Coral Bleaching and Global Climate Change: Scientific Findings and Policy Recommendations

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Abstract: *In 1998, tropical sea surface temperatures were the highest on record, topping off a 50-year trend for some tropical oceans. In the same year, coral reefs around the world suffered the most extensive and severe bleaching (loss of symbiotic algae) and subsequent mortality on record. These events may not be attributable to local stressors or natural variability alone but were likely induced by an underlying global phenomenon. It is probable that anthropogenic global warming has contributed to the extensive coral bleaching that has occurred simultaneously throughout the reef regions of the world. The geographic extent, increasing frequency, and regional severity of mass bleaching events are an apparent result of a steadily rising baseline of marine temperatures, combined with regionally specific El Niño and La Niña events. The repercussions of the 1998 mass bleaching and mortality events will be far-reaching. Human populations dependent on reef services face losses of marine biodiversity, fisheries, and shoreline protection. Coral bleaching events may become more frequent and severe as the climate continues to warm, exposing coral reefs to an increasingly hostile environment. This global threat to corals compounds the effects of more localized anthropogenic factors that already place reefs at risk. Significant attention needs to be given to the monitoring of coral reef ecosystems, research on the projected and realized effects of global climate change, and measures to curtail greenhouse gas emissions. Even those reefs with well-enforced legal protection as marine sanctuaries, or those managed for sustainable use, are threatened by global climate change.*

Blanqueamiento de Coral y Cambio Climático Global: Información Científica y Recomendaciones Políticas

Resumen: *En 1998, las temperaturas superficiales en mares tropicales alcanzaron los niveles más altos reportados, sobrepasando una tendencia de 50 años en algunos océanos tropicales. En el mismo año, los arrecifes de coral alrededor del mundo sufrieron el evento más extenso y severo de blanqueamiento (pérdida de algas simbióticas) y una subsecuente mortalidad récord. Estos eventos pueden no ser atribuibles a estresores locales o a la variabilidad natural por si sola. Por el contrario, las elevadas temperaturas superficiales y los eventos de blanqueamiento del coral fueron muy probablemente inducidos por un fenómeno a escala global. Es probable que el calentamiento global antropogénico haya contribuido al blanqueamiento extensivo del coral que ocurrió simultáneamente a lo largo de las regiones coralinas del mundo. La extensión geográfica, la frecuencia creciente y la severidad regional de los eventos de blanqueamiento masivos son un resultado aparente del aumento de las temperaturas marinas de base, combinadas con eventos regionales específicos como El Niño y La Niña. Las repercusiones del blanqueamiento masivo de 1998 y de las mortalidades están lejos de alcance. Las poblaciones humanas dependientes de los servicios de los arrecifes enfrentarán pérdidas de biodiversidad marina, pesquerías y protección de la línea costera. Los eventos de blanqueamiento del coral pueden ser más frecuentes y severos con el continuo calentamiento del clima, exponiendo a los arrecifes de coral a un ambiente cada vez más hostil. Esta amenaza global a los corales combina los efectos de factores antropogénicos más localizados que ya están poniendo en riesgo a los arrecifes. Se requiere de una atención significativa al monitoreo de los ecosistemas de arrecifes, de una investigación de los efectos espera-*

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dos y observados del cambio climático global, y medidas para eliminar las emisiones de gases causantes del efecto invernadero. Aún aquellos arrecifes con protección legal bien aplicada en forma de santuarios marinos, o manejados para un uso adecuado, se encuentran amenazados por el cambio climático global.

Introduction

At the close of 1998, marine scientists urged officials of the U.S. Department of State to investigate the link between recent mass coral bleaching events and global climate change. After consultation with internationally recognized experts in the fields of marine biology and climatology, the State Department released a report in March of 1999 on coral bleaching and global climate change which concluded that the geographic extent, increasing frequency, and regional severity of mass coral bleaching events in 1997–1998 were an apparent consequence of a steadily rising baseline of marine temperatures associated with regionally specific El Niño and La Niña events (Pomerance et al. 1999). In response, the U.S. Coral Reef Task Force passed a resolution stating that conservation goals can no longer be achieved without taking global climate change into account (http://www.coralreef.gov). We review the scientific information that led to the conclusion of the State Department report and highlight the actions taken within the policy community since the report was released. The current state of coral reefs at the beginning of the twenty-first century suggests that, without immediate action, the massive world decline of coral reefs will continue.

Value of Coral Reefs

Coral reefs are one of the most productive ecosystems on Earth (although there are limits to the amount of harvestable productivity; Grigg et al. 1984) and the most complex, species-rich, and productive marine ecosystem (Stafford-Deitsch 1993; Sebens 1994; Bryant et al. 1998). Much of this productivity is derived from the substantial concentration of marine biodiversity in coral reefs. One estimate (Reaka-Kudla 1996) proposes that coral reefs have about 1 million species, of which only 10% are described. Large fish typically school along the reef, whereas small ones pack into the extensive network of crevices within the reef. The benefits of coral reef services are both immediate and long-term, making them a priority for conservation and a major resource for sustainable development (Table 1).

