EFFECTS OF RISING SEAWATER TEMPERATURE ON CORAL REEFS

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Summary

Abnormally high temperatures trigger physical, chemical, and biological changes in the oceans that affect coral reefs and fisheries, both directly and indirectly. The mechanisms responsible for those changes are qualitatively reviewed in this chapter. Almost all are potentially detrimental to reef ecosystems. The most dramatic is the uncoupling of symbiosis among corals and their zooxanthellate algae, on which coral reef construction depends. This obligate symbiosis is destroyed by small increases in temperature. Additional increases threaten the viability of corals and their symbionts. Coral reef ecosystems are vulnerable to thermal stress because they live very close to their upper tolerance limit for temperature. Coral reefs throughout the world have already been exposed repeatedly to excessive temperatures starting in the 1980s. Coral mortality has ranged from mild to catastrophic. Continued climate changes, including global warming, will trigger the demise of reef-building corals, leading to the collapse of our most productive, biodiverse, and economically valuable coastal marine ecosystem, the coral reef.

Global reef and pelagic fisheries are also vulnerable to climate change. Reef fisheries are threatened by the loss of habitat, and pelagic fisheries are vulnerable to bottom-up trophic collapse from warm surface waters that block nutrient upwelling. While declines in global fisheries is often blamed on top-down effects from over-fishing, changes in ocean circulation patterns from climate instability pose serious threats from below. Failure to recognize the impacts of these large-scale changes make conventional fisheries management strategies, based on controlling fishing efforts, increasingly irrelevant. Marine protected areas are insufficient to restore these fisheries when habitats have been destroyed or the food chain has collapsed. Reduction of global greenhouse gas concentrations is the sine qua non for preservation of coral reef ecosystems and reef fisheries, and for conservation of pelagic fisheries.

1. Introduction

Coral reefs are ancient, majestic, highly productive and exceptionally diverse tropical marine ecosystems. However they are also fragile, sensitive and easily stressed by environmental change. Since the mid 1980s there has been a progressive global decline of robust and dynamic coral reefs into fragmented and degraded communities. This disaster has been driven by impacts of global warming, exacerbated by man-made pollution, destructive fishing practices, over-harvesting and environmental mismanagement. Long-term impacts from sea level rise and oceanic acidity may soon compound other sources of stress. Here we review the physical, chemical, and biological mechanisms by which elevated temperatures affect coral reefs and fisheries, including their interactions with other environmental determinants, and how global warming affects coral reef ecosystems and associated marine fisheries.

2. Direct Thermal Effects

2.1. Sea Level Rise

Increasing temperature causes seawater to expand in volume and at the same time accelerates the melting rate of glaciers and continental ice caps. Both of these processes contribute to rising sea level. The expansion of polar waters due to reduced salinity further promotes sea level rise. Healthy reefs, completely covered with rapidly growing coral colonies, a common sight in tropical waters only a few decades ago, are able to grow upwards faster than the rate of sea level rise. For example, many Jamaican reefs had grown up to 30 meters in thickness since sea level stabilized around 6000 years ago (a rate of about 5 millimeters per year), more than the current rise in sea level of around 2.8 millimeters per year. However the rate of sea level rise rate is accelerating and the degraded reefs that now predominate worldwide have too little live coral cover (often only a few percent to a few tens of a percent), and are growing far too slowly for the reef framework to keep up with sea level rise. These compromised reefs will eventually be drowned, resulting in enhanced rates of coastal erosion.

2.2. The Solubility of Carbon Dioxide and Oxygen in Seawater

Carbon dioxide (CO_2) solubility in water decreases as temperature increases. Consequently warm tropical oceans are a major source of atmospheric carbon dioxide, which dissolves in colder polar waters. As global warming continues, the tropics will become a larger source of carbon dioxide out-gassing, contributing a positive feedback mechanism that amplifies the build-up of greenhouse gases.

Oxygen (O_2) is less soluble in water at higher temperatures. At the same time, dissolved oxygen-dependent respiration rates of most microbes, macrofauna and algae increase markedly. Increasing temperatures exacerbate low oxygen stress and promote the expansion of anoxic dead zones, especially in marine areas with high coastal organic carbon loading from sewage discharge, solid waste disposal, and agricultural waste releases, and in coastal waters and deep basins with poor circulation. Therefore, coral reefs in such regions could die from oxygen deprivation and toxic sulfide accumulations that develop in back reef lagoons during summer nights. For example, after high temperature exposure, many enclosed atolls in French Polynesia experienced severe mortality from anoxia and bacterial infections, wiping out previously flourishing pearl farms. Also, increasing levels of organic pollution loaded into the Pearl River, which drains an area of rapid human population growth in China, caused anoxia and environmental toxicity that killed coral reefs in Hong Kong. Reef mortality will increase in frequency, intensity, and duration as sea temperatures and uncontrolled pollution increase.

2.3. Limestone Solubility in Seawater

Limestone (calcium carbonate or $CaCO_3$) is an exceptional mineral that becomes less soluble as temperature rises. Recent claims have been made that increasing CO_2 may dissolve coral reefs. In fact, tropical coral reefs should not be affected until long after polar waters and the deep sea are affected, because of the decreased solubility of both carbon dioxide and limestone in seawater at elevated temperatures, and because coral reefs have large amounts of exposed limestone sediments which buffer acidity of seawater. Half of all limestone burial in the oceans takes place in coral reefs, which cover only 0.1% of the ocean floor. Ocean acidification from increasing atmospheric CO_2 concentrations will have the least effect at lowering pH in warm tropical surface ocean waters. Thus, coral reefs in the tropical zone will be the last ocean realm to be affected by ocean acidification.

However, increases in CO_2 concentrations at current trends are expected to be much larger than declines in CO_2 and limestone solubility. The CO_2 gas infrared absorption bands are already largely saturated, so higher concentrations of CO_2 will absorb less heat per molecule than lower concentrations. Ocean acidification rises more directly with increases in CO_2 concentration, so the acidity increase will eventually outweigh the thermal impacts of increased CO_2. Acidification of reefs to the point that corals dissolve would take so long compared to the direct thermal impacts on corals themselves that if CO_2 buildup from fossil fuel use continues without control, corals will die from direct thermal bleaching many decades before the limestone reef frame dissolves. Corals are already living near, at, or occasionally beyond their maximum tolerance limit for temperature, but they are still far from having reached any acidity limit.

Biogenic limestone deposition decreases as water becomes more acidic because the concentration of carbonate ions available for calcification is lowered. However, the internal pH of coral tissues can be very different than ambient seawater due to internal production of CO_2 by respiration and its removal by photosynthesis of symbiotic algae. In addition, corals actively pump calcium and hydrogen ions. As coral grows its skeleton, a protected compartment is created between the tissue laying down calcium carbonate crystals and the underlying substrate. Within that compartment, crystal embryos are developed and juvenile skeletal growth ensues by nucleation catalysis. This area of nascent skeletogenesis is isolated from direct exposure to seawater and insulated from ambient acidity. An acidic shift in seawater would not necessarily disrupt skeletal productivity because of the coral soft tissue veneer covering the skeleton. Deep sea corals are able to grow their skeletons slowly even in water that is under-saturated for calcium carbonate.

