Ecological and Socioeconomic Impacts of 1998 Coral Mortality in the Indian Ocean: An ENSO Impact and a Warning of Future Change?
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The year 1998, was the warmest year since the start of temperature recordings some 150 years ago. Similarly, the 1990s have been the warmest decade recorded. In addition, 1998 saw the strongest El Niño ever recorded. As a consequence of this, very high water temperatures were observed in many parts of the oceans, particularly in the tropical Indian Ocean, often with temperatures of 3° to 5°C above normal. Many corals in this region bleached and subsequently died, probably due to the high water temperatures in combination with meteorological and climatic factors. Massive mortality occurred on the reefs of Sri Lanka, Maldives, India, Kenya, Tanzania, and Seychelles with mortalities of up to 90% in many shallow areas. Reefs in other parts of the Indian Ocean, or in waters below 20 m, coral mortality was typically 50%. Hence, coral death during 1998 was unprecedented in severity. The secondary socioeconomic effects of coral bleaching for coastal communities of the Indian Ocean are likely to be long lasting and severe. In addition to potential decreases in fish stocks and negative effects on tourism, erosion may become an acute problem, particularly in the Maldives and Seychelles. If the observed global trends in temperature rises continue, there will be an increased probability of a recurrence of the phenomenon observed in 1998 on the coral reefs of the Indian Ocean, as well as in other parts of the tropical oceans in coming years. Coral reefs of the Indian Ocean may prove to be an important signal of the potential effects of global climate change, and we should heed that warning.

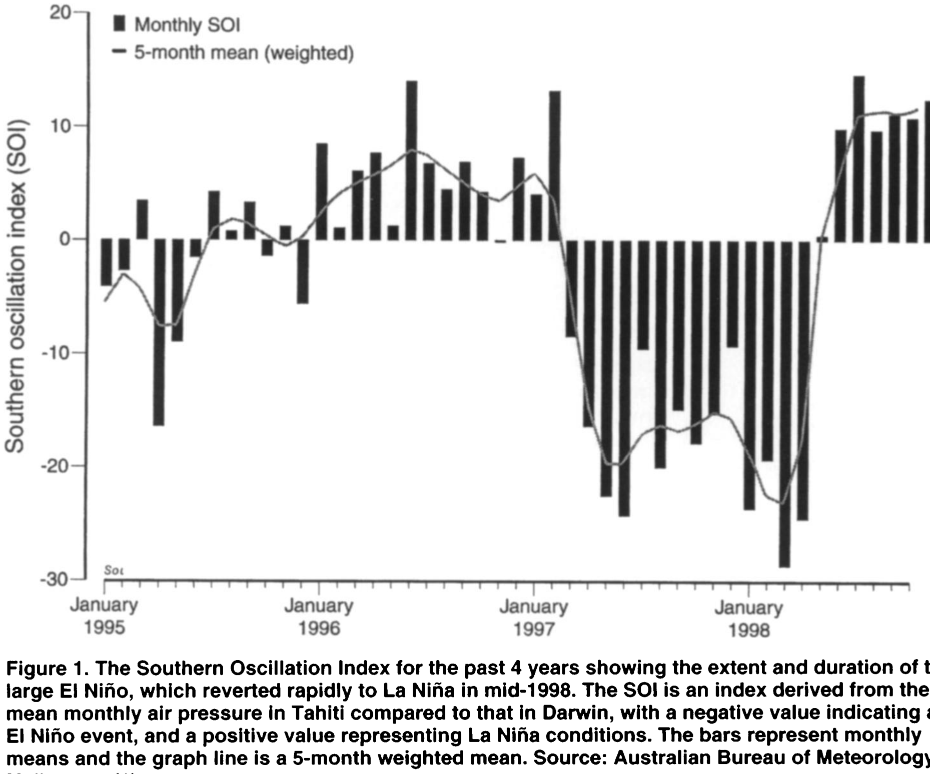


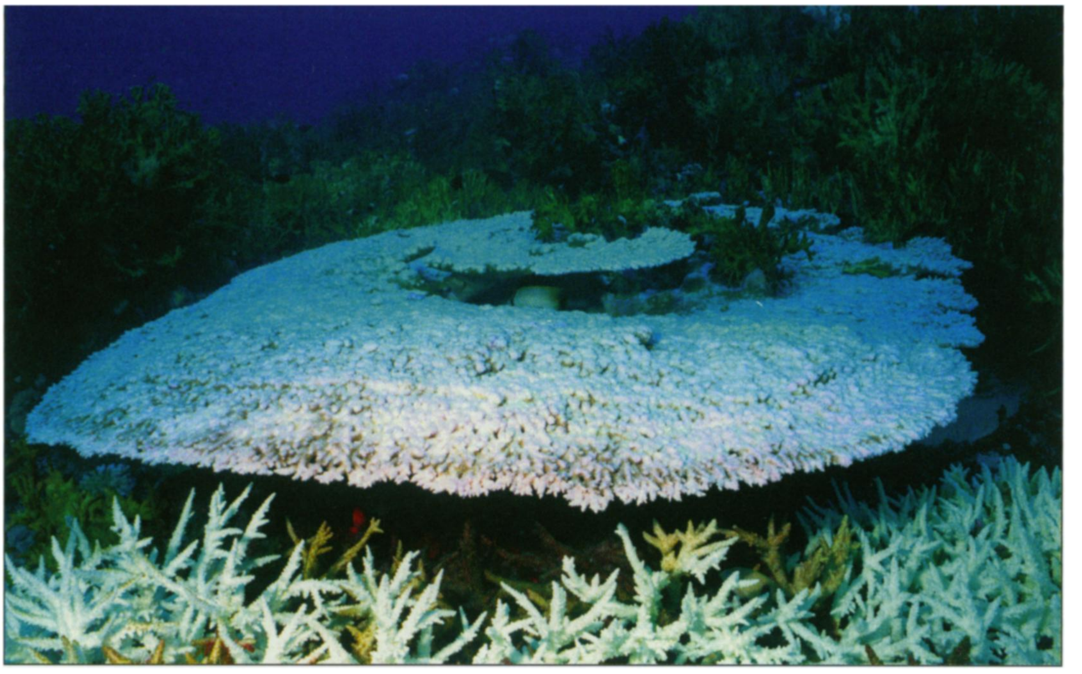
Figure 1. The Southern Oscillation Index for the past 4 years showing the extent and duration of the large El Niño, which reverted rapidly to La Niña in mid-1998. The SOI is an index derived from the mean monthly air pressure in Tahiti compared to that in Darwin, with a negative value indicating an El Niño event, and a positive value representing La Niña conditions. The bars represent monthly means and the graph line is a 5-month weighted mean. Source: Australian Bureau of Meteorology, Melbourne (1).

