaching events have been severe enough to leave entire reefs dazzling white (Brown & Ogden 1993) and, on a global scale, have resulted in immense coral mortality with many affected reefs failing to recover (Williams & Bunkley-Williams 1990; Glynn 1991, 1993; Brown & Ogden 1993).

Over the last two decades there has been a dramatic and unaccountable increase in the frequency and intensity of mass bleaching episodes in reefs worldwide (Glynn 1991; Buddemeier & Fautin 1993). According to Glynn (1993), while some 60 major coral reef bleaching events were reported between 1979 and 1990, only nine were documented between 1969 and 1979, yet both periods were times of active coral reef research. We emphasize that prior to the late 1960s, reports of coral bleaching were scattered and almost nonexistent in the literature, and it is only since the late 1970s that the large-scale mass bleaching of reefs has become prominent and of considerable concern. It is possible that mass coral reef bleaching has been occurring unobserved throughout the last centuries but has only been noticed in recent decades, e.g. with the availability of SCUBA equipment. (Note though, that mass bleaching is sometimes so striking that it can be observed easily without the need for SCUBA.) However, many of the finest coral reef ecologists consider that mass bleaching, on the scale that it has been observed over the last decades, is a new phenomenon (Glynn 1991; Buddemeier & Fautin 1993). For example, after a detailed study of coral banding patterns and growth rates of Florida's reefs, Goreau & MacFarlane (1990) concluded that massive bleaching could not have occurred between 1918 and 1983. Goreau's (1992) study of the corals of Jamaica resulted in a similar conclusion: "Mass coral reef bleaching has a unique pattern. It first appeared in Jamaica in 1987 … Mass bleaching did not occur in Jamaica from 1951 through 1986 and it is not possible that it could have happened without our knowledge because of frequent field work and regular contact with divers and fishermen around the island."

We are interested in determining and examining those factors that might be responsible for the sudden increase in the bleaching phenomenon in the late 1970s. Perhaps the most widely accepted explanation to date is that bleaching is a response to the recent trend in global warming observed over the last few decades (Glynn 1991; Sebens 1994). Unfortunately there is little quantitative evidence to defend this contention and it should be viewed more as an untested hypothesis, supported so far only by circumstantial evidence. Williams & Bunkley-Williams (1990) proposed a more complicated climatic connection and suggested that bleaching is a combined outcome of conditions due to El Niño events "riding on a progressively higher base of elevated temperature [i.e. global warming] and increasing reef deterioration". Huppert & Stone (1998) examined the recent temporal dynamics of mass bleaching events focusing exclusively on what has been referred to as the "coral reef bleaching cycle". However, these studies made no attempt to resolve the more difficult question addressed here; namely, what caused the sudden appearance of mass bleaching in the 1970s? We now propose a new connection between the initiation of the bleaching phenomenon in the 1970s and interdecadal changes in El Niño activity.

PHYSICAL AND CLIMATIC FACTORS RESPONSIBLE FOR BLEACHING

Coral reefs are highly vulnerable to rising temperatures because corals generally live very close to their upper temperature tolerances (Jokiel & Coles 1990; Glynn 1993; Podestá & Glynn 1997). They cope poorly with the large temperature increases associated with El Niño events which heat vast areas of the Pacific Ocean to levels far above (often by 3–4°C or more) average conditions (Fig. 1). These El Niño heating events occur in an erratic or possibly chaotic cycle (Huppert & Stone 1998) that recurs approximately every 3–4 years and is referred to as the El Niño Southern Oscillation (ENSO, see Fig. 1b). The link between elevated sea surface temperatures (SST) induced by El Niño, and mass bleaching, is strikingly recorded in an unusual 3–4 year "coral reef bleaching cycle" (Fig. 2), which is believed to have emerged in the late 1970s and has maintained synchronization with El Niño ever since (Williams & Bunkley-Williams 1990; Goreau & Hayes 1994; Hoegh-Guldberg & Salvat 1995; Huppert & Stone 1998). Thus mass bleaching events in the Pacific over the years 1979–80, 1982–83, 1986–87, 1991, 1994 and 1997–98 were all periods of El Niño activity, with heightened SST anomalies. Major bleaching events also occurred at reefs in the Indian Ocean and the Caribbean Sea in these same El Niño years, indicating the important role of "teleconnections", whereby El Niño events in the Pacific project climatic anomalies to other regions of the globe (Bjerknes 1969; Gordon 1996; Charles *et al.* 1997).