2.4. Influences of the Hydrological cycle

2.4.1. Salinity

Corals are probably not directly sensitive to evaporation or rainfall per se, but they are highly sensitive to both salinity and light levels, both of which are proportional to the difference between evaporation and rainfall. Corals, adapted to normal ocean salinity (roughly 35 + 3ppt) cannot tolerate brackish water exposure for long and may be damaged by excessive salinity. However, there is a species-specific gradient of tolerance in both directions, with a few coral species found in hyper-saline environments (e.g. the Arabian Gulf) and a few species that can grow close to river effluxes. Evaporation increases sharply with increasing temperature, so as the Earth has warmed in recent decades there has been a measurable increase in tropical lower atmosphere humidity and cloudiness. Although it is clear thermodynamically that ocean evaporation will rise sharply with global warming, most evaporation from the ocean rains out over the ocean, so the net change in surface salinity should be small. However, there has been a minor but detectable increase in the salinity of the tropical oceans due to increased excess of evaporation over rainfall.

Along continental margins, a significant fraction of increased ocean evaporation moisture is transferred by winds to land masses, causing increased rainfall in mountainous coastal areas. Increased rainfall along coastal fringes may be more than balanced by increased drought in the interior areas of large continents. The continental interiors are far from ocean moisture sources that mostly rain out before they reach the interiors, which will get drier as elevated temperatures increase evaporation. Some coastal zones may get more freshwater if the rivers flowing into them originate in mountainous coastal regions, lowering salinity, but regions where rivers originate in continental interiors should have less river runoff due to lower rainfall and increased evaporation, leading to higher coastal zone salinity, especially where river flow is tapped by dams for irrigation. Thus the coastal salinity changes to be expected from climate change will be a very complicated function of regional topography and hydrology, and are very hard to predict accurately from climate models because of the large scale spatial averaging and lack of fine-scale local topographic detail built into such models. Oceanic islands should have increased evaporation and rainfall in much closer balance, and suffer smaller changes in salinity, compared to continental coastal zones.

2.4.2. Light Penetration

Corals require light in the photosynthetically active radiation (PAR) wavelengths for photosynthesis, which controls the rate of coral skeletal growth. PAR is a function of surface solar irradiance, which is largely controlled by cloudiness. While ultraviolet (UV) radiation is a potentially damaging factor, corals have very high levels of ultraviolet screening pigments: even fully bleached corals whose tissues are completely transparent to visible light have so much UV screening pigments that they are opaque to UV light sources. Stratospheric ozone layer depletion leads to increased UV at the surface (if the light is not blocked by increasing cloudiness), but ozone depletion is highest over the poles and there has been little or no statistically significant decline in ozone levels over the tropics.

Due to increases in UV-absorbing atmospheric pollutants, especially sulfur, nitrogen, and hydrocarbon gases that produce haze (that also reflects PAR), a general decline in both UV and PAR at the Earth’s surface, known as "global dimming", has been reported. Global dimming has masked the full impact of global climate change and has caused the rate of atmospheric warming to be less than that predicted from greenhouse gas increases alone. However this effect of global dimming is only temporary, because CO2 has a lifetime of 150 years in the atmosphere, while most aerosols last only days to weeks. Continued masking of the greenhouse effect would require exponential increases in air pollution. As greenhouse gases continue to rise, and as acid rain pollutants and aerosols that contribute to global dimming are controlled for public health reasons, the masking effect has already declined to the point that it has reversed decades of global dimming of PAR and UV caused by atmospheric pollution. As aerosols become far less effective at blocking sunlight, the warming rate is expected to rise even more sharply in the future.

Overall, climate change should result in higher mean ocean cloudiness due to higher evaporation and atmosphere moisture content, which should lower coral growth rates, which are directly dependent on photosynthesis rates. However, this depends strongly on the local details of atmospheric circulation, and increased cloudiness will be greatest in low-pressure equatorial zones and least in high-pressure zones at the latitudinal limits of corals. As a result, the inhibition of coral growth by reduced light should show a latitudinal gradient, being greatest in equatorial zones and being least near the northern and southern limits of coral growth. Predictions of changes in cloudiness and rainfall are the most uncertain predictions made by global general circulation models, due to the great uncertainty in how to parameterize cloud formation and rainfall processes at model sub-grid scales, the great range of mathematical algorithms used in different models, and their poor calibration in terms of empirical data, which make model predicted values poor fits to actually measured values.

2.5. Ocean Thermoclines and Upwelling

Oceans are warmed from the top down by sunlight absorbed by the uppermost layer of the ocean (the photic zone) in which the depth of light penetration depends on water clarity and the high thermal capacity of water. The tropical ocean is the major heat reservoir for the global climate system. Heat transport from the tropics drives global heat budgets of cooler waters and the atmosphere via ocean currents, winds, and thermal changes due to the latent heat of evaporation and condensation. Global warming will expand the cap of warm surface water toward the poles, expanding the tropical area and increasing the potential habitat for corals. Corals are already expanding poleward in the Sea of Cortez and South Africa. Global warming also expands warm water downward by pushing thermoclines to deeper depths.

The maximum depth of coral growth is more often controlled by lack of light than by excessively cold water, so corals would not be expected to increase in depth range in most places unless the water becomes more transparent. Most coastal waters have actually become more turbid due to erosion of soil and sediment from land and because of increased chlorophyll levels following eutrophication from nutrient-loading with domestic sewage, animal waste and agricultural fertilizers. Large, dead reefs can be found in deep offshore sites, for example, along the Caribbean coast of Panama, because once clear, blue water has been replaced by dark, green water due to soil erosion after deforestation.

But the opposite trend takes place in open ocean upwelling zones where the major source of nutrients is not coming from land-based sources but from deep water upwelling. Increasing thickness of warm, nutrient-poor surface layers will push thermoclines deeper and reduce nutrient transport upwards. A decline in phytoplankton chlorophyll and biological productivity has been documented in tropical open ocean waters while a chlorophyll increase in mid latitude open ocean regions has been found. There was an unusually low global ocean net primary productivity in the record hot year of 1998. That productivity rose sharply in the cooler year that followed and steadily dropped in subsequent years as climate change continued. In areas where upwelling is reduced, corals might grow deeper, but they would have less zooplankton for a food supply. Where wind speeds increase, the water will become greener and coral ranges reduced due to decreased light, despite higher food levels. These changes will be strongly affected by shifts in currents and winds, driven by changing temperature gradients.

As the tropical ocean warms, increased warm current heat transport is displaced poleward and increased evaporation results in increased humidity and rainfall. As the heat released when rain condenses drives further convection, wind speed is increasing in many locations. Because the Earth does not heat up at the same rate everywhere due to local topographic factors affecting circulation of air and water, atmospheric pressure differences between areas warming more rapidly and those that are warming more slowly drives increased wind speeds. Increased wind speeds have been documented for most of the ocean, especially around Antarctica, the North Atlantic, and in the mid latitude interiors of the deep ocean basins. These sites are precisely those where the rate of sea surface warming is the lowest. Increases in chlorophyll and productivity in surface water take place where winds have increased and surface water has mixed with deeper water that transport nutrients upwards. In those areas, coral reefs could be overwhelmed by excess nutrients through natural eutrophication as is seen in some open ocean Pacific reefs, for example in the algae dominated reefs of the Northwest Hawaiian Islands and Central Pacific. Coral reefs affected by increased upwelling could change into algae/sponge/tunicate/soft coral communities, such as those found off Cap Vert in Senegal.