INTRODUCTION

In 1998, there was unprecedented bleaching and subsequent mortality of hard and soft corals over large areas of the world, with the most severe bleaching ever reported occurring around the central Indian Ocean islands of the Maldives, the Seychelles, and Sri Lanka, and on the coasts and islands of India, Kenya, and Tanzania. The start of bleaching during the peak of summer in the Southern Hemisphere in February 1988 coincided with a large El Niño event, and bleaching then stopped, but started in South-east and East Asia just as the Asia-Pacific climate switched over to a strong La Niña in June (Fig. 1; 1). Experienced observers in countries of the Indian Ocean Region reported that bleaching on this scale or of this severity had not occurred over the past 40 years. The bleaching often affected around 90% or more of the living corals and resulted in death of many of these (2). At the same time severe bleaching was occurring in the Middle East, and in Southeast and East Asia, Far West, and Far East Pacific. Bleaching also occurred at several locations in the Caribbean Sea and Atlantic Ocean. Coral bleaching events have been recorded since the late 1800s and usually involve a few locations with minor damage to reef corals. The massive coral bleaching and mortality in 1998 should be considered against the backdrop of decades of rapid deterioration of coral reefs all over the world; mainly due to human activities (3, 4). What was alarming about the 1998 bleaching event, was high mortality and the widespread occurrence, and that many reefs previously regarded as near-pristine were seriously affected.

A variety of environmental stresses are known to cause bleaching whereby the corals lose their endosymbiotic algae, the zooxanthellae (5, 6). The most frequently reported bleaching stress is a rise in water temperatures of only a few degrees above the typical seasonal maximum for the corals (7, 8). The bleached coral appears white because the skeleton is visible through the transparent tissue. If the algae, which also exist in a flagellated planktonic form outside the coral, return and repopulate the coral, it will recover and continue to grow normally. If not, after several weeks to months the coral will die. Similar types of bleaching are known to occur in other organisms, e.g. giant clams and sponges.

The bleaching and mortality of corals in the Indian Ocean has already had a severe impact on coral communities and species composition on many reefs throughout the region. It is too early to determine how widespread and long lasting the effects will be on the coastal ecosystems of large areas of the tropical Indian



Massive bleaching among table-forming and branching *Acropora* spp. the photo was taken at 18 m depth at St. Pierre, Farquhar Group, Seychelles, April 1998. The temperature in the water was 31 to 34°C. Photo: A. Maslennikov.

Ocean. Of a far greater concern, however, are the socioeconomic consequences for the millions of peoples who depend on the reefs for their food, income, protection from ocean waves, and recreation. To determine the extent of these ecological and socioeconomic effects and the path of recovery are the targets for several recent research projects (9). Widespread coral bleaching also poses the question: is this a unique catastrophic event or a portent of similar serious imbalances in the ecosystems as a result of global climate change?

We have focussed on the Indian Ocean because the 1998 bleaching event was most severe in the region, and because bleaching on this scale has not been witnessed before. This paper aims to combine perspectives from several disciplines and to synthesize the likely consequences of this event immediately after it has happened. Therefore, much of the following will be speculative, but we hope to focus the attention of readers on this event so that action will be taken to ameliorate the consequences for the peoples in the region.

EXTENT OF BLEACHING IN THE INDIAN OCEAN

Using satellite data, it was possible for the National Oceanographic and Atmospheric Administration of USA (NOAA) to advertise the location of anomalously high sea surface temperature (SST) over the Internet. This alerted scientists and recreational SCUBA divers to report on incidences of bleaching and, when possible, carry out surveys of affected areas to detect the extent of the coral bleaching and mortality (Table 1). Reports were requested over the Internet by the Global Coral Reef Monitoring Network and NOAA in late September 1998 and these were assembled (2). This widespread publicity had two conflicting effects: it provided reports with widely different levels of

Table 1. Summarized reports of bleaching and post-bleaching mortality on coral reefs in some Indian Ocean countries. The % values for "bleached" and "mortality" are a mix of actual survey data and estimates from experienced coral reef researchers. Where available bleached is divided into "shallow" (less than 10 m depth) and "deep"—more than 20 m depth. Maximum water temperatures were also provided for many sites.

Country	% Bleached	% Mortality	Start - Finish	Max t°c	Refs
Australia Scott (Timor Sea)	70–100 (shallow) 40 (deep)	80 40?	April–May		2
Australia Cartier, Hibernia, Seringapatam reefs	slight	slight	–		2
Chagos atolls	unknown	unknown	–		–
Comores	high?	high?	May - ?		2
India Lakshadweep	?	90+	May–June		10
India Andamans	range 50—93 mean 80	range 60—95 mean 70	May–June		11
India Gulf of Mannar	mean 85	mean 73	May–June		12, 13
India Gulf of Kutch	10–30	?	June - ?		14
Kenya	90–100 (shallow) 50 + (deep)	50–90 (shallow) 50 + (deep)	March–April	32	2
Madagascar (mid-west)	30	?	February - March	33	2
Madagascar (Mananara)	40–80 (shallow) 10–40 (deep)	? high	February–March		2
Madagascar (Tulear)	near 0	near 0	–		2
Maldives (6 atolls throughout)	80–95 (shallow) 30–40 (deep)	80-90 + (shallow) ?	April–May	32 shallow 30 deep	15
Mauritius	1–15	slight	April only	30	2
Oman	75–95 (in parts)	5–10 ?	May- ?	31.5	2
Mayotte	up to 80%	high	April only		2
Réunion	30–50	slight	February–March		2
Seychelles	40–95	range 50–95 mean 75	March–May	34	2
Sri Lanka NE coast Pigeon Id	none	none	–		16
Sri Lanka SW coast	75–90+	80+	April–June	35.5	16
Tanzania Southern	15–25	50?	April–June	30.5	2
Tanzania Zanzibar	25–50	20–40?	April–June	30.5	2
Tanzania Tanga	25	?	April–June	30.5	2
Tanzania Mafia Island	80–100	80–100	April–June	30.5	2

Note: Specific details for countries in Wilkinson (2) were obtained via e-mail correspondence and the sources of that information are listed in that report.

accuracy from a wide range of reefs throughout the world; and also it stimulated reporting of bleaching that was previously regarded as normal.