More generally, it has been demonstrated that bleaching episodes may be triggered in localized regions of the ocean whenever the sea surface temperatures become anomalously warm and exceed a certain threshold level. For example, after an extensive study of available field data, Goreau & Hayes (1994) concluded that mass bleaching occurs when reef waters exceed 1°C above long-term monthly averages. This has led to the implementation of remote sensing programs for the purpose of monitoring potential bleaching sites by identifying the ocean's "hot spots" via satellite. Figure 1 shows the spatial distribution in temperature across the Pacific in October 1997 during the build up of what was to be one of the strongest El Niño's this century. Large areas of the equatorial Pacific had SST anomalies $> 1°C$ (i.e. $> 1°C$ higher than the mean monthly average SST). "Hot spots" in the ocean with elevated SSTs of this severity have, in the last two decades, almost always led to mass bleaching in nearby coral reefs (Goreau & Hayes 1994). Figure 1 indicates that thousands of square kilometers of coral reefs in the Pacific were at risk (Hoegh-Guldberg & Salvat 1995) from the large scale 1997/1998 El Niño warming event. It is still too early to survey and document the extent of the bleaching that was most likely induced by the 1997/1998 El Niño, but the many reports compiled so far indicate that it was a disaster of fierce and unparalleled proportions (Strong *et al.* 1998; C. Wilkinson, internet posting).

There is strong experimental evidence to support the hypothesis that temperature increases are able to induce bleaching. For example, when corals (both in the laboratory and ocean) were subjected to temperature increases of more then 1°C, severe bleaching occurred (Glynn & D'Croz 1990; Jokiel & Coles 1990). Although temperature is a major cause of bleaching, and this is the main working assumption in this paper, it is believed that solar radiation, especially ultraviolet (UV) radiation, is also responsible. Spatial patterns in cloud distribution over the Pacific Ocean are thus considered important because they control radiation levels at the sea surface (Brown 1997). In El Niño years, the Western equatorial Pacific is characterized by clear skies and doldrum-like conditions (Glynn 1993; Huppert 1997), which enhance the penetration of solar/UV radiation and promote bleaching. There are also indications that temperature and UV may operate synergistically to induce bleaching (Brown 1997). Furthermore, other specific causes of bleaching have been noted. For example, recently it has been reported that bleaching

