Pacific Science (1992), vol. 46, no. 3: 374–382

Coral Reefs and Environmental Change—The Next 100 Years: A Synopsis and Abstracts of Papers Presented at a Symposium of the XVII Pacific Science Congress[1]

RICHARD W. GRIGG[2]

Abstracts of 14 papers presented in a symposium held at the XVII Pacific Science Congress in Honolulu in May 1991 follow. The symposium, sponsored by the Pacific Science Association's Scientific Committee on Coral Reefs and the Western Society of Naturalists, addressed the problems of man-induced and natural environmental change to coral reefs on both short- and long-term time scales.

The plenary address by Donald W. Kinsey on the greenhouse effect and coral reefs provided an overview of how change associated with global warming might affect coral reefs over the next several centuries. In the papers that followed, the effects of sea-level change on atolls were discussed by Colin Woodroffe and Roger McLean, who showed how the growth form of microatolls might be used to interpret average water level and hence past and present trends in sea level. In another paper on sea-level change, F. J. Murphy, D. R. Stoddart, C. E. Cook, and C. A. Cartier illustrated how dating and geomorphological analysis of motus can be used to determine past sea-level history. Two papers dealing with climate variability on the order of decades focused on the effects of El Niño–southern oscillation (ENSO) events on coral reefs. C. M. Eakin described the severe mortality and bioerosion that took place in the eastern Pacific following the ENSO event in 1982–1983 and warned that if global warming leads to an increase in the magnitude and frequency of ENSO events, coral reefs in the eastern Pacific might be threatened with extinction. The effect of ENSO events in Indonesia was examined by Lisa Wells, Michael Moore, and Richard Fairbanks, who, by analyzing humic acids and oxygen-18 in the annual bands of coral colonies (*Porites lobata*) in Indonesia, showed that the characteristics of ENSO events in that area are virtually the opposite of those in the eastern Pacific: drought, low river discharge, and cool high-salinity surface water.

Three papers in the symposium dealt with change on coral reefs caused by anthropogenic sources of stress: heated effluents from power plants and point-source discharges from ocean sewer outfalls and sugar mills. Tsu-Chang Hung, Che-Chung Huang, and Kuang-Lung Fan described the impact of effluent from a nuclear power plant in southern Taiwan where coral mortality occurred in areas where water temperature exceeded 31°C but the effects were highly localized. The effects of hot water effluent from a diesel-fired power plant averaging 34°C on a fringing reef in Guam were described by H. G. Siegrist, K. G. Bowman, R. H. Randall, and P. B. Stifel: scleractinian corals were killed over an area about 10,000 m square. R. W. Grigg, dealing with point-source pollutants, showed that impacts of sugar mill effluents discharged in Hawaii are

[1] Manuscript accepted 9 September 1991.
[2] Department of Oceanography, University of Hawaii at Manoa, Honolulu, Hawaii 96822.

significant but localized; in contrast, ocean outfalls in Hawaii apparently produce no negative environmental impacts.

Another series of papers dealt with the need to monitor long-term environmental change on coral reefs globally. Bernard Salvat argued for a world coral reef site network to establish a global database. On this scale, impacts to coral reefs might serve as a means of assessing global climate warming. S. L. Olhorst, W. D. Liddell, and R. J. and J. M. Taylor offered several approaches to reef censuses and concluded that no one census method could be utilized on all reefs. C. W. Evans described patterns of recovery and change of coral reefs in Kaneohe Bay, Hawaii, and C. Hunter and J. Maragos discussed the potential of using recreational divers to conduct large-scale long-term monitoring studies of coral reefs.

In the final paper, Susan M. Wells provided an overview of human impact on modern reefs worldwide, arguing that over the short term coral reefs must be viewed as fragile ecosystems in need of conservation, while at the same time recognizing that on longer time scales, coral reefs have weathered and survived significant climate changes including cycles of sea level rise and fall.

The most difficult challenge faced by coral reef biologists to emerge during the symposium is the problem of separating anthropogenic change from natural variability on coral reefs. Long-term monitoring studies in a variety of reef settings are needed to establish baselines against which anthropogenic impacts can be measured. Coping with this problem on a global scale and developing successful management strategies will be the challenge of the future to coral reef science.