Bleaching was most pronounced in shallow water (less than 15 m) and particularly affected staghorn and plate *Acropora* and other fast-growing species (*Echinopora, Montipora,* and others), and with a high proportion of coral deaths. Slower growing massive species, like *Porites*, also bleached, but many recovered within 1 to 2 months. Warm surface waters developed and then progressively warmed-up waters from south to north during the first 6 months, with considerable coral reef bleaching occurring in each locality. The warm pool of water was first observed in satellite images from NOAA, USA, in January 1998, with the first bleaching being reported one month later as these warm waters intersected coral reefs. Bleaching in 1998, in parallel with NOAA's satellite SSTs (Fig. 2), is similar, but more severe than the 1987/1988 El Niño in the Indian Ocean, which caused some mortality. Below the bleaching in each country is classified under two broad headings.

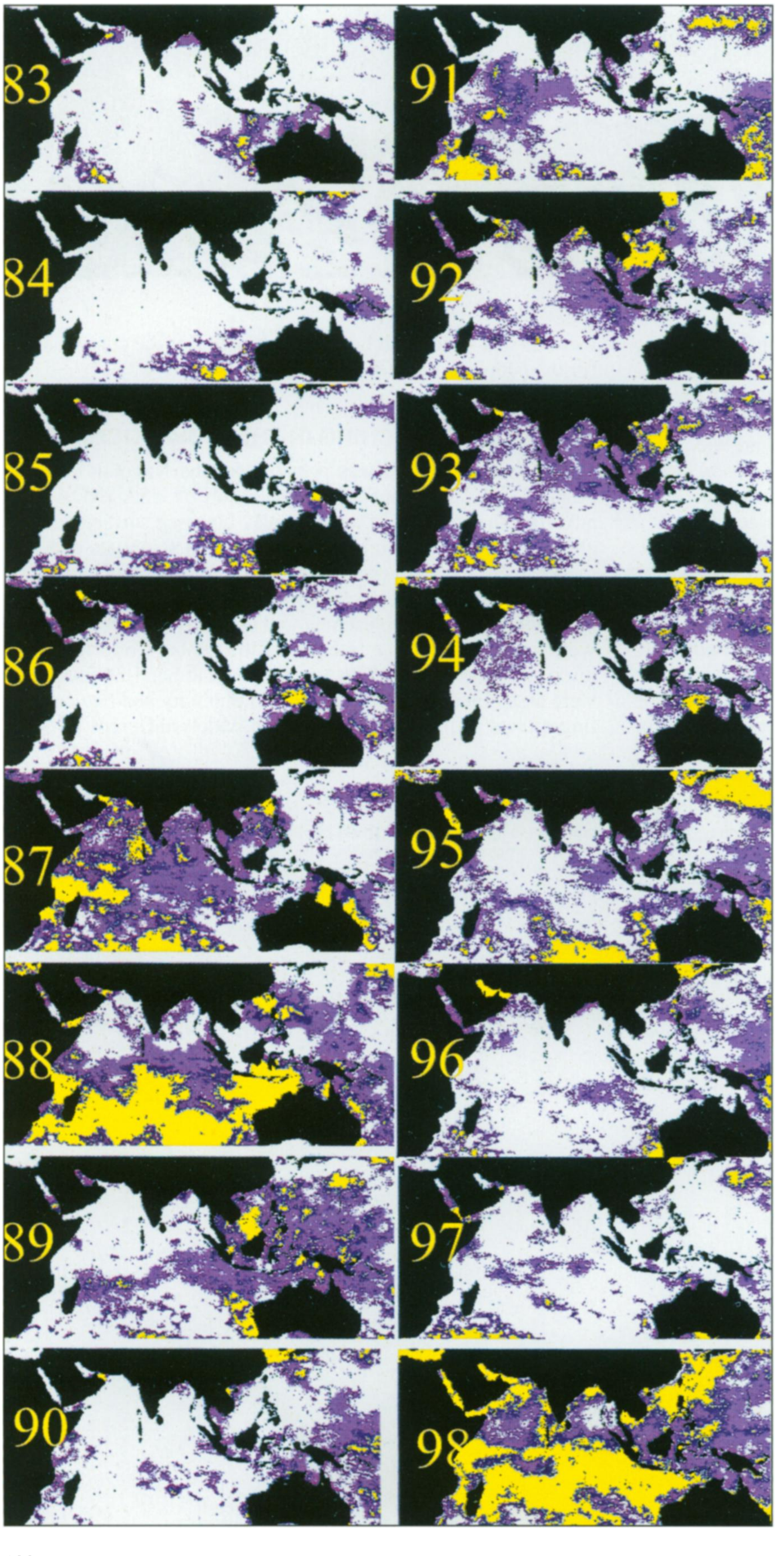


Figure 2. Sea surface temperatures (SSTs) in the Indian Ocean up to 1998. Each is a composite figure of the 12 monthly mean SSTs as they exceeded the maximum summertime climatological values and clearly shows 'HotSpots'. These 'HotSpot' anomalies, defined as SSTs equal to or greater than 1°C above the summertime level, are colored yellow to orange. The earlier years are hindcast composites generated from archived monthly mean data from NOAA going back to the first satellite observations in 1982. These composites demonstrate that 1998 was an unprecedented year for elevated SSTs and also for coral reef bleaching. The area involved during 1998 far exceeds anything shown previously, with the most significant previous 'HotSpot' year with high potential for bleaching being 1988. Some other years showed lesser amounts of heating. Region shown: 35°N to 35°S and 20°E to 165°E.