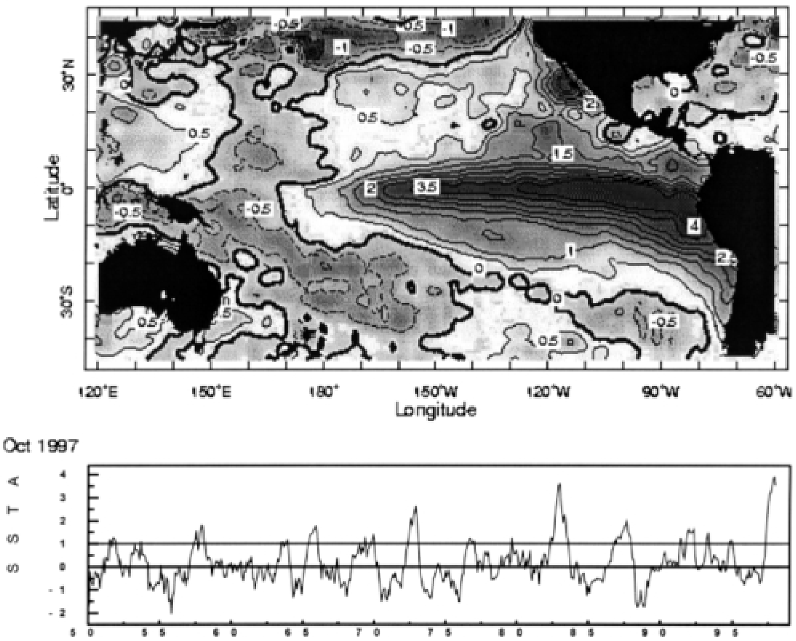

Figure 1 (a) October 1997 Sea Surface Temperature anomaly (i.e. temperature difference from annual monthly mean) blended from ship buoy and satellite data indicative of El Niño conditions. The shaded dark grey region or "tongue" spreading from the coast of South America along the equator almost to Australia represents an anomalous pool of warm water some 3–4°C higher than average conditions for this time of year (with permission of Lamont Doherty Earth Observatory Climate Group). (b) Time series of the spatially averaged SST anomaly in the eastern Pacific NINO3 region (5°S–5°N 90°W–150°W) 1950–98. Peaks in the graph illustrate the 3–4 year ENSO cycle and indicate maxima in the heating of the Pacific, i.e. when El Niño is most intense (e.g. 1976–78, 1982–83, 1986–87, 1997–98). For purposes of illustration a straight line 1°C anomaly has been added and might represent the threshold beyond which bleaching is enhanced.

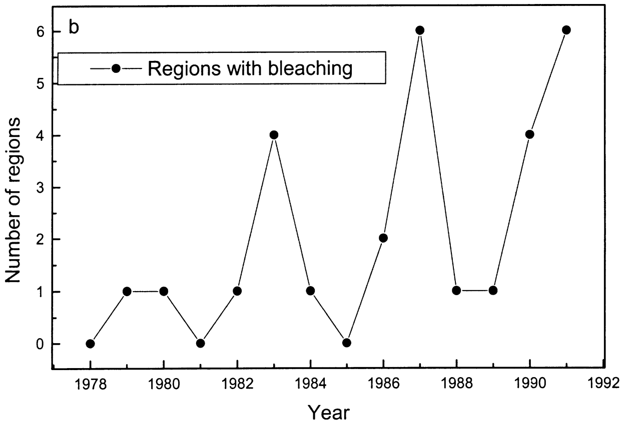

Figure 2 The number of major reef provinces in which mass bleaching events were reported in the period 1978–90 [from Goreau & Hayes (1994) with permission of T.J. Goreau]. The coral reef bleaching "cycle" is easily observed and peaks in years of El Niño events.

of the coral *Oculina patagonica* from the Mediterranean sea is a result of bacterial infection (Kushmaro *et al.* 1998). All of these direct and indirect factors represent ways in which El Niño may affect bleaching dynamics.

BLEACHING: AN OUTCOME OF INCREASED EL NIÑO ACTIVITY?

The circumstances which ushered in the mass bleaching phenomenon witnessed over the last two decades are far from clear, and are the main concern of this paper. Here we propose a new explanation for this phenomenon based on studies that demonstrate stronger and more frequent ENSO activity over the last two decades (Trenberth & Hoar 1996; Rajagopalan *et al.* 1997). For example, in the period 1977–88 there were three consecutive El Niño warming events with no compensating La Niña cold event, while the El Niño-related warming over the years 1990–95 was of a duration unprecedented in the 100 year historical record.

There are already a number of long-term studies which demonstrate a recent increase in strong El Niño events from an examination of records kept over the period 1525–1987 (e.g. Quinn *et al.* 1987; Glynn 1988; Quinn 1992; Solow 1995). However, most of these are based on Quinn *et al.*'s (1987) historical (and sometimes anecdotal) data which only provide a list of years in which El Niño occurred, and a rough score as to whether each event was weak, moderate, strong or very strong. Among other things, the data provides no information whatsoever about the Pacific Ocean's temperature dynamics, or ENSO's important cool phase "La Niña", which also plays an important role in the climate, and thus most likely the bleaching dynamics. Analyses based on Quinn's data should thus only be viewed as a first approximation. Solow (1995) examined some problematic aspects in analyses of Quinn's data and demonstrated that the conclusion of a recent increase in El Niño activity could be an artifact. It was found that the increasing trend could also simply be due to the overall increase in the completeness of the historical record. Solow's (1995) analysis of strong

El Niño events alone revealed no significant trends at all. This has the very important implication that, if there is a relationship between mass bleaching trends and El Niño activity, it will be difficult to extract from Quinn's data; a more refined data-set is needed.

