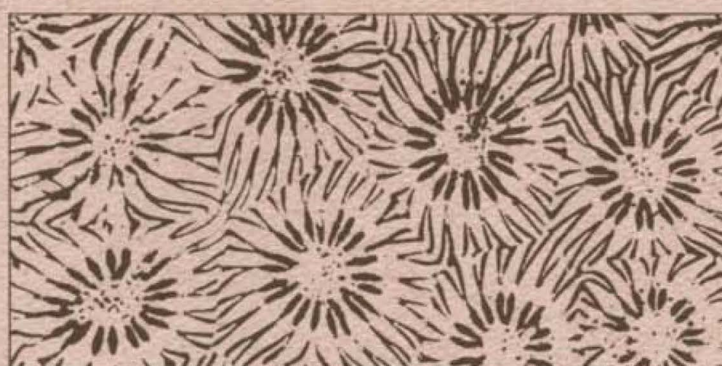
MARYLAND SEA GRANT COLLEGE

WORKSHOP ON CORAL BLEACHING, CORAL REEF ECOSYSTEMS AND GLOBAL CHANGE: *REPORT OF PROCEEDINGS*

Brickell Point Sheraton, Miami, Florida
June 17-21, 1991



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Sponsored by:

National Science Foundation
Environmental Protection Agency
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A Maryland Sea Grant College Publication

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SUMMARY

A workshop on coral reef ecosystems and global change was held June 18-21, 1991 in Miami. The meeting was sponsored by the National Science Foundation, the National Oceanic and Atmospheric Administration, and the Environmental Protection Agency in response to rising concerns about widely reported episodes of coral reef "bleaching" and deteriorating ecosystem health and reef environmental quality.

The workshop had three specific aims:

- To examine recent evidence about the phenomenon of coral bleaching and to determine what additional approaches and information are needed.
- To understand and predict the responses of coral reefs to global climate change.
- To suggest priorities for future research to provide agencies with a starting point for developing further initiatives.

The group of international experts that attended the meeting consisted of approximately fifty scientists representing disciplines ranging from coral biology, ecology, and geology to climate modeling, oceanography, and meteorology. In response to the objectives of the workshop, the group reviewed and produced a series of documents defining the status of present knowledge about coral reefs and the environment, as well as identifying key research and information needs for the future. The present report represents a compilation of these documents.

A major conclusion of the group was that much subjective evidence exists to indicate that there is a worldwide decline in the overall "health" of coral reef and related ecosystems, but there are not adequate baseline and survey data to provide a rigorous scientific assessment of the nature and extent of the problem. The group therefore strongly recommended the development and expansion of a scientifically based, internationally coordinated long-range monitoring program oriented toward reef environments and biology. The assembled experts emphasized in very strong terms that such a program would yield immediate important results in terms of major theoretical and applied scientific questions related to spatial variations, in addition to providing the longer-term data base needed for other studies.

With respect to the issue of coral reef "bleaching," the group concluded that recent increases in reported events were indicative of increasing ecosystem stress, and that many of the events appear to be associated with local high temperatures. However, other stresses are also known to cause bleaching, and our knowledge of both coral stress responses and the detailed nature of climate change make it impossible at present to claim that coral bleaching is an early indicator of the global greenhouse effect. This detailed finding was seen as strong reinforcement of the perceived need for systematic monitoring as a basis for research.

In identifying the probable present and future environmental threats, the workshop found that although global climate change represents an important long-term challenge, the most immediate concerns and the strongest stresses and environmental "signals" stem from local and regional anthropogenic sources — the results of human population growth, land use, resource exploitation, waste disposal, etc. Such effects correlate and interact with environmental signals resulting from longer-term climate change and from natural environmental variability. A matter of particular concern is the sometimes subtle effect of long-term nutrient loading in coastal areas or enclosed basins.

Physiologists are making substantial strides in developing a mechanistic understanding of bleaching and other stress responses. Ecological, environmental, and climatic data will take longer to develop and understand. The group endorsed the importance of redressing this imbalance with "retrospective monitoring" — the use of environmental information contained in the chemical and physical records of the annual growth bands of corals to reconstruct environmental variations and organism responses of the recent past.

Reefs are ecologically and structually important features; they are important resources, both economically and in terms of biodiversity; they have potential to serve as sensitive environmental recorders and indicators, particularly of the vulnerable and important coastal and shallow-water regions of the world's tropical and subtropical regions. It is important to note, however, that they are not sinks for atmospheric carbon dioxide; contrary to some assertions, on time scales of concern to humans, marine calcium carbonate production results in the release rather than the absorption of atmospheric carbon dioxide. On the scale of anthropogenic carbon dioxide releases, however, reef-induced fluxes are insignifcant.

The interdisciplinary and issue-oriented nature of the workshop resulted in a strong emphasis on time and space scales and on environmental interactions not normally emphasized in more traditional conferences. The workshop organizers hope that the present document provides a starting point for the development of an international and interdisciplinary research effort to evaluate the response of coral reefs and other shallow water tropical marine ecosystems to global climate change.

INTRODUCTION

Workshop Format and Venue

The workshop on "Coral Bleaching, Coral Reef Ecosystems, and Global Change" was convened in Miami from June 17-21, 1991. This was undertaken as a scientific community activity with joint support by the National Science Foundation, the Environmental Protection Agency, and the National Oceanic and Atmospheric Administration. The three coordinators were: Christopher F. D'Elia (Maryland Sea Grant College), Robert W. Buddemeier (Kansas Geological Survey), and Stephen V. Smith (University of Hawaii). The Federal coordinator was Phillip R. Taylor, National Science Foundation. Logistical considerations were coordinated by the Maryland Sea Grant College.

The workshop had three specific aims:

- To examine recent evidence about the phenomenon of coral bleaching and to determine what additional approaches and information are needed.
- To understand and predict the responses of coral reefs to global climate change.
- To suggest priorities for future research to provide agencies with a starting point for developing further initiatives.

An operational goal of the workshop was to produce a working document, generated during the meeting, to assess our state of knowledge about the phenomenon of coral bleaching and the sensitivity of coral reef systems to environmental change, and to articulate and recommend research priorities for coral reef ecosystems in the context of global climate change. The present document includes the results of that effort (i.e. "the work group reports") as well as some supplementary material provided to summarize and clarify the more detailed work group reports.

Participation in the full workshop was by invitation only, owing to limited space, funding, and a need to have international representation from a broad variety of disciplines (see accompanying table). However, the workshop is regarded as a first step in a process involving a much broader segment of the scientific community, and thus opportunities to participate in the process exist for those who were not present. Indeed, an initiative based on this workshop will require substantial participation by a larger group of individuals than were present in Miami.

To provoke thought and provide a point of departure for people with varying disciplinary backgrounds, all workshop participants were sent an "Issues List" (Appendix A) before the meeting, and were asked to come prepared to critique it. In a further effort to provide all participants with the latest information on the state of our knowledge about coral bleaching and the response of coral reefs to global change, four leading scientists were invited to make plenary introductory presentations. Thereafter the group subdivided into two groups, the "climate group," and the "bleaching group" for intense deliberations. Two final plenary sessions occurred, one for a series of five-minute contributed talks, and the other a final session on the last day to review the proceedings of the workshop and come to consensus on conclusions.

A complete agenda for the workshop is given in the accompanying table.

Workshop Rationale and Background

The issue of climate change has, in the space of a few years, shifted from a subject of specialized scientific interest to a major focus attention in the public and in national and international agencies, with a U.S. Global Climate Research Program being articulated by the Committee on Earth and Environmental Sciences (CEES). This rapid escalation to an issue of policy and applied science has bypassed the normal process of gradual diffusion of concepts into other scientific disciplines. A coherent, cost-effective analysis of the important issues requires effective interdisciplinary communication and planning.

Shallow tropical marine environments, and in particular coral reef ecosystems and adjacent communities, may be especially vulnerable to the effects of climate change. In addition to, and in part because of these vulnerabilities, coral reef research may be presented with opportunities to: (1) contribute to a developing understanding of the detailed nature and effects of climate change; (2) exploit that change as a large-scale experiment to understand the response mechanisms of reef ecosystems; and (3) use these systems as early indicators of environmental change.

Coral reefs are geologically ancient ecosystems that have provided excellent paleoecological evidence of past global climatic changes and some of the best indications extant of ecosystem response to such changes. Coral reefs are believed by some to be indicators of global climate change in more than just the geological record; there has been considerable recent speculation in the press, discussion among reef researchers, and testimony in Congress on the topic of coral "bleaching."

Two hearings have been held (one in 1987, the other in 1990) in the U.S. Senate addressing the bleaching issue, i.e., the phenomenon of hermatypic corals

Workshop on Coral Bleaching, Coral Reef Ecosystems and Global Climate Change

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Agenda

TUESDAY, JUNE 18

Public Plenary Session

9:00-9:30	*Introductory Remarks* Christopher D'Elia Maryland Sea Grant College
9:30-10:00	*Agency Perspectives* Phillip R. Taylor National Science Foundation
10:00-10:30	Coffee Break
10:30-11:30	*Systems Level Management, Monitoring, and Research: The Australian Perspective on Environmental Change* Donald W. Kinsey Great Barrier Reef Marine Park Authority, Townsville
11:30-12:45	Lunch
12:45-1:45	*Coral Reefs, Environmental Change, and Global Climate Issues* Robert W. Buddemeier Kansas Geological Survey, Lawrence
1:45-3:15	*Coral Bleaching: Ecological and Cell Biological Perspectives* Leonard Muscatine University of California at Los Angeles Peter Glynn Rosenstiel School of Marine and Atmospheric Science

End of Public Plenary Session

3:15-3:30	Coffee Break
3:30-5:00	*Workshop* - Two working groups will be convened to discuss and respond to the Plenary Session presentations.
5:30-7:00	*Reception* at Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami

WEDNESDAY, JUNE 19

8:30 am	*Workshop* - Groups will reconvene with the option of breaking into smaller groups.
12 noon	Lunch
1 pm	*Workshops* (continued)
4 pm	Plenary Sessions (participants) - Workshop progress to be discussed.

