EFFECTS OF SEA-LEVEL RISE ON CORAL REEFS

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Summary

The potential outcomes of sea-level rise on coral reefs are reviewed in the light of the measured global temperature changes attributed to the enhanced greenhouse effect. Events in earth's history that illustrate similar changes in global systems are seen to contribute to the evaluation, but are not sufficient to support predictions in the absence of an understanding of direct and indirect influences on coral ecology, distribution, growth, and reproduction, together with life-supporting and threatening processes in the

present day. Relevant aspects of coral ecology and reef-building and degrading processes, including coral growth rates, the role of symbiotic zooxanthellae, location of reefs in the photic zone, availability of suitable substrate, ocean circulation patterns, wave action, sediment transport, nutrient delivery and recycling, bioerosion, and, importantly, temperature, are considered as contributing to change in combination with sea-level dynamics. The relationship of human activities in coral reef regions with changing sea level is examined, in terms of the impacts of coastal communities on coral reefs and the vulnerability of coastal communities to sea-level rise. Coral bleaching is viewed as symptomatic of probable outcomes for coral reefs as they respond to these influences and the measured changes. The study draws on the Great Barrier Reef, Australia, for examples of processes and influences because it is the largest series of coral reefs in the world and the ecosystem is relatively intact. Implications for management and research directions are briefly considered. There is a need for policy coordination within and among governments responsible for the care of coral reefs.

1. Introduction

The impact on coral reefs from a rapid rise in sea level cannot be envisaged by considering the response of corals to sea-level change in isolation from other influences that presently govern coral growth. Although the direct response of corals to sea-level rise has been discussed by many authors, the inclusion of a range of indirect factors is essential to give an accurate outlook on the fate of coral reefs. Initially, the growth of many coral reefs may keep pace with rise in sea level. This outlook is based on the assumption that there are no other influencing factors such as sea-temperature rise, increased pollution, increased tourism, and other anthropogenic factors. If the trends experienced in recent years are any indication of future events, the likelihood of this is slight. In the longer term, coral growth may reach a threshold and be outpaced by sea-level rise, leading to the drowning of many coral reefs. However, the direct effect of a rise in sea level on corals is only part of the story. Coral-reef ecosystems are one of the most complex ecosystems on earth. They are vulnerable to human disturbance, yet have a resilience that scientists who study them are only beginning to understand.

This study draws on the Great Barrier Reef off the northeast coast of Australia for examples of processes and influences, because its critical systems are relatively intact. This reef system is by far the largest in the world, but is by no means the most important in supporting human populations. About 40% of the world’s mapped reefs are in the Pacific Ocean and 60% of these were assessed in the 1998 report *Reefs at Risk*, by the World Resources Institute, Washington, as being at low risk. Coral reef degradation can occur through natural processes, of which sea-level rise may be one. The history, distribution, and ecology of coral reefs and sea-level dynamics in relation to reef building and persistence are reviewed. The development pressures on reefs and outcomes for the human populations of some of the most vulnerable reef complexes are examined, together with management and research needs.

2. Coral Reefs in Earth’s History

To understand the significance of the effects of sea-level rise on coral reefs it is vital to review the events of earth's history, especially the Cainozoic period, beginning 65 million years ago, which was the precursor of the events of the Quaternary, the very latest period and the one in which humans radiated over the face of the earth. These were times of great changes in land and sea regions and climates. Today's observed global temperature changes and their possible effects on coral reefs must be viewed against this dynamic background before the impact of human activities can be evaluated.

The energy flows that govern the environment of the earth are driven by both external and internal processes, linked in systems and with a variety of feedback mechanisms. The dominant external influence is the amount of solar radiation received through the atmosphere. One of the chief internal influences is earth cooling and radioactive decay, expressed in the geometry and the movement of the lithospheric plates. The plates move over the crustal surface because of differential heating. There is intense heat and pressure in the core of the earth. The insulating effect of large landmasses restricts the escape of geothermal heat and convection in the mantle and warping of the crust result, so that the plates move and jostle. Plate boundaries become geologically active areas, causing sections of continental crust to collide. Oceanic crust moves under continental crust, melting and forcing magma up to form volcanoes, and subducting oceanic crust gives rise to island arcs and trenches, in episodes of orogeny, or mountain building.