The Greenhouse Effect and Coral Reefs

D. W. KINSEY[3]

Current predictions concerning the greenhouse effect contain many uncertainties. However, some significant sea-level rise reaching at least 6–8 mm/yr by 2050 seems likely. Coral reefs can achieve vertical growth of perhaps 15 mm/yr for short periods and a sustainable modal maximum of about 8 mm/yr. Thus they could keep pace with any likely short-term greenhouse scenario. Whether they will, in fact, respond with recolonization of presently depauperate reef flats and renewed vertical growth is subject to controversy. In the past, reefs have both succeeded and failed to do so without clear explanation. Most other attributes of the greenhouse effect could discourage renewed growth—temperature increase, increased storminess, freshwater and nutrient run-off, decreased insolation. However, these predictions relate principally to subtropical latitudes. Presently, temperature is receiving the most attention. Recent worldwide coral bleaching is commonly attributed to early indications of the greenhouse effect. It seems more probable that it should be attributed to a period of temperature instability unrelated to the greenhouse effect. In fact there is little reason to predict that a slow, steady temperature increase of 1–2°C over 50 yr or more could not be tolerated by all but reefs in the most extreme locations. Increased storminess could act to slow down recolonization. Increased run-off is certainly a negative influence, but at least most open-water reefs are not particularly vulnerable. On balance, it seems that the

[3] Great Barrier Reef Marine Authority, Townsville, Australia.

short-term response to the greenhouse effect is likely to encourage increased reef growth provided weather and temperature changes are not too erratic. The role of reefs as carbon sinks has received some popular attention. They are portrayed as major sinks for CO_2 and therefore as potential saviors from increases in greenhouse gases. In fact, they presently act as a sink for the equivalent of only about 2% of the anthropogenic CO_2. Although this could double in the most optimistic 100-yr scenario, this is still of limited significance. More important, the marine deposition of limestone actually decreases the ability of the ocean to absorb CO_2 from the atmosphere. The fate of coral cays is probably less controversial. Redistribution of reef sediment reserves will facilitate island perimeters generally keeping pace with rising sea level until the sand reserves are depleted. The cays will then erode rapidly. The time scale for these responses is variable, reef to reef. Notwithstanding the positive value of this early dynamic response to sea level, the penetration of salinity into the freshwater lenses of the islands will be a major negative effect for island communities even in the short term.

Coral Atoll Development: A Holocene Perspective on Response to Sea-level Change

R. F. McLean[4] and C. D. Woodroffe[5]

Coral atolls in the Indian and Pacific oceans consist of sheltered lagoons encircled by reefs upon which are low-lying islands of generally unconsolidated sand or shingle. These reef islands appear particularly vulnerable to inundation should the sea level rise as is anticipated as a result of the greenhouse effect. Entire atoll rims, with associated islands, have developed under conditions of changing sea level. Investigation of the stratigraphy, chronology, and pattern of Holocene geomorphological development of coral atolls allows us to decipher some of the responses to different rates of sea-level change in the past. The complex surface morphology of most atolls results from a period of sea-level stability, if not sea-level fall over the last 3000–6000 years. The landforms are likely to exhibit some resilience in the face of gradual sea level rise, but are unlikely to be preserved in their present form if the sea rises at the most rapid of the rates predicted.

Coral Microatolls and Recent Sea-level Change on Atolls

C. D. Woodroffe[6] and R. F. McLean[7]

Microatolls are colonies of massive corals that generally are dead on their upper surface but alive around their perimeter. Their upward growth is constrained by the water level of exposure during low spring tides. X rays of vertical slices through these corals reveal annual density banding that can be interpreted to reconstruct year-to-year changes in the upper limit of coral growth, indicating trends in sea level. Microatolls thus act as long-term water-level recorders and are of special significance on low-lying coral atolls where sea-level rise could have devastating effects.

[4] Department of Geography and Oceanography, Australian Defense Force Academy, Canberra, Australia.
[5] Department of Geography, University of Wollongong, P. O. Box 1144, Wollongong, N.S.W. 2500, Australia.
[6] Department of Geography, University of Wollongong, P. O. Box 1144, Wollongong, N.S.W. 2500, Australia.
[7] Department of Geography and Oceanography, Australian Defense Force Academy, Canberra, Australia.

Geomorphology of the Motus of Moorea, French Polynesia

F. J. MURPHY, D. R. STODDART, C. E. COOK, AND C. A. CARTIER[8]

The physical structure of motus is highly sensitive to environmental influences. Precise field surveying and laboratory analysis of rock and sediment samples allow a categorization of geomorphologic features in both time and space and a reconstruction of the evolutionary history of the motus with respect to sea-level fluctuations, storm activity, and tidal cycles. In this paper, geomorphological data collected from three of the five motus on the island of Moorea are presented. Geomorphological features on these motus include conglomerate platforms, beachrock, cay sandstone, and sedimentary environments ranging from fine-grained sandy beaches to boulder fields. Mapping was carried out using laser surveying equipment (EDM), which produces exactly vertical and horizontal coordinates for each point surveyed and is the most accurate method available for determining the positions of coastal features.