THURSDAY, JUNE 20

8:30 am	*Workshop* - After assessment of progress, working groups will reconvene, with refinement of goals and exchange of participants if appropriate.
12 noon	Lunch
1 pm	*Workshop* - Reports from the working groups will be assembled.
5 pm	Break for evening meal
7 pm	Complete assembling of reports

FRIDAY, JUNE 21

8:30 am	Summary and report presentation
12 noon	Lunch and Departure
1 pm	Conference organizers and key individuals reconvene for post-workshop discussion.

losing their algal endosymbionts, the zooxanthellae. In fact, the FY91 Senate appropriations bill for NSF required NSF to develop by May, 1991, a plan to address research on bleaching and reefs in the context of global change. The view of several panelists who testified was that elevated sea surface temperatures (SST's) are likely to be the cause of the bleaching, and that the phenomenon was the harbinger of global warming. Wary heads of federal agencies represented at the hearings have sensed the need to cover their bases — not only for political reasons, but also because of concern about the scientific basis for legitamately viewing the phenomenon as an indicator. Accordingly, the topic of coral bleaching as an indicator of global climate change has particular currency in Washington.

While the present interest in coral bleaching has certainly motivated a response by politicians and science policy makers, there are sound *a priori* scientific reasons why coral reef ecosystems (which are used here as a convenient proxy term for a range of related or associated tropical marine communities, including sea grasses and mangroves) need more attention than they have traditionally received:

- Tropical coastal systems such as coral reefs are extremely vulnerable to the current scenarios of environmental perturbations, because many organisms of reef systems exist near upper limits of thermal tolerances in shallow seas that are more susceptible to temperature excursions;
- Little attention has been paid to tropical coastal systems in climate change research and planning, yet these systems may be important sinks and sources of greenhouse gases;
- Reef systems are sensitive to locally generated factors such as sedimentation and nutrient loading, which may interact synergistically with the effects of climate change;
- Reef systems may provide "litmus" tests for the response to climate changes (e.g., coral bleaching, invertebrate die-offs, etc.);
- Reefs are valuable natural resources in terms of biological diversity, fisheries, coastal protection, and tourism.

With the previous information in mind, it now seems timely to consider carefully what is known about coral reef ecosystems, particularly in the context of global climate change. Accordingly, the National Science Foundation, the Environmental Protection Agency and the National Oceanic and Atmospheric Administration sponsored a workshop directed to understanding the state of our knowledge about reef ecosystem health, including the issue of coral bleaching and, in the larger sense, to consider research needs for the next decade for understanding the effects of potential global climate change on shallow water tropical marine ecosystems such as coral reefs.

WORKSHOP PROCEEDINGS

Organizing Committee's Overview

Purpose of Overview

This overview of the workshop proceedings was prepared by the organizing committee neither to duplicate nor replace the output of the working groups, but rather to provide integrative comments and highlights of the discussions and submissions in the context of the overall results of the workshop.

Although every effort has been made to reflect the spirit of the discussions and to ensure consistency with the working group reports, it was deemed impractical to circulate this summary to all participants for review. Therefore it cannot necessarily reflect the views of all of the participants. In the text that follows, an author citation refers to the oral or written presentations submitted to the workshop; these are listed in Appendix C.

The Bleaching Question – A Case Study

Physiology. Bleaching, the loss of symbiotic algae by reef corals and other symbiotic organisms, is recognized as stress response to a variety of environmental perturbations, among them extremes of light, temperature, and salinity. Muscatine (plenary) presented research results suggesting that the mechanism for loss of zooxanthellae involves cell adhesion disfunction. Under stress, host cells containing zooxanthellae may lose their ability to adhere to the tissue layer with which they are associated and are subsequently expelled from the host. The process occurs in stressed aposymbiotic coelenterates, but is enhanced when symbiotic algae are present. This interaction of the algae with the host animal's stress response identifies a possible pathway for stress synergism; conditions that affect physiology or population of the algae (e.g., light, nutrients) may indirectly alter the host's susceptibility to bleaching in response to other stresses.

Environmental Correlates. A significant impetus for this workshop was the debate about whether the recently reported increases in the incidence of coral reef bleaching were real, and if so, the significance of these observations with respect to general ecosystem "health" and the possible effects or detection of global climate change.

There have been suggestions that increased bleaching is the result of increases in temperature that might be attributable to global climate change (Goreau et al., Bunkley-Williams and Williams). Halley and

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Hudson (also, Hudson et al.) showed that there was no reliable correlation between temperature and bleaching on the basis of a long-term monitoring program in the Florida Keys. Although particular instances of bleaching were attributed to high temperature, other episodes of similarly high — or even greater — temperature were not accompanied by bleaching. Kinsey (plenary) cautioned that it can be very difficult to identify the proximate cause of bleaching, for triggering events may be transient, and by the time bleaching is noticed (even the following day), it can be attributed to a different environmental perturbation. Elms presented 40-year records of sea surface temperature for the greater Gulf-Caribbean area that indicated an overall temperature decrease during that period.

Perceptions of the bleaching phenomenon showed strong regional differences. Kinsey (plenary) stated that the Great Barrier Reef had shown no significant increase in the amount of bleaching, and that a majority of the bleaching episodes observed were related to stresses other than high temperature, often low temperature. Glynn (plenary) reported on his extensive work with Eastern Pacific bleaching, which was due to high temperature resulting from El Niño conditions. In general, Caribbean workers were most convinced that they were observing real increases in bleaching that were related to elevated temperatures, but could not be attributed to a specific, identifiable phenomenon such as El Niño. It was recognized that an increase in the frequency of brief high temperature excursions in shallow water was not necessarily inconsistent with the data from shipping lanes presented by Elms.

Both the "climate" and "bleaching" working groups considered in some detail the issues of climate signal prediction, identification, and detection, particularly with respect to uncertainties in the database (Maul) and problems of the scales of the effects and the observations. Some of these issues are discussed further in the section on sensitivity below. ***The overall conclusions reached were that (1) there probably have been some regional increases in the frequency of bleaching, (2) some of these appear to be related to high temperature events, but (3) these are best regarded as indicators of environmental stress and cannot be considered indicators of global climate change.***

Coral Reefs: Monitors of Environmental and Climate Change

Scales and Sensitivities. Because of their obligate relationships to light, temperature, and sea level, corals and reefs have long been regarded as both vulnerable to climate change and reliable indicators of past climate. Although this is true in a broad sense, the geologic record is a limited source of insights into our present situation.

Today's reef organisms and communities come to us through the filter of the Quaternary climate oscillations — and have arrived with minimal evidence of change or extinction along the way. Jackson noted that the zonation and community structure of Caribbean reefs seems to have been the same in the Pleistocene as it is today. Although this robustness is encouraging from the standpoint of probable survival, the time resolution of the fossil record is far too coarse to provide information about responses on the time scale of present-day human observations (Buddemeier and Hopley).

The space and time scales of climate are by definition global and long-term, while coral reef observations tend to be local and of limited duration (Buddemeier, plenary). Relating reef or organism responses to local or regional environmental change is a practical and worthwhile objective, but determining responses to a specific climatic component of environmental change will require careful design and intensive data collections that do not currently exist. In any case, a useful perspective to maintain is that reefs respond directly to short-term and local effects (e.g., eutrophication) and less directly to long-term and regional effects (e.g., biogeography).

Participants emphasized the importance of reef ecosystems on both scientific and practical levels. Reef communities (or related communities) either do or can occupy much of the coastal zones or shallow-water areas in the tropics and sub-tropics — a significant fraction of the world's total. These same areas are home to large and growing human populations, for which the coastal marine communities provide important immediate resources in addition to their larger role in global biodiversity. In spite of their importance on a variety of levels, ***coral reef CO_2 fluxes are not a factor in climate change*** (Smith; Kinsey and Hopley); the global reef-induced net calcification flux is insignificant compared with anthropogenic CO_2 releases. Contrary to frequently expressed assumptions, marine calcification is a source rather than a sink for atmospheric CO_2 on time scales relevant to rapid climate change (Ware et al.; Smith).

Real-time Observations and Retrospective Records. Workshop participants generally agreed that subjective evaluation of trends in coral reef observations suggest an increase in reef stress and a deterioration in the "health" of reef environments. However, quantitative examination of the possibility of climate trend detection by population and community changes (Connell) revealed a requirement for long-term observations of large numbers of samples — which do not exist at present. A signal/noise evaluation of coral bleaching as an indicator of global temperature trends (Ware and Reaka-Kudla) suggested that a mean temperature increase on the order of a degree would be required to bring the climate-induced bleaching signal above the noise of natural climate variability. Few would argue that such a temperature change has occurred as yet.

The problem of interpreting responses to environmental change is further complicated by sensitivity variations within and between taxa, and by uncertainties in the taxonomy of both corals (Knowlton et al.) and their algal symbionts (Rowan). Knowlton volunteered to serve as collector and collator of records of reef surveys over time that might produce specific data on trends, and asked participants to notify their colleagues and send her any available data. In subsequent discussion, Connell pointed out that coral reef scientists tend to select healthy reefs for study, thus biasing subsequent observations against possible improvement and in favor of deterioration. ***Overall, participants recognized that rigorous characterization of either ecosystem health or environmental trends would require more extensive, longer-term, and better-coordinated observations than currently exist.***

The use of retrospective records to reconstruct proxy baselines for variables without adequate historical records received considerable attention. Since coral skeletal growth bands contain both an intrinsic chronology and physical, chemical, and isotopic records of various aspects of their depositional environment (Dunbar and Wellington, Shen), it is possible to develop time series of both environmental variation and coral responses, providing a partial substitute for the missing records. After a thorough discussion of applications, potential limitations, and uncertainties, ***both working groups recommended increased emphasis on the use of retrospective records to expand understanding of past environmental changes and their effects on corals and their communities.***

Environmental Factors and Their Effects

Dominant Sources of Near-term Stress. The workshop used and reviewed a draft list of environmental factors known to influence or stress coral growth and reef development. The revised version of that list is presented in appendix A as a summary status of present knowledge on reef-environment interactions. Buddemeier (plenary) suggested two possible approaches to classifying present and potential future coral reef stresses: (1) whether they were more likely to result from climate change or from other non-climatic but probably anthropogenic sources; and (2) by the dominant pathway of delivery of the stressor to the reef – atmospheric, hydrographic, or hydrologic.