Worldwide, all the major upwelling zones have maximum temperatures rising faster than the ocean average, reducing nutrient input to the surface waters and causing food chains to collapse from the bottom up. It is therefore possible that some coastal areas that are now too cold and nutrient rich for corals to survive will become more favorable for them. In those open ocean areas where upwelling appears to be increasing, reducing the regional rates of surface temperature rise, corals may be regionally protected from the direct thermal effects of global warming. However, increased upwelling of cold water also brings increased nutrients, causing a shift away from corals towards algae, sponges, tunicates and soft corals. Indonesia is also warming more slowly than the tropical ocean average, and it appears that increased flow of surface waters from the Pacific to the Indian Ocean (the Indonesian Throughflow), a major regulator of global inter-hemispheric heat exchange, is entraining more cold waters. In areas where the Indonesian Throughflow is strongest, surface water can be as cold as 15 ºC near the equator and the reefs most directly affected by the Indonesian Throughflow are dominated by algae, tunicates and other filter feeding organisms, not by reef-building corals. So while these reefs are spared from exposure to elevated SSTs because of local circulation patterns, they are more vulnerable to eutrophication.

2.6. Dynamics of Reef Frame Growth

Coral skeletal growth rates, as measured by reef frame accretion, rise sharply with increasing temperature, reach a maximum, and then fall even more sharply to zero only slightly above the temperature optimum at which the coral tissues die. Reef coral calcification is proportional to the rate of photosynthesis by symbiotic zooxanthellae. All reef-building corals have an obligate relationship to a specific algal strain, each of which has a distinct temperature optimum and a maximum limit beyond which bleaching ensues. The bleaching threshold is approximately 1.0 ºC above the average monthly temperature in the warmest season. At a molecular level, induction of heat shock protein (HSP) in corals represents the initiation of a thermal stress response. This is the point where normal protein abundances in coral tissues are changed. Studies on the inducible expression of the ubiquitous HSP-70 show that this response initiates at 24 ºC and increases with additional temperature elevation.

2.7. Global Distribution of Coral Reefs

The possibility that coral reefs might extend into areas of sub-optimal temperature as a consequence of changing climate has been often suggested. This implies that corals might rapidly expand their ranges away from the tropical zone. However, this idea ignores the fact that corals quickly die when only slightly above their optimal growth temperature. While new coral colonies may begin growth in some newly warmed areas that are currently too cold to support coral growth, any reefs formed in newly suitable habitat would take thousands of years to mature into ecosystems that could compare to natural reefs that have been killed in warmer areas, and global warming could wipe them out long before large reefs can form. The spread of reefs to higher latitudes would probably be prevented by light limitations or high nutrient levels from coastal upwelling, and sedimentation, and pollution caused by dense coastal populations in temperate zone coastal areas.

2.8. Coral Reef Bleaching

2.8.1. Historical Observations

Corals have been known for nearly a century to be severely damaged by high temperatures. The tissues of corals growing in tide pools in Florida and Australia that were cut off from seawater circulation during clear, sunny, hot, low tide conditions lost all of their intrinsic color, turning transparent and exposing the white limestone skeleton beneath ("bleached"). Although these corals appeared dead, careful observation revealed that they were still alive. Laboratory experiments with corals exposed to elevated temperatures in tanks showed that if the water temperature was raised roughly 1 ºC above the normal seasonal temperatures in the warmest part of the year, the corals bleached. If high temperatures decrease quickly enough, bleached corals can recover, but this can take up to a year for some species. If temperatures were raised to 2 ºC or more above normal warm periods, or if the exposure time was prolonged, the corals died. Therefore, corals in both the Caribbean and the Indo-Pacific live under ambient conditions very near their upper temperature tolerance limits. These corals are irreparably harmed by what appear to be only very slight increases in temperature. Once bleached, corals are unable to grow a skeleton, reproduce, or defend themselves against natural predators.

Numerous histological and physiological studies document that bleaching is a stress response of reef organisms, triggered by environmental conditions that cause the expulsion of symbiotic algae along with a release of copious amounts of mucus from the host animal tissues. Biochemical analyses of the bleaching response show that the photosynthetic mechanism in these algae fails. Bleaching coral tissues express high levels of heat shock proteins and oxidative enzymes. The susceptibility of symbionts to bleaching is related to the thermal properties of their internal membrane lipids, whose composition varies among different strains. Bleached corals will die if thermal stress lasts too long, although mortality depends upon both the species and the degree of temperature elevation. Once the temperature is restored to seasonal levels, some corals are able to recover. The recovery rate is species-specific and depends upon the intensity and duration of the thermal stress. Some corals recover quickly and others take as long as a year for normal color to be restored. Experiments show that high temperature triggers the most rapid bleaching, and PAR (rather than UV) intensifies bleaching only after the temperature threshold is surpassed.

Half a century after the first recorded work on thermal bleaching, seawater desalinization plants were found to be sites of bleaching wherever they released hot brine waste onto coral reefs. Once again, it was shown that only about a degree of warming caused bleaching, and slightly higher levels were lethal. But all these events were very localized, and it was only in the 1980s that large scale mass bleaching began to take place across large regions of the ocean, where the only abnormal condition appeared to be a slight elevation of temperature. In all of these cases it was noted that only very small increases of temperature threatened corals, but it was hard for most coral researchers to accept that corals everywhere could be threatened by such small changes, and most thought it easier to assume that these findings were due to some peculiar abnormal local response of corals at certain locations rather than being of global relevance.

2.8.2. Mass Bleaching Events

By the late 1980s it became apparent from repeated coral bleaching events at the same temperature thresholds that these events were systematic, predictable and widespread patterns of coral thermal sensitivity. Studies of long-term satellite sea surface temperature data clearly revealed that monthly averages of no more than 1.0 ºC above the historic mean temperatures during the warmest months caused large scale Caribbean coral reef bleaching, and that similar elevations were also associated with all large scale reef bleaching events in the Pacific and Indian Oceans.

Those results meant that the location, timing, and intensity of coral bleaching could be predicted accurately, even before it was visible in the field, by mapping the global surface ocean 1.0 ºC monthly average thermal anomaly with regard to the long term average value for the warmest month. Locations where these anomalies occurred in the warmest season of the year were defined as Coral Bleaching HotSpots. In round numbers, a 1.0 ° C anomaly over the long term average maximum monthly average for a month duration caused large scale reef bleaching, but if the average temperature reached 2.0 ° C above for one month, or 1.0 ° C above for two months, severe large scale coral mortality followed. Of course these "thresholds" are really gradients rather than step functions, and they vary according to species.

The U.S. National Oceanic and Atmospheric Administration has now dedicated a web site to near real time global maps based on the HotSpot method (http://www.osdpd.noaa.gov/PSB/EPS/SST/climohot.html), however they show only the instantaneous HotSpots, which must remain above these levels for a month to cause bleaching, and must be time-integrated. When used properly, the HotSpot method has accurately forecast or hindcast all major coral reef bleaching events since the global satellite data first came available in 1982. Its continued accuracy indicates that there is no thermal adaptation of corals to higher temperatures underway, as this would cause the thresholds to rise with time. Reduced mortality of corals in subsequent bleaching events is therefore not the result of adaptation to higher temperatures, but simply the result of the most vulnerable species dying off first.