Pathway to Coral Bleaching and Death

When corals are physiologically stressed, the critical balance that maintains their symbiotic relationship with the algae (zooxanthellae) that inhabit their cells is lost. The coral may lose some or most of their algae, a major source of nutrition and color (Muscatine 1973; Trench 1979; Jaap 1985; Kleppel et al. 1989). Tissue growth, skeletal accretion (Goreau & Macfarlane 1990; Leder et al. 1991), and sexual reproduction are usually suspended (Szmant & Grassman 1990), and the corals, now devoid of color, are referred to as "bleached." Corals survive if the stress is brief but die if it is prolonged (Glynn 1996; Wilkinson et al. 1999). Sublethal stress may make corals more susceptible to infection by a variety of opportunistic pathogens, and disease outbreaks (epizootics) may result in significant coral mortality (Kusamano et al. 1996; Hayes & Goreau 1998).

Once mortality occurs, the reef's bare skeleton is colonized by rapidly growing seaweeds and other opportunistic organisms (Hayes & Goreau 1998). As long as the physical structure of coral reefs is maintained, they offer protection to a variety of marine life. Provided that favorable conditions are sustained and there is a supply of coral larvae, reef-building corals may recolonize bare surfaces and renew the reef-building process. Where large populations of parrot fish, sea urchins, worms, and other invertebrates erode the dead reef skeleton, however, the reef breaks down and becomes vulnerable to destruction by storm surges (Hutchings 1986; Glynn 1988; Eakin 1996; Reaka-Kudla et al. 1996; Wilkinson et al. 1999). Once the reef is reduced to rubble, fish and other marine organisms cannot be supported. Local human populations are thus placed at risk as fisheries stocks become greatly diminished, shoreline erosion increases, and the tourist industry declines (Roberts et al. 1998; Wilkinson et al. 1999).

Coral bleaching is most often associated with a significant rise in sea surface temperatures (Cook et al. 1990; Gates 1990; Glynn 1991; Goreau et al. 1993; Glynn 1996; Brown 1997; Winter et al. 1999). On-site observations and National Oceanic and Atmospheric Administration (NOAA) satellite-derived sea surface temperature records from North Atlantic and Caribbean reef locations show a significant correlation between all large-scale bleaching events and high sea surface temperatures (Goreau et al. 1993; Gleason & Strong 1995; Strong et al. 1998). The term *bleaching HotSpot* is now used to describe anomalies in sea surface temperature in coral reef regions that approximate or exceed by at least 1.0° C the sea surface temperature expected climatologically during the warmest months of the year (Goreau & Hayes 1994; Strong et al. 1997). (The spelling of the word *HotSpot* originated with a 1998 paper published in *Reef Encounters* and has been adopted by the U.S. National Oceanic and Atmospheric Administration in an attempt

Table 1. Coral reef services.

Value	*Description*
Tourism	• Most island populations in the Indian Ocean and the Carribean depend on income derived from tourism. • In the Maldives, 45% of the gross national product stems directly and indirectly from tourism revenues, generated largely from diving and other coastal tourism (H. Cesar, personal communication). • In 1990 alone, reef- and beach-based tourism added $89 billion to the gross domestic product of the Carribean region (Jameson et al. 1995). • Tourism on the Great Barrier Reef generates $1.5 billion each year for Queensland, Austrailia (Richmond 1993; Done et al. 1996). • Florida's reefs bring in approximately $1.6 billion annually (Birkeland 1997).
Fisheries	• Most of the world's poor are located within the coastal zones of developing regions and many depend directly on reef species to meet their protein needs (Bryant et al. 1998). • Although reefs cover <0.2% of the ocean's area, they contain 25% of marine fish species (Roberts et al. 1998). • Coral reef fisheries yield at least 6 million metric tons of fish catches around the world annually, excluding local subsistence fisheries (Munro 1996), and reefs provide one-quarter of the fish catch in developing countries and employment for millions of fishers (Roberts et al. 1998). • Around 50% of the estimated 100,000 full-time fishers and several hundred thousand part-time fishers along the coastline of Eastern Africa risk losing their livelihood if the coral reef ecosystem is degraded further (Moffat et al. 1998).
Shoreline protection	• The protective services to coastlines provided by reefs reduce storm damage, erosion, and flooding by intense wave action. • Over geologic time, coral reefs have enabled the formation of lagoons and calm shorelines where seagrass beds and mangroves can flourish, providing habitat for numerous species at the interface of land and sea (Baskin 1997; Bryant et al. 1998). • The Sri Lankan government has already spent approximately $30 million to prevent coastal erosion (Berg et al. 1998).
Medicines	• About half of the potential pharmaceuticals being developed and tested are from the oceans, many from coral reef ecosystems (reviews by Fenical 1996; Hay & Fenical 1996). • Several promising drugs have already been identified, developed, and tested (Carte 1996).
Environmental indicators	• Coral reefs are valuable environmental indicators (Hayes & Goreau 1991). • Because of the potential vulnerability of modern corals to high temperature, coral reefs were projected to be among the first systems to show signs of ecological stress from global warming (Intergovernmental Panel on Climate Change 1998) on a worldwide scale.

to differentiate coral bleaching HotSpots from biodiversity and other types of hotspots.) Sea surface temperatures of even 1° C above normal summer maxima and lasting for at least 2–3 days appear to provide a potentially useful predictor of subsequent bleaching (Goreau & Hayes 1994; Strong et al. 1998). Although there are differences in response among species and populations, most corals are likely to bleach but survive and recover if temperature anomalies persist for <1 month. The chronic stress of high temperatures or frequent high temperature episodes, however, can cause irreversible damage (Wilkinson et al. 1999).