Climate change appears most likely to account for changes in temperature, global sea level, CO_2 chemistry of the oceans, incident visible light, and current, wave, and storm regimes; it may also be a significant factor in changes in fresh water and related fluxes, especially near land masses. Other (non-climatic) sources are likely to dominate near-term changes in the effects of ultraviolet light, nutrient loading, sedimentation, toxic chemicals, turbidity, some aspects of fresh water delivery, and human exploitation of resources (e.g., fisheries). It is particularly significant that most of the non-climate stressors are delivered primarily through the hydrologic pathway; unlike the atmospheric and hydrographic pathways, the hydrologic pathway has an amplifying effect on environmental change signals. Runoff can integrate the effects of precipitation, pollution, erosion, or other terrestrial changes over areas ranging from watersheds to significant fractions of continents (e.g., the Mississippi River drainage) and focus the products into restricted coastal zones or basins.

For these reasons and because of recognition of the current importance of widespread local and regional anthropogenic stresses on coral reefs, ***there was general agreement that at present and for the coming years to decades, anthropogenic stresses resulting directly from population growth and development are the strongest environmental signals and the greatest threats to coral reefs. Impacts of these stresses will be preferentially felt by reefs experiencing the influence of land masses.*** Climate change is a significant factor in the future of coral reef ecosystems, but on a somewhat longer time scale; its effects will be felt (although not necessarily to the same extent) by both oceanic and nearshore reef systems. It must be emphasized that separation of "climatic" and "other" stresses is a convenient but arbitrary conceptual device; a scientifically sound approach to addressing the impacts of environmental change on time and space scales appropriate to the distribution and development of reefs must deal with both sources and their various combinations.

Non-climate Stresses. Among the potential stressors likely to arise from non-climatic environmental alteration, the two most prominently considered were increased ultraviolet light flux and nutrient (or sediment) loading. The UV exposure problem is global in scale as a result of stratospheric ozone depletion, and although subsurface flux data are scarce, there is substantial evidence that UV light is a significant stressor for shallow-water corals (Wellington and Gleason; Shick and Lesser). ***Nutrient loading was identified as a subject of major concern on the Great Barrier Reef (Kinsey, plenary) and in the Gulf/Caribbean system (Hallock-Muller), which receives runoff of***

increasing nutrient concentration from both the North and South American continents. Hallock pointed out that Mississippi River effluent has undergone an increase in nitrate concentration of nearly an order of magnitude in approximately 20 years. High nutrient levels function as a chronic stress that can cause a shift to algal dominated communities if coral communities are killed or destabilized by an acute stress. They may also have significant direct effects on reef organisms; Hopley showed abnormal calcification resulting from phosphate loading, and Muscatine (plenary) discussed the effects of nutrients on the growth and standing stock zooxanthellae in corals.

The current primary sources of high nutrient levels are waste disposal and land-use practices (deforestation, agricultural fertilization); the effects are thus concentrated in the vicinity of land masses, and are often accompanied by increases in the more localized effects of sedimentation, turbidity, fresh water, and the concentration of biocides or other toxic chemicals. ***In the longer term, climate-induced shifts in upwelling and circulation may increase or decrease oceanic nutrients levels on a regional basis, but such possible effects are not currently predictable, and appear at present to be minor compared to anthropogenic discharges.***

An additional locally significant non-climate factor is resource exploitation; on land it may increase the impacts of terrigenous stressors (erosion, agricultural chemicals), but one of the primary marine examples is local fisheries. Herbivorous reef fish are an important ecological balance on algal growth, and their removal can exacerbate the problems of increased algal standing stock due to increased nutrients or substrate modification.

Climate-related Stresses. Climate-related changes in storms, waves, currents, and incident visible light will be local or regional in their effects, are not at present predictable, and probably will not result in a net increase in reef stress when viewed in global terms and in the context of natural variability. ***Sea level rise, at the rates presently forecast for the next century (increases of a few mm/yr), was also not seen as a major source of additional reef stress overall, and might, ironically, prove to have a net beneficial effect.*** The effects of CO_2-induced changes on the carbonate saturation state of tropical oceans, and hence on calcifying communities, has not been the subject of any significant research; although the possible significance of this predictable chemical change is obvious, its actual ecological effect is unknown (Smith).

Temperature is potentially the most significant long-term climatic stressor. Mearns presented a variety of GCM results of sea surface temperatures in reef areas; the results consistently suggested an increase in SST, but calibrations against present climate were not always impressive, and the model oceans are highly simplified. Paleoclimate studies suggest that tropical regions may have been no warmer, and possibly even cooler, than present during past warm periods (Buddemeier, plenary). Because of the known sensitivity of corals and other reef organisms to elevated temperature (Glynn, plenary), ***the question of whether there will be significant tropical SST increases is almost certainly the most important specifically climatic question relevant to coral reefs.*** Accordingly, a crucial issue for physical oceanographers and climatologists to resolve will be what regulates SSTs and whether feedback mechanisms (e.g., cloud formation) exist that create upper limits to SSTs.

Consequences, Uncertainties, and Research Needs. In general, the effects of many types of environmental change on corals and reefs are reasonably well understood; they are summarized in the status-of-knowledge list (Appendix A), and discussed here and in the working group reports. ***Three critical areas of ignorance can be identified. One is outside the realm of specifically reef-related studies, and involves the uncertainties in climate models and predictions.*** As climate and ocean models improve and as the signal of climate change emerges from the noise, we may expect significant improvements in further predictions. It will be important for the reef research community to stay abreast of these developments. ***A second area, in which some research is already occurring, is that of synergism or interactions between multiple stressors, at both organism and the community levels.*** We know that this is an issue and what to look for, but we are far from having either predictive mechanistic models or reliable empirical calibrations. ***Third, we have neither the records nor the models needed to understand the long-term effects of either persistent or transient environmental perturbations*** — that is, how population dynamics and community structure respond to perturbations on time scales relevant to the lifetimes of the framework corals and the geological development of reef structures.

Research and Monitoring. The working group documents present specific recommendations for research priorities that will not be duplicated here. Instead, we attempt to draw some supplementary conclusions based on the nature of the specific recommendations and the general ambience of the workshop.

Contrary to what might have been expected beforehand, ***the workshop participants strongly and unanimously recommended development of a global-scale, coordinated program of coral reef monitoring.*** It was made abundantly clear that the vision was a recognition that research on global problems can be effective only when supported by scientifically-based data collection on time and space scales relevant to the questions being addressed. This outcome not only challenges the traditionally perceived "monitoring vs. research" conflict in the U.S. science establishment, but also challenges U.S. agencies and institutions to participate in the development of more effective international ties than now exist.

Recommendations by both working groups strongly endorsed expanded research on the use of the environmental signals extractable from coral skeletal growth chronologies to extend retrospectively our baseline data on change, variability, and biological responses in coral reef environments. Paleoclimate studies have traditionally co-existed uneasily with modeling and empirical observations in the terrestrial environment, where instrumental and historical records are of longer duration. In shallow tropical marine environments, however, the length and geographic extent of direct observations are clearly inadequate for present needs, and the high temporal resolution and variety of environmental signals inherent in coral skeletons suggest that the use of retrospective environmental proxies may make major contributions to our understanding of these environments and ecosystems.

Research activities are recommended at all scales — laboratory, microcosm, and field. Iimplicit in these recommendations is ***the need for a more coordinated, interdisciplinary and collaborative approach to reef studies than has been the case in the past.*** Just as disciplines such as oceanography, astronomy, and physics have recognized that the necessary tools and approaches can be supported only on a communal basis, needs such as for sophisticated microcosm facilities that are beyond the reach of individual investigators and for data comparability between individual studies seem likely to force coral reef scientists, institutions, and supporting agencies to reappraise the social and economic framework of research design and support. This institutional requirement for collaborative, interdisciplinary, and coordinated research offers special challenges that have never before been faced by the coral reef research community.

Workshop Conclusions

The primary conclusion that reflects the sentiments of workshop participants and is currently based, out of necessity, on diverse observations and anecdotal information is as follows: ***on a global average basis, coral reefs are being lost or degraded at an alarming rate.*** If true, this is potentially serious because of their biotic and economic importance, but ***at present we lack the data needed to confirm, quantify, or explain this trend on a scientific basis.***

Bleaching is one symptom of increased environmental stress; its frequency of occurrence has apparently increased in some areas, with some but not all of the events attributable to local high temperatures. ***Bleaching merits serious study as an indicator of coral stress and environmental quality; however, on the basis of present understanding, definitions, and environmental records, there is no credible theoretical or empirical basis for the claim that bleaching is or can be used as a reliable indicator of global climate change.***

Anthropogenic environmental alterations on global, regional, and local levels are reason for serious concern about the health and local survival of coral reef ecosystems. Now and in the near future, concerns about the direct effects of the human population explosion, resource exploitation, and development outweigh the longer-term threat of climate change, but an appropriate research and monitoring program will identify and address problems stemming from environmental change regardless of its ultimate cause.

Recommendations for scientific action include prompt development of a research-oriented coral reef monitoring program of global scale, a coordinated program of research at laboratory, microcosm, and field scales, and continued interdisciplinary review and coordination of research needs and opportunities in the area of overlap between coral reef studies and larger environmental and geoscience issues. Specific research topics and priorities are presented in the reports of the working groups.