These results are those that are expected, because almost all coral species are associated with a unique symbiotic algae species as the result of long co-evolution, and corals are unable to change their algae to a different species that might tolerate higher temperatures. The vast majority of corals tolerate only a single strain of symbiont and the few corals that have been reported to have more than one strain have geographically separated populations, each with a single, but different, strain of symbiont. Only one species has been reported to harbor several different symbionts, and only at one place. This obligate specificity definitively demolishes claims that bleaching is a positive adaptation that allows corals to survive increased temperatures by expelling temperature sensitive symbionts that are replaced with other symbiont strains able to tolerate higher temperatures—the so called "Adaptive Bleaching Hypothesis".

2.9. Coral Reproduction

Coral reproductive output decreases sharply as temperature rises, because increased respiration and thermal stress reduces the energy available for gonad development (the reproductive organs that make eggs and sperm), even before bleaching happens. Bleached corals do not reproduce at all. Thermal bleaching causes premature release of immature eggs and sperm, in effect causing mass abortion. Therefore global warming will greatly reduce sexual reproduction of corals. Increased temperatures also reduce larval coral survival as well as larval competence (the ability to metamorphose into juveniles and settle to produce a skeleton), so global warming will also greatly reduce coral dispersion and recruitment.

2.10. Proliferation, Mutation and Virulence of Marine Microbes

Bacteria increase growth rates with increasing temperature up to a species-specific limit. Global warming will cause a shift to higher temperature adapted species, which generally grow much faster than cold adapted species. At present bacteria are more abundant in colder waters than warmer ones, but this is a function of higher nutrient levels and productivity of cold water, not of temperature effects on proliferation. Global warming will increase thermal stratification and thermocline depth, and decrease upwelling nutrients, which would be expected to decrease bacterial levels in open ocean surface waters. On the other hand, coastal ecosystems derive most of their nutrients from land-based sources of sewage and fertilizers, which are both steadily increasing, causing increasing eutrophication. Populated coastal areas will have greatly elevated nutrients, pushing them towards algae dominance, and increased bacterial levels, pushing coral reef ecosystems towards sponges (which feed on bacteria), and detritus and zooplankton feeders like soft corals and tunicates, at the expense of reef building corals.

Increasing temperature has three effects on bacteria. First, increased temperature accelerates the rate of cell division, leading to increased proliferation. Second, because of the shorter generation intervals, mutations accumulate more rapidly with time. Mutant strains emerge more frequently at high temperatures, each of which has the potential to become a pathogen. Third, extra-cellular enzymes and environmental toxins are released and accumulate in higher concentrations at higher temperatures, for example cholera and shellfish toxins. The virulence of the bacterial strain increases directly as a function of these released toxic substances.

3. Indirect Thermal Effects

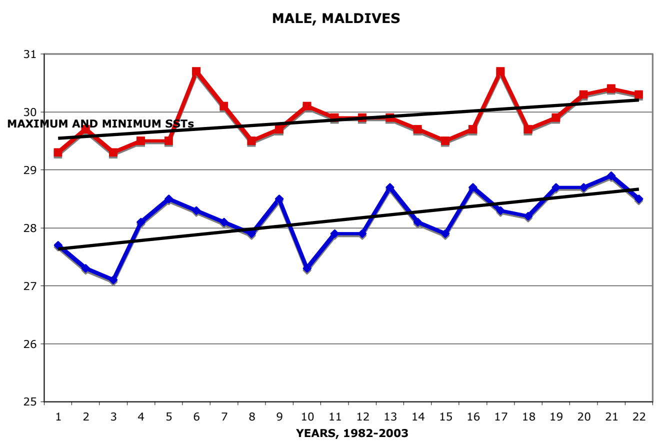
3.1 Impacts from Mass Bleaching Events

All known coral bleaching events before the 1980s were very local in extent, and their distribution was limited by clear locally anomalous conditions. Since the 1980s coral bleaching has taken place on scales ranging up to the width of the major ocean basins, with the exception only of two small regions, the northernmost Red Sea and parts of eastern Micronesia. Today, large-scale coral bleaching, intense enough to cause serious mortality (e.g. up to 99% of corals), has taken place in every coral reef region of the world, and in many places repeatedly. Field and laboratory studies showed that reef corals worldwide are in fact growing at temperatures very close to their upper tolerance limits. Their extreme sensitivity makes them harbingers of global warming, and since they can stand no more warming they will be the first ecosystem to be driven to mass extinction if global warming continues.

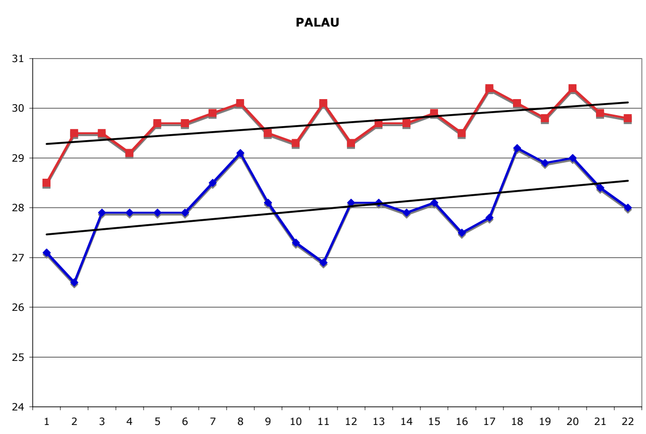
Projections of current long term sea surface temperature records of hundreds of coral reefs all over the globe show that almost all of them have long term temperature increases such that the average long-term monthly thermal maximum will sooner or later exceed their bleaching temperature thresholds every year, at least as long as there are any surviving corals to bleach. If coral reef ecosystems are to be saved, they can tolerate absolutely no further warming, and "business-as-usual" climate change scenarios that commit the Earth to several degrees of warming in the coming decades are a guaranteed death sentence for the remaining corals. In most places this will happen within a few years to a decade if the currently measured mean temperature trends continue, less if they accelerate. Although natural year-to-year fluctuations around the seasonal mean make it impossible to predict beforehand in which year these terminal conditions will finally strike, an extreme high temperature event would cause catastrophic mortality in coral reefs even sooner than mean trends predict. In contrast, studies that use climate model predictions for future mean temperatures, instead of the actual long-term measurements, predict such chronic bleaching to lie decades to centuries in the future.

Long-term linear trends based on satellite sea surface temperature records show general increases in coral reef temperatures, through both El Nino Southern Oscillation (ENSO) and non-ENSO years. Figures 1 and 2 show the annual monthly average maximum and minimum temperatures for sites in the Maldives and Palau, respectively.

Maximum temperatures during the warm season are generally emphasized in discussions of global warming, and they are rising beyond pre-1980 long-term average values. However, winter season low temperatures are also rising at a rate equal to or even faster than the summer extremes in most locations, reducing the post-bleaching recovery period, thus offering inadequate relief from successive summertime heat extremes. The cool season trend has now reached a point where current lows have nearly exceeded earlier warm season highs in many places. These sea surface temperature (SST) trends indicate that coral reef organisms experience decreasing relief from thermal stress after exposure to heat shock. The persistence of high temperature exposure and reduced seasonal ranges delay or even inhibit any effective recovery.



Figures 1. Annual monthly average maximum and minimum temperatures for sites in the Maldives.