The present layout and shape of the plates developed by the breakup of the ancient super-continent of Pangea, which was a single landmass, and the ancestral super-ocean, now called Tethys, which existed for hundreds of millions of years. Coral reefs occurred in the warm Tethys seas. Pangea began to break up in the Jurassic, around 180 million years ago (Ma BP). Early rifting opened the proto-Atlantic Ocean and the modern oceans followed in the Mesozoic era (Jurassic, Cretaceous, Triassic). The Southern Ocean developed about 50 Ma BP, almost entirely within the Cainozoic era. The mantle warmth built up under Pangea dissipated so that smaller continental fragments cooled and subsided as they moved. At the same time the old Tethys ocean floor was replaced with younger, warmer, more buoyant oceanic crust squeezed up at the new spreading centers, and the overall elevation of the seafloor rose. Coral reefs came and went.

The breakup of Pangea was accompanied by increased igneous activity along the rift systems and the new continental margins. The volcanic activity caused a rise in carbon dioxide (CO_2) concentrations in the atmosphere, both by direct emission, and because the global marine transgression reduced the area of exposed land on which chemical weathering could take up CO_2 from acidified rain. Positive feedback reinforced this tendency. For example, increased CO_2 led to greenhouse warming, which warmed the surface of the ocean, reduced the solubility of CO_2, and further enhanced the warming, as would the blanket of water vapor resulting from evaporation on the warm sea surface. The warming would cause thermal expansion of the seawater, so that it further transgressed the land. Because less of the sun's heat is reflected from a smaller land surface, the warming trend would be enhanced. Through feedback chains like this, major climatic change can be triggered by relatively minor events, and can occur over a short timescale.

The result of the breakup of Pangea was a major marine transgression on a global scale and many coastal lands were flooded by the sea. The system of ocean circulation of the old Tethys was replaced by smaller gyres transporting heat in a circular motion across the oceans, initiating the global oceanic circulation known today. Coral reefs again proliferated intermittently. The southern continental mass of Gondwanaland broke up and the parts separated, India heading northward, colliding with the Asian landmass and pushing up the Himalayas; Australia and Antarctica rifted and separated, Australia moving northwards. High levels of carbonate sedimentation in the oceans, including species-rich reefs, typically marked the warmer episodes, such as occurred in the Miocene period. The rock record shows that biogenic limestones and marls were often followed abruptly by sandstones, silstones, and spiculites, suggesting sea-level rise (or continental margin sinking) and burial of reefs and neighboring carbonate depositional environments by siliceous sediments.

The closure of the Panama isthmus between 12 Ma and 3 Ma BP and the opening of Drake Passage caused rapid changes in oceanic circulation patterns. For example, the closing of Panama caused northward movement of the Gulf current that provided warm oceanic moisture from which evaporation drew the precipitation needed for ice accumulation. Again, coral reefs disappeared. As plate movement changed the geometry of the landmasses and ocean basins, causing sea levels to rise and fall in relation to many land areas, fluctuating regional changes in climate were produced, setting the scene for evolutionary changes in plants and animal species that produced the biological diversity known today.

The onset of cyclic cooling and warming of the earth's surface with glaciation in the Quaternary was accompanied by the rise and succession of another species, *Homo sapiens* and its predecessors. The earth currently is in a relatively warm interglacial period. Based on oxygen isotope data from the Greenland Ice-Core Project, the previous interglacial period (known as the Eemian of Europe) was up to 2°C warmer on average, but also experienced transient temperature jumps of 10°C or so in a few decades, and intervening cold swings of 4°C–5°C. Increases in atmospheric concentrations of greenhouse gases since pre-industrial times have caused radiative forcing of climate and an enhanced greenhouse effect, leading to measurable global warming (0.3°C–0.6°C mean surface air temperature) and sea-level rise (an estimated 1–2.5 mm yearly). The increased greenhouse gases in the atmosphere, chiefly CO_2, methane (CH_4), and nitrous oxide (N_2O), are attributed to human activities, particularly fossil fuel use, land-use change, and agriculture.

The level of uncertainty in sea-level rise estimates is illustrated by recent South Australian work on Holocene sea levels, showing that land-level changes significantly affect tide gauge records, so that sea-level rise may be overestimated two to three times when such influences are ignored. However, even a small rise in temperature could trigger climatic instability of the kind seen in the isotopic record of the last interglacial period. Rather than seeking direct analogues with the past, we may gain better answers from trend analysis of data accurately measured, the directions and rates of change, and the responses of the biota. Coral reefs appear to be under pressure as coral bleaching attributable to a small rise in sea temperature is reported from many reef locations. The possibility of polar ice melting and raising the level of the oceans is thought to constitute a direct threat to coral reefs, particularly those of the small island nations.