Acknowledgments

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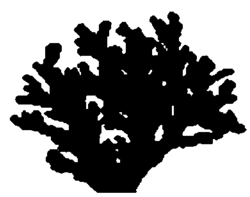

CLIMATE WORK GROUP

Sub-Group 1: Reef Response to Change

Facilitator: Don Kinsey. Participants: Bruce Chalker, Joe Connell, William Davis, Gary Hendrix, Nancy Knowlton, Yosi Loya, Claes Rooth, Malcolm Shick

I. WHY REEFS?

Reefs are but one of many ecosystems threatened by short and long term effects of man's activities. Nevertheless, reefs have special features which justify intensive and immediate study:

A. General Importance to the World

1. protection of coastlines — property and lives
2. tourism — recreation for participants and economy
3. food — commercial and subsistence
4. biodiversity — intrinsic value and natural products
5. established ecosystem — intrinsic value as for rainforests
6 scientific understanding (e.g., paleoclimates, functioning of complex ecosystems)
7. environmental indicators — potentially definable responses to environmental stress

B. Specific Importance to the U.S.

1. substantial areas of reef in U.S. territorial waters (Florida, Hawaii, Puerto Rico, U.S. Virgin Islands, U.S. Trust territories)
2. enormous importance of reefs to developing nations in our hemisphere (e.g., Caribbean Basin Initiative)

II. WHICH REEFS?

Which reefs should be studied is a necessary compromise between the desire to have broad geographic coverage and the need for detailed information. We propose areas of specific interest based on the following general objectives and specific criteria:

A. General Objectives

1. broad geographic coverage
2. information on major reef systems with comparisons within them across important environmental gradients
3. reefs in extreme habitats of particular interest in the context of local and global environmental change
4. potential to compare closely related species or populations from major reef systems and more extreme sites
5. transects across turn-on/turn-off regional gradients

B. Specific Criteria

1. previous history of study
2. logistical support
3. interest to the United States

C. Suggestions (* U.S. waters or government laboratories)

1. Major reef sites
   a. Caribbean: island (*U.S.V.I., *Puerto Rico) continental (*Panama, *Belize)
   b. Central-West Pacific: high island (*Guam, Moorea/Tahiti) atoll (*Enewetak, Tuamotos)
   c. Central Great Barrier Reef: inshore, offshore
   d. Southeast Asian fringing reefs
2. Reef sites in extreme or isolated environments
   a. *Florida Keys (including Dry Tortugas)
   b. *Hawaii
   c. *Gulf of Mexico (Flower Gardens)
   d. *Eastern Pacific (upwelling and not upwelling)
   e. Bermuda
   f. Eilat
   g. Heron Island
   h. Okinawa
   i. Western Australia (e.g . Abrolhos as latitudinal extreme)
   j. Lord Howe Island (latitudinal extreme)

III. COMPLEXITY OF THE PROBLEM

Understanding the impact of environmental change on coral reefs is an enormous problem because of the number of potential factors to be considered (including interactions between them) and the need to study numerous sites and numerous species within these sites. Interactions are critical because the effects of two or more factors are often not additive. The dramatic response of chronically stressed but superficially normal reefs to an acute stress is a particularly important example of this phenomenon. Multiple sites and species are critical because different communities may have different responses and even the same species at different sites may have different responses because of the effects of past evolutionary selection.

We list the primary anthropogenic factors, plus a limited set of interactions among them. For each factor, we indicate the pattern of expected change. Experimental treatments need to reflect as best as possible the relevant time scales of the expected changes (e.g., pulse perturbation, press manipulations with gradual or sudden onsets). Many more and more complex interactions than those listed are expected, but constraints on replication and statistical analysis require focus on a limited number of at most three-way interactions.

A. Factors (in Isolation)

1. Temperature (changing mean and variance)
2. Sea Level (changing mean)
3. Sedimentation (changing mean and variance)
4. Wave Energy (changing mean and variance)
5. CO_2 (changing mean)
6. U.V. and visible radiation (changing mean)
7. nutrients (changing mean and variance)
8. overfishing (changing mean)
9. toxic pollutants (changing mean, variance perhaps)
10. fresh water (changing variance)

B. Interactions of Special Importance

1. temperature + light + nutrients
2. temperature + nutrients + biological interactions
3. temperature + light + pollutants
4. storms + nutrients (study where opportunistically possible)

IV. BACKGROUND INFORMATION REQUIRED FOR PLANNING STUDIES

Planning studies of the effects of environmental change on reefs requires two important sets of background information. Of particular importance are:

A. Projections for Future Climate Change

Our experiments are necessarily designed to reflect likely changes. Realistically, we should concentrate on likely changes within the next decade to century. We need information both on magnitude and rates of projected mean change, but in some cases changes in variance are even more important. We have general predictions from modelers but in particular feel that temperature effects in nearshore tropical environments are critically important but poorly understood. This is a problem of Modelling coupled with testing through continued Monitoring of physical parameters.

B. Information on Past Conditions and Communities

This is critical because we need to distinguish potential changes which may have been experienced by reefs in the not too distant past from those which have never been experienced. As with the above, both means, variances and rates of change need to be considered. It would be predicted that changes previously experienced and survived pose less of a threat. However, since some of the changes are certainly novel, one cannot assume that a previously survived condition will be equally manageable when combined with novel stresses. This is a problem of detailed Paleontological Observations (see climate group 2 report, below).

C. Basic Information on the Nature and Mechanisms of Biological Interactions

Many aspects of normal reef functioning are poorly understood, making it difficult to predict the effects of man's activities. A particularly important example is the role of disease on reefs. Field and Laboratory Experimentation (including microcosms) and complex Computer Simulations are all valuable approaches to this basic problem.

D. Systematics

Even the best studied of reef organisms are not well categorized systematically, with even model taxa containing unrecognized sibling species. Also, for many region, no adequate manuals for the identification of even the corals exists. This problem could be solved by an investment in Systematic Studies followed by publication of Manuals with keys and illustrations usable by all reef workers.

V. GENERAL EXPERIMENTAL PROTOCOL

If we are to understand the effects of environmental change on reefs, we must attack the problem at a variety of hierarchical levels. Most central is the individual, which is the unit of birth and death. In some cases we may need specific information on the physiology and cell biology of the response, particularly to clarify future research directions. Moving up the hierarchy, interactions between individuals will eventually translate into a community response. Different hierarchies demand different methods. In general, we recommend the following approaches, listed without implication of priority:

A. Cell Biology — Laboratory Experiments

B. Physiology — Laboratory Experiments

C. Individual growth, reproduction, mortality — laboratory or microcosm experiments (depending on scale) field monitoring

D. Community Structure — Microcosms (Especially for Competition, e.g., Algae vs. Corals) Theoretical Modelling Field Monitoring and Field Experiments

Laboratory experiments have a long tradition and the methodologies are well established. Theoretical modelling requires access to advanced computers and programming expertise which are available but scarce resources. Field monitoring requires good management and support for manpower, into the indefinite future. Field monitoring also requires good designs based upon maximizing statistical power (e.g., sufficient power, randomized plots, etc.). Properly designed observations can test hypotheses and are in some cases the only alternative because of the large scale of the processes involved. Microcosms have been underutilized because of the capital expense, especially with adequate replication. These are the method of choice for a number of critical experiments. Marine facilities are currently very limited but the technology exists and several such facilities should be a top priority.

VI. SPECIES TO BE STUDIED

The species to be studied at the cell, organismal and community levels will vary depending on the questions asked. Not everything can be studied. Some species will be intensively studied at all levels because of their importance as model systems. A limited number of other species of considerable importance in reef communities will be studied in less detail (e.g., tests for sensitivity to temperature and U.V.). We recommend that the systematic status of all model system species be clarified as soon as possible to facilitate interpretation and comparison of results.

We make the following suggestions of criteria for these two categories of subject species. For model systems, the more criteria which can be satisfied, the better, since only a limited number of model systems are feasible.

A. Model systems

1. Indicator species (species with special sensitivity to changes in temperature, nutrients, toxic pollutants, U.V., etc.)
2. Species with broad geographic ranges (these may be species complexes but nevertheless have enormous potential for comparative studies aimed at detecting evolutionary responses to different environmental regimes)
3. Ecologically key species
4. "Lab rats" for physiological and cell biological studies.
5. Species of great paleontological importance

B. Other important species

1. Representatives of major morphological strategies in corals(branching, massive, and weedy)
2. Important competitors of corals (especially algae)
3. Important predators of corals and algal grazers

VII. PRIORITIES FOR THE NEXT FIVE YEARS (UNRANKED)

A. Experiments to determine the response of model system species to the effects of radiation and temperature

These studies will involve both laboratory and field manipulations. Radiation (via changes in cloudiness, turbidity, and ozone) and temperature (via the green house effect) are the most important Long-term changes expected as a function of anthropogenic modifications to the environment.

B. Establishment of a world-wide monitoring system of physical and biological parameters on reefs

Changes can only be detected if we begin a sophisticated and well managed program now. Field experiments relevant to the problem of global change should be coordinated with this monitoring network.

C. Development of microcosm facilities for bridging the laboratory to field spectrum.

Nutrients in particular are difficult to manipulate in the field at a scale required to study community level effects, are one of the most important Short-term consequences of human activity and population growth.

D. Increased use and development of complex model simulations both for physical effects in nearshore tropical environments and biological interactions in high diversity reef communities.

E. Where needed, publication of well illustrated manuals with workable keys permitting reef scientists and technicians to identify major taxa, particularly for regions to be intensively studied.

This should be backed up by systematic research where necessary.

VIII. EXPERIMENTAL PROTOCOLS — DETAILS FOR SPECIFIC FACTORS

Our choice of experimental designs reflects the consensus that both the long-term effects of climate change and the short-term effects of human activity and population growth need to be investigated.

A. Sea Level Rise

Of little effect at least over the short term, except on reef flats where negative effects of extreme low tides may be mitigated.

B. Temperature

Over the short term, increased variability likely to be more important than gradual mean increase. Proposed research: monitoring (including comparisons of sites with different temperature regimes), transplants within regions between sites of different temperature regimes (e.g., within Red Sea or within Eastern Pacific), laboratory tests of temperature sensitivities (both to variation and mean increase).

