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Coral Bleaching and Ocean "Hot Spots"

Global sea-surface temperature maps show that mass coral-reef bleaching episodes between 1983 and 1991 followed positive anomalies more than 1 °C above long-term monthly averages ("hot spots") during the preceding warm season. Irregularformation, movement, and disappearance of hot spots make their detailed long-term prediction impossible, but they can be tracked in real time from satellite data. Monitoring of ocean hot spots and of coral bleaching is needed if the Framework Convention of Climate Change is to meet its goal of protecting the most temperature-sensitive ecosystems.

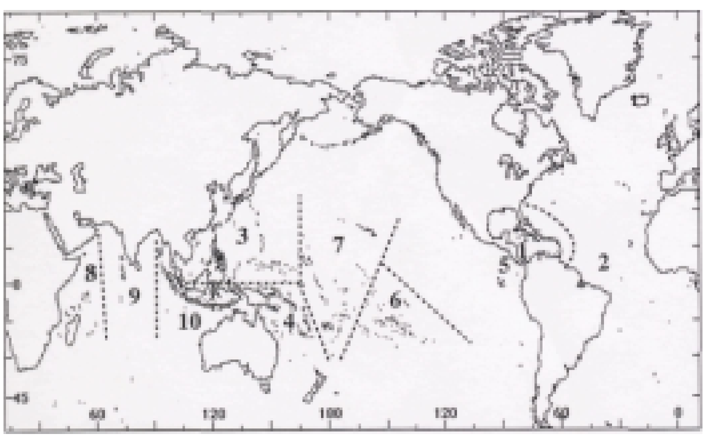


Figure 1a. Reef regions of the world, divided into 10 major reef provinces of roughly comparable area. These regions do not necessarily correspond to biogeographic provinces.

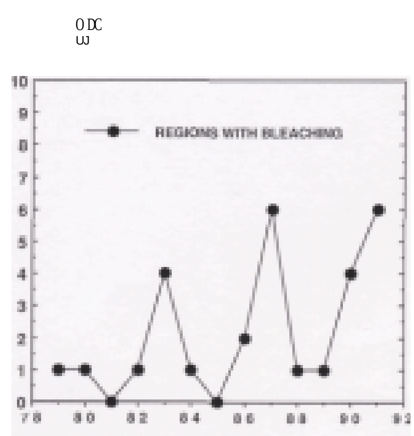
CORAL BLEACHING EVENTS

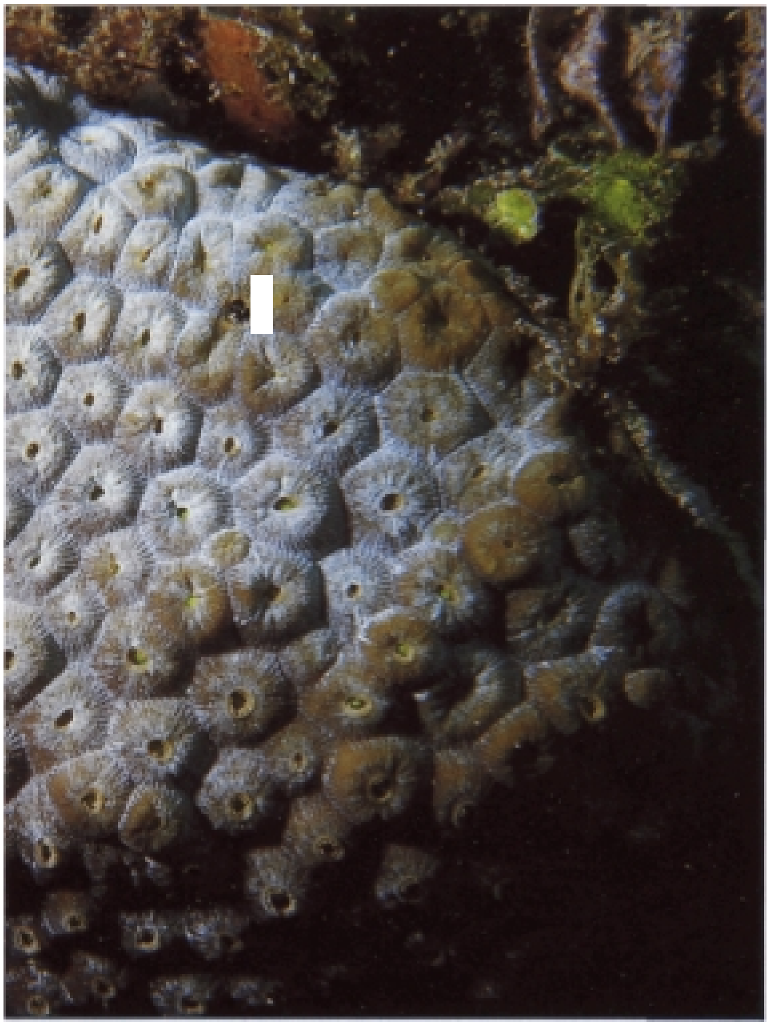
Coral-reef bleaching (1-13), or expulsion of symbiotic zooxanthellae algae, became more frequent, widespread, and severe in the 1980s (6-13). Zooxanthellae provide reef corals most of their carbon (14, 15), limestone depositing ability (16), and color (17). Bleaching causes corals to turn white or pale, because loss of pigment allows the limestone skeleton to become visible through transparent tissues. Local bleaching due to poor water circulation (1 -3) or freshwater and sediment from rivers (4,