3. Coral Ecology and Reef-Building Processes

3.1. Coral Reef Distribution

Coral reefs cover about 600 000 km^2 of the earth's surface. The Great Barrier Reef system is 6000 km long and covers 350 000 km^2, consisting of approximately 3000 reefs, well over half the globe's total reef area. Coral reefs are mainly found in tropical waters. This is due to the temperature limitation on growth and reproduction of corals, which survive in water temperature averaging above 20°C, and below 30°C–35°C. Their temperature tolerance is critical for the long-term health and distribution of coral reefs. Another important factor in the global distribution of coral reefs is their location in relation to areas of past high volcanic activity.

3.2. Coral Reef Morphology

Coral reefs form as three main types:

1. Fringing reefs
2. Barrier reefs
3. Atolls

There are many geomorphological, ecological, and biological differences between all three, and a brief summary of each type follows.

1. Fringing reefs are the most common types of reefs, developing near shore where hard surfaces occur. Their name describes their growth in a narrow band or "fringe." A distinctive element of fringing reefs is the inner reef flat, which is the widest part of the reef, separating the land from the outer reef slope. The reef flat is a shallow, low-gradient structure that is often exposed at low tide, unlike the reef slope, which is quite steep. The reef flat has far less diversity and quantity of corals than does the reef slope, consisting mainly of sediment, rubble, and a greater proportion of seaweeds and seagrasses. Waves wash away sediment from the reef flat and carry in nutrients. Fringing reefs are much closer to land than other types of reefs and so they experience much more influence from shoreline processes than do barrier reefs or atolls.
2. Barrier reefs differ from fringing reefs mainly by the distance they occur from land. Like fringing reefs, they form a band adjacent to the coast, but at considerably greater distance. A relatively deep lagoon separates them from the land. Within the lagoon, columns of corals called knolls or pinnacles grow virtually to the water surface. The reef slopes are much steeper and a well-developed back-reef slope occurs. The lagoons of barrier reefs are largely protected from waves and sea currents by the rest of the reef. Coral growth is usually more vigorous at the crest of the fore-reef slope than on the reef flat, which may house a number of coral or sand islands formed by the deposition of the sediments formed by progressive breakdown by waves and currents. These islands are called cays or keys.
3. Atolls can occur far from land, often rising up from depths of thousands of meters. Their ring-type structure is formed initially as a fringing reef around a volcanic island, which slowly subsides leaving a ring of coral reef surrounding a shallow lagoon. The reef crest of an atoll is strongly influenced by wind and waves. Most atolls lie in the zone of the trade winds, and winds usually come from one consistent direction, which controls the morphology of the reef. Encrusting coralline algae, tolerant to strong wave action, build a distinct ridge

on the reef crest of the side facing the prevailing winds. The side experiencing little wave action tends not to develop an algal ridge. Most atolls occur in the Indo-West Pacific region and are homes to thousands of islanders.

3.3. Coral Ecology

The ecology of coral reef ecosystems is highly complex and not clearly understood. The considerable lack of understanding of these systems means that predicting effects of changes such as sea-level rise is difficult, especially when coupled with the uncertainties surrounding the greenhouse debate. Many coral reefs remain interconnected with coastal and other systems, further complicating the issue. However, the study of coral reefs has identified certain responses to environmental parameters that can be used to predict how corals themselves are likely to respond to the rapid rise in sea level forecast from human-induced global warming.

3.3.1. Reef-Building Corals

Corals are animals (phylum Cnidaria) that reproduce asexually and proliferate to form reefs. Most reef building corals are colonies of many polyps that arise when planktonic coral lavae (planulae) settle onto a hard surface and metamorphose, given the right conditions, which vary considerably among species. The polyps then divide continuously to form a colony of corals. The skeletons of corals, living and dead, are composed primarily of calcium carbonate, which forms the major structural component of the reef.

Nearly all reef-building corals contain in their tissues zooxanthellae, which are round, unicellular algae, specifically a dinoflagellate, that have a symbiotic relationship with the coral. Zooxanthellae are responsible for the array of color exhibited by corals but, more importantly, they provide corals with the photosynthetic organic material they need to make reefs. Most of the corals' waste products, particularly nitrogen and phosphorus, are taken up by the zooxanthellae for food production, which is then absorbed by the corals. Although making up less than 5% of the reef plant mass, zoothanthellae provide coral with up to 90% of its nutrition. Without the zooxanthellae, corals produce their calcium carbonate skeletons too slowly to form a reef.