Coral reefs are bathed in unusually warm waters through at least two nonexclusive conditions: doldrum-like conditions and current transport. Weather patterns typified by clear skies and slight or still wind or waves result in little or no mixing of warm and cold waters, enabling solar radiation (particularly when the sun is overhead) to warm surface and shallow waters. Ocean currents transport "pools" of warm water. Sometimes these pools are delivered to reef regions, where they can linger for months before moving or dissipating (Wilkinson et al. 1999).

Stress-related bleaching can also be induced if corals are subjected to reductions or increases in salinity, intense solar radiation (especially ultraviolet wavelengths; Jokiel 1980; Fisk & Done 1985; Oliver 1985; Lesser et al. 1990; Gleason & Wellington 1993), exposure to air by low tides or low sea level, sedimentation, or chemical pollutants such as copper, herbicides, and oil (reviewed by Glynn 1996; Brown 1997). These conditions may be an indirect consequence of extremes in weather (such as hurricanes and typhoons) or climate (such as El Niño) that are proceeded by or occur concurrently with elevated sea surface temperatures. Consequently, multiple factors act in concert to cause bleaching, but high solar irradiance, particularly of ultraviolet wavelengths, is considered especially stressful to corals when coupled with elevated sea surface temperatures (Hoegh-Guldberg & Smith 1989; Gleason & Wellington 1993; Glynn 1996; Lesser 1996).

Coral Reef Bleaching and Mortality Trends

Nearly 80 years ago, Alfred Mayer described coral bleaching as a natural event, when he observed small scale bleaching in overheated tide pools (Goreau & Hayes

1994). Because the events were rare, localized, and corals typically recovered, bleaching events caused little concern (Hayes & Bush 1990; Hayes & Goreau 1991; Hoegh-Guldberg 1999; Goreau et al. 2000). In the early to mid 1980s, however, coral reefs around the world began to experience large scale bleaching (Goenaga & Canals 1990; Goreau 1990; Williams & Bunkley-Williams 1990; Glynn 1991; Hayes & Goreau 1991; Goreau 1992; Glynn 1996; Brown 1997). Since then, such events have taken place almost every year (the exception being the 2 years following the 1991 eruption of Mt. Pinatubo), at one time or another affecting every reef region in the world, across all depths of the tropical reef (Hayes & Goreau 1991; Wilkinson 1998; Hoegh-Guldberg 1999; Wilkinson et al. 1999; Goreau et al. 2000). Corals have died throughout entire reef systems following mass bleaching events (Wilkinson 1998; Brown & Suharsano 1990).

The coral bleaching events of 1987 and 1990 were sufficiently alarming (each unprecedented in scale and severity) that hearings were held before the U.S. Senate (27 November 1987, U.S. Senate Committee on Appropriations; 11 October 1990, U.S. Senate Committee on Commerce, Science, and Transportation). Witnesses confirmed that the frequency and extent of coral bleaching represented a severe threat to coral survival and reef preservation (Hayes et al. 1990). Furthermore, they affirmed there was sufficiently strong evidence to suggest that tropical corals may be responding to trends in global warming (Goreau 1990; Hayes et al. 1990).

Although highly variable spatially, the coral bleaching of 1998 was the most geographically extensive and severe on record (Strong et al. 1998; Hoegh-Guldberg 1999; Wilkinson et al. 1999; Goreau et al. 2000). Coral bleaching was reported in at least 60 countries and states in the Pacific Ocean, Indian Ocean, Red Sea, Arabian Gulf, and the Caribbean. Only the central Pacific seemed to have been unaffected. Unlike most previous bleaching events, which were most severe at depths <15 m, the effect of the 1998 event extended to depths as great as 50 m in some locations (Wilkinson 1998; Wilkinson et al. 1999). In these areas, virtually all species of hard and soft corals, as well as many other zooxanthelate invertebrates (e.g., giant clams; Gomez & Mingoa-Licuanan 1998), suffered bleaching (Hoegh-Guldberg 1999; Wilkinson et al. 1999; Goreau et al. 2000).

The severity of the coral bleaching ranged from catastrophic, mass mortality of at least 80% of a reef system, to negligible where only small patches of reef bleached and then recovered (Wilkinson 1998; Wilkinson et al. 1999). This variation likely reflects differences in species and population-specific responses (Rowan et al. 1997), location of the reef (e.g., depth), strength of the stressor(s), as well as the duration and frequency of the stress (Wilkinson 1998; Hoegh-Guldberg 1999).

Preliminary assessments indicate that the Indian Ocean was the most severely affected region, with devastating coral mortality (Sheppard 1999). Greater than 70% mortality was observed off the coasts of such regions as Kenya, the Maldives, the Andamans, and the Lakshadweep Islands (Wilkinson et al. 1999; Goreau et al. 2000). About 78% of the corals have been reported dead in the Seychelles Marine Park System and the Mafia Marine Park (Wilkinson et al. 1999).