Severe to Catastrophic Bleaching

There was severe damage to coral reefs in the central tourism region of the Maldives, with around 80% of corals wholly or partially bleached in shallow water, and around 30–45% at depths of between 10 and 30 m. Bleaching was also seen at 50 m. About 95% of shallow-water corals died, as well as most soft corals and anemones. Similar bleaching was observed by seaplane operators throughout the Maldives. Some recovery began in May, but was not rapid. Bleaching started in Sri Lanka in April after the warm pool of water migrated from the Maldives, and was most severe in the southwest (Hikkaduwa Marine Sanctuary, over 75% bleached; and Buona-vista, 90–95%), with almost all coral species affected. By late April, bleaching had spread to reefs off Colombo and was noticeable down to 42 m on the southeast coast near Battilacoa in May. Some recovery of corals was seen in June, but most branching and tabulate *Acropora* and *Pocillopora* colonies were dead. Bleaching like this has never been seen on the southwest coast before, but no bleaching was observed on the northeast coast near Tricomalee. Bleaching in India commenced after Sri Lanka, on the outer-atoll seaward slopes of the Lakshadweep Islands, with about 90% mortality of what had been excellent live coral cover (up to 80–90% in places). Bleaching extended to at least 10 m. Similar severe bleaching was observed in the Gulf of Mannar and around the Andaman Islands, however, further to the east there was no bleaching on the Andaman Sea coasts of Myanmar and Thailand. Moderate bleaching was seen further north in May in the Gulf of Kutch on the northerly Gujarat coast.

There was extensive bleaching throughout the Seychelles, e.g. with 40–50% bleached down to 23 m in the south on Aldabra, Providence Group and Alphonse Group during March–May. About 75% of corals had recently died in the Seychelles Marine Park system, but other reports were of only moderate bleaching. Further west in Kenya, bleaching started in mid-March and continued during April, with some reports as low as 50%, but most bleaching was near 100% on almost all reefs in shallow water, and 50% or more at 20 m. Coral mortality was high (50 to 90%) and reefs now have about 1–10% coral cover. Corals bleached in mid-May along the whole coastline of Tanzania, with reports varying from 15% to 25% of corals bleached, to over 50% in some areas. *Acropora* species were severely affected with over 80% mortality in most areas, e.g. in the 'coral gardens' of Kinasi Pass, 80 to 90% of *Acropora* died, and 80–100% of corals died in Mafia Marine Park, which was probably the best coral reef in the country with 80 to 90% mixed community coral cover over vast areas.

There was 70 to 100% bleaching and mortality of corals down to 9 m, and 40% at 30 m depth on the remote Scott atoll in the far east Indian Ocean. Shallow sites previously had up to 75% coral cover, which dropped to 15% with some very large corals dying. Other remote reefs—Cartier, Seringapatam, and Hibernia—were only slightly bleached.

Mild to Zero Bleaching

Reefs in large areas of the southern Indian Ocean suffered only mild bleaching, that was not exceptional. About 30 to 40% of corals on parts of the west coast of Madagascar bleached, but other sites and the east coast were apparently unaffected. Likewise on Mauritius and Réunion, bleaching was minor (1–15%), with some small localized areas of moderate bleaching up to 50%, with corals showing minor loss of color and some mortality on Réunion. Information for Comores, Mayotte, and Chagos is sparse or nonexistent, but some anecdotal reports of bleaching were received.

SPECIFICITY OF CORAL BLEACHING

Bleaching is a general stress syndrome in reef building corals, as well as other reef organisms, which live symbiotically with photosynthetic microalgae. These minute single-celled organisms are dinoflagellates, e.g. zooxanthellae (*Symbiodinium* sp.). During coral bleaching, the zooxanthellae are lost from the coral or the zooxanthellae die in the tissue of the polyp, or there is a loss of chlorophyll pigment (5, 6). As a result of this loss, the coral polyp turns transparent and the white that the observer sees is the coral skeleton. The stress that causes bleaching can be of several different types, but high and low temperatures, particularly increases of just a few degrees above the normal summer maximum, are known to be major causes of bleaching (6–8). Other known stress factors are high or low levels of visible and UV radiation when the water is calm and clear, low tides, i.e. long periods of exposure to air, low or high salinity and pollution. Coral bleaching is often the first sign of stress, and if the conditions do not return to normal quickly, the coral will die after weeks or months, depending on the sensitivity of the coral and/or the severity of the stress.

The post-bleaching period is particularly critical for a coral, because it is without its major 'energy manufacturing system', and is in effect starving. Growth and reproduction stop or are markedly reduced, susceptibility to disease increases, ability to compete decreases, and the ability to shed sediment decreases. During this stage the coral is just surviving on previous energy reserves and on any new energy it is able to capture via predatory feeding. If conditions improve, the coral may start to recover either by regenerating its algal population from a few remaining cells, or by capturing new algae from the surrounding water and establishing new symbiotic relationships with these. The net effect for the coral and the reef will be slowed growth and probable loss of reproduction for a year.

If the stress conditions are particularly severe or prolonged, or another stress event is imposed on the corals (e.g. decreases in salinity because of heavy rain, or increases in pollution) then recovery will be impeded and death will follow. Obviously corals that are already under stress from pollution or excess sediment, or are under strong competition from other animals (e.g. sponges, ascidians) or macroalgae, have reduced recovery potential.

Normally, low level or chronic bleaching only affects the fast growing corals, especially the *Acropora* species, and the larger, massive and slow-growing species are rarely damaged. If these more resistant species do bleach, they are often the first to recover. During the 1998 bleaching event, however, a much wider range of species was affected, and in some instances almost all corals on the reefs of the Maldives, Sri Lanka, Kenya, and Tanzania bleached. In addition to *Acropora*, massive bleaching and mortality were observed in *Astreopora, Echinopora, Galaxea, Lobophyllia, Millepora, Montipora, Pocillopora, Porites,* and *Seriatopora*. The soft corals (Anthozoans), anemones, tridacnid clams and some sponges with cyanobacterial symbionts were also affected. Some coral species appear not to have bleached significantly; including *Diploastrea* and *Pachyseris*. Observations coincident with the Mafia Island, Tanzania, bleaching in 1998, showed that there are separate genetic clones within the same species of coral that are less susceptible to temperature increases and survived (U. Lindahl and O. Linden, pers. comm. of data from ongoing research at Mafia Island, Tanzania). The observations concern *Acropora formosa,* but the phenomenon may be true also for a number of other common coral species. Variations in the amount of bleaching may either be due to an inherent property of the host coral or of the symbiont zooxanthellae. Will the surviving corals have greater resistance to future bleaching stress after this bleaching episode? It has been suggested that corals will adapt to increasing temperatures (more bleaching stress) by obtaining new, more resistant zooxanthellae from the environment (17).

