EFECTS OF CLIMATE CHANGE ON CORAL REEFS

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Summary

Coral reefs are complex systems that form in the warm sunlit waters of shallow tropical and subtropical oceans. Like all organisms, changes to the environmental conditions in which these organisms live can have quite substantial changes to their physiology and ecology. Mounting evidence has revealed that aspects of the global climate are changing under the force resulting from the rapid increases in greenhouse gases in the earth's atmosphere. While global temperature has increased by 0.6 °K since the beginning of last century, tropical sea temperatures have increased by 1-2 °K. This has led to large-scale mass bleaching of the world's coral reefs. Mass coral bleaching occurs when symbionts are damaged by elevated sea temperatures and are expelled from the coral host. Large-scale mortality events have followed many mass coral bleaching events and have led to alarm among both reef scientists and managers.

The change in the concentration of carbon dioxide since the late 1800s (280 ppm to almost 330 ppm) has also reduced the alkalinity saturation state of the world's oceans and led to the additional concern that reef-builders like corals will have increasing difficulty in laying down the calcium carbonate that is necessary for reef growth. Projections from global circulation models suggest that stresses such as these that have arisen from a changed global climate will increase over the next 100 years and may eliminate reef-building corals and other symbiotic invertebrates as the dominant coral reef organism. Given that at least 100 million people depend on coral reefs for the daily subsistence, these changes in the health of the world's coral reef resources have become a major political and socio-economic concern.

1. Introduction
(see also Marine Biogeochemical Cycles: Effects on Climate and Response to Climate Change)

Biological systems have evolved over time to operate within fairly narrow environmental limits. Changes in sea temperature, salinity, pH, solar irradiance and other factors can have substantial impacts on the physiology and ecology of organisms and as a result, will impact their distribution and abundance. Coral reefs for example appear to require warm, sunlit conditions in shallow coastal areas. As with other organisms, sudden decreases in environmental factors like salinity, light or temperature will cause corals and their dinoflagellate symbionts (zooxanthellae) to die. This is often seen at a local scale after heavy rainfalls and solar warming of reefs exposed at low tide.

It is now almost certain that the world is undergoing a rapid change in temperature and other aspects of the atmosphere. Many now believe that the conditions under which corals can grow has begun to change and has led to a decline in the health of the world's coral reefs. The evidence for these changes is reviewed in this chapter. Principally, three types of changes associated with greenhouse gas forcing of the atmosphere are explored. These are increased sea temperature, decreased alkalinity and increased sea level. Concern over the impact of these changes has been heightened due to the damage associated with recent mass bleaching events and due to the high value of coral reefs to human economies.

2. Climate change in tropical regions

(see also Physical Oceanography Topic Overview, Chemistry of the Oceans)

The scientific community is virtually unanimous over the conclusion that the earth's climate is changing in response to the burning of fossil fuels and other associated human activities. These gaseous constituents change processes that interact to determine the heat budget for our planet. In particular, recent increases in carbon dioxide, methane, nitrous oxide, chlorocarbons, sulphate aerosols and ozone have forced changes in global temperature which, in turn, have had effects on the air and sea temperature, weather patterns and water movement. Since the industrial revolution, the concentration of carbon dioxide has risen rapidly from 280 ppm to almost 330 ppm. Similar increases have occurred with the other greenhouse gases. Global temperatures are now approximately 0.6 ºK higher than they were at the beginning of last century (1900-2000) and the past three of the past eight years are warmer than any other year since (at least) AD 1400.

Changes in air temperature and other factors have also led to changes in the temperature of the world's oceans. Tropical seas records show steady increases since the beginning of this century rates of 1-2^{o}C per century. Recent warming is unprecedented. J. Lough from the Australian Institute of Marine Sciences, for example, has revealed that sea temperatures seen in tropical Australia over the past 30 years are the warmest for the past 1000 years at least. While these trends may reflect longer-term cycles of change, they have been confirmed by a growing number studies of sea surface temperature trends going back 40-150 years using other data sets and such sources as coral cores. There is no evidence of a slowing or reversing of this rate of change and rates of change appear to be increasing with rates over the past 20 years being higher than those averaged over the past 100 years. Data sets are highly corroborative with rates being similar between measurement systems. Measurements made by researchers at the research station at La Parguera in Puerto Rico, for example, registered a rate of change of 2.53^{o}C per century while the satellite data sets (IGOSS-NMC data from NOAA) for the same area records a rate of increase of SST (sea surface temperature) of 2.29 ^{o}C per century.