A complete assessment of the ramifications of the 1998 mass bleaching event will require years. Undoubtedly, some corals will recover, and perhaps they and their zooxanthellae may become more stress-tolerant (Buddemeier & Fautin 1993; Ware et al. 1996), although there is little evidence that this occurs (Hoegh-Guldberg 1999). Rather, corals may have endured such significant physiological and metabolic stress that they will be more susceptible to the effects of future stress events (Hoegh-Guldberg 1999; Wilkinson et al. 1999). Thus, episodes of coral morbidity and mortality may follow the primary insults of bleaching.

Global Climate Trends

In some regions, local and regional stressors such as increased sedimentation and pollution, abnormally low tides, and freshwater inundation undoubtedly contributed to the coral bleaching events of 1998 (Wilkinson et al. 1999). Nevertheless, anomalously high sea surface temperatures closely preceded and/or correlated with reports of mass coral bleaching worldwide (Strong et al. 1998; Hoegh-Guldberg 1999; Wilkinson et al. 1999; Goreau et al. 2000). Combined land-air and sea surface temperatures made 1998 the warmest year of the century (National Oceanic and Atmospheric Administration 1998*a*), with both land and sea surfaces experiencing record high temperature anomalies (National Oceanic and Atmospheric Administration 1999; Fig. 1). Tropical sea surface temperatures were the highest on record, and the bleaching HotSpots of the world's tropical oceans were more extensive in the first 6 months of 1998 than in any previous year (Strong et al. 1998).

There is considerable support for the hypothesis that anomalously high sea surface temperatures have caused the recent episodes of mass coral bleaching and mortality. However, the specific mechanism(s) driving the rise in sea surface temperatures remains uncertain and thus controversial (Hoegh-Guldberg 1999; Wilkinson et al. 1999). Three predominant theories, representing potentially interacting scenarios, have been explored: (1) stochasticity and chaos, (2) El Niño and other variations in climate, and (3) global warming (Table 2).

Although a statistical analysis has not yet been performed, the chance that all of the 1998 bleaching events occurred as a result of independent local causes or independent weather events seems highly improbable. In many parts of the world, El Niño and La Niña, in combination with related variations in climate, appear to have

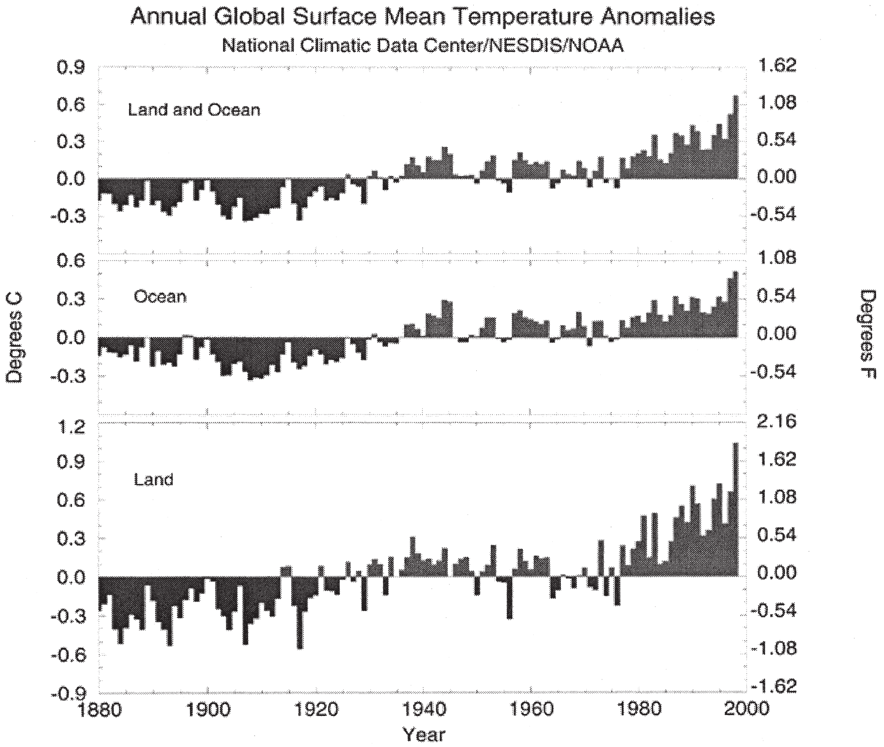

*Figure 1. Annual global surface mean temperature anomalies. Yearly amount of temperature fluctuation above and below the annual global surface mean temperature (at 0° C) from 1880 to 1998 (National Oceanic and Atmospheric Administration 1998*a*).*

been a significant factor in severe coral bleaching events (Coffroth et al. 1990; Wilkinson 2000). There were nearly comparable amounts of bleaching under both El Niño and La Niña conditions throughout the world, signifying two important conclusions: (1) bleaching may be region-specific, and (2) it is more the degree of change that influences the severity of the effects than it is the nature of the change (Wilkinson 2000).

According to Wilkinson (2000), major El Niño–associated bleaching events occurred as follows: in 1997, far-eastern Pacific between May and December, Colombia starting in May, Mexico from July to September, Panama in September, and Galapagos in December, and in 1998 Indian Ocean between March and June, Kenya and Tanzania from March to May, Maldives and Sri Lanka from April to May, Western Australian reefs from April to June, India from May to June, Oman and Socotra in May, Southeast Asia between January and May, Indonesia from January to April, Cambodia, Thailand, and East Malaysia from April to May, Eastern Australia and Great Barrier Reef in January and February, and southern Atlantic Ocean off Brazil in April.