The 1982–1983 El Niño: Impact of Eastern Pacific Reef Carbonate Budgets and Implications for Severe Bleaching Disturbances

C. M. EAKIN[9]

Sea surface warming during the severe and prolonged 1982–1983 El Niño–southern oscillation (ENSO) event resulted in bleaching and mortality of over 50% of reef coral cover at Uva Island, Panama. Subsequently, densities of the eroding echinoid *Diadema mexicanum* increased from pre-ENSO values of 3 individuals/m^2 to at least 50 individuals/m^2 in the seaward reef base zone, where erosion of the reef framework currently exceeds 13 kg $CaCO_3/m^2/yr$, producing a vertical loss of 22 mm of framework per year. A preliminary $CaCO_3$ budget of Uva Island reef has been calculated from estimates of production by corals and coralline algae, framework destruction by *D. mexicanum*, infaunal eroders, fishes and other motile eroders, and sediment retention within the framework. Damselfish and their algal lawns protect portions of the reef from erosion, contributing significantly to the budget. The combination of coral mortality and increased densities of eroding echinoids resulted in a 60% decline in net $CaCO_3$ deposition. The budget for the seaward reef base has shifted from net carbonate deposition to a net loss of almost 3 kg $CaCO_3/m^2/yr$. Mortality due to thermal stress such as severe ENSO events may not only alter the structure of coral reef communities, but also lead to destruction of reef frameworks.

[8] Department of Geography, University of California at Berkeley, Berkeley, California 94720.

[9] Rosenstiel School of Marine and Atmospheric Science, Division of Marine Biology and Fisheries, University of Miami, Miami, Florida.

Climate Variability of the Indonesian Low and Southern Oscillation Reconstructed from the Geochemistry of Annually Banded Reef Corals

L. WELLS,[10] M. MOORE,[11] AND R. FAIRBANKS[12]

Precipitation and sea surface temperature (SST) in Southeast Asia are closely coupled to the southern oscillation (SO) because their variability is a function of the intensity and position of the Indonesia Low, itself a measure of the heat flux that drives Walker Circulation. SO positive phases produce heavy rainfall; high river discharge; and anomalously warm, low-salinity surface waters. SO negative phases (ENSO) produce drought; low river discharge; and cool, high-salinity surface waters. Precipitation records substantiate the correlation between Southeast Asian rainfall and the SO: wet-season peak rainfall is at or below the annual mean, indicating failure of the wet-season monsoon during 64% of historical ENSOs; only two significant failures of the monsoon occurred during years not recognized as ENSOs. Because the position of the Indonesia Low is an index of the SO, proxy data recording fluctuations of the Indonesian Low also serve as proxies for the SO. Annual bands in Indonesian reef corals (from Sulawesi, Bali, Lombok, and Ambon) are sampled every mm to reconstruct near-monthly climate variability. Stable isotope variations record SST and salinity: $\delta^{18}O$ time-series display maxima during ENSO and minima during SO positive phases. Chemical fluorescence variations record freshwater discharge into the littoral: fluorescent banding shows strong minima during ENSO and maxima during SO positive phases. Coral proxy data are used to present a regional picture of variability of the Indonesian Low and the SO for the past 100 yr.

Factors Affecting Shallow Coral near the Taiwan Third Nuclear Power Plant

TSU-CHANG HUNG,[13,14] CHE-CHUNG HUANG,[13] AND KUANG-LUNG FAN[13]

Since the Third Nuclear Power Plant in Taiwan started to operate in January 1987, two incidents of massive but localized death of corals have occurred. Heated water discharged from the outlet was the major factor causing mortality. Therefore, since July 1987, we have closely followed the thermal effects on coral reefs along the shallow-water coast. In general, except for temperature, the water sampled along the shallow bay meets the criteria set by the Taiwan Environmental Protection Administration. Temperature of the surface water (to 3 m) near the outlet usually exceeds 31°C. Growth rate of corals in the shallow bay showed a steady decrease during the period July 1987 to October 1988. However, after the discharge rate was increased by 10% in May 1989, coral growth rates stabilized. In this paper we summarize the results and discuss data collected up to September 1990.

[10] Department of Geography, University of California at Berkeley, Berkeley, California 94720.
[11] Museum of Paleontology, University of California at Berkeley, Berkeley. California 94720.
[12] Lamont Doherty Geological Observatory, Palisades, New York.
[13] Institute of Oceanography, National Taiwan University, Taipei, Taiwan.
[14] Institute of Chemistry, Academia Sinica, Taipei, Taiwan.