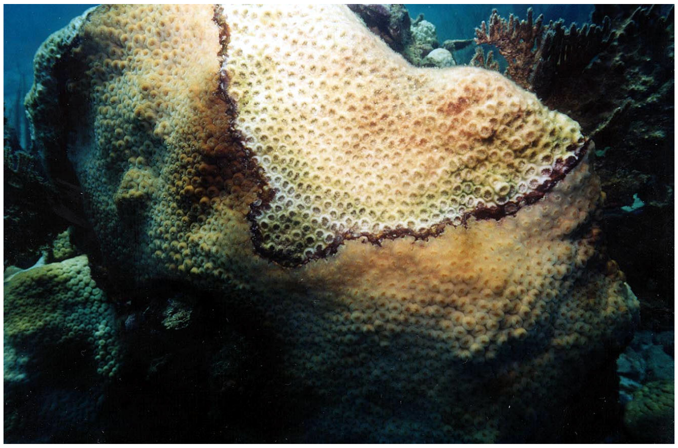
Figures 2. Annual monthly average maximum and minimum temperatures for sites in the Palau.

ENSO events have long been appreciated for having major influences upon both terrestrial and marine ecosystems. El Nino episodes are significant drivers of the world's climate, not just across the Pacific, but globally. During these events, ambient temperatures are elevated, rainfall distribution is shifted and patterns of incident sunlight are altered in certain regions. ENSO years amplify the warm thermal signal in areas where temperatures are positively correlated with ENSO, but do not alter the slope of the baseline trend. However many locations are negatively correlated with ENSO, getting cooler during El Nino events, and most parts of the ocean show no significant relationship with ENSO. Even in those areas where local temperatures are positively correlated with ENSO. Bleaching takes place in El Nino and non El Nino years, in both places positively and negatively correlated with the ENSO signal, so it is the rising baseline associated with global warming that is the ultimate cause of bleaching even in areas where ENSO might be the proximate cause.

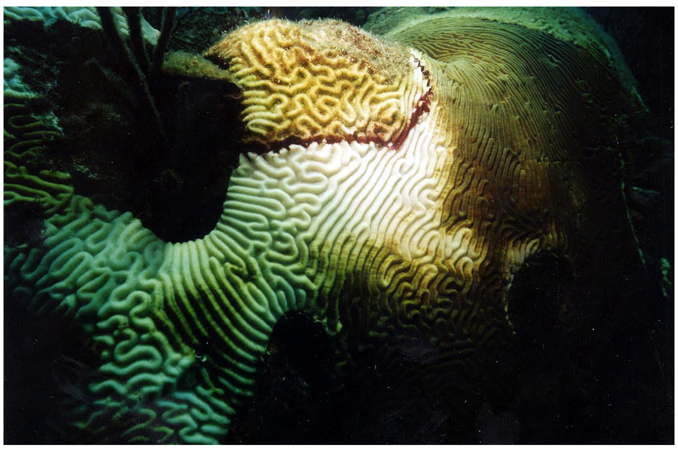
Changing climate in turn affects primary productivity, survival, maturation, reproduction, and mortality of plant and animal species, so that normal relationships among organisms in ecosystems are challenged or destroyed. Organisms are expanding their ranges at different rates, often leaving behind those other species that depend on them at critical phases of their life cycle. Since warm seasons start earlier and end later, migratory organisms are increasingly phase shifted with regard to the other organisms they rely on, for instance arriving after their food supply has matured or left, causing large scale ecological disruptions and possibly extinctions.

3.2. Impacts from Emerging Marine Infectious Diseases

New diseases are increasingly affecting most groups of organisms in coral reefs, including corals, sponges, algae, sea urchins, fish, and turtles. While they are caused by proliferation of new pathogens and not by temperature per se, the growth of coral bacterial pathogens is accelerated and their virulence intensifies at higher temperatures because of increased release of toxins. As a result global warming should accentuate the incidence and prevalence of microbial diseases in corals. Figures 3 and 4 show individual coral colonies with bleaching and black band disease, indicating that infection and stress effects are often simultaneous, exacerbating mortality in affected reef organisms.



Figures 3 Individual coral colonies with bleaching



Figures 4 Individual coral colonies with black band disease

Options for coral defense against microbial pathogens are limited and largely due to a protective mucus layer. Production of the mucous coating between coral tissues and bacteria is stimulated with elevated temperature. High temperatures can affect the biochemical composition and the bacterial flora on mucus, and can lead to replacement of beneficial species by opportunists and pathogens. The mucus layer serves as a protective insulation against foreign invasion and as support for bacterial colonization eventually fragments and degrades from microbial enzyme activity. Once the mucous layer overlying the outer epithelial layer of the coral is breached, bacteria are able to gain access to thin and vulnerable coral tissues that lack any further effective antibacterial resistance. The pathogens penetrate coral cell membranes and invaded tissues are destroyed. These attacks are irreversible and strip tissue from the underlying skeleton, leaving necrotic residues that attracts opportunistic microbes, parasites, pathogens, and turf algae.

3.3. Impacts from Extreme Events: Tropical Storms

When ocean surface temperatures rise, tropical storms become much more intense because they are driven by the energy released from the latent heat of condensation of water evaporated from the sea, which rises sharply with increased temperature. Satellite images show that size and strength of hurricanes dramatically increase as soon as they cross warmer water, and decrease in strength over cooler water. The increase in strength with rising temperature is inevitable thermodynamically. The only controversy was whether the frequency of tropical storms would also increase with rising temperature along with their strength. The formation of hurricanes, typhoons, and cyclones depends on the initiation of rotary motion that is amplified by energy released by rain, and it was long uncertain from physical principles whether more of these initial rotations would follow from rising temperature. It is only in the last few years that long-term data on the number of tropical storms as well as the strength of those storms have been tabulated. The results showed that both are increasing dramatically. Therefore, as sea surface temperature rises, tropical storms will become much more common, be far stronger, perhaps track differently, and the annual storm season will be extended. These effects have serious implications, because the passage of a tropical storm destroys the structural and functional integrity of coral reef ecosystems.

Increased tropical storm frequency and intensity will translate into much greater physical damage. In the past, coral reefs would recover from even the worst storm damage after 10-30 years, because severe storm damage was focused in a very narrow band, usually no more than 10-20 kilometers wide around the eye, and because healthy reefs outside the damaged areas were sources of new coral larvae. With the recent threats of global warming, new diseases, and land-based sources of pollution, reef degradation is accelerating everywhere, so there are no spatial or temporal refuges for recovery. Reefs are now being battered everywhere by stresses that never end, and the natural capacity for recovery has largely been lost.

Following an intense tropical storm, coral skeletons are broken and colonies are displaced. Sponges, soft corals and other attached organisms are ripped loose and thrown on the shore, fill holes and crevices in the reef, or wash out to the deep sea. Sediment is scoured out of lagoons and sand channels, either forming new beaches and sandbars, or swept into deep water and lost from the reef. These shifts result in the loss of soft bottom filter feeding and deposit feeding fauna, like clams, worms, crabs, snails, sea cucumbers, and sea urchins that many fish rely on for food. Immediately following catastrophic tropical storms fishing is usually exceptionally good because stunned fish hover in confusion over the broken rubble, unable to find shelter. However, because the fish are easily caught and because habitat recovery is slow, fish catches later decline sharply.