	REGION	
	Atlantic-Central	X X XX X X X
Q	Atlantic-Peripheral	X X
Ei		
3.	Pa fic-NorthWest	X X X
4.	Pa ific-SouthWest	X X X
5.	Pa ific-East	X
6.	Pa ific-SoutriEast	X X X
7.	Pa ific-Central	x x X
10.	Indian-East	
8.	In an-West	X XX
9.	In an-Cenlral	X
		YEAR: 79 an B1 »? B3 B4 85 86 87 B8 B9 90 91

Figure 1b. Major bleaching events reported in reef regions since 1979. Bleaching events are taken from published citations and summaries in reference 6, updated by more recent reports

Figure 1c. Frequency of worldwide bleaching events since 1979. In the early 1980s, most reported bleaching events took place in only one reef province per year. In the late 1980s, bleaching events occurred at sites in around half of all reef provinces every year.





Closeup of *a Montastrea cavernosa* coral head in Negril, Jamaica, in September 1992, slowly regaining pigmentation after being bleached for more than a year. Polyps are around 1 centimeter across. Photo: P.O. Goreau.

5) cannot account for the spatial or temporal pattern of mass bleaching events in the last decade. These events affected shallow and deep corals across large regions, including reefs remote from local stresses (6-13, 18).

Major bleaching events were reported for all major reef provinces in the past decade (Fig. la). In 1983, 1987, and 1991 mass bleaching was reported in all tropical oceans (Fig. Ib). El Nino warming events can partially explain this global pattern. Thus, 1983 had the strongest El Nino on record, 1987 had a moderate El