C. Ocean Currents and Wave Climate

No major trends expected over the next decade

D. Storms

No major effects over the short term, although increased storm effects predicted in context of mean temperature increase. Proposed research: monitoring of recovery on fine spatial scales in monitored sites experiencing storm damage. Computer simulations are important because experimental simulation usually impossible.

E. Radiation (U.V. and visible)

Predicted effects are an increase in U.V. via ozone depletion, plus changes in visible light due to changes in cloud patterns and turbidity of water. Proposed research: urgent need to establish monitoring network in tropics using scanning spectroradiometer (290-750) at depths from surface to 5% visible light. Laboratory experiments using both acute and gradual exposures.

F. Sedimentation and Turbidity

Will be influenced by a variety of climate changes (e.g., rainfall, storms, etc.). Proposed research: monitoring (*in situ* and remote sensing), lab and microcosm studies and field experiments including transplants.

G. Nutrients

Due to increased activities of man, although perhaps some upwelling changes. Proposed research: monitoring (water quality, remote sensing, community changes), microcosm experiments to look at competition between coral and algae, where possible (enclosed lagoons and tidal flats) manipulations in the field.

H. CO_2

Predicted gradual increase. Proposed research: tropics not likely to differ from other already monitored sites. Laboratory and microcosm experiments to determine effects on algae, zooxanthellae (free) and corals.

I. Toxic and Artificial Substances

Already present due to man's activities and may continue to increase. Proposed research: Monitoring and laboratory sensitivity studies.

J. Overfishing and Related Activities

Biological interactions have been and are being modified by activities which change the relative abundance of reef organisms. Proposed research: Monitoring abundance and distribution of reef organisms at all trophic levels, field manipulations of important predators, competitors, grazers, symbionts and bioeroders on reefs. Microcosms and complex computer simulations of interactions.

Overall, we feel the following factors are in most urgent need of investigation: temperature, light, nutrients, and biological interactions (especially algae, corallivores, and grazers).

Sub-Group 2: History of Environmental and Ecological Variability from Coral Reefs

Participants: Julia Cole, Margaret Delaney, Bob Halley, David Hopley, Paul Ringold

I. INTRODUCTION

Coral reefs have obviously survived past environmental changes on global to local scales. The nature of these changes and the associated reef responses are preserved in records from modern and fossil reefs. These records represent outstanding opportunities for defining the relationship between natural environmental variability and reef response on time scales ranging from seasonal to thousands of years. Coral records also provide histories of anthropogenic impacts on reefs in recent decades. Improved understanding of past reef variability will provide a strong foundation for the anticipation and recognition of future environmental impacts on reefs.

A. Contributions from the Paleoenvironmental Records of Reefs

Cores of long-lived individual coral heads have the potential to delineate the range of natural climate variability in tropical reef environments over the last several centuries. Longer cores through reefs encounter massive corals that provide windows of high-resolution record throughout the Holocene and late Pleistocene. Many skeletal parameters can be applied to reconstruct independent aspects of reef environmental variability at annual to subseasonal resolution; these are detailed in Table 1.

The length of continuous chronologies is limited by the age of the coral and can extend to several centuries. Older discontinuous chronologies are possible throughout the Holocene and late Pleistocene, with absolute dating provided by radiometric methods. Over timescales of centuries to millennia, the presence of shallow dwelling fossil corals has provided the basis for sea level estimates throughout the Quaternary. These coral records can address times of important global climate change during the past several thousand years. Such reconstructions will greatly improve our understanding of the sensitivity of tropical environments to large-scale climate forcing on a range of time scales.

Time periods that should yield useful insights include times thought to be generally warmer (the Medieval Warm Period, the mid-Holocene Climatic Optimum) as well as times of large scale global climate change of (e.g., the Little Ice Age, the Younger Dryas and the last deglaciation).

High-resolution records spanning the past several centuries will document the range of past natural climate variability over time scales more relevant to the human experience. A detectable record of bleaching events may be incorporated into the coral skeleton, via chemical or growth rate perturbations. The pursuit of this record should be a priority, as should the development of new indicators for other reef processes and perturbations.

B. Ecological and Paleoecological Studies

Reef growth and change on the scale of centuries to millennia can be addressed using classic paleoecological techniques including description of community structure, function, and composition. Taphonomic studies of modern reefs in crisis will more clearly define interpretations from these geologic records of reef growth. Corals growing near the limits of their environmental tolerances may show particular sensitivity to past and future environmental change. Existing reef cores have provided histories of reef sedimentation during the Holocene. These cores should be reexamined along with new cores and outcrops for changes in zonation and community structure during sea level rise, global warming, and other changes in physical and environmental parameters.

These studies should delineate reef community perturbations on the scale of hundreds of years that must be understood to put present-day observations in a long-term perspective.

C. Rates of Climate Change and Coral Response

Future climate change will include changes in mean conditions, variability, and the frequency of extreme events. Records from coral reefs will help define variability and shifts in mean states of past climates in the regions of the reefs themselves. Anticipating the response of reefs to future climate change rests in part on identifying thresholds in absolute values and rates of change beyond which reef organisms cannot survive.

D. Monitoring, Calibration and Quality Control

Many aspects of the paleoenvironmental record would benefit from further calibration by laboratory and field studies. There is a particular need for seawater analyses of components significant in the coral paleoclimatic record such as stable isotopes and trace metals. Existing collections of reef material should be analyzed to derive maximum benefit from minimal destructive sampling.

E. Summary

Refining the techniques discussed in this report and demonstrating their usefulness will be shown by targeting coring programs in areas of well-documented perturbations through which at least continuity of coral growth has occurred. Paleoenvironmental studies on reefs represent retroactive monitoring programs that can produce results over long time spans at resolutions comparable to those achievable in the modern record, for a comparatively small investment of time and resources. More specific research recommendations are outlined in the section on skeletal tracers of coral bleaching (see below).

Sub Group 3: Data Required by Researchers

Participants: George Dennis, Mark Eakin, Pamela Hallock-Muller, George Maul, Linda Mearns, Gene Rasmussen, Charles Yentsch

I. ISSUES

A. What is the role of climate models in the investigation of environmental effects on reefs?

Indicators\Processes	SST	Salinity	Upwelling, nutrients	Anthropogenic inputs	ENSO	Terrestrial runoff	Rainfall	Light	Productivity	Environmental stress	Resuspension, sediment diagenesis, volcanic inputs
18O/16O	++	++			++		+				
13C/12C			+	+	+			+	+		
Bomb radionuclides			+	++							
Growth rates, hiatuses			+	+	+	+		+		++	
Band density			+				+			+	
UV fluorescence						++					
Ba	+	+	++		+	+					
Sr	+		+								
Cd	+		++	+	+						
Mn			+		+						+
Pb				++							
Geomechanics			+	+							
Crystallography			+							+	

Table 1. The potential use of various indicators to identify changes in environmental processes.

The application of these indicators to defining variations in these processes can be site specific at present.

(++) indicates strong signals with known wide geographic applicability

(+) indicates signal strongly correlated with processes at some sites, with strong events at many sites, or reqiring further development.

Which parameters can be estimated? What scales are important to reefs? What can reef researchers provide to modelers?

At the present state of the art of atmospheric general circulation models coupled to ocean general circulation models (AGCMs/OGCMs) or as the art will develop in the near future (e.g., within the next several years) the following climate variables and estimates of how they would change under transient CO_2 increase scenarios could be provided on at least daily time scales (and/or daily maximum/minimum values) at relevant selected locations. These variables are those deemed most important for determining climate effects on coral reef ecosystems:

- Sea surface temperatures, ocean temperatures to 100-m depth
- Wind speed and direction
- Salinity
- Absorbed solar radiation at the surface
- Barometric pressure
- Near-surface air temperatures
- Near-surface vapor pressure
- Regional rainfall and runoff (for determination of sediment loads related to coastal reefs)
- Sea level changes

The prototypical AGCM which is or will be available for providing these variables will have the following characteristics: horizontal resolution of 2.5° x 2.5°, with a minimum of 12 vertical layers, coupled to a full OGCM with 1° x 1° horizontal resolution and 20 vertical layers.

Currently, the coarse resolution (e.g., 5° x 5°) models can provide these variables but due to the complex climate interactions in the tropics, higher resolution models would be particularly desirable. Current models do not in general perform well in the tropics. In the future, finer scale resolution in space and time will provide projections at a level more meaningful to coral ecosystems.

The (hopefully) detailed climate change scenarios will help indicate future environmental stresses to which the ecosystems may be subjected. Therefore, it is possible that detailed analysis of relevant climate variables will aid in guiding bioassays of corals, such as determining levels of thermal stress for tolerance experiments

Additionally, the monitoring system to be established for coral reef ecosystems could help to validate the climate models, especially finer resolution limited area models (LAM) nested within the coarser resolution GCMs. The LAM/GCM will be of particular use in coral reef studies due to the finer scales relevant to these systems. Development of LAM/GCMs for coastal areas should be investigated. Such a modeling system for eastern Australia is being developed by Macquarie University in cooperation with NCAR (National Center for Atmospheric Research).

For specific case studies, calculations from operational models, such as the ECMWF (European Centre for Medium Range Weather Forecasting), should be used to provide boundary conditions for LAMs. Within the LAM area, even higher spatial and temporal resolution data should be used in diagnostic mode to improve understanding of the processes involved that affect coral reef communities. This approach is recommended as part of the design experiment for a monitoring network. It is anticipated that site-specific monitoring networks will be required, and we should be prepared to be very flexible in this regard.

B. How can we distinguish direct anthropogenic signals from global climate-change signals?

As a result of ever-growing human populations, anthropogenically induced environmental perturbations are occurring worldwide. Effects range from local physical damage (e.g., destructive fishing, recreation and construction activities) to global climate change as the result of atmospheric buildup of CO_2 and other greenhouse gases in the atmosphere.

Two types of pollution that have tremendous potential for altering ecosystems worldwide are anthropogenic enhancements of totally natural and essential chemicals: CO_2 and nutrients. Humans have severely altered the distribution of these chemicals in the environment almost certainly causing stress in many reef environments.