Tropical storms also produce intense freshwater runoff with dissolved chemical and sediment releases from land. These effluxes lead to non-thermal coral reef bleaching, the death of marine organisms that do not tolerate low salinity, and smothering of reefs by mud and sand. Swollen rivers can dump large amounts of trash, nutrients, pollutants, and soil onto reefs. When Hurricane Mitch struck Honduras during the last week of October 1998, land that had been previously deforested for decades was severely eroded, dumping soil onto coral reefs. Mangroves are the slowest recovering of all coastal habitats after intense storms. The mangrove trees are completely defoliated and take years to recover. Thus, their functional roles as sediment barriers protecting offshore reefs and as habitats for juvenile fish and shellfish are impaired.

Surprisingly, storms may provide transient ecological benefits to reefs subjected to severe land-based sources of eutrophication. Larval corals (planulae) are unable to settle and attach to surfaces due to the dense bottom cover by turf and weedy algae. Storm surge and wave action strip the fleshy algae lawns from the dead reef rock, exposing bare substrate temporarily for larval settlement. If the timing of the storm coincides with coral reproductive activity, mature coral planulae settle on these newly cleaned areas in the narrow window of days to weeks before the land nutrient-fueled algae grow back, and may have the chance to survive. Most recovery of Jamaican reefs reported over recent decades were ephemeral local events on wave-scoured promontories. The short term gains on the reefs were soon lost through bleaching, microbial infection, or algal overgrowth. The local coral recovery observed in Jamaica was followed by the death of the young corals from high temperatures. In reefs that are severely degraded, storm waves sweep away the garbage that defiles them, especially plastic. This cleansing has led some people to regard storms as beneficial. The residents of Guanaja in the Bay Islands of Honduras are said to have thanked hurricane Mitch for sweeping unsightly trash off their reef, and Jean Michel Cousteau, on behalf of the Cayman Tourism Agency, engaged in a publicity campaign proclaiming that "thanks to the hurricane, Cayman reefs are now better than ever".

Besides the direct physical impacts, there are also indirect chemical and biological impacts of tropical storms. Hurricanes flush nutrients from agricultural soils, wetlands, sewage and animal waste storage facilities, and garbage dumps. This refuse can cause previously healthy reefs to be overgrown with weedy algae that are over-fertilized by excess nutrients. Upwelling caused by the low pressure in the wake of a hurricane entrains cool, deep and nutrient-rich water to the surface. Satellite sea surface temperature data show that these upwellings can last days to weeks, depending on the weather conditions after the storm has passed. These cool water tracks are drawn from below the ocean thermocline and account for the onset of phytoplankton and bottom reef algal blooms over coral reefs. Hurricane Mitch caused massive algae blooms that killed the reefs on the seaward sides of Cozumel and Banco Chinchorro in Mexico, and on the barrier reef off Belize, while sparing the leeward sides of the same areas. Because the post-hurricane algal blooms are dependent on ephemeral, not sustained sources of nutrients, the algae eventually die back. These impacts would be expected to increase as the strength, duration and frequency of tropical storms increases.

3.4. Impacts from Losses in Natural Shoreline Protection

Coral reefs are the most effective form of natural shore protection from erosion because corals are the only organisms that form a continually growing reef structure that slows or breaks waves, reducing their energy at the shore line from erosional to depositional conditions, allowing the growth of beaches. In most tropical white sand beaches every single grain of white sand is made up of the remains of reef organism limestone skeletons (except where sand is supplied to the shoreline by rivers carrying sand grains eroded from highland). The unique feature of reefs is that they are continuously growing structures that, at least in the past, would recover after any catastrophic storm damage, grow back up and repair themselves, and could keep up with rising sea level. Reef recovery after physical fragmentation is possible only as long as the reef is dominated by live growing hard coral that can settle and fill any empty spaces and whose growth compensates for the never ending damage caused by bio-eroding organisms that excavate their skeletons (sponges, clams, worms, algae, fungi, and bacteria), and by the forces of wave erosion.

The physical morphology of the integral reef frame and its component colonies creates both extreme high energy wave-breaking habitats in front of the reef and almost totally protected calm environments in close proximity behind the reef, which are linked together by a maze of channels, canyons, holes, and caves that provide access to all habitats, hiding places for fish, and habitat for their food organisms. The growing coral framework is therefore responsible for the remarkable biomass, species diversity, and productivity of coral reefs, all of which are several orders of magnitude higher than the ocean waters that bathe them. After a coral reef is degraded, the structural functions gradually disappear. Recently killed reef corals may remain physically sound wave barriers for a while, but the protection they provide is temporary, because bio-erosion gradually hollows the dead coral skeleton out from inside, so they eventually collapse from wave forces. At that point waves can pass unimpeded to the shoreline, turning beaches from depositional to erosional environments. Where this is coupled to land based sources of nutrients, the dead reef is overgrown with fleshy (non-calcareous) algae that are not sources of sand, so the supply of new sand vanishes, and the beach is doubly affected: there is more erosion and there is less new sand to replace that eroded. The result is that around the world almost all beaches located behind degraded reefs are eroding, many with dramatic erosion scarps.

3.5. Impacts of Losses in Other Reef Benefits

Environmental economists evaluate coral reefs in terms of their monetary benefits and services to local or regional human populations. Tropical tourism is heavily dependent on the reef ecosystem, because of the attractiveness of the reef for watersports such as snorkeling and SCUBA diving. Activities as diverse as underwater photography, maritime archaeology, marine aquaria, sailing, fishing and even beachcombing are dependent upon the presence of a well-integrated and fully functional reef ecosystem. Estimates of the annual regional income from tourism in the Caribbean routinely reach no less than billion dollar levels.

4. Reef and Pelagic Fisheries

The severe ongoing decline of fisheries is almost universally blamed on overfishing, but in fact loss of carrying capacity through habitat degradation from global warming and pollution is also responsible, and will prevent recovery of fisheries unless this relationship is also addressed. Degraded reefs show a progressive decline in fish species diversity and abundance as live corals die and as shelter and habitat vanish. Many fish and marine invertebrates will only live in or around living coral, and quickly abandon coral after it dies. Following the severe bleaching mortality in the Maldives in 1998, the large schools of planktivorous fish and many invertebrates abandoned the dead corals they had lived in, even though they were structurally intact. As a result, the carrying capacity of degraded reefs for fisheries steadily collapses. This has not been well understood by most conservationists and fisheries professionals, who continue to describe as "coral reefs" those underwater sites with as little as 1% live coral cover. In essence, such marginalized and individual remnants are simply coral communities, dominated by organisms other than reef-building corals, and unable to support the structural, functional and metabolic associations of a coral reef ecosystem. These communities cannot provide shelter and habitat required by reef organisms. For example, dead reefs have lost essentially all their ecosystem services and habitat qualities for sustaining reef fisheries. Turning such degraded structures into Marine Protected Areas will not result in a recovery of their original carrying capacity for standing stocks of reef fishes, no matter how effectively local fishing is banned. Many coral reef Marine Protected Areas and Fisheries Reserves encompass such degraded habitats, and therefore will not be able to serve the biodiversity and fisheries management roles that those setting them up envision. Only ecologically sound and vital coral reefs can sustain such management goals.