Table 1. Rates of warming in tropical oceans for period 1981-1999. Rates determined from regressions done on Integrated Global Ocean Services System (IGOSS) nmc blended weekly Sea Surface Temperature data obtained from data sets available at the Lamont Doherty Earth Observatory server (http://rainbow.ldgo.columbia.edu/). Adapted from Hoegh-Guldberg (1999)

Location	**Significant of trend**	**Rate ^{o}C per 100 years**	**Other data sets**
Jamaica	< 0.001	2.29	2.53, Winter et al. (1998)
Phuket	< 0.001	2.30	1.26, Brown (1997a
Tahiti	< 0.001	1.44	
Rarotonga	< 0.001	2.27	
Southern GBR	< 0.001	2.54	
Central GBR	< 0.001	2.59	
Northern GBR	< 0.001	0.47	

Table 1. Rates of warming in tropical oceans for period 1981-1999.

3. Coral reefs as vulnerable ecosystems

(see also Coral Reefs as a Life Supporting System)

The effect of climate change on coral reefs has been discussed by a number of authors including the climate scientist B. Pittock (CSIRO, Australia) who points to three factors associated with climate change that are likely to influence coral reefs. These are: changes to the sea temperature, sea level and the carbonate alkalinity or aragonite saturation state of the waters surrounding coral reefs. Additional concerns surround changes to the patterns of water flow such as the El Niño Southern Oscillation (ENSO). These factors are exacerbated when combined with the many other anthropogenic stresses now facing coral reefs.

4. Sea temperature and coral bleaching

(see also Physical Oceanography Topic Overview)

Corals and their dinoflagellate symbionts are sensitive to temperature. When exposed to higher than normal temperatures, corals undergo a process that results in a loss of colour (bleaching). The colour change that accompanies stress in symbiotic organisms (from brown to white) is due to damage and subsequent loss of symbionts from symbiotic organisms after heat stress. Almost all symbiotic invertebrates have been reported to bleach. Corals are among the most prominent organisms affected – “coral bleaching” has been reported in six major episodes since 1979. During these periods ("mass coral bleaching events"), thousands of square kilometres turn white as the damaged symbiotic dinoflagellates are expelled. Normally, population densities of symbiotic dinoflagellates in reef-building corals range between 0.5 and 5 x 10^6 cell.cm^{-2} with very low rates migration or expulsion of symbiotic dinoflagellates to the water column. During periods of stress, rates of expulsion rise rapidly and may be as much as 10 000 to 100 000 higher than during periods when corals are unstressed.

While sudden reductions in the density of symbiotic dinoflagellates may result under a range of physical and chemical conditions, most evidence now points to the role of changing sea temperatures in the recent bout of coral bleaching. For example, all major bleaching events in 1998 the worst period of coral bleaching reported, were predicted days in advance by tracking positive thermal anomalies of one degree or more from NOAA satellites. Increasing water temperature experimentally will also rapidly cause symbiotic dinoflagellates to leave the tissues of reef-building corals and other invertebrates resulting in a reduced number of symbiotic dinoflagellates in the tissues of the host.

Changes to PAR (photosynthetically active radiation) or UVR (ultra- violet light) aggravate the effect of temperature. The secondary role of light is related to the site at which damage first occurs when corals and their symbiotic dinoflagellates experience thermal stress. As in higher plants, thermal stress in symbiotic dinoflagellates begins with the failure of the dark reactions of photosynthesis. The failure of the dark reactions reduces the availability of electron acceptors that would normally pass excitation energy from the light reactions into the production of organic carbon. Because of the reduced availability of electron acceptors associated with the dark reactions, excitations are passed to oxygen, which form active oxygen (superoxide and singlet oxygen). Active oxygen can lead to extensive intracellular damage, as it will rapidly oxidize any proteins that may contact it. If temperature and light stress continues, symbiotic dinoflagellates become dysfunctional and are removed from the symbiosis either through the direct loss of the host cells that contain them or via exocytosis. The overall removal of the symbiotic algae from the tissues leads to a reduction in the brown colour of the tissues (bleaching).