In February 1999, 80 to 90% of the bleached corals in the more severely affected areas had died, including previously resistant species, and many of the remaining corals were still bleached or had reduced color. Thus, it is uncertain whether these will survive, because of the prolonged period that these corals have been without the energy produced by their symbionts. The bleaching in the Indian Ocean coincided with the 1998 annual Reef Check surveys of coral reefs throughout the world (18). The resulting mortality was sufficiently extensive to lower the proportion of live to dead coral across the whole Indian Ocean between 1997 (80% live; 20% dead) and 1998 (64% live; 36% dead).

In many areas, the first species killed were branching corals, particularly of the genus *Acropora* (and *Montipora* in the Pacific), that often dominate shallow reef flats. In cases where the heated water subsequently reached to the base of the reef, corals with a massive growth form such as *Porites* were killed. An indication of the severity of bleaching was provided on some reefs where corals many centuries old have now succumbed. On Scott Reef in the eastern Indian Ocean, massive *Porites* colonies several 100-years old were extensively bleached and some died (2). Similar reports of the death of old corals, some as old as 700 years, have been reported from eastern Australia and Vietnam (2). Chronic bleaching normally affects only shallow water corals, usually because the warmer waters remain on the surface, however, during the 1998 bleaching event, large areas of deep water (> 20 m) corals were affected. There were reports of bleaching of corals down to 25 m in Kenya and the Seychelles, > 40 m in Sri Lanka, and > 50 m in the Maldives. Such bleaching was not the result of localized heating of surface waters, but because atmospheric conditions had warmed a large pool of water which then moved over the reefs. Moreover, the bleaching was not a transient event, but it started in late summer (February and March) in the Southern Hemisphere, and followed the sun from south to north for several monthes. There were reports in late May and June of fresh outbreaks of bleaching in areas previously not seriously affected.

EL NIÑO, GLOBAL CLIMATE CHANGE AND INDIAN OCEAN CORAL BLEACHING

The global mean surface temperature in 1998 was the highest on record (Fig. 3), which also coincided with the most extreme El Niño ever recorded (Fig. 1). Beginning in late 1997, and continuing through to late 1998, sea temperatures rose sequentially around the world. The monthly progression of high sea-surface temperature (SST) anomalies was clearly seen in AVHRR satellite images. In many tropical areas where coral reefs are found, sea-surface temperatures rose 2°–3°C above the normal seasonal maximum, but in some locations 4°–6°C increases were recorded (Fig. 2). Records obtained from divers and other sensors indicate that temperature increases were not only confined to surface waters, but extended to 40 to 50 m depth.

The powerful El Niño started off Ecuador, and was visible in NOAA satellite images at the end of January 1997. SSTs were as much as 4°C above normal seasonal maximum and expanded in the eastern Pacific by July 1997. By January 1998, the El Niño was continuing in the eastern Pacific, and patches of anomalous hot water appeared in the Indian Ocean off east Africa, Madagascar, and along the east coast of Australia. Heating intensified in February, and bleaching was simultaneously reported at these sites. The pool of hot water (HotSpots) in the Indian Ocean increased in size and spread northwards by May reaching the south coast of India. Severe bleaching occurred in the Maldives, Sri Lanka, the Andamans, and Lakshadweeps, followed by high levels of mortality, starting in April and being progressively later to the north (Table 1). As low level winds began to increase, the Indian Ocean then started to cool, while the South China Sea and far west Pacific started to heat up coinciding with a strong La Niña that commensed in June and July (Fig. 1).

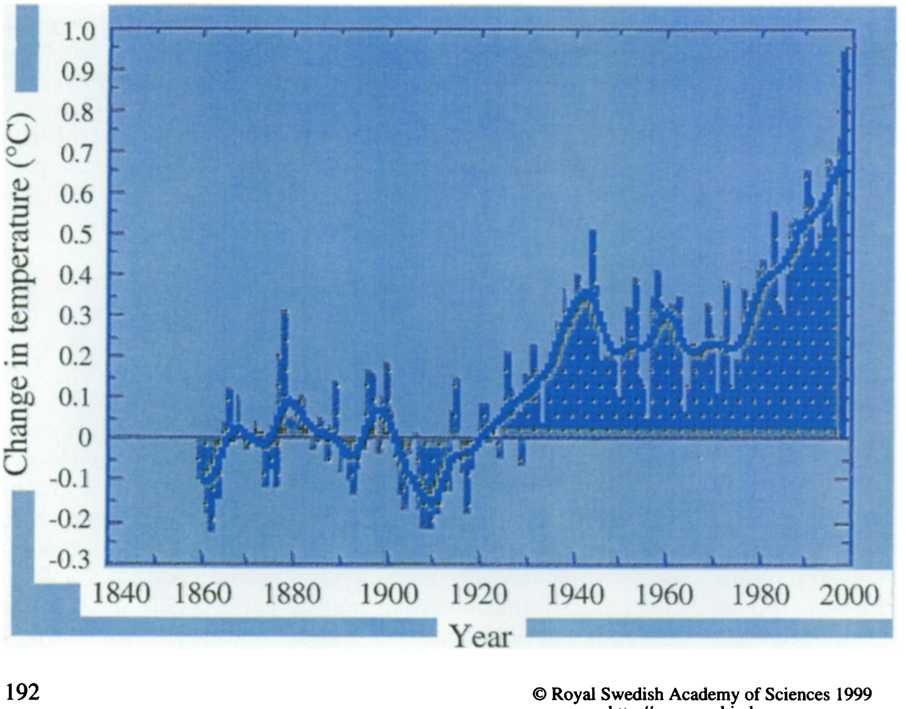
The proximal cause of bleaching and mortality has not been accorded universal acceptance (19). While the SST anomalies have proved to be a reasonably good predictor of where coral bleaching may occur (21), the actual cause of bleaching at a particular reef may be a combination of physical factors such as temperature, number of days of sunlight, UV level, and biological factors such as the health of the coral (5–8). There were stressors unrelated to temperature and large regional effects like El Niño that apparently caused bleaching in 1998, including low temperatures (Sulawesi; 2), low salinity due to high terrestrial runoff during large storms (Comores and Réunion; 2) and exposure during extreme low tides (Samoa and Tanzania; 2).