3.3.2. Reef-Forming Processes

Almost all the sediment that comprises the reef comes from fragments of corals and the skeletons or shells of other organisms. Coralline algae assist the growth of reefs through the deposition of considerable amounts of calcium carbonate. Although not as important to corals as zooxanthellae, they are important in the formation of reefs, in the Pacific more so than in the Atlantic reefs. Green coralline algae (*Halimeda*) is one of these, depositing calcium carbonate within its tissues and accumulating as calcareous remnants on the reef. Encrusting red coralline algae (*Porolithon*, *Lithothamnion*, *Lithophyllum*) are important to reef formation, as they bond loose unconsolidated sediments together to blanket the reef, together with their own calcium carbonate skeletal remains. Other organisms that help make up reef fabric include tests (i.e. the hard covering) of foraminifera, sea urchins, molluscs, bryozoans, crustaceans, and sponges, although only the calcareous schlerosponges directly contribute to reef growth.

A gradual rise in sea level, independent of any other factors, is likely to have minimal impact on the reef-building organisms. The symbiotic relationship between zooxanthellae and corals would probably remain undisturbed, and the other organisms such as the encrusting algae would probably continue to shape the reef in a similar manner. Some adjustments might be made at threshold depths, but some compensation would occur closer to the new surface. However, should the rise be unusually rapid (i.e. a rate exceeding the natural variation in sea level) or be coupled with other factors that are likely to accompany sea-level rise, there are a number of reef-forming processes that are likely to be disrupted.

In any ecosystem, a range of environmental factors exists that enable the species to survive and reproduce efficiently. Coral reefs are no exception, with a range of factors identified as influential to reef growth. Such conditions include temperature, to which the zooxanthellae are particularly responsive, currents, winds and storms, wave action, geological factors, and sea level, which is of particular importance as this affects many of the other factors. Many past predictions of reef response relate only to the direct effects of a sea-level rise. Because of the complexity of coral reef ecosystems, the indirect factors of reef formation and growth such as water quality and biological interactions must be considered, together with human-induced changes.

3.3.3. Sea-Level Dynamics and Reef-Forming Factors

Sea level is largely responsible for the balance of erosive and constructive processes that shape a reef, for the dynamics of waves and ocean currents, and for the distribution of nutrients within reefs. Sea level has fluctuated through the course of the earth's history. Generally, sea level has oscillated within a range of 100 m, with rates of change often exceeding 10 m per 1000 years. Some studies have concluded that, irrespective of human-induced greenhouse effect, sea levels would probably continue rising until the end of the twenty-first century. Opinions on the extent that sea level is projected to rise are mixed. Some scientists believe there is insufficient evidence to conclude even an acceleration in sea-level rise over the twentieth century, while many others feel that there is an abundance of firm evidence, particularly from glacial retreat and coral reef records.

Earlier, the Intergovernmental Panel on Climate Change (IPCC) estimated a sea-level rise somewhere in the magnitude of 10–30 cm by about 2030 and 21–71 cm by the year 2070 (with best estimate of 44 cm), and about 1 m in the twenty-second century. Australian researchers have predicted a rise of between 0.2 m and 1.4 m by 2050. The above estimates all relate to a global sea-level rise, that is, a mean sea-level rise, and the IPCC is constantly working to refine and revise them. The most recent IPCC report concludes that tide gauge records for the twentieth century give a mean sea-level rise of 1–2 mm per year with a central value of 1.5 mm per year, far less than that recorded by prehistoric sea-level transgression (over 24 mm per year), while the data from southern Australia suggests even lower rates. Regional differences must be considered when predicting the impacts on coral reefs. Regional sea levels are determined by several local factors, including thermal expansion, glacial isostacy, tectonic changes, and variations caused by climatic fluctuations such as ocean circulation. The sea-level rise resulting from these factors is likely to be uneven across the globe, as are the implications for reef morphology and processes.

Change in sea level will not result in the destruction of the world's reefs if the change is within the range of natural fluctuations. The present-day coral reefs would not be where they are today were it not for the fact that the sea level has changed in the past. In fact, without some change of sea level relative to the land during the existence of the fringing reefs, it is unlikely that atolls and barrier reefs would form. All coral reefs that exist today near, or at, sea level are growing on substrates that stood above sea level during the Pleistocene epoch. Good evidence of this exists where coral reef terraces are found well above present sea level, such as in New Caledonia and the Huon Peninsula, New Guinea. Geological evidence from drilling and radiocarbon dating of coral reefs has suggested that the sea level may have transgressed many times in the past. A problem exists when there is a question as to the difference between natural fluctuation in sea level, and fluctuations of anthropogenic origin, making predictions based on past evidence less reliable. It becomes necessary then to look locally at the evidence for sea-level rise, and try to assemble a picture of when and where human influence has had an effect.