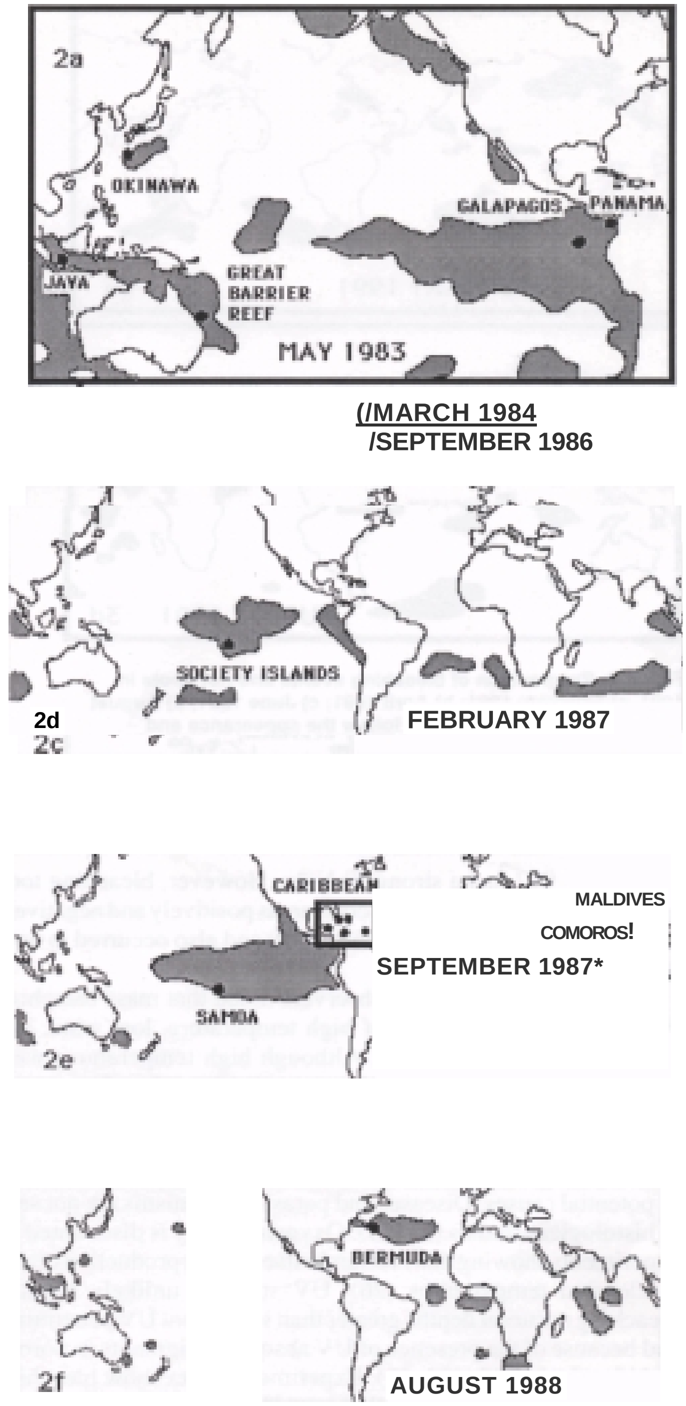


Figure 2. Bleaching events and "hot spot" regions, areas of the ocean with temperature anomalies over 1°C above long-term averages, a) May 1983; b) March 1984; c) September 1986; d) February 1987; e) September 1987; f) August 1988. All hot spots in global monthly average anomaly data in tropical and subtropical zones are shown, but some small hot spots outside these zones are not shown. Major bleaching sites in subsequent months are named and indicated by black circles. Most reports of bleaching at nearby reefs in the same regional hot spots are not shown. Bleaching also took place in the Caribbean in 1989 and 1990 (not shown). It should be noted that although May 1983 water temperatures in the Great Barrier Reef were anomalously high they had already fallen below their maximum seasonal values, and the bleaching event indicated there actually took place in early 1982, before satellite-based global ocean

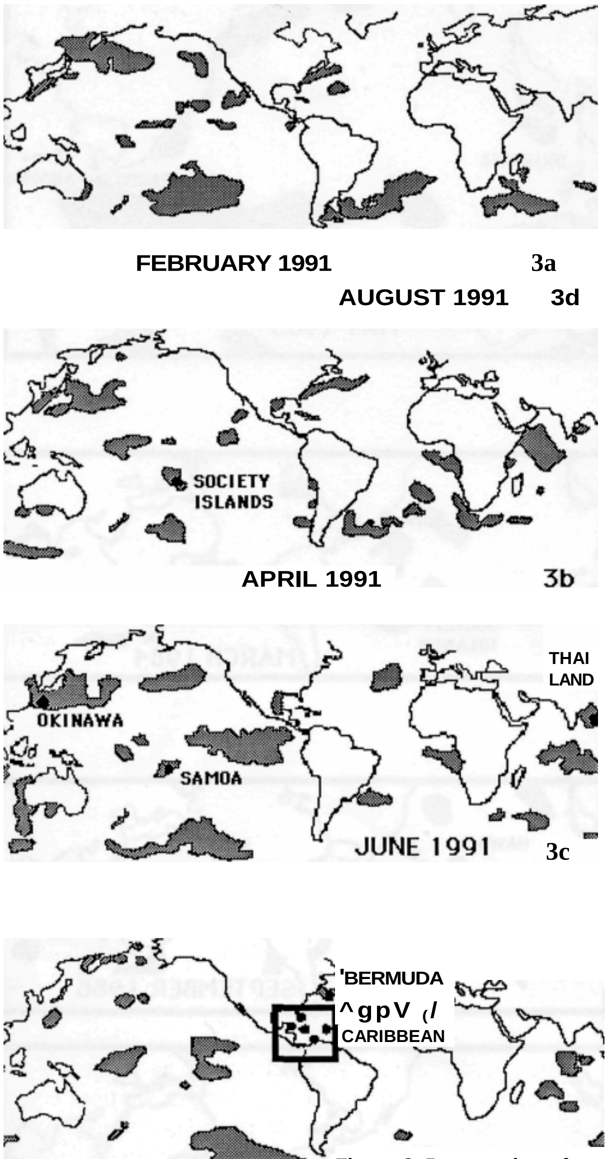


Figure 3. Progression of bleaching events and hot spots in 1991. a) February 1991; b) April 1991; c) June 1991; d) August 1991. Mass bleaching events follow the appearance and movement of hot spots as the warmest season of the year progresses from South to North.