A major challenge to scientists studying reef communities is to distinguish the effects of different classes of perturbations, particularly natural climatic variability as compared to anthropogenically-induced changes. Responses at the organism and community levels reflect all environmental factors. Therefore distinguishing among, e.g., the effects of temperature, increased ultraviolet radiation, or nutrient enrichment, will be very difficult and will require carefully designed and controlled experimentation and diagnostic numerical modelling (LAMS). Such work should be a priority of reef researchers.

To separate global-scale community effects, such as warming or increased U.V. from local or regional anthropogenic effects such as nutrient pollution, reef communities must be monitored to make interregional comparisons. We must keep in mind that regional anthropogenic effects are more prevalent in regions of continental influence such as the Caribbean/Gulf of Mexico and the Indo-western Pacific, while the effects of global change may be the major anthropogenic influence on isolated reefs of the tropical Pacific.

C. What are the monitoring requirements of reefs and physical parameters?

In the last decades there have been reports of widespread deterioration in vast areas of coral reef ecosystems. These were attributed to the spread of *Acanthaster planci*, bleaching events, direct destruction due to various human activities and global, climate-change related phenomena. Without an integrated and comprehensive program, it will be impossible to provide a balanced scientific assessment of future trends in coral reefs, nor to suggest any local or international course of action, if deemed necessary and feasible.

To diagnose the causes of ecological stress-events on coral reefs, a program of Synoptic Environmental Assessment (SEA) is needed to monitor and analyze the physical and biological observations needed on relevant temporal and spatial scales. The following is a list of critical observations to be included in such a program.

Near Surface Physical:

- Atmospheric temperature
- Spectral irradiance
- Barometric pressure
- Wind speed and direction
- Rainfall
- Humidity

Sedimentological:

- Composition
- Organic content
- Grain-size composition

Water column, biological:

- Phytoplankton (chlorophyll) concentration
- Zooplankton concentration

Ocean observations:

- Sea surface temperature
- Sea level (incl. vertical geodetic stability)
- Current speed and direction
- Wave energy
- Nutrient levels (incl. nitrogen, phosphorus, total inorganic carbon and iron)

Profiles of:

- Salinity, temperature, water transparency, radiation, sediment load and turbidity
- Bottom topography

This might be accomplished by forming a network of permanent stations at two levels. Level one would comprise combined research and monitoring stations conducting standard monitoring, calibration of monitoring activities and sophisticated monitoring of physiological responses. Some five facilities capable of carrying out such a program already exist or could be formed by relatively minimal upgrades. These require full scientific staff as well as adequate instrumentation, and should be funded as research programs leading to the development of uniform protocols and integrated databases over the first 3-5 years.

At least twenty additional monitoring-only stations (level two) would supplement the level one stations. These might be operated by semi-skilled personnel equipped with robust, nearly maintenance-free tools. These should be funded as permanent environmental monitoring facilities, feeding into a worldwide "coral watch" database.

It will be difficult to interpret these local observations in the context of the large scale fields resolved by current GCM's. The output of those models can define the scale of pelagic variables (temperature, salinity, etc.) but proper interpretations of the observations in the neighborhood of the reef requires a nested numerical modelling approach. We believe that the Marine Ecosystem Analysis (MESA) program can serve as a model for this observation/diagnostic approach. A mixture of physical measurements and diagnostic numerical modeling was used in that program to define fields of variables pertinent to ecological stress.

In summary, a parallel theoretical/observational approach is proposed whereby the cause and effect relationships can be quantified at carefully selected sites and then applied to the generic problem. We recommend that a meeting be held specifically to address the design of the monitoring program and distribution of monitoring stations.

D. What historical data are available for correlation?

1. Historical data from colonial records, ship records, older aerial photographs, etc.
2. Data sets that are not specific to reefs that are potentially useful to reef researchers:

Institutional:

- NOS (National Ocean Service)
- NCDC (National Climatic Data Center)

- NODC (National Oceanographic Data Center)
- World Data Center A (Washington) and B (Moscow),

Data sets:

- Comprehensive Ocean-Atmosphere Data Set (COADS)
- ISCCP (International Satellite Cloud Climatologic Project — high resolution cloud data set a decade in length)
- CZCS, AVHRR and other sea surface satellite data

Other sources:

- Military data sets
- Privately held data (oil companies, fishing companies (Japan), shipping companies, etc.)

A significant effort could be funded to obtain, digitize, and distribute these data.

3. Paleoclimatological records from terrestrial and deep sea sources (published records).
4. Transects and field sampling sites in reef environments sampled a decade+ ago. (Resurveys of these sites should be a priority because of their potential to identify changes and possible trends in populations and communities.)

E. What value can we place on reefs to reinforce the research efforts being generated?

The loss and degradation of reef habitat has important economic implications, particularly for island nations. Healthy reefs are major tourism resources, with revenue from vacationers, divers, recreational fishing, and others. Reef and associated seagrass and mangrove communities provide nurseries and habitat for many commercially important species such as lobster and shrimp, and is a major source of subsistence protein in many island nations. Coral reefs and associated communities support exceptionally diverse accumulations of taxa; the potential of these taxa for providing biochemicals of medical and industrial value is just being realized. The harvest of reef resources, including fisheries, biochemical sources, and even sediments for building materials must be carefully managed as renewable resources for sustainable yields.

Coral reefs provide natural breakwaters for coastlines and harbors and will become increasingly important for storm protection as sea level rises. A healthy reef should keep pace with the anticipated rate of sea level rise, while a dead or damaged reef can degrade at rates up to 5-10 times higher than the accretion rates of healthy reefs. Thus, even without sea level rise, loss of reefs will subject currently protected coastlines to higher wave energy regimes within a few decades.

Protection of coral reefs as unique and intrinsically valuable resources in their own right is an ethical position which is being taken by this group.

II. THE NEED FOR REMOTE SENSING OF CORAL REEFS

Coral reefs are ideal candidates for remote sensing, especially those techniques which employ optical sensors about environmental effects of Global Climatic Change. We must now begin to plan how to develop technology and research strategies for assessment of coral reef biomass and measurement of growth levels using these optical sensors.

Crucial to this is the state of the art of optical remote sensing using active (LIDAR) or passive (wavelength scanners) instrumentation. Both systems have been used to study the characteristics of vegetation. Both have limitations as to areal coverage and/or detection specificity. Present scanners have a spatial resolution of 40-1000 meters. LIDAR probes have approximately one meter resolution based largely on aircraft altitude.

The capabilities of optical remote sensing are outlined in Table 2. LIDAR should be able to measure the fluorescence of chlorophyll F_{chl}, phycoerythrin F_{pe}, phycocyanin F_{pc}, and the blue green fluorescence F_{bg} characteristic of most corals. Sun-induced fluorescence of zooxanthellae also could be measured.

Reflectance (spectral) through radiometry would allow measurement of chlorophyll as well as water clarity. Reflectance from a pulsed laser at the appropriate wavelengths can be used for measurement of chlorophyll and water clarity.

Coral photosynthesis can be estimated using chlorophyll light (incoming) and water clarity. Ataxonomy through the detection of different color groups can be used to identify the algae in coral reef *communities. Correlations of fluorescence with reflectance signals $F_{chl/chl}$ would provide a measure of* photosynthetic efficiency. A study of the fluorescence signals from chlorophyll and accessory pigments could be used as a diagnostic to measure algal invasion after a bleaching event.

Although satellite remote sensing techniques are useful to monitor changes in many large ecological systems, the resolution of these data is such that current remote sensing of coral reefs should be directed at high resolution airborne systems and associated ground truthing. These have the ability to produce pixel sizes equivalent to the scale of coral colonies. Of particular use will be the definition of spectral signatures over wavelengths ranging from U.V. through visible to at least the near-IR. Data already at hand indicate that in near-IR wavelengths small variations in spectral signatures may be identified among different species of corals. Signatures certainly change as corals undergo stress. Expansion of this type of work will allow researchers to gather data at scales needed to discern regional to global scale changes in coral reef ecosystems.

Complementing these optical (visible) wavelength observations will be reflected IR and emitted IR. Reflected IR will provide high definition of land - sea boundaries, and assist in the quantification of areal mapping. Emitted IR, particularly multispectral sensing, will provide SST information at the scale of interest to the local patchiness that may be typical of the SST on coral reefs. Here again, aircraft observations will probably provide data at the scale required, and with less atmospheric influence form the lower altitudes, the higher accuracy required.

Other remote sensing should also be kept in mind. HF coastal radar has been shown to provide high resolution maps of sea surface current vectors at 1-2 km spatial resolution and at 3-hour time steps; typically 100 square kilometers of coverage from two HF stations is possible. Synthetic Aperture Radar (SAR) or Side-Looking Airborne Radar (SLAR) can also provide important information on currents and internal waves that may be affecting the circulation around coral reefs; both SLAR and SAR can be obtained from aircraft, but SAR at 25-meter pixel resolution is available from satellite. Finally, scatterometer data from either aircraft or satellite can provide detailed information on the wind stress vector in and around coral reefs, and this will be most valuable in data assimilation modeling of the currents and wave energy that may be affecting a particular reef.

Table 2. Capabilities of Optical Remote Sensing.

REMOTE METHODS		
A. Fluorescence	LIDAR	Fchl, Fpe, Fpc, Fbg
	Sun Induced	Fchl
B. Reflectance	Radiometry	chl, clarity
	Laser	chl, clarity

SCIENTIFIC USES	
1. Photosynthesis	chl, clarity
2. Ataxonomy	Fchl, Fpe, Fpc, Fbg
3. Physiological Status	Fchl/chl, Fchl/pe, Fchl/pc

CORAL BLEACHING WORK GROUP

Facilitator: Jeremy Jackson. Participants: Terry Done, Zvy Dubinsky, Robert Dunbar, Joe Elms, David Enfield, Peter Glynn, Paul Jokiel, Michael Lesser, Leonard Muscatine, Caroline Rogers, Robert Rowan, Deborah Santavy, Glen Shen, Gerard Wellington, Robert Wicklund, William Wiebe, Ernest Williams

Bleaching is a symptom of the expulsion of symbiotic algae by corals and other reef animals in response to environmental stress. There is a perception that bleaching of reef corals may be a preview of future effects of global warming.