Indicators for declining biodiversity in coral reef ecosystems include reduction of goods and services, slow recovery from environmental stress, and persistent poor water quality. Reports of such changes in coral reefs on a global scale have been accumulating for over 35 years. However, the collapse of reef fisheries worldwide now signals a clear disruption of the marine food chain, habitat insufficiency, and deteriorating water quality. Well intentioned calls for more or larger Marine Protected Areas and for reduced fish harvests are woefully insufficient to reverse the current rate of biodiversity losses on coral reefs. Climate change abatement demands targeted solutions directed toward the root cause of this global problem—greenhouse gas emissions. Control of waterborne and airborne pollutant release into the oceans requires new containment technologies and more thorough waste treatment processes. These and other strategies must be designed and implemented with dispatch and precision in order to have any lasting impact.

5. Coral Reefs as Endangered Marine Ecosystems

5.1. Threats from Coral Reef Collapses

Coral reef ecosystems, as rich habitats built only by dense healthy coral populations, appear to be on the verge of mass extinction from global warming, but this does not mean that all coral species will become extinct. Many species, perhaps even most, might survive in marginal habitats as coral communities, in which hard corals are present but are overwhelmingly dominated by non-reef building organisms. The coral reef ecosystem is threatened by mass extinction, but not necessarily all its component species, even hard corals. But these will be small, isolated, slow-growing, largely present in deeper and colder waters, and will not provide the same ecosystem services that healthy reefs do. The current focus on endangered species provides an impossible burden of proof in showing that the species are endangered everywhere they occur, and miss the point that the coral reef ecosystems may be more vulnerable than their individual species.

Natural regeneration is becoming increasingly uncommon, with large areas of reef totally failing to recover naturally, or doing so only episodically during short good periods, only to be more than set back by the next adverse extreme weather episode. The accelerating stresses of global warming and pollution will make such regeneration increasingly impossible in the future world-wide, so counting on natural regeneration is clearly a strategy that is doomed to failure to an ever-increasing extent. Yet natural regeneration is the strategy that is counted on by policy makers, managers, and funding agencies to provide the coral reefs and fisheries of the future. As a management strategy, based upon the claim that coral reefs can bounce back from stress because they are "resilient" ecosystems, natural regeneration is destined to fail. Examples of resilience that are often cited are not cases of corals that survived stresses that killed other corals, but cases of corals that suffered less stress than corals in other places, usually due to local water circulation, for example, corals in areas of local upwelling might be spared not because they are more resilient but because they did not get as hot.

5.2. Resilience of Reef Organisms

Elimination of the most stress sensitive species and survival of the most stress tolerant species provides no evidence of resilience. Most healthy Indo-Pacific coral reefs were overwhelmingly dominated by Acropora species prior to severe bleaching, but afterwards they were overwhelmingly dominated by Porites. Porites can withstand much more stress, within limits, than Acropora, but provides a lower profile and less protective fish habitat. The modern coral reef communities of both the Indo-Pacific and the Atlantic migrated from their center of maximum diversity in the Tethys Sea which was squeezed out of existence when Africa, Arabia, and India collided with Europe and Asia, leaving only the Mediterranean as a remnant. In Miocene times there were around 500 coral species in the Mediterranean, but as the conditions deteriorated, they steadily vanished until there was only one, a member of the genus Porites. This was not because it was "resilient" in the sense of being able to adapt to stress, but simply because it was the hardiest and last to die. Coral resilience is essentially a politically-motivated and abstract concept, copied from mathematical models, not one based in empirical coral reef ecology, and serves to justify a lack of activity directed toward reducing lethal environmental stresses on corals.

6. Needs and Recommendations

Ocean warming and the contributions from fossil fuel use constitute real and pressing priorities requiring prompt attention. The current rise of shallow water, near-shore sea temperatures in virtually all coral reef habitats around the world gives reefs only a few years to a decade or so before they lose their remaining living hard corals, if warming continues at the present rate, less if it accelerates. The fact that all major areas of coastal upwelling, responsible for the bulk of the Earth's pelagic fisheries, are warming faster than the global average indicates that the growing thickness of the warm surface layer is making upwelling less effective at bringing cold nutrient-rich water to the surface, causing the collapse of pelagic food chains from the bottom up. This will happen even in the absence of the overfishing that has often been blamed as the only cause of fisheries decline. While increased wind speeds in the interiors of the ocean basins may cause increased wind-induced upwelling in some areas, these are biological deserts and the increase in fisheries in these areas will not compensate for the decline of coastal productivity, because they are also very far from the coastlines, require much greater fishing effort for less return, and much higher transportation costs. Global warming is therefore a threat to both coral reef and pelagic fisheries, but for different reasons, and serious, comprehensive, and complete global efforts to reverse it are essential to preserve capture fisheries.

Analyses of satellite-derived sea surface temperature (SST) at over 200 globally-distributed reef sites between 1982-2003 indicate that coral reefs have not only been exposed repeatedly to high summer SST anomalies, but also essential relief from thermal stress in the winter is failing. Since reef organisms live very close to their physiological tolerance for temperature, a mere 1.0 ºC rise in SST results in stress induced bleaching of reef-building corals. Bleaching results from uncoupling of the normal symbiosis between unicellular algae (zooxanthellae) and coral soft tissue. Without their symbiotic algae, starving corals no longer produce a skeleton, defend themselves against predators, or reproduce. Warmer seas also promote microbial growth, responsible for infectious diseases in reef organisms. The same warming energizes intense tropical storms (hurricanes and typhoons) that physically damage reefs and disrupt ecosystem functions. Habitats are destroyed, pelagic organisms are dispersed, biodiversity declines, and water quality deteriorates following storm exposure.

Reef ecosystem goods and services that coastal and island populations depend upon to sustain their livelihood and (tourist) economies are at risk as living reefs lose their biodiversity and as reef organisms die. Human health (and also wealth) is also at risk from the spread of water-borne diseases and as anxiety mounts over jobs, seafood safety, and recreational security. Economic and societal impacts from global coral reef degradation are now of critical significance to perhaps a billion residents of over 100 countries, both small island states and continental shoreline states. Any hope for the preservation of coral reefs will require immediate and coordinated actions and funding of restoration programs, reduction of greenhouse gas emissions, and control of pollutant discharges into the sea. Therefore, we recommend these actions be instituted immediately on behalf of the remaining coral reefs of the world in order to provide some chance that generations to come might enjoy the benefits of this valuable ecosystem in the future, such as we know them today.

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Related Chapters

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Glossary

Algae
 : Non-flowering stemless aquatic plants, including macroscopic seaweeds and microscopic phytoplankton.

Anoxia
 : A condition characterized by the complete lack of oxygen in an area or in a body of water.

Biodiversity
 : The variability in genera and species of living animals and plants.

Biomass
 : The total quantity or weight of organisms in a given area or volume.

Carbon
 : An element of the periodic table, number 12, that is widespread in distribution and found in all living organisms.

Coral reef bleaching
 : A non-specific stress response of coral reef organisms that harbor unicellular dinoflagellate algae or zooxanthellae, during which the algae are sloughed and mucus is released from the animal tissues.

ENSO
 : Acronym for El Niño Southern Oscillation, a climatological phenomenon in the tropical Pacific Ocean in which westerly trade winds diminish or reverse and anomalously warm seas accumulate along eastern Pacific shores.

Erosion
 : The wearing away of substance from underwater formed structures, such as coral reef frameworks, beaches, or rock cliffs, or the loss of soil or rock from land sources.

Eutrophication
 : An accumulation of nitrate and phosphate wastes in an aquatic environment that favors the growth of algae.

Fishing effort
 : Harvesting pressures introduced by fishing activities within an area of the sea.