Major La Niña–associated bleaching events occurred as follows in 1998: Southeast and East Asia from July to October, Philippines from July to September, Vietnam in July, Japan and Taiwan from July to September, Singapore and Sumatra, Indonesia in July, Arabian Gulf and Red Sea from August to October, Bahrain, Qatar, and United Arab Emirates in August and September, Eritrea and Saudi Arabia (Red Sea) in August and September, throughout the Caribbean Sea and Atlantic Ocean from August to October, Florida from July to September, Bahamas, Bonaire, Bermuda in August and September, Barbados, British Virgin Islands, Caymans, Colombia, Honduras, Jamaica, and Mexico in September, far-west Pacific from September to November, Federated States of Micronesia in September, and Palau in September to November.

El Niño–La Niña events, however, cannot account for the extreme warmth of 1998: connections between these regional phenomena and coral bleaching are not apparent for all Pacific locations or for the Indian Ocean and Arabian Gulf (Strong et al. 1998; Wilkinson et al. 1999). Rather, these regional events could be part of larger climate patterns that influenced temperatures across the tropical Indian and Pacific Oceans (Hoegh-Guldberg 1999; National Aeronautics and Space Administration 1999; Goreau et al. 2000).

The mass coral bleaching and mortality events of 1998 may not be accounted for by localized stressors or natural variability alone. Rather, the effect of these factors was likely accentuated by an underlying global cause. It is probable that anthropogenic global warming has contributed to the extensive coral bleaching that has occurred simultaneously throughout the disparate reef regions of the world. Thus, the geographic extent, increasing frequency, and regional severity of mass bleaching events are an apparent result of decades of rising marine temperatures and strong regional climate events (Hoegh-Guldberg 1999; Wilkinson et al. 1999; Goreau et al. 2000).

Table 2. Factors proposed to explain anomalously high sea surface temperatures in 1997–1998.

Factor	*Evidence*
Stochasticity and chaos	• At any location, variations in weather can be large and are often unpredictable. Natural climate variability, resulting from both internal fluctuations and external causes (e.g., solar variability), provides the background against which all anthropogenic climate change is measured (Intergovernmental Panel on Climate Change 1996). • Many factors that contribute to "bleaching conditions," including wind direction and speed, rates of upwelling, and days of cloud cover, vary naturally.
El Niño and other variations in climate	• The 1997–1998 El Niño Southern Oscillation (a natural oscillation of the coupled ocean-atmosphere system in the tropical Pacific) was the strongest on record (Fig. 2), due at least in part to it being superimposed upon naturally occurring decadal time-scale fluctuations (e.g., the Pacific Decadal Oscillation; Trenberth & Hurrell 1994; Mantua et al. 1997; Kerr 1999; McPhaden 1999; Saji et al. 1999; Webster et al. 1999) and anthropogenic global warming (Hoegh-Guldberg 1999; Trenberth 1998). • The associated La Niña events were also particularly strong. • The 1993 and 1987–1988 mass coral bleaching events also corresponded with record El Niños, and high sea surface temperatures diminished within a year after the El Niños dissipated (Glynn 1984; Wilkinson et al. 1999).
Global warming	• Global warming has been implicated in phenological changes (Beebee 1995; Sparks & Yates 1997), range shifts (Barry et al. 1995; Parmesan 1996; Parmesan et al. 1999), population declines, and species extinctions (Roemmich & McGowan 1995; Laurence 1996; Pounds et al. 1999) of a variety of organisms at regional scales. • Over much of the world, temperatures in 1998 were probably the warmest in at least 600 years (Mann et al. 1998), as far back as global estimates of climate have been made. • Globally, average surface air temperatures are about 0.5° C higher than average temperatures in the nineteenth century (National Oceanic and Atmospheric Administration 1997). • In 1996 the IPPC concluded that global warming is measurable at about 0.3–0.6° C (Intergovernmental Panel on Climate Change 1996), and 1997 and 1998 have each been warmer than any previous year. • Analyses by the National Atmospheric and Space Administration (National Aeronautics and Space Administration 1999) indicate that the rate of warming is the most rapid of any previous period of equal length in the history of instrumental records. • For some of the tropical oceans, significant increases in sea surface temperature have been observed over the last 50 years (Cane et al. 1997; Winter et al. 1999). Detailed analysis of satellite records of sea surface temperature from near all coral reef sites shows that, in most Northern Hemisphere locations, tropical seas have been warming faster than the global average over the past 17 years (A.E. Strong, personal communication). For example, La Parguera research station in Puerto Rico has registered a rate of change of 2.5° C per century (Winter et al. 1999).