There are three general aspects of coral reef bleaching:

- The nature of the evidence for coral reef bleaching and its association to environmental variation.
- Possible mechanisms and consequences of bleaching for reef corals and other symbiotic animals.
- Possible long-term consequences of coral reef bleaching.

I. THE NATURE OF THE BLEACHING PHENOMENON

A. Specific Questions Addressed:

1. Is coral reef bleaching an important source of coral mortality, and is it increasing?

Intensive underwater observations on coral reefs began in the late 1950s in the Caribbean and the 1960s elsewhere. Since then, coral reef bleaching and associated death of reef corals has occurred more frequently and on a larger scale within the past ten years. This is especially true in the eastern and central Pacific during the 1982-83 El Niño event, and in the Caribbean from the late 1980s to present. Bleaching in the western Pacific has been more sporadic. There is also paleoecological evidence that extreme bleaching and mass mortality comparable to the 1982-83 event had not occurred in the eastern Pacific during the previous approximately 300 years. There are no comparable data from elsewhere.

2. What is the evidence that bleaching is caused by high temperature or by other factors? In this regard, is bleaching an indicator of climate change?

There is strong evidence, particularly from the central and eastern Pacific, that widespread bleaching is associated with unusual increases in temperature. Laboratory experiments demonstrate that high temperatures can induce bleaching in a manner consistent with field observations. However, there remains serious question about the closeness and universality of the association of bleaching with high seawater temperatures, and the likely role of other factors that may cause bleaching on local and regional scales.

Numerous workers have shown that loss of zooxanthellae occurs during excessive sea water warming under both laboratory and field conditions. Bleaching typically occurs when water temperatures rise only 2-3°C above ambient over a period of some 3-5 weeks. Slightly higher water temperatures can induce bleaching over shorter time intervals. Bleaching can also result from factors such as low temperature, reduced salinity, high sedimentation, and anthropogenic effects, but most recent events of concern have been associated with high temperature stress.

Widespread bleaching and mortality of reef-building corals on a large scale were first reported during the 1982-83 El Niño. Bleaching also extended westward to Indonesia and Australia during the 1982-83 ENSO. Sea warming was also implicated in a series of major bleaching events during 1987 in the Caribbean. In 1990, severe coral reef bleaching occurred throughout the tropical and subtropical western Atlantic region, and in 1991 severe bleaching also occurred in French Polynesia.

In most cases, abnormally high sea temperature was associated with the bleaching, although other factors such as irradiance, altered salinity, altered oxygen concentration, and human induced changes may also be involved. Although the relationship between high temperature and bleaching is incontrovertible in many instances, data are insufficient in some documented bleaching events to confirm this relationship unequivocally. There is no clear evidence for the coupling of coral reef bleaching and global warming because of the lack of relevant data.

3. Aside from bleaching, are coral reefs in general decline? If so, what are the major factors apparently responsible?

Most participants believe that coral reefs are seriously endangered in many areas, but that few quantitative data are available to sustain or reject this perception. Fringing reefs in areas of intensively increasing agriculture, deforestation, and urban development may be particularly threatened.

B. Summary

The correlation of elevated sea water temperature and coral bleaching is compelling. Elevated temperature as a consequence of a putative global warming trend is not yet established. The glaring lack of a retrospective field data base on global and local warming trends, or any other factors affecting the general health of coral reefs, emphasizes the need for sustained field ecological research by interdisciplinary teams and the immediate need for an institutionally supported coral reef ecosystems monitoring effort. The scale of this effort with regard to coral bleaching should be appropriate to the questions of the link between global warming and elevated temperature and the link between temperature and coral bleaching. Other scales may be appropriate for assessment of other potential anthropogenic effects on reef ecosystems.

C. Research Priorities

1. Establishment of a Global, Long-term Research and Monitoring Network to Follow Climate Change and Anthropogenic Input Effects on Coral Reefs.

It is the unanimous opinion of workshop participants that sustained ecological monitoring at several sites is an absolutely essential component of ecological research on coral reefs. Long-term data are crucial to the interpretation of short-term ecological experiments, regional or global occurrences of coral bleaching, and possible global climate change.

Such data can only be gathered through a network of extensive and intensive permanent monitoring stations where identical instrumentation and standardized procedures are used. The monitoring of biological parameters should be non-destructive, allowing for prolonged observation of particular localities and even individual coral colonies. Strategically distributed stations would combine research and monitoring functions, in addition to calibration activities, sophisticated monitoring of physiological processes, and technical staff training.

Five to ten facilities capable of conducting such a program either exist already or could be created by relatively minimal up-grading. These intensive stations require full scientific staff, adequate instrumentation, and funding for a period sufficient to develop protocols and integrated databases. Twenty additional, extensive, monitoring-only stations would supplement these. Such stations would be operated by trained field technicians equipped with robust, nearly maintenance-free tools. These should be funded as permanent environmental monitoring facilities, the function of which would be to feed data into a worldwide database.

a. Choice of sites

- Extensive: in carefully selected coral reefs representing diverse conditions and various disturbance levels.
- Intensive: existing marine labs or MAB sites.

b. Spatial scales

- Large scale — using satellites, LIDAR aircraft, oceanographic vessels, GIS, etc.
- Community — physical parameters (temperature, salinity, tide, etc.), community structure (by means of biotic surveys, etc.), community physiology, etc.
- Organism/suborganism — physiology, biochemistry, life histories, etc.

Data management through a centralized, integrated program for validation, storage, and dissemination would comprise a major effort of the program. We see a need for development of standardized methods and instrumentation, and for increased support for strengthening support of taxonomic and paleoecological studies.

II. CORAL STRESS, BLEACHING, AND RETROSPECTIVE STUDIES

A. Background

Although we reached an apparent consensus that coral bleaching events have become more frequent during the past decade, much of our evidence is anecdotal and our direct observations extend back only 30 to 40 years.

The extent to which current bleaching represents an unusual, or possibly even unique, event over longer time-scales is unknown. This is an important issue to resolve before a clear link can be established between bleaching and specific causative stresses related to global climate change. Retrospective studies using corals are a potentially rich source of information about the frequency and spatial distribution of bleaching events. Skeletal growth records in living, massive corals extend back as far as 200 to 500 years in many areas where bleaching is now occurring; longer time series are available using fossil corals.

Major bleaching events that result in coral mortality or lengthy intervals of zero growth leave behind a skeletal signature as a perturbation in growth band morphology or as an actual hiatus or unconformity. Stress bands or hiatuses can result from a variety of influences such as grazing, predation, thermal shock, salinity variation, disease, and storm damage, not all of which promote bleaching. The spatial distribution of synchronous stress horizons should allow discrimination between biological forcing factors and regional physical parameters linked to climate.

Further characterization of a bleaching-type origin for specific stress surfaces will probably require chemical or isotopic analyses. However, in the context of assessing regional and global "health" of coral reef systems, the identification of all widespread stress events in the skeletal record should be of interest, regardless of whether they can or cannot be clearly linked to coral bleaching.

Apart from growth hiatuses, a variety of chemical constituents found in corals may be used either to identify past bleaching/stress episodes or to describe conditions that existed during such events. At present, an explicit bleaching "marker" does not exist; however, stressful conditions can be identified through time-series measurements of these chemical tracers. At uncomformities, such measurements may yield insights as to the environmental stressors responsible for catastrophic events culminating in mortality. The stable isotopes of oxygen and carbon can delineate temperature, solar radiation, and salinity changes over very brief time intervals (e.g. monthly to seasonal) in a coral's growth history. Skeletally-bound trace elements such as cadmium and barium relate to ambient nutrient levels that existed at the time of precipitation and can also be correlated with temperature in reefs exposed to oceanic upwelling. Other skeletal components such as trapped humic/fulvic material (and Ba) can be measured to trace the influence of runoff - a recognized cause of bleaching in localized settings. Still other trace constituents (e.g. Pb) may be used to identify the influence of anthropogenic pollutants on a coral reef.

One suggested line of research with implications for reconstruction of bleaching episodes involves characterization of the organic matrix left behind in coral skeletons. All previous retrospective studies have focused on the inorganic portion of the skeleton. Since the bleaching response consists of an ejection of photosynthetic algae, a residual chemical imprint might be expected as a consequence of a rapid change in the metabolic fractionation of light and heavy isotopes of carbon and nitrogen. Development of such an indicator in the remnant organic content of corals would circumvent ambiguities associated with interpretation of the carbonate C-O isotopic systems.

Paleoecological studies using reef framework samples have seldom been attempted. However, from discussions at this conference it is apparent that there is no viable substitute for the long-term perspectives that this kind of research can provide to studies of community succession and response to environmental perturbation. Accessibility to the paleoecological record will vary depending on study site. Examination of drowned reefs would, for example, require extensive drilling to achieve adequate spatial coverage. Uplifted terraces could be closely inspected on a broader scale for evidence of historical stress events and successional evolution.

It is important to note the link between paleoclimate/paleoecological studies using corals and the need for comprehensive reef environmental monitoring programs. Careful in-situ monitoring of environmental parameters such as T, S, water chemistry, and light provides the best means for accurately calibrating the climate record contained within coral skeletons.

B. Research Priorities

1. Laboratory and field experiments for calibration of specific coral-based traces. Verification of signal fidelity using skeletal tracers to reconstruct well-documented climatic and anthropogenic changes in the past century.
2. Acquisition and analysis of longer coral-based time series to discern secular variability, long-term trends (including major climatic transitions/forcing), and catastrophic events.
3. pursue paleoecological studies to provide estimates of long-term reef system responses to previous perturbations: initially use uplifted reef tracts; develop new sampling systems for submerged reefs. Note — reef ecologists must be active participants along with geologists and paleoclimatologists.