Nino, and 1992 had a strong El Nino. However, bleaching took place in both shallow and deep coral areas positively and negatively correlated with El Nino influences (19) and also occurred in non-El Nino years.

In almost all cases, local observers noted that mass bleaching followed extended periods of high temperature, low wind, low cloudiness, and low rainfall. Although high temperatures were thought to be the most probable cause (6-13), rarity of long-term water temperature records in reef habitats made this issue controversial. Disease (20), oxygen toxicity (21), high ultraviolet (UV) light exposure (22), and pollution (23) were also proposed as potential causes. Diseases and parasitic organisms are not seen in histological studies (24, 25). Oxygen toxicity is discounted by experiments showing that zooxanthellae oxygen production ceases at elevated temperatures (26). UV stress is unlikely because bleaching occurs at depths greater than significant U V penetration and because of the presence of UV absorbing pigments in normal and bleached corals (27-29). Experimental data show bleaching elevated temperature (30-32). Pollution is ruled out because mass bleaching is often more frequent on pristine reefs than inshore and lagoonal reefs subject to freshwater, sewage discharges, and other stresses (6,10-12,18,33). Other potential causes, such as excess turbidity, darkness, or cold, are ruled out by field observations. Nonparametric statistical analysis of reef stress patterns show the spatial distribution of bleaching either does not correlate with or is negatively correlated with all major anthropogenic stresses to reefs (18).

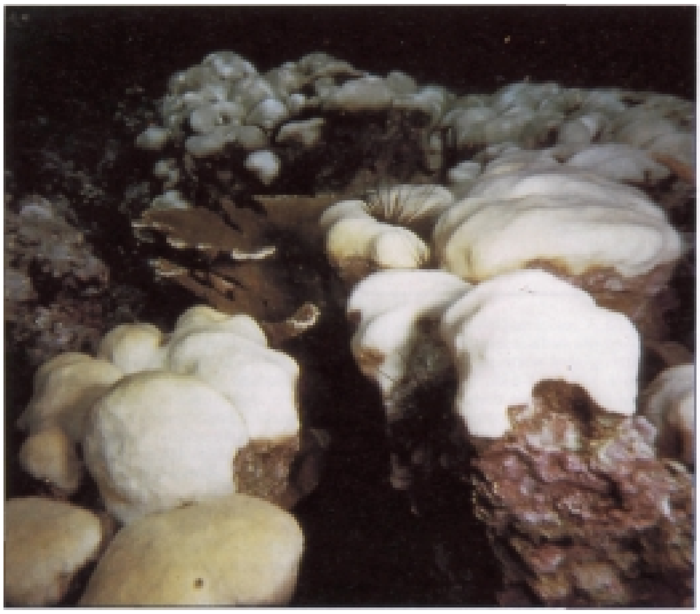
In situ observations and NOAA satellite-derived sea-surface temperature records at seven Atlantic reef locations show that mass bleaching events took place following the warmest periods recorded (34). At each site a threshold monthly mean temperature, approximately 1°C above long-term averages for the warmest months was found, above which bleaching always took place and below which it did not (34). Threshold temperatures are higher at sites with higher mean temperature, indicating that coral populations are adapted to local conditions (34). Mass bleaching was reported in some of the coldest and hottest coral reef areas, showing that both are vulnerable (6). Temperature records at 5 of 7 sites studied in the Caribbean had statistically significant warming trends during the last decade (34). Yet most sites also had significantly decreasing monthly temperature variability and seasonal temperature ranges, with the greatest warming occurring in winter (34).

BLEACHING AND OCEAN HOT SPOTS

We have identified areas where ocean surface temperatures exceeded long-term averages by more than 1 °C ("hot spots") during the warmest months preceding major reported bleaching events (Figs 2 and 3). Data are derived from global ocean-temperature anomaly maps published in the NOAA Climate Diagnostics Bulletin (35, 36), and from published bleaching reports, supplemented by field observations and personal communications from divers. Because bleaching rates are much higher at elevated temperatures (30-32), very hot intervals which are too short to appear on monthly mean anomaly data could also cause bleaching, but the fact that most major bleaching events appear to fall within one degree anomalies suggests that such events are fairly rare. This implies that global monthly average sea-surface temperature records are adequate to detect most bleaching conditions, except in the Caribbean, where records with higher spatial resolution are needed (34, 37).