Future Scenarios

Recovery of coral reefs is dependent on numerous factors, including the local severity and duration of thermal stress; species-specific growth rates and sensitivity to stress; infections due to disease; fragmentation of remaining coral reefs; recruitment of coral larvae in the area; and timing and severity of additional stresses (Wilkinson et al. 1999). Coral reefs damaged by acute, local stresses such as ship groundings, hurricanes, or pest outbreaks can recover in a few decades as long as surrounding reefs are healthy. But recovery to previous levels of coral cover and community structure following chronic, widespread stresses could take decades to possibly hundreds of years (Intergovernmental Panel on Climate Change 1998; Wilkinson et al. 1999; Wilkinson 2000). Some corals have survived the mass extinctions brought on by natural climatic variabilities in the past (e.g., 75,000 years ago). Because of the rapid rate at which significant climatic changes could now proceed, however, the ability of most corals to acclimatize, migrate, or adapt is uncertain and unsubstantiated (see discussion by Hoegh-Guldberg 1999).

Where coral mortality was catastrophic to severe in 1998, there will be fewer corals of the affected species reproducing in coming years and hence a much reduced source of new coral larvae (Wilkinson et al. 1999). Even if there were an adequate supply of coral larvae, reef recovery will be hindered around populated shores by pollution (sewage, soil erosion, fertilizers), over-fishing, and physical damage. In the Carribbean, recent increases in the incidence of coral disease have further reduced the numbers of some important reef-building corals, such as the *Acropora* species (Bryant et al. 1998).

Significant changes in community composition often occur following mass mortality events. In some cases, hardier species replace less stress-tolerant species ("strategy shift"; Done 1999) because of differential mortality

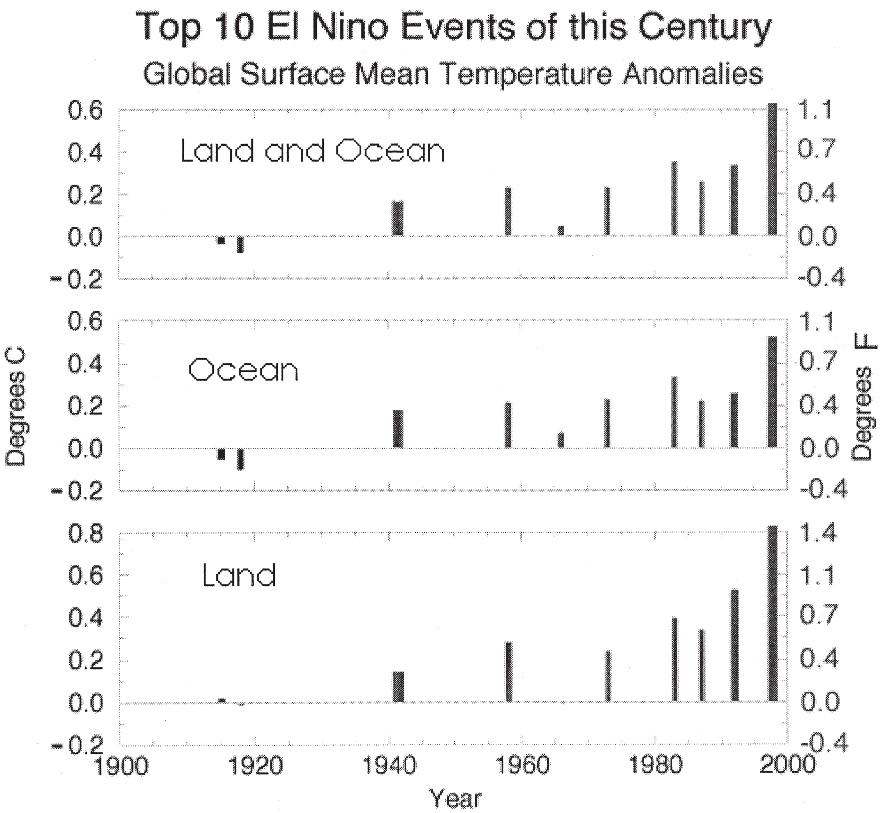

Figure 2. Global surface mean temperature for the top 10 El Niño events of the twentieth century.

(e.g., Hoegh-Guldberg & Salvat 1995). Under more extreme scenarios, corals are replaced by other groups of organisms, such as seaweeds ("phase shift"; Hughes 1994; Shulman & Robertson 1996; Done 1999).

There have been strong regional differences in warming rates and average sea surface temperatures in the Southern Hemisphere sites have been showing either no increase or cooling (National Oceanic and Atmospheric Administration 1999; Wilkinson et al. 1999). Nevertheless, global climate change poses an increasing threat to coral reefs regardless of its contribution to date. An increase in carbon dioxide in the atmosphere can reduce the ability of corals to form limestone skeletons, slowing their growth and making them fragile (Gattuso et al. 1999; Kleypas et al. 1999). Global mean sea surface temperatures are projected to increase approximately 1–2° C by the year 2100 (National Oceanic and Atmospheric Administration 1998*b*), and if the frequency of high-temperature episodes increases as mean temperatures gradually rise, corals will experience more frequent and widespread disturbances (Intergovernmental Panel on Climate Change 1998; Done 1999). Bleaching HotSpots would become even more widespread and protracted (Goreau & Hayes 1994; Strong et al. 1998). Also, these thermal effects are projected to coincide with rising sea levels, more frequent tropical storms and El Niños, and, consequently, greater coastal erosion, turbidity, and sedimentation in many reef locations (Intergovernmental Panel on Change Control 1998). Stressed by any of these factors, the ability of coral reefs to withstand high waves and recover from breakage or bleaching events may be significantly reduced (Wilkinson 2000).