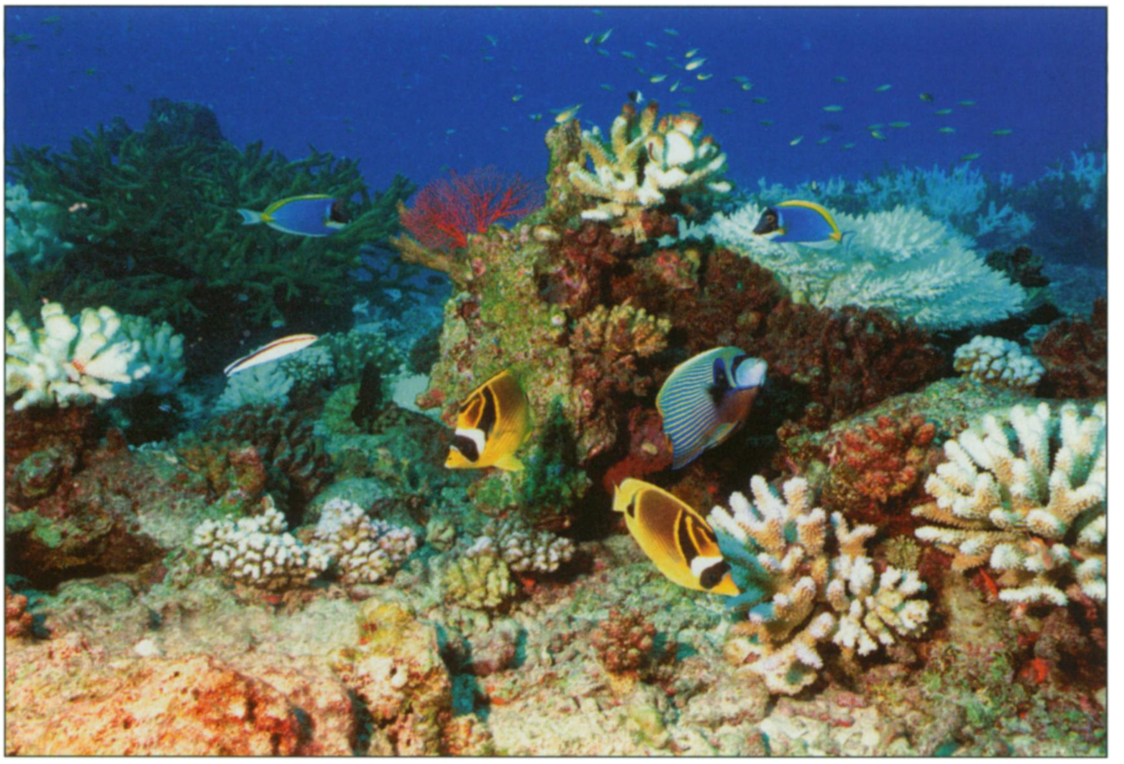
There are 3 general categories of potential causes for the 1998 SST anomalies: (a) a stochastic event; (b) El Niño; and (c) global warming. The variability in weather patterns is naturally high and it is possible that the unusually hot 1998 was also an unusually calm year with less strong winds than previously experienced. Other factors such as the level of storm activity, upwelling, number of days of cloud cover, or strength and direction of winds would all affect whether the solar heating would be dissipated by mixing or would build up to lethal levels. Coral bleaching events appear to have increased in frequency, and it has been hypothesized that global warming is one cause (7, 8). From an historical perspective, the 1998 bleaching was a rare event, possibly a 1000-year event. If similar events occur in the forthcoming decade, then this may be a sign of global warming being the cause of bleaching, as is being suggested by the increasing trends in global mean temperatures over the past 100 years (Fig. 3). Only time will tell whether the stochastic character of the event can be excluded.

The ENSO (El Niño Southern Oscillation) event was responsible for heating of the eastern Pacific, and pressure gradients over both the tropical Pacific and Indian oceans weakened dramatically. As trade winds began to increase at the end of the ENSO event, the improved surface mixing also corresponded with the end of the high SSTs over the Indian Ocean. Is it, however, very coincidental that the end of the ENSO event also corresponded with the end of the high SSTs. A somewhat similar ENSO reversal occurred during 1987 and 1988 (between El Niño and La Niña) with similar high temperatures in the Indian Ocean, primarily over only the southern Indian Ocean reefs with some bleaching, but nothing like the 1998 bleaching in severity (Fig. 2).

It is not possible to determine how much global warming has contributed to the high SST anomalies. The Intergovernmental Panel on Climate Change (IPCC) concluded that global warming is already measurable at about 0.3° to 0.6°C (22). The latest climate model released from the Hadley Climate Centre (20), predicts a seawater temperature increase of 2°C within 50 years due to global warming. If these predictions are correct, and all other factors remain equal, then the immediate future of coral reef ecosystems is threatened unless global warming is reversed or corals adapt rapidly. This is irrespective of whether this year's event was due primarily to ENSO, chance, or global

Figure 3. Global mean temperatures over the past 140 years showing an unambiguous increase in mean temperatures with 1998 being the warmest on record. Source: Hadley Centre (20).





Bleached and partly bleached *Acropora* sp. and *Pocillopora* sp. and various reef fishes including butterfly fishes, emperors, cleaner wrasse and surgeon fishes. The photo was taken at 15 m depth at St. Pierre, Farquhar Group, Seychelles, in April 1998. The temperature in the water was 31 to 34°C. Photo: A. Maslennikov.

warming. A major difficulty in interpretation is that multiple factors can impact simultaneously. This makes observations from areas remote from continental land and local changes in vegetation cover particularly valuable. One such area where data have been reported recently is the Chagos Archipelago (British Indian Ocean Territories), where there has been a clear trend of rising temperatures over the last 25 years (23). The average temperature has risen nearly 1°C with a corresponding or greater rise in 95 percentile temperature values, i.e. the warmer periods have become even warmer; in parallel, there has been a significant reduction in cloud cover over the same period. Cloudiness has decreased from 25% 25 years ago to 15% in 1998, meaning that these reefs now receive a considerably larger amount of solar radiation, including UV. As the Chagos Archipelago is truly mid-oceanic, the climate changes recorded here may provide evidence for a regional warming trend.