The mass mortality of corals is one of the most obvious impacts of coral bleaching. Mortality estimates following mass bleaching range from close to zero in cases of mild bleaching to close to 100% and depend on the intensity and duration of the associated thermal stress. Many reports of bleaching events during 1998 listed mortality rates that ranged upward of 80% in places like Okinawa, the Maldives and Palau. Baird and Marshall and Marshall and Baird reported substantial mortalities among corals on the inner reefs of the Great Barrier Reef. Mortality in most cases is family specific with staghorn corals (Acroporidae) being the most susceptible. Acroporids were consistently affected during the bleaching events of 1998, with the long- lived *Porites* being less so. While a case for different strains of dinoflagellates of having different sensitivities, differences among corals probably relate to differences between corals with respect to the light history and environment. Deep tissued corals like *Porite*s, for example, may protect the symbiotic dinoflagellates from light stress as the dark reactions of photosynthesis fail. The observed resilience of *Porites* to thermal stress is probably associated with the ability to retract polyps that contain the symbiotic dinoflagellates out of the light.

There is a growing case for the recent mortality events after mass bleaching to be unprecedented in recent history. Aronson and co-workers investigated this question in associated with recent mass bleaching and mortality on Belizean reefs off Central America. The first case of bleaching was recorded in 1995 and bleaching in 1998 caused a mass mortality to occur among *Acropora* species. Coral cores were investigated at various sites on the same reefs and inspected for evidence of similar scales of mortality. The conclusions of the study were clear. Mortalities of a similar scale had not occurred with the past 3000 years at least.

In cases of low intensity stress, reef-building corals may bleach but may recover their symbiotic dinoflagellates. Mass coral bleaching may have series of insidious effects on growth and reproduction of corals, however. In a study done by S. Ward and co-workers, the effect of coral bleaching on the reproductive capacity of reef-building corals was investigated. In this study, 200 colonies of reef flat corals at Heron Island were examined following the 1998-bleaching event in order to compare the fecundity of bleached and unbleached coral colonies. The effect of bleaching stress on corals was dramatic. Bleaching reduced reproductive activity in most reef flat corals examined. Bleached colonies of many important reef flat species contained no eggs at all despite the fact that they were supposed to be reproducing months later *(Symphyllia* sp, *Montipora* sp, *Acropora humilis, Favia* sp, *Goniastrea* sp, *Platygyra daedalea*).

How the sea temperature in tropical and sub-tropical regions will change is of paramount importance given the tight causal connection between sea temperature and the incidence in coral bleaching. The increasing precision of the general circulation models in projecting sea temperatures has allowed projections of sea temperature to be possible on a regional and even local scale. Using these projections under the IS92a climate change scenario (a doubling of atmospheric CO_2 or equivalents by 2100) and the behaviour of coral reefs to changes in sea temperature, it has been possible to project in turn how the intensity and frequency of coral bleaching will change over the next century. Estimates using general circulation models from the three major climate projection centres (Max Planck, CSIRO, Hadley Centre) show that the frequency and intensity of coral bleaching is set to increase in all parts of the world such that bleaching events on the scale and intensity of the 1998 become commonplace within the next 20 years. Even more alarming is the projection that bleaching events will become annual events in most parts of the world by 2040.

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Biographical Sketch

Ove Hoegh-Guldberg is the Founding Professor of Marine Studies and Director of the University of Queensland's Centre for Marine Studies. Professor Hoegh-Guldberg specializes in the physiology and ecology of reef-building corals and began his studies at the University of California at Los Angeles (UCLA) and obtained his Ph.D. in the laboratory of the eminent reef physiologist, rofessor Leonard Muscatine. Following his studies at UCLA, Professor Hoegh-Guldberg held a ostdoctoral fellowship at the University of Southern California before returning to Australia to take a post at the University of Sydney. In 1999, Professor Hoegh-Guldberg moved to the University of Queensland and has focussed on the impact of human activities on coral reefs. He is particularly interested in coral bleaching and global climate change, and was awarded the Eureka Prize for his research in this area in 1999.