Hoegh-Guldberg (1999) examined four predictive climate-change models to project the increasing frequency and severity of mass coral bleaching events. All four models confirmed the same trends: (1) the frequency of bleaching will rise rapidly, more slowly in the central Pacific and most quickly in the Caribbean; (2) the severity of bleaching will increase at a rate proportional to the probability that sea surface temperatures will exceed thermal maxima; and (3) within 3–5 years most regions will experience mass bleaching annually. The essential conclusions are undeniable: if sea temperatures continue to rise and corals are unable to acclimatize or adapt rapidly, corals will experience mass bleaching with increasing frequency and severity. If tropical oceans annually experience temperatures that greatly exceed those of 1998, the models project that by approximately 2050 coral reefs as we now know them will not be able to survive.

Policy Recommendations

The repercussions of the 1998 mass coral bleaching and mortality events will be far-reaching. Even under ideal conditions, significant changes in community structure will occur. In the meantime, human populations that depend on reef services face losses of marine biodiversity,

Table 3. Results of the expert consultation on coral bleaching.

Issue	*Action*
Information gathering	
Ability to adequately project, and thus mitigate, the effects of global warming on coral reef ecosystems and the human communities that depend on coral reef services is limited by the paucity of information on (1) taxonomic, genetic, physiological, spatial, and temporal factors governing the responses of corals, zooxanthellae, the coral-zoxantellae system, and other coral-reef-associated species to increases in sea surface temperature; (2) role of coral reefs as critical habitat for marine species and natural resources for human communities; (3) current status of coral reef health and threats to coral reefs; and (4) potential capacity of corals to recover and resilience of the ecosystem after mass mortality.	(1) Implement and coordinate targeted research programs, including predictive modeling, that invesitgate: tolerance limits and adaptation capacity of coral reef species to acute and chronic increases in sea surface temperature; relationship among large-scale coral bleaching events, global warming, and the more localized threats that already place reefs at risk; and frequency and extent of coral bleaching and mortality events, as well as their effects on ecological, social, and economic systems. (2) Implement and coordinate baseline assessments, long-term monitoring, and rapid-response teams to measure the biological and meteorological variables relevant to coral bleaching, mortality, and recovery, as well as the socioeconomic parameters associated with coral reef services. To this end, support and expand the Global Coral Reef Monitoring Network, regional networks, and data repository and dissemination systems, including Reefbase—the Global Coral Reef Database. Current combined Sida-SAREC and World Bank program on coral reef degradation in the Indian Ocean (CORDIO), as a response to the 1998 coral-bleaching event, could be used as an example. (3) Develop a rapid-response capability to document coral bleaching and mortality in developing countries and remote areas. This would involve the establishment of training programs, survey protocols, availability of expert advice, and establishment of a contingency fund or rapid release of special project funding. (4) Encourage and support countries in the development and dissemination of reports on status of the reefs and case studies on the occurrence and effects of coral bleaching.
Remoteness of many coral reefs and the paucity of funding and personnel to support on-site assessments of coral reefs requires that remote-sensing technologies be developed and applied in the evaluation of coral-bleaching events.	Extend use of early-warning systems for coral bleaching by (1) enhancing current National Oceanic and Atmospheric Administration AVHRR HotSpot mapping by increasing resolution in targeted areas and carrying out ground-truth validation exercises; (2) encouraging space agencies and private entities to maintain deployment of relevant sensors and to initiate design and deployment of specialized technology for shallow-oceans monitoring; and (3) making the products of remote sensing readily accessible to coral reef scientists and managers worldwide with a view to those scientists and managers based in developing countries.
Capacity building	
There is a lack of trained personnel to investigate the causes and consequences of coral bleaching events.	Support the training of and career opportunities for marine taxonomists, ecologists, and members of other relevant disciplines, particularly at the national and regional level.
Coral bleaching is a complex phenomenon. Understanding the causes and consequences of coral bleaching events requires the knowledge, skills, and technologies of a variety of disciplines. Any action aimed at addressing the issue should take the ecosystem approach, incorporating both the ecological and societal aspects of the problem.	Encourage and support multidisciplinary approaches to coral reef research, monitoring, socioeconomics, and management.
Public awareness and education are required to build support for effective research, monitoring, and management programs, as well as policy measures.	Build stakeholder partnerships, community participation programs, and public education campaigns and information products that address the causes and consequences of coral bleaching.
Policy development and implementation	
Nearly 60% of the world's coral reefs are threatened by localized human activities that have the potential to exacerbate the effects of coral bleaching events. Evaluations of the 1998 coral bleaching events suggest that marine protected areas alone may not provide adequate protection for at least some corals and other reef-associated species as sea surface temperatures rise.	Use existing policy frameworks to implement the multiple conservation measures outlined in the International Coral Reef Initiative Renewed Call to Action, and develop and implement comprehensive local- to national-scale integrated marine and coastal area management plans that supplement marine protected areas.

continued

Table 3. (continued)