Each region where mass bleaching has been reported since 1983 lay within or on the edge of a warm season hot spot (Figs 2 and 3). Regions where mass bleaching was not reported were not impacted by warm-season anomalies, and hot spots during the cool season were not followed by bleaching. During early 1991, a hot spot formed in the South Pacific outside the coral zone (Fig. 3a). As it disintegrated one portion migrated northwest, passing over the Society Islands, Samoa, and Nauru, before dying out near the equator (Fig. 3b-c). Bleaching and high coral mortality followed in its track (12-13), but were minor in the nearby Tuamoto Islands, which normally have similar climatic conditions to the Society Islands, but lay outside the 1991 hot spot (12). Bleaching later in 1991 at North Pacific, Indian Ocean, and Atlantic sites followed formation of new hot spots (Fig. 3d).

In 1992, in sharp contrast to 1991, very little significant new coral bleaching was reported; 1992 was unusually cold worldwide because high altitude aerosols from the eruption of Mount Pinatubo reflected sunlight back to space. Although El Nino warming affected Eastern Pacific surface waters, the warm-water pool was not suitably timed or located to cause bleaching in major reef areas. Hot spots were virtually absent elsewhere in 1992, but other local stresses to reefs continued to increase. Depite little new bleaching in 1992, the great majority of two of the major reef



Completely bleached heads of the major Caribbean reef building coral, *Montastrea annularis,* contrast sharply with an unbleached colony of the branching coral *Acropora palmata* (brown with white tips), following hurricane caused bleaching in Jamaica in 1963. Photo: T.F. Goreau.

Normal (dark brown), partially bleached (light brown), and completely bleached (white) plate corals of several *Agaricia* species and an unbleached encrusting coral *(Porites astreoides,* upper right), Jamaica, 1963. These are among the first photographs ever taken of bleaching. Photo: T.F. Goreau.

siderea, still had not fully recovered from the 1991 bleaching event, as late as early 1993. Because these species recovered more rapidly after the three prior mass bleaching events, they may be weakened from repeated stress and could be more strongly affected by subsequent bleaching. After the Pinatubo stratospheric aerosols settle, and the temporary cooling effect wears off, high tropical ocean temperatures could return. The resumption of mass bleaching following the next suitable hot conditions after the Pinatubo cold event would provide strong confirmation that temperature is the major correlative stress to bleaching (47). Divers should therefore remain alert for coral bleaching if warmer conditions return, as even the most pristine reefs could be affected.

TRACKING AND PREDICTION OF HOT SPOTS

Hot spots, like other extreme weather patterns, form, move, and disappear irregularly and unpredictably; their shape, direction of movement, and duration are extremely variable (38). Chaos in the climate system makes detailed long-term prediction of ocean hot spots unlikely. Extreme atmospheric temperatures usually last only a few weeks, but ocean hot spots typically last a few months due to the greater "memory" of the ocean for temperature changes (39). As a month or more of water temperatures 1 °C above average in the warmest months precedes most recorded mass bleaching events, tracking ocean thermal anomalies in real time could allow warning of sites where mass bleaching may be about to start.

There appear no clear latitudinal, regional, or seasonal trends in hot-spot distribution. Model-based projections suggest global warming rates should be greater in polar than equatorial regions, causing assessments of the potential ecological impacts of climate change to focus primarily on colder regions (40). Many tropical organisms, including both corals and major tropical plant crops, show strong stress responses under high temperature conditions, even when all otherenvironmental factors are adequate. Neglecting ecophysiological impacts of high temperature on tropical biomes is especially unwise because most tropical organisms live much

Widespread evidence that coral reefs around the world underwent episodic high temperature stress over the past decade makes bleaching a harbinger of reef ecosystem stress from ocean warming (6-10,42). Global warming rates over the past century and a half have been quite similar over oceans and land, and Northern and Southern Hemispheres, with the 1980s marking the highest values in the record (43). Previously unaffected regions could be impacted if hot spots continue with the frequency of the 1980s, and the health of coral-reef ecosystems globally could be compromised if hot spots become more frequent and intense, as predicted by model global warming scenarios (38). Bleached corals either fail to grow and reproduce until after they recover during the following cool season (44), or die if stress is excessive (1, 12, 13, 30-32). Continued or increased mass coral bleaching would seriously impact marine biodiversity, fisheries, tourism, shore protection, and the ability to adapt to rising sea level in the over 100 countries where coral reefs are major natural and economic resources.