Sea level varies relative to the land surface for a number of reasons. Firstly, there are isostatic adjustments where sea-level changes occur due to tectonic and crustal movements. The atoll reefs of the globe are the result of these processes, which are rarely predictable. Some coral reef terraces that today exist above present sea level are a source of evidence of tectonic movement. These processes will result in regional differences in sea level across the globe, making generalizations difficult. It is safe to assume that reefs occurring in regions with active tectonic movement are likely to experience a change in reef morphology. However, some reefs occurring around tropical islands where there is crustal plate convergence, such as those in New Guinea and Barbados in the Caribbean, may experience continual uplift at a rate that is able to compensate for an actual rise in sea level, although this is quite improbable.

Studies have revealed that sea-level trends have varied considerably because of tectonic movement in recent years. Data sets from ten water-level stations in the Pacific Ocean that have been operational between 34 and 88 years revealed that sea-level trends varied considerably from station to station, with only one station, Hilo, Hawaii, experiencing a trend exceeding that of global sea-level rises (0.2 mm per year). Sea levels actually dropped in some areas, notably Guam and Midway. In this 1988 study, Parker suggested that this was caused by vertical land movement differences, as climatic conditions are similar in the region studied. Hilo is situated near the youngest volcano in the Hawaiian chain, and therefore subsidence from cooling and contraction of the oceanic crust would be greatest there. It is imperative that these tectonic differences are recognized when predicting future sea levels, and the effect that this will have on coral reefs. Many Pacific islands are sites of major tectonic activity, whereas it is unlikely that tectonic forces will influence the future sea level experienced on the Great Barrier Reef, because of the relative stability of the Australian continental margin.

Secondly, and more relevant to human-induced climate change, are the eustatic changes that are likely to influence sea level. Eustatic changes include changes in absolute sea level, such as those arising from glacial retreats and advances, and thermal warming. Regional rebound of the land surface after ice melt has occurred constantly throughout the history of the earth, as has a rising sea level due to this factor. Separating the natural fluctuations in climatic events from those of anthropogenic nature is difficult, because of the lengthy timescales needed and the absence of data. Although a wide range of opinion exists among scientists on the extent of human-induced climatic variation, it is accepted that humans have altered the CO_2 in the atmosphere sufficiently to force the retreat of glaciers, the main threat from the disintegration of the West Antarctic ice sheet being a rise in sea level.

The threats to sea level from glacial retreat are by no means equal around the earth. In order to predict the effects on corals from rising sea levels, it is necessary to recognize those variables that will alter from region to region. Variance results from wind, ocean currents, tides, tectonics, the efficiency of ocean circulation, and thermal expansion. Thermal expansion is a widely recognized factor in regional predictions of sea-level rise, contributing to an estimated 2 cm to 6 cm rise in sea level over the period 1880–1985. Nevertheless, it has been ignored in some estimates of future transgression (e.g. the IPCC prediction of 10 cm to 30 cm by about 2030), perhaps because of the complexity of the issue. This complexity is illustrated by the fact that water expands a different amount at different temperatures. At 5°C the increase in water volume is 1 in 10 000 for each degree, and at 25°C (typical of tropical regions) the increase is 3 in 10 000 for each degree. The effective prediction of sea level may need to incorporate regional thermal warming factors to gain an accurate representation of future events.

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Biographical Sketches

Stuart Peevor graduated with a bachelor's degree in environmental management from Flinders University of South Australia, majoring in geography, environmental studies, and economics. Like most young Australians he worked his way through university, in Stuart's case as a storeman and nightfiller in a supermarket chain. On graduation he obtained a position in the Australian Bureau of Statistics, a Commonwealth Government department, and currently lives in Canberra, ACT. Stuart has particular interests in environmental impact assessment, environmental management systems, and sustainable development policy.

Jan Carey has a B.A. with first class honours in geology and a Ph.D. in environmental studies (Macquarie University, 1987). Her doctoral studies explored a framework for marine ecological monitoring, utilizing tropical and temperate benthic macroinvertebrates, together with reconstructions of Quaternary nearshore fauna and their palaeoenvironments. Dr. Carey lectures in environmental risk management and coordinates the UNEP–University of Adelaide International Graduate Program in Environmental Management, offered in Adelaide and Singapore. She was earlier employed in Australian national, state, and local government agencies, including the Great Barrier Reef Marine Park Authority, Australian National Parks and Wildlife Service, Maritime Services Board of NSW, and NSW Transport Department.