FATE OF BLEACHED INDIAN OCEAN CORAL REEFS

The 1998 bleaching event will have both immediate and long-term impacts on Indian Ocean coral reefs. Coral reef bleaching is a common phenomenon. However, the ecological effects of such an extreme event as the one in 1998 are not easily predicted. There are many biological and physical factors that will affect the outcome. Near complete recovery is expected for most reefs that did not suffer major damage, i.e. those in the southern Indian Ocean (Comoros, Madagascar, Mauritius, Mayotte, and Réunion), whereas in other areas, mortality is already high and whole reefs have in effect died. The immediate impact is a loss of amenity for tourists; an algal covered reef lacks many of the attractive colors and shapes of a living reef. But the long-term consequences are far more severe, particularly if the 1998 bleaching is repeated.

Recovery of Reefs that Bleached but did not die

Growth and reproduction stop or are reduced in bleached and recovering corals, therefore coral productivity is lowered and susceptibility to other stresses increases. Generally, if conditions improve, corals recover with the net effect for the coral and the reef being slowed growth and probable loss of reproduction for a year. Enough corals typically survive in deeper waters, and these can provide new larvae for recovery in damaged areas. In addition, there are often some living polyps in otherwise dead colonies; these may reproduce asexually and overgrow the dead areas. This will be the case for most reefs in the southern Indian Ocean where no major mortality has been reported. Hence, it can be assumed that many reefs in the Comoros, Madagascar, Mauritius, and Réunion will probably recover relatively rapidly—within 5 to 10 years—possibly with a small shift from susceptible corals to less susceptible species, e.g. fewer *Acropora* species, initially. However, the stress was apparently more severe in large parts of the northern Indian Ocean in 1998, where coral mortality was high.

Recovery of Dead or Severely Damaged Reefs

Large areas of reefs in the Maldives, the Seychelles, Sri Lanka, parts of India, Kenya, and Tanzania have died during 1998. In many areas, virtually all corals in shallow waters (less than 10 m depth) bleached and died. Factors affecting recovery and recolonization include:

- presence of small patches of living polyps, perhaps not easily visible on the lower parts of the colony or in shaded areas;
- survival of some corals, particularly in deeper water (> 20 m), capable of reproducing sexually or asexually;
- continuation of physical conditions suitable for larval settlement and growth;
- no repeat of high temperatures in the next few years;
- absence of other stress factors such as pollution or sedimentation.

For a reef to recover and return to normal, there must be sufficient areas of living coral on reefs upstream of the affected areas that are able to provide new larvae. If only part of a reef has died, recovery of relatively fragile, fast-growing branching and foliose corals may take 5 to 10 years in shallow water. Deeper sections of reefs previously dominated by slower growing massive and encrusting corals will take much longer to recolonize, perhaps 25 to 50 years. Initially, however, faster growing 'weedy' species may provide some coral cover. New recruits are likely to settle during the coming spawning seasons and recovery will commence, provided that there are no major additional stresses and that there are sufficient populations of algal grazing fishes and sea urchins to clear away the mats of turf algae. Overfished or polluted reefs will recover much more slowly.

If an isolated reef is effectively dead and there are few or no larvae available, the prognosis for long-term recovery of the reefs to their former condition is poor. Recovery will take at least 20 years and maybe longer. A dead reef will initially be dominated by algae, which form thick green or brown mats. Fish productivity may remain stable or show increases in herbivore species such as parrot fish, surgeon fish, and rabbit fish. There will be some losses of species that depend on live corals, like butterfly fish, which are important for the aquarium fish trade. However, the extent of bioerosion caused by mollusks, sponges and worms will increase, resulting in a massive weakening of the fabric of the reef. As a result, the coral reef framework will gradually collapse and degenerate into a low profile pile of rubble. Such rubble will provide very limited hiding places for fish and poor substrata for new coral recruitment. Fish productivity will most likely fall slowly and remain low until there is reasonable recovery of reef structure. This is a possible and perhaps the most likely scenario for large parts of the Maldives, Lakshadweeps, the Seychelles, Kenya, and Tanzania.

SOCIOECONOMIC IMPACTS ON THE PEOPLES OF THE INDIAN OCEAN REGION

The Indian Ocean region has the most densely populated coastal areas in the world, with 135 persons km^{-2} (24). Most of the population is poor and dependence on fisheries for both income and protein intake is high. In the Southern Indian Biosphere Reserve in the Gulf of Mannar, nearly 200 000 people earn their livelihoods directly from the sea (one-third of the population) and 90% of fisherfolk are artisanal, relying on harvesting nearshore reef-related fisheries, and seaweed resources. Overfishing is already a major threat and the coral bleaching effect could worsen this. For instance, along the reef coastline of Eastern Africa, around 50% of the estimated 100 000 full-time fishers and several hundred thousand part-time fishers risk losing their livelihood if overfishing is allowed to continue (25). An additional impact linked to the coral bleaching event, is that some fish may become toxic, because levels of ciguatera poisoning in the French islands of the Indian Ocean have increased in recent months. There has also been an increase in ciguatera in Réunion and other French territories in the Indian Ocean, apparently as a result of the bleaching disturbance (J.-P. Quod, pers. comm.).

In other areas, diving and coastal tourism are the main income generating activities, such as in the Maldives where 45% of GNP stems both directly and indirectly from tourism revenues. Coastal tourism is already under pressure in places like Kenya where 90 000 out of 150 000 employees have lost their jobs in recent years (25). Coastal lands around the Indian Ocean are prone to seasonal cyclones, but the coral reefs form natural barriers and can thus reduce erosion. In Sri Lanka, severe coastal erosion has already occurred in areas where the reef substrate has been heavily mined and further damage to the reefs from bioerosion of dead coral will introduce a heavy financial burden. Revetments, groynes, and breakwater schemes to prevent further erosion have already cost the Sri Lankan government around USD 30 million (26).

The impact of the 1998 massive coral bleaching on the people in this region is likely to be severe, given the high dependence on the functions and services that coral reefs provide to the tens of millions of people around the Indian Ocean. However, a precise estimate of human impacts is difficult to make at this early stage. This is due to the uncertainty surrounding many of the relationships between coral bleaching and mortality on the one hand, and ecosystem services, such as fisheries, tourism, and coastal protection on the other. Moreover, the rate of recovery of reefs after widespread mortality is difficult to predict. Two extreme scenarios, as well as many intermediate pathways are conceivable:

i) damage to the reef is not too dramatic and recovery is relatively rapid;
ii) damage is severe and there is very slow or no recovery, which will result in long-term severe impacts.