Greenhouse gases (GHG)
: Gases that trap heat radiating from the surface of the Earth to produce a warming effect in the lower atmosphere (troposphere).

Heat shock protein (HSP)
: A specific protein synthesized by a cell in response to abnormal elevation in environmental temperature. HSPs protect nascent proteins of the cell from degradation or conformational modification under stressful conditions. They are usually classified according to molecular weight (e.g., HSP 70 has a molecular :weight of 70 kiloDaltons).

Miocene
: A geological epoch within the Tertiary era of geological history, approximately 10 million years ago.

Organic
: Biological in origin from either plant or animal substances and containing carbon-based compounds.

Over-fishing
: Harvesting of local fish stocks above and beyond the capacity for those stocks to reproduce, replenish, and grow to individual adult sizes and numbers.

PAR
: Acronym for photosynthetically active radiation, the light exposures that stimulate the capture of CO_2 by plant cells in photosynthesis.

Parts per thousand (ppt)
: A way to express small levels of solutes in a liquid as weight ratio of the solute to the liquid solvent.

Pelagic
: Marine life occupying the upper layers of the open sea.

pH
: The negative logarithm of the H^+ ion concentration in a solution. pH is expressed in units of 1-7 (acidic), 8-14 (basic) and 7 (neutral).

Planktivorous fish
: Fish that eat plankton (free-floating marine algae) from the sea.

Productivity

: A measure of the amount of metabolic biomass that organism generates per unit time.

Soft corals
: Members of the phylum Cnidaria which are relatives of stony corals, anemones and jellyfish, but which do not produce a calcified skeleton. These are represented in the coral reef by sea fans, sea whips and gorgonians.

Sponges
: Members of the phylum Porifera that filter sea water and trap bacteria and other particles.

Sea surface temperature (SST)
: The temperature of the upper few centimeters (the "skin") of the ocean, as documented in infrared radiation data from satellites.

Symbiosis
: Animal and plant organisms co-existing in close partnership and providing natural benefits to one another throughout their conjoint lives; the respective partners are termed symbionts.

Tethys Sea
: The original sea that separated primordial continents that now represent Eurasia and Africa; the residual waters now represented by the Mediterranean Sea and the Black Sea.

Thermocline
: A region of abrupt change in the temperature and density of sea water relative to overlying water layers.

Trophic
: An ecological term referring to the relative position that an organism occupies within the food chain.

Tunicates
: The sea squirts, marine organisms of the subphylum, Urochordata, with a rubbery exterior.

Under-saturated
: The condition at which more solute may be dissolved in a solvent at a constant temperature and pressure before the mixture has reached a state of saturation.

Upwelling
: An oceanic process of water movement in up-moving currents from the bottom to the top layer in a regional area; the transport of deep, cold and nutrient-enriched water up to the warmer, nutrient-depleted interface of the atmosphere and the ocean.

UV (ultraviolet)
: A segment of the electro-magnetic radiation that is characterized by a wavelength just beyond the violet end of the visible spectrum

Zooxan-

thellate
: A condition in which an organism has formed close associations with unicellular dinoflagellate algal cells in a symbiotic union.

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Biographical Sketches

Dr. Tom Goreau, President of the Global Coral Reef Alliance, a non-profit organization for coral reef protection and sustainable management, has dived longer and in more coral reefs around the world than any scientist. His father was the world's first diving marine scientist, and he grew up swimming in coral reefs as soon as he could walk. He was previously Senior Scientific Affairs Officer at the United Nations Centre for Science and Technology for Development, in charge of global climate change and biodiversity issues. He has published around 200 papers in all areas of coral reef ecology, and on global climate change, the global carbon cycle, changes in global ocean circulation, tropical deforestation and reforestation, microbiology, marine diseases, soil science, atmospheric chemistry, community-based coastal zone management, mathematical modeling of climate records, visualizing turbulent flow around marine organisms, scientific photography, and other fields. He developed the method to predict the location, timing, and severity of coral bleaching from satellite data with Ray Hayes. He holds patents with Wolf Hilbertz for new methods for preserving coral reefs from global warming and pollution, restoring marine ecosystems, shore protection, mariculture, and non-toxic methods of preserving wood from marine boring organisms, termites, rot, and fire, in order to increase the lifetime of wood and decrease logging. In 1998 he and Wolf Hilbertz were awarded the Theodore M. Sperry Award for Pioneers and Innovators, the top award of the Society for Ecological Restoration. Dr. Goreau led developing country NGO efforts in marine and climate issues at the United Nations Conference on Environment and Development (Rio de Janeiro, 1992), the UN Summits on Development of Small Island Developing States

(Barbados, 1994, Mauritius, 2005), and the UN World Summit on Sustainable Development (Johannesburg, 2002). Dr, Goreau works with tropical fishing communities around the world to restore their coral reefs and fisheries, especially the Kuna Indians of Panama, the only Native people of the Americas who have preserved their cultural and political independence. He is also a hereditary leader of the Yolngu Dhuwa Aboriginal clan of Arnhem Land, Australia, that preserves the oldest creation myth in the world. Of Panamanian origin, he was educated in Jamaican primary and secondary schools, at MIT (B.Sc in Planetary Physics), Caltech (M.Sc in Planetary Astronomy), Yale, Woods Hole Oceanographic Institution, and Harvard (Ph.D. in Biogeochemistry), and is a certified nuisance crocodile remover.

Dr. Hayes is a Professor Emeritus at the Howard University College of Medicine in Washington, DC, USA. He received his education at Amherst College, Amherst, MA (B.A., cum laude, 1959) and the University of Michigan, Ann Arbor, MI (M.S., 1961, and Ph.D., 1963). He has served on the faculty of several medical schools, including the Harvard Medical School (Boston, MA), the University of Pittsburgh School of Medicine (Pittsburgh, PA), the Morehouse Medical School (Atlanta, GA) , Howard University College of Medicine and the University of the West Indies (Mona, Kingston, Jamaica). He is the immediate past Vice-President of the Association of Marine Laboratories of the Caribbean, a Corporation Member of the Marine Biological Laboratory (Woods Hole, MA), and a Fellow of the American Association for the Advancement of Science. He is also a certified SCUBA instructor, an Associate Member of the Advisory Council on Underwater Archaeology, and a member of the Board of Directors of two international maritime archaeological societies and the Global Coral Reef Alliance. He is currently a volunteer for the American Red Cross (Disaster Relief), the Smithsonian Institution (American History) and the U.S. Naval Historical Center. For many years, he has been a national lecturer for the Undersea and Hyperbaric Medical Society and a congressional advocate for the Physicians for Social Responsibility. He is the co-founder the Human Health and Climate Change Symposium of the International Conference on Global Warming and serves as a moderator and spokesperson for the International Planning Committee for the Global Warming International Center. His bio-medical research contributions have addressed the morphogenesis and differentiation of skeletal muscle in vitro, the fibrillogenesis of embryonic connective tissues, the pathogenesis of Progressive Systemic Sclerosis (Scleroderma), and the experimental induction of calcinosis in mammalian soft tissues. His recent marine biological research interests focus upon the cell biology of skeletal formation in stony corals, the histo-pathology of coral reef bleaching, emerging infectious diseases in coral reef organisms, reef and coastal marine ecosystem degradation, and the impacts of and linkages among extreme climate events, elevated ocean temperatures, and global climate change upon human health and marine environmental integrity. Dr. Hayes is married with four adult children.

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