Diagenetic Effects Related to Hot-water Effluent in a Modern Reef on Guam

H. G. SIEGRIST,[15] R. G. BOWMAN,[16] R. H. RANDALL,[17] AND P. B. STIFEL[16]

Hot-water effluent, averaging nearly 34°C, from a diesel-fired power plant has been discharging onto a fringing reef along the north-central leeward coast of Guam for nearly 20 yr. Early estimates of coral mortality showed that the plume was ca. 10,000 m^2 in area. Recent reexamination of the affected reef suggests that major differences appear to be biological. Highly significant increases in bioeroders (principally sipunculans, polychaetes, and clionid sponges) and persistent but less significant increases in encrustion (by coralline and blue-green algae, vermetids, and *Homotrema*) mark all substrates of the affected reef. Diagenetic cements at affected sites show no significant difference in styles, diversity, volume, or trace-element composition in comparison to cements forming at the control site; however, whole-rock strontium showed major depletions on the affected reef owing to encrusters replacing coral populations. These results show that hot-water effluents produce both biological and geochemical changes on fringing reefs.

Environmental Impacts of Point-source Pollution on Coral Reef Ecosystems in Hawaii

R. W. GRIGG[18]

In 1989, the State of Hawaii initiated a long-term multidisciplinary cooperative research program called the Main Hawaiian Islands Marine Resource Investigations. The purpose of this program is to assess the status of nearshore marine resources in Hawaii and to improve methods of management. The results of one of the projects in the program that deals with environmental impacts of man-induced point-source pollution on nearshore coral reef ecosystems is described in this paper. Two major sources of point-source pollution exist in Hawaii. These consist of discharges from ocean sewage outfalls and sugar mills. Surveys show that the impacts associated with each are highly localized. In the case of sewer outfalls, no significant changes in surrounding benthic ecosystems have occurred. Fish populations near the outfalls and outfall pipelines are substantially enhanced. Impacts from sugar mills on benthic ecosystems and reef-fish populations are largely confined to within 1 mile (1.6 km) of discharge points. Within these areas, which are designated zones of mixing by the State Department of Health, the diversity and abundance of coral and reef-fish populations are depressed. Sedimentation appears to be the cause.

[15] WERI–UOG, Mangilao, Guam 96923.
[16] Department of Geology, University of Maryland, College Park, Maryland 20742.
[17] Marine Laboratory, University of Guam, Mangilao, Guam 96923.
[18] Department of Oceanography, University of Hawaii at Manoa, Honolulu, Hawaii 96822.

World Coral Reef Site Network: A Long-term Global Plan to Monitor Coral Reefs for Natural and Anthropogenic Change

BERNARD SALVAT[19]

Coral reefs have been described alternatively as "delicately adjusted climax ecosystems" or "successional temporal mosaics." Stability or instability in time and space is the question. Also there is a need to discriminate between natural and anthropogenic, and short- and long-term population changes in reef communities. Global climate change may cause sea-level rise, as well as increased precipitation and sedimentation on reefs, increased frequency of cyclones and typhoons, and rising sea temperature. Clearly there is a need to monitor these changes over the long term on coral reefs worldwide. It is recommended that a Coral Reef Site Network be established and that it be internationally coordinated and maintained over many decades. Major sites need to be selected and a standardized monitoring program needs to be developed. Coral reefs can serve as sentinels of future anthropogenic and natural change. As such they may assist mankind in understanding and coping with global climate change.

An Evaluation of Coral Reef Census Strategies: Implications for Monitoring Programs

S. L. OLHORST,[20] W. D. LIDDELL,[21] R. J. TAYLOR,[22] AND J. M. TAYLOR[22]

Development of efficient and accurate census strategies for coral reefs and other marine environments is of the utmost importance, particularly now, as coastal settings are increasingly impacted by the harvesting of resources, development, and recreation. We have evaluated a number of the commonly used census methodologies through the use of computer simulations and field studies. The former allowed the sampling of "known" reefs of differing diversities, spatial heterogeneities, and size ranges of organisms, while the latter provided the amount of real time required to perform the various methods and revealed practical limitations in the application of certain methods. Our results indicate that no one census method is universally applicable to all community types. Preliminary evaluation of population and community parameters is essential to the development of the optimal census strategy. Given this caveat, certain generalizations may be made; for example, with increasing community complexity (increased species number and variation in size and spatial patterns), point methods (linear point intercept, planar point intercept) appear to provide better estimates of community parameters than other methods. Examples of the influence of community structure on census method performance are presented.