Because of such problems, climatologists have switched approaches over the last few years, and now prefer to study more precise oceanographic and atmospheric indices to gain insights into ENSO trends. Trenberth & Hoar (1996) discussed the problems of choosing the most suitable spatially resolved ENSO index which takes into account those regions of the tropical Pacific whose SST's make the most contribution, as well as their link to the ocean circulation component – the Southern Oscillation (SO). In addition, the integrity and signal-to-noise ratio of such an index must be checked. After an extensive analysis they concluded that the best continuous record of data is the sea level pressure (SLP) measured at Darwin, Australia, which they found to be the best available long-term index of the SO. [The Darwin SLP is in fact a component of the well known Southern Oscillation Index (SOI).] The level of detail obtained from the Darwin SLP index is far better than Quinn's historical data.

For the purpose of studying coral bleaching, we thus decided to follow the guidelines of Trenberth & Hoar (1996) and examined time series (1882–1995) of the Darwin Sea Level Pressure (DSLP) as well as the more traditional Southern Oscillation Index (SOI). These time series (1882–1995) are considered to be the most reliable long-term records available of the ENSO signal (Trenberth & Hoar 1996). Monthly data for the DSLP time series are available for a period that covers the last 100 years. Data of similar resolution are available for the SOI, although some months are missing prior to 1935. The SOI is plotted in Fig. 3 for the years 1890–1995. Note that large negative anomalies in the SOI (e.g. 1982/83, 1986/87) correspond to periods of strong El Niño activity. Our analysis required converting both the DSLP and the SOI datasets into binary sequences, the two states representing the presence or absence of an anomaly in a given season (four seasons per year: DJF, MAM, JJA, SON). Positive seasonal anomalies were defined as having occurred whenever the average seasonal value of the index was greater than the long-term mean of the time series. The converse indicated a negative anomaly.

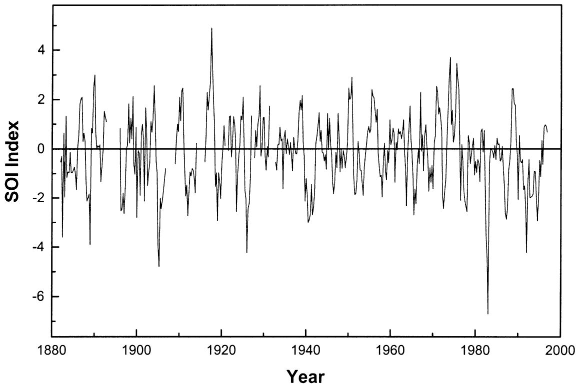

Figure 3 Time series of the Southern Oscillation Index (SOI) which measures the pressure difference between stations at Darwin and Tahiti. The major dips or large negative anomalies in the SOI indicate years of strong El Niño activity.

We then estimated the probability (or rate) of occurrence, *P*, of a positive seasonal anomaly in the DSLP time series and the probability of a negative anomaly in the SOI time series, both of which signal the possibility of El Niño conditions. The seasonal occurrence of anomalies was modelled as a Poisson process with a time varying rate of occurrence. The local rate, *P*, was estimated by smoothing the binary sequence using a nonparametric estimator for determining the weighted moving average of the occurrence rate over time (see Rajagopalan *et al.* 1997 for details). The resulting rate (*P*) plotted from 1890 to 1995 is shown in Fig. 4. What stands out in both the DSLP and the SOI time series, is that the occurrence probability, *P*, dramatically increased in the 1970s, indicating what appears to be a "climate shift".