Issue	*Action*
Most coral reefs are located in developing countries, and the majority of the people living near coral reefs are poor. Thus, even minor declines in the productivity of coral reef ecosystems as a result of coral bleaching events could have dramatic socioeconomic consequences for local people who depend on coral reef services.	Identify and institute additional and alternative measures for securing the livelihood of people who depend on coral reef services.
Coral bleaching is relevant not only to the Convention on Biological Diversity but also the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Wetlands. The ultimate objective of the UNFCCC is to reduce emissions in a manner that "allows ecosystem to adapt 'naturally' to climate change." The UNFCCC calls upon parties to take action in relation to funding, insurance, and technology transfer to address the adverse effects of climate change. The Convention on Wetlands provides guidance on the conservation and wise use of wetlands, including coral reefs.	Initiate efforts to develop joint actions among the Convention on Biological Diversity, the UNFCCC, and the Convention on Wetlands to (1) develop approaches for assessing the vulnerability of coral reef species to global warming; (2) build capacity for predicting and monitoring the impacts of coral bleaching; (3) identify approaches for developing response measures to coral bleaching; and (4) provide guidance to financial institutions, including the Global Environment Facility, to support such activities.
Coral bleaching has the potential to affect local fisheries, as well as certain high-value commercial pelagic fisheries and coastal ecosystems.	Encourage the Food and Agricultural Organization of the United Nations and regional fisheries organizations to develop and implement measures to assess and mitigate the effects of rising sea surface temperatures on fisheries.
Coral bleaching events are a warning of even more severe effects to marine systems. If anamalous seawater temperatures continue to rise, become more frequent, or become prolonged, the physiological thresholds of other organisms will be surpassed.	Emphasize that coral bleaching can be monitored as an early warning of the effects of global warming on marine ecosystems and that the collapse of coral reef ecosystems could affect ecological processes of the large marine system of which coral reefs are a part.
The observations of the 1998 coral bleaching events suggest that coral reef conservation can no longer be achieved without consideration of global climate systems and that it requires efforts to mitigate accelerated global climate change.	Emphasize the interdependencies and uncertainties in the relationships among marine, terrestrial, and climate systems.
Financing	
Because the issue of climate change is global and long-term, governments around the world need to work together to make funds available to implement initiatives to address the causes and consequences of coral bleaching.	Mobilize international programs and mechanisms for financial and technical development assistance, such as the World Bank, United Nations Development Program, the Global Environment Facility, regional development banks, as well as national and private sources to support implementation of these priority actions.

fisheries, and shoreline protection. A preliminary attempt to estimate the damage of the 1998 coral bleaching event in the Indian Ocean, based on best- and worst-case recovery scenarios, put losses in the range of $706 to $8190 million (U.S.) (Wilkinson et al. 1999).

Trends of the past century and projection models suggest that coral bleaching events may become more frequent and severe as the climate continues to warm, exposing coral reefs to an increasingly hostile environment. Furthermore, these models imply that any strategy to maintain coral reefs must include reduction of greenhouse gas emissions. All reefs, even those granted well-enforced legal protection as marine sanctuaries or managed for sustainable use, are threatened by global climate change.

As with all environmental conservation and ecosystem management challenges, it is critical to establish better baseline data and develop well-coordinated, interdisciplinary programs to address gaps in current knowledge. For example, we need information on the long-term effects of coral bleaching and mortality on ecological, social, and economic systems; on the physiological tolerance and adaptation capacity of corals to acute and chronic temperature stress; and on the links between coral bleaching and disease. This information must then be translated effectively into public policy and communicated to funding agencies and the public.

The Convention on Biological Diversity (CBD), the Ramsar Convention on Wetlands, and the Framework

Convention on Climate Change (FCCC) all provide avenues through which countries can develop policies and initiate funding mechanisms to address the effects of climate change on biological diversity. In October 1999 the CBD's Subsidiary Body on Science, Technology, and Technical Advice (SBSTTA) held an experts consultation on coral bleaching. They called upon the conventions to give urgent attention to the effects of climate change on coral reef systems by jointly undertaking a variety of actions (http:www.biodiv.org/sbstta5/docs.html; Table 3). In the same month, the International Coral Reef Initiative (ICRI) endorsed the recommendations made to the CBD and issued resolutions directly to the CBD and FCCC (http://www.environnement.gouv.fr/icri).

In late February 2000 the fifth meeting of CBD's SBSTTA considered the findings of the experts' consultation on coral bleaching. More than 100 governments concluded that there is significant evidence that global climate change is a primary cause of the 1997–1998 mass coral bleaching events and urged the CBD's Conference of Parties (COP) to endorse the findings of the expert consultation at its fifth meeting (May 2000, Nairobi; http://www.biodiv.org), which the COP did.

Although the activities of these international bodies are encouraging and could provide much of the political and financial response needed to address the causes and consequences of coral bleaching, the process through which they operate is typically slow. Coral reefs need immediate conservation attention, and many of the actions most important for their survival are already recognized and best administered at local to regional scales. We need to increase the urgency and effectiveness with which we manage the stressors that already place reefs as risk. Programs to reduce pollution, sedimentation, anchor and net damage, and overfishing, and to establish marine protected areas will give corals their best chance to respond to climate change naturally. If we do not heed the warning of climate-induced ecosystem collapse provided by mass coral bleaching events, similar catastrophies will follow throughout marine, freshwater, and terrestrial systems.

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