[19] E.P.H.E, Université Perpignan, France.
[20] Department of Fisheries and Wildlife, Utah State University, Logan, Utah 84322-5210.
[21] Department of Geology, Utah State University, Logan, Utah 84322.
[22] Logan, Utah 84321.

Patterns of Recovery and Change of Coral Reef Communities in Kaneohe Bay, Hawaii

C. W. EVANS[23]

Kaneohe Bay offers an excellent example of a large coral reef ecosystem disturbed by factors associated with urbanization. Early research in the 1970s showed that eutrophication and sedimentation caused declines in coral reef communities and an explosive growth of the green alga *Dictyosphaeria cavernosa*. In 1983, 6 yr after major sewage discharges were diverted from the bay, surveys showed a significant decrease in the *Dictyosphaeria* algal cover and a remarkable recovery of coral reef communities. Researchers hoped that this pattern of recovery would continue; however, re-surveys in 1990 indicate that algal populations may once again be increasing and coral recovery rates may have slowed or, in some places, reversed. Periodic sewage bypasses and overflows from the old sewage-treatment facilities in combination with non–point source sewage discharges may be the cause. Alternatively, natural fluctuations and/or other environmental factors may explain these changes. Continued monitoring of water quality and more extensive sampling of coral reef communities are needed before the question can be answered definitively.

Methodology for Involving Recreational Divers in Long-term Monitoring of Coral Reefs

C. HUNTER[24] AND J. MARAGOS[25]

The health and protection of coral reefs are essential to the economic well-being as well as the maintenance of biological diversity of island states and nations throughout the Pacific. Widespread concern about coral-reef deterioration has arisen in response to increasingly numerous reports of coral mortality resulting from various environmental influences. However, long-term monitoring data to base quantification of perceived changes and to provide early warning of degradation of reefs are notably sparse. In light of global climatic changes as well as rapidly accelerating urbanization pressures, we believe that there is an immediate need to implement a permanent reef monitoring program in Hawaii and other tropical Pacific areas. In the past, accurate censusing of reef habitats required the labor, time, and cost-consumptive work of highly trained professionals. Studies done to date have therefore been sporadic, geographically scattered, and of short duration, lasting only as long as various or temporary funding allowed and involving a variety of techniques that were often inconsistent. New technologies in underwater video and computer software have been developed within the past year that allow precise, quantitative surveys to be conducted rapidly and with high resolution. We suggest that a great untapped resource exists among recreational divers that can be utilized to conduct video surveys of reefs. Many of these dive groups visit reefs on a daily basis and have an economic as well as a personal interest

[23] Department of Geography, University of Hawaii at Manoa, Honolulu, Hawaii 96822.
[24] Hawaii Institute of Marine Biology, University of Hawaii, Kaneohe, Hawaii 96744.
[25] Environment and Policy Institute, East-West Center, Honolulu, Hawaii 96848.

in ensuring that reefs are protected. A focus of effort should be applied to train these enthusiastic divers in proper survey techniques, water-quality sampling, and awareness of potential reef problems. Monitoring should be conducted under the guidance of professional scientists and in conjunction with standard field-survey techniques for supplemental data collection and quality control. Long-term monitoring of changes in species abundance, diversity, and cover within and between reef communities will provide a necessary database from which to develop improved management decisions, and may provide an early warning system for possible degradation of reef habitats. Community involvement in conducting such a research endeavor will allow the public to "own" the responsibility for fostering and protecting reef resources for generations to come.

Human Impact on Pacific Reefs Today: Priorities for Conservation in an Era of Global Climate Change

S. M. WELLS[26]

Coral reefs in the Pacific region have come under increasing pressure in recent years from impacts associated with a variety of human activities. An overview of the major problems is given. These may seem to be small scale in the context of potential long-term changes on reefs from climate changes. Nevertheless, they may be significant. Human-induced damage to reefs exacerbates damage caused by natural events such as hurricanes, predator outbreaks, and disease, and impairs regeneration. Reefs with lowered diversity, topography, and living cover result in reduced fishery yields and potentially reduced income from recreational activities. With many Pacific countries dependent on reef resources for subsistence or income, and with the expansion of the tourist industry in this region, the importance of maintaining healthy reefs becomes self-evident. Furthermore, healthy reefs may be able to withstand the negative impact of global warming more successfully than reefs under stress from other factors. Conservation priorities in the region are discussed in this long-term context.

[26] 56 Oxford Road, Cambridge, CB4 3PW, United Kingdom.