In the optimistic Scenario *i.*, the likely socioeconomic effects are:

- a possible slight decrease in tourism-generated income and employment, as some dive tourists may stay home or go elsewhere. However, most tourists will not alter their behavior;
- some changes in the fish species composition, both in the water and in fishery landings. Initially, total fish productivity may increase with larger populations of herbivores, though there may be reductions in the catches of certain target fish for niche markets, such as the ornamental fish trade;
- no major change in the coastal protection function, as bioerosion of dead reefs and coral growth and new recruits will be approximately equal.

In the Pessimistic Scenario *ii.*, socioeconomic effects could be very severe:

- there may be major direct losses in tourism income and employment as the information is spread throughout the diving community through dive magazines and the Internet. This is especially likely when charismatic marine fauna disappear as a result of the bleaching and resulting mortality;
- fish productivity may drop considerably as the reef structure disintegrates resulting in reduced catches for the fishermen, less protein in the diet, particularly for coastal communities, lower health status and possible starvation particularly among the poorer segments of the community. Fishermen could experience a major loss of income and reduced ability to purchase other food;
- a possible collapse of the protective barrier function of the reef, which could result in greater coastal erosion. This will be exacerbated by sea level rise.

A preliminary attempt to determine an economic value for these possible scenarios is presented in Table 2. This estimation is based on the valuation per km^2 of coral reefs in previous studies (27, 28). These values are multiplied by the area of reefs in the Indian Ocean 36 100 km^2 (4). The economic estimates are difficult because data and information on the extent and severity of the bleaching are preliminary and incomplete, assessments of damage to ecosystems are speculative, and there are large uncertainties about the flow-on relationships between coral death and economically valuable products like fish. The basis for these preliminary estimates is presented in Wilkinson and Buddemeier (29). It needs to be stressed that damage was not equally distributed among nations, with the major damage likely to be seen in the Maldives and the Seychelles.

In the Pessimistic Scenario *ii*, the total damages over a 20 year

Table 2. Estimates of the economic damage due to 1998 Indian Ocean coral bleaching. Net present value in million USD over a 20-year time horizon with a 10% discount rate.

Coral reef ecosystem services	Optimistic Scenario *i.*	Pessimistic Scenario *ii.*
Food production (e.g. fisheries)	260	1361
Tourism and recreation	332	3477
Disturbance regulation (coastal protection)	0	2152
Other services	114	1200
Total	706	8190

Bleached and partly dead branches of *Acropora* corals. The brown branches are dead and covered by epiphytic algae and bacteria.
Photo: A. Maslennikov.

time period exceed USD 8 billion (Table 2), primarily from coastal erosion (USD 2.2 billion), tourism loss (USD 3.5 billion) and fishery loss (USD 1.4 billion). In the Optimistic Scenario *i*, the losses are still considerable, but an order of magnitude less than the pessimistic scenario, stemming mainly from losses in tourism (USD 0.3 billion) and fisheries (USD 0.3 billion). However, the potential human suffering resulting from the coral bleaching and mortality, of possible malnutrition and increased poverty, as well as unemployment is more than dollar values can express. It is certain that further monitoring and research into both the bio-physical and socioeconomic aspects are required. However, it can be predicted that the massive bleaching will mean that national economies will be damaged and the international aid community will be called on for far greater support.

WHAT CAN BE DONE ABOUT THIS BLEACHING EVENT?

Resource managers are only able to effect changes at the local and regional scale; however the causes of this major bleaching event may result from activities at global scales. Reefs that are healthy and unstressed are more likely to recover than damaged or polluted reefs (30). In general, well managed, or reefs unstressed by anthropogenic impacts, have higher coral cover and presumably unstressed corals produce more coral larvae. In contrast, corals that are already under other stresses, e.g. pollution, excess sediment, increased competition from algae and other competitors, will succumb more readily to bleaching stress and more likely die. Moreover, those that survive will produce fewer larvae to repopulate damaged areas. Thus, the message is to increase current efforts at reef management through reducing anthropogenic impacts through the implementation of integrated coastal management.

At the global scale, the problems and solutions are more extensive and have been discussed at Global Climate Change Convention meetings over the past decade. If global warming is a result of anthropogenic activities, and is damaging coral reefs, then the solutions are both local and global—reducing green-house gas emissions, reducing consumption practices, reducing forest logging, planting more trees, etc. These are beyond the direct responsibility of the reef manager, other than by informing the global community of the current status of coral reefs. This can either be directly to the public, or through international forums such as United Nations convention meetings (Convention on Biological Diversity; Convention on Sustainable Development), to the Intergovernmental Panel on Climate Change, at meetings of Small Island Developing States, and to the United Nations General Assembly. This is one task that the International Coral Reef Initiative is undertaking.

CONCLUSIONS

If the coral bleaching event of 1998 is a rare, chance event, then affected reefs in the Indian Ocean area will recover within 25 to 50 years and, thus, global actions are not needed. Efforts would only be required to implement urgent measures to protect the people who have lost their livelihoods because of the bleaching. Any reef management that reduces concurrent stresses to coastal tropical ecosystems is essential, because reefs that are healthy and unstressed are more likely to recover than damaged and polluted reefs (30). In a geological perspective, the 1998 coral bleaching may not be an unusual event. Reefs in past geological ages have been almost obliterated many times, e.g., 75 million years ago or during the last ice age, but recovery has followed, although over time scales of thousands to tens of thousands of years. However, recovery over geological time scales will not help people who are currently dependent on coral reefs for their livelihood.

If, however, the 1998 bleaching and mortality event in the Indian Ocean was mainly the result of global climate change and this change is continuing, there is greater reason for concern. This may be a chaos situation, whereby small changes in the global climate may be amplified in a region and trigger large impacts on coral reefs and other ecosystems. The 1998 bleaching event coincided with both the warmest year on record and strong El Niño and La Niña events.

If this is the case, there are no solutions to the problems of coral mortailty similar to what has happened 1998. In addition, greater problems may soon arise if the climate change continues with further temperature increases, as land ecosystems of critical importance to billions of people may start to break down in a similar way to coral reefs. The 1998 bleaching event may yet prove to be the first widespread warning of more serious changes due to global warming, e.g. destabilization of terrestrial ecosystems, and hence affect billions of people.

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