This change in ENSO activity should be compared with the record of bleaching events at the time. Superimposed on Fig. 4 is a graph adapted from Glynn (1993) detailing the number of major coral reef bleaching events reported over the period 1870–1990. The unusual increase

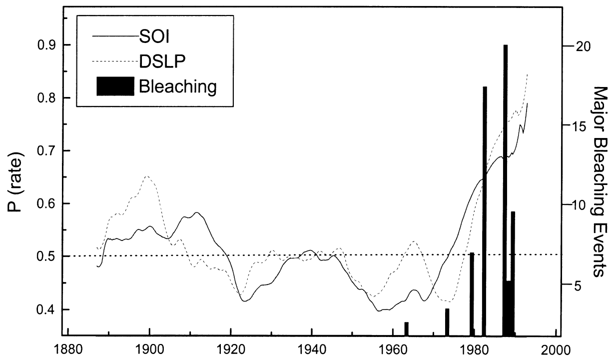

Figure 4 Probability (or rate) of occurrence *P* of a positive anomaly in Darwin Sea Level Pressure (DSLP, solid line) and a negative anomaly in the Southern Oscillation Index (SOI, dotted curve). Superimposed on this figure is a graph (adapted from Glynn 1993) displaying the number of major bleaching events reported over the period 1890–1990. For reference purposes, the long-term average occurrence probability $<P>$ (i.e. the ratio of the number of seasonal anomalies to the total number of seasons) of both time series was found to be $<P> = 0.5$, as indicated by the dotted horizontal line.

in bleaching since the late 1970s appears to be highly synchronized with the increase in ENSO activity in that period. This, we suggest, is because heightened ENSO activity causes warmer SST anomalies and changes in solar radiation – stressors which tend to increase the occurrence of coral reef bleaching.

DISCUSSION

Our study has rested on the reasonable premise that changes in temperature are the major cause of bleaching. Yet, it is a curious phenomenon that many intertidal corals which regularly experience such changes under low-tide conditions, do not bleach, or bleach only partially and recover after a few months. Such observations were noted in the reefs of Okinawa, Japan, after the mass bleaching that occurred there in the summer of 1988. Interestingly, many intertidal corals either partially bleached or were largely unaffected during the bleaching episode (Nakano, personal communication; Loya, unpublished). These corals are presumably better adapted to environmental changes because of their ability to withstand the harsh low-tide conditions (high air temperatures and irradiation) which they are exposed to annually. Another reason for this may be that some of these intertidal corals (e.g. *Coeloseris mayeri*, *Leptoria phrygia*, *Goniastrea retiformis* and *Galaxea fascicularis*; see Brown *et al.* 1994) exhibit extreme tissue retraction during periods of exposure to sunlight. This leads to significant paling in colony colour without any reduction in either zooxenthallae abundance or chlorophyll concentration. We are far from a complete understanding of how some corals are able to endure large temperature changes without bleaching.

Returning to our general theme, we summarize our findings by noting that any theory put forward to explain the bleaching phenomenon must be able to account for the two following apparent trends: (i) the recent 3–4 year bleaching cycle; (ii) the emergence of this cycle over the last few decades. The influence of the ENSO cycle accounts for both of these features admirably. The 3–4 year cycle of bleaching corresponds to the intrinsic frequency of ENSO (Huppert & Stone 1998). The initiation of the bleaching events in the 1970s (see Fig. 4) corresponds to the observed climate shift in which El Niño warming events intensified. We suggest that these intensified events might well be responsible for the "birth" of the bleaching cycle.

Nevertheless, we cannot rule out that other possibly interdependent factors such as global warming and increased greenhouse gases are involved as well. (Note, however, that unlike the theory we put forward here, global warming can never on its own be a sufficient explanation for the increase in mass bleaching events simply because it fails to predict a 3–4 year bleaching cycle.) It is more appropriate to perceive these anthropogenic factors as synergistic rather than mutually exclusive to the observed decadal-timescale climate variation (Rajagopalan *et al.* 1997). We suggest that the inevitable continuation of these climatic trends will only further enhance current rates of reef bleaching, a situation which, to echo Goreau & Hayes (1994; p. 179), will "seriously impact marine biodiversity, fisheries and tourism ... in over 100 countries where coral reefs are major natural and economic resources." The last major bleaching event over 1997/1998 should thus be viewed as a continuation of a larger more worrying pattern of global coral reef decline.

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Editor, F. Boero
Manuscript received 25 May 1999
First decision made 25 June 1999
Manuscript accepted 19 July 1999