CORAL REEFS AND THE CLIMATE CHANGE CONVENTION

Coral reefs are perhaps the most vulnerable ecosystems to rising temperatures, sea levels, soil erosion, and to excess nutrients from sewage and fertilizers. This gives them a central role if the Climate Change Convention, signed in Rio de Janeiro, is to meet it's own stated goal of protecting Earth's most climatically sensitive ecosystems. However, the Convention failed to require immediate monitoring of the most sensitive ecosystems, or to set acceptable limits of climate change at values below their tolerance limits. Global monitoring of both hot spots and coral bleaching should be promptly begun to determine the current extent and impact of large-scale temperature stress and whether current rates of climate change are within the ability limits of reef corals to adapt. If not, more stringent limits on greenhouse-gas emissions may be required. If global warming continues almost all ecosystems can be replaced by migration of species from lower latitudes, except for a much slower process than migration. Research on physiological tolerance and adaptation capability of tropical organisms should be central to any effort to protect the most biodiverse, productive, and beautiful tropical ecosystems; coral reefs and rainforests. Large-scale funding for long-term research in these habitats is critically needed yet woefully inadequate in current international environmental protection and development policies.

Protecting coral reefs for future generations may be the truest test of international commitments to sustainable development, because it places some of the most stringent constraints on doing the right thing for the environment (halting overfishing, reforesting coastal watersheds, providing complete tertiary sewage treatment, limiting climate change) at local, regional, and global scales simultaneously.

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37. Although global thermal anomaly maps arc successful at identifying hoi spots preceding mass bleaching in the Pacific and Indian Oceans they do not work well in the Caribbean region (marked by a rectangle in Figures 2 and 3). The Caribbean is apparently a special case because the effective pixel si/e of the global maps is actually several hundred km. {R. Reynolds, pers. comm.). which is too large to resolve the Caribbean's complex fine-scale current Hows and temperature patterns (A. Strong, pers. comm.). High resolution Caribbean satellite ocean temperature images with spatial resolution of 4-50 km are also available which show hot spots that are not visible in lower resolution data (Strong, A.E. and McCormack, R.C. 1991. Coral bleaching and sea surface temperatures. *Proc. Oceanog. Soc. Con]'..* St. Petersburg. Florida). An intermediate resolution satellite data set. the Ocean Features Analysis, prepared by NOAA for identifying eddies in the Gull Stream region (J. Clark, pers. comm.) was directly calibrated against measured *in situ* surface water temperatures in Jamaica and Grand Cayman, and found generally accurate to around 0.2"C (34). This data set also resolves Caribean hot spots which do not show up in the low resolution Oceanographic Monthly Summary data. Low resolution Caribbean data (Atwood, D.K., Sylvester. J.C.. Corredor, J.E., Morell, J.M., Mendcz, A., Nodal, W.J.. Huss. B.E. and Foil/. C. 1988. Sea surface temperatures anomalies for the Caribbean. Gulf of Mexico, Florida reef track, and Bahamas considered in light of the 1987 regional coral bleaching event. *Proc. Ass. Island Mar. iMbs. Carib. 21,* 47) are not well correlated with *in situ* surface water temperature measurements, and underestimate observed values by up to several degrees (34). Confusion between these data bases has resulted in publication of high resolution Caribbean temperature images which accurately show hot spots above 3I"C at bleaching sites (see images in Brown. B.. Ogdcn. J. 1993. Coral bleaching. *Sci. Am. 268,* 64-70 which were provided by A.E. Strong), juxtaposed with conclusions based on low resolution maps that show spuriously low temperatures around 29 Celsius at the same time, which were used to conclude that bleaching is not linked to high temperature (Alwood. D.. Hendee. J. and Mende/. A. 1992. An assessment of global warminiz stress on Caribbean coral reef ecosystems. *Bull. Mar. Sci. 51.* 1 18-130).
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46. This paper is dedicated to the memory of Dr. Carlos Goenaga. a brilliant researcher on corals and bleaching at the University of Puerto Rico at Mayague/. tragically killed by a wave while working on March 10. 1993.
47. Mild bleaching took place in 1993 in Jamaica. Florida, and the Bahamas following at small Western Caribbean hot spol. The I'irsl hot spot in the Pacific reached the Society Islands in February 1994. and mass bleaching began in March.

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