III. CORAL-ALGAL FUNCTIONAL BIOLOGY

Recent observations of bleaching on coral reefs, particularly in the Caribbean and eastern Pacific, have focused our attention on the coral-algal symbiosis as a potential indicator of the health of reef ecosystems. However, a better understanding of symbiosis biology is required in order to evaluate this issue.

Bleaching has been described as the expulsion of zooxanthellae from the animal host or the diminution of photosynthetic pigment in the algal cells, or both. As currently understood, bleaching should be distinguished from photoacclimation, which involves only changes in the concentration of photosynthetic pigments as a response to variable light levels. In contrast to photoacclimation, bleaching is a manifestation of a change in the essential relationship between host and symbiont populations. Bleached corals exhibit reduced fitness in terms of growth and reproduction.

The association of bleaching with a variety of environmental extremes, most notably elevated sea water temperatures, strongly suggests that bleaching is a symptom of stress. Although it has been suggested that bleaching may be an early warning sign of global warming, it can be difficult to distinguish elevated sea water temperatures from direct anthropogenic inputs that may predispose or directly cause coral bleaching. orals are also exposed to high fluxes of ultraviolet (U.V.) radiation compared to temperate or polar marine organisms. This consistent exposure to U.V. radiation may be an important physical parameter affecting the distributions and abundances of reef-building corals. It is important to recognize and distinguish between different sources of stress if we are to understand the underlying mechanisms of coral bleaching and to use them as indicators of environmental quality.

Whereas field data will continue to be an important source of information on the causes and long-term ecological significance of coral bleaching, laboratory investigations should be used to define more accurately the causes and cellular mechanisms of bleaching. Extant field observations can serve as immediate sources of testable laboratory hypotheses. Laboratory studies should examine the efficacy of various agents in inducing bleaching, the possibility that different agents lead to distinguishable "bleached phenotypes," and the physiological consequences of experimentally-induced changes in zooxanthella populations. Although recent work has begun to describe the effects of U.V. radiation on organismal performance, its role in bleaching, alone or in concert with elevated sea water temperatures, remains incompletely understood. As part of the effort to elucidate and understand the effects of U.V. radiation, robust action spectra (biological weighting functions) for processes of interest (e.g., photosynthesis) in corals should be developed. The coordination of laboratory studies with on-going ecological and paleontological studies is a high priority. Collectively, the data may allow us to explain and predict patterns of bleaching.

With respect to the population and community level effects of bleaching, it is important to know why corals manifest variability in their bleaching response. Field observations indicate that the onset of, and recovery from bleaching varies within and between taxa. Some coral species exhibit different sensitivity to bleaching at different geographic locations. It is not known whether the basis of this variability is physiological or genetic. Also, taxonomic uncertainties make it difficult to conclude that individual coral species really do exhibit bleaching variability. The zooxanthellae, which represent the other biological half of the bleaching equation, are also a collection of species. No attention has been paid to zooxanthella taxonomy in the context of coral bleaching. Clearly, more taxonomic and population genetic work on both corals and zooxanthellae is required before any predictions can be made about the evolutionary consequences, short- and long-term, of an increase in bleaching episodes.

In conclusion, studies should focus on establishing:

A. What factors contribute to the stability or instability of the coral-algal symbiosis.

B. Manifestations of destabilization of the symbiosis at the cellular, algal population, and individual coral levels.

C. Individual variation within and among species of corals and zooxanthellae in their susceptibility to bleaching.

IV. LONG-TERM ECOLOGICAL CONSEQUENCES

A. Background

Bleaching kills or injures corals and other reef biota and at some places, the extent, and recent frequency of mortality has been so great that it has caused local extinctions of dominant species, cessation of reef growth, and initiation of major reef erosion (Glynn, P.W. and W.H. deWeerdt, *Science* 252, in press). However, in the majority of cases the long-term consequences are not so obvious (Williams, D.H. Jr., and Bunkley-Williams, L., *Atoll Res. Bull.* No. 335: 1-71, 1990); local extinctions and major erosion have not occurred even though bleaching episodes may have revisited the same coral stands on more than one occasion. This raises questions as to whether repeated bleaching-related coral death is ecologically sustainable. How often is too much and how much is too much? The questions may be addressed using transition matrix models that have been used to investigate the same questions in relation to *Acanthaster planci* damage on the Great Barrier Reef (Done, T.J., *Coral Reefs* 6:75-90,1987; Done, T.J., *Marine Biology* 100:51-61 1988). Starting conditions for the simulations are field estimates of coral population structure and injury at particular places. Model outputs are long-term population structures under regimes of simulated disturbance, colony growth, repair, background mortality and recruitment. The approach may also be used to retrospectively assess whether current population structures could have developed under a regime of bleaching (or comparable disturbance) as that witnessed over the last decade. Bleaching followed by major coral mortality has downstream effects on ecosystem structure and function. Filamentous algae invariably colonize newly killed coral surfaces. However the biological succession which follows is known to be highly variable, depending upon the density and composition of grazing organisms, of bioeroding organisms, and of planktonic propagules of benthic plants and animals. Major shifts in trophic structure and function will accompany such biological transitions.

B. Research Priorities

1. Assemble field data and run simulations to investigate the sustainable levels of mortality in reef populations recently affected by bleaching.
2. Look for ecosystem level responses in addition to primary colonization by filamentous algae, which are common to all bleaching episodes.
3. Investigate how regional and local differences in pre-bleaching community structure (including all other reef biota in addition to corals) affect the ecosystem response to and recovery from bleaching.
4. Link matrix or other population models to climate models on the one hand and cellular/physiological models, on the other, to improve the realism and predictive utility of the population models.

ORGANIZERS' NOTE ON MONITORING

Both working groups produced extensive documents on monitoring recommendations and data needs. These were edited to eliminate redundancy and produce a general statement of needs and objectives (below) and compilation of more detailed technical discussions (Appendix B).

Development of a Monitoring Program: Philosophy and Rationale

THE NEED: Most workshop participants believe that coral reefs are seriously endangered in many areas, but few quantitative data are available to support or reject this perception. Fringing reefs in areas of increasing agriculture, deforestation, and urban development may be particularly threatened. The glaring lack of retrospective field data on baseline conditions of presumably healthy coral reefs, as well as on global and local warming trends or any other factor affecting the general health of coral reefs, emphasizes the need for sustained field ecological research by interdisciplinary teams.

Anthropogenic environmental perturbations are occurring worldwide as a result of ever-growing human population. A major challenge to reef scientists is to distinguish among the effects of various classes of perturbations, particularly natural climatic variability, global-scale trends such as warming, and local or regional anthropogenic effects such as nutrient pollution. Monitoring data are essential to this effort, for regional anthropogenic effects are more prevalent in areas of continental influence (such as the Caribbean/Gulf of Mexico) and around high islands (such as Hawaii and the Philippines), while the effects of global change may be the major influence on atolls and other isolated reefs of the tropical Pacific.

Without an integrated and comprehensive program, it will be impossible to provide a balanced scientific assessment of future trends in coral reefs, or to suggest any local or international course of action, if deemed necessary and feasible.

FUNCTIONS OF A MONITORING NETWORK: It was the unanimous opinion of workshop participants that immediate establishment of an institutionally-sponsored, long-term research and monitoring network to assemble directly comparable data sets from coral reefs throughout the tropics is an absolutely essential component of ecological research on coral reefs. The long-term data derived from such sustained monitoring at strategically distributed sites, using standardized procedures and intercalibrated instrumentation, are crucial to the interpretation of short-term ecological experiments, regional or global occurrences of coral bleaching, and possible global climate change. Data must be gathered at several scales to be appropriate for the assessment of each class of potential anthropogenic and climate change effect on reef ecosystems.

The value of corals as paleoclimate/paleoecological recorders will be enhanced by accurately calibrating the record contained within their skeletons through verification of signal fidelity of well-documented climatic and anthropogenic changes in the past century, and henceforth of environmental parameters such as water chemistry (stable isotopes, trace metals, temperature, salinity) and light at monitoring sites. Therefore, biological parameters should be monitored non-destructively, allowing for prolonged observation of particular localities and individual coral colonies. A monitoring system could also help to validate climate models, especially finer resolution limited area models (LAM) nested within the coarser resolution GCMs.

MONITORING SITES: Five to ten facilities capable of conducting a sophisticated program of monitoring physiological and physical processes either exist already or could be created by relatively minimal up-grading. These *intensive* stations will require full scientific staff, adequate instrumentation, and additional start-up funding for a period sufficient to develop protocols and integrated databases. As well as combining research and monitoring functions, these stations would deal with calibration activities and technical staff training. Twenty additional monitoring-only stations, operated by trained field technicians equipped with robust, nearly maintenance-free tools, should be funded as permanent environmental monitoring facilities to gather *extensive* data for a worldwide database.

FINDINGS AND RECOMMENDATIONS

The information and discussions presented in this document led the workshop organizing committee to a series of recommendations arising from the workshop. One set of recommendations concerns implementation of an important collection of working group topics that should be pursued further. The second set concerns conceptual and philosophical approaches to the study of reefs and climate change.

1. Information about the future and past environmental status of coral reefs is required to transfer an intuitive sense that coral reefs are deteriorating into a scientifically substantiated conclusion. Accordingly, **we recommend that five international working groups be established as soon as possible to plan a rigorous assessment of the environmental status of coral reefs and to address the impact of present and future environmental conditions on reefs.** Each working group should be coordinated by a steering committee and each consisting of 6-8 individuals. These groups might be formed the aegis of an appropriate international institution (e.g., ICSU, IGBP, SCOR, IOC) or a consortium of scientific societies with relevant interests.

Each working group should convene an initial meeting before or during the 1992 Coral Reef Symposium in Guam. The working groups should each hold an informational meeting for the coral reef scientific community during the Guam meeting. Each group should host larger workshops within one year after the Guam meeting. We note that one of the strengths of the Miami workshop was the active participation of oceanographers, climatologists, and others from outside the boundaries of the traditional "coral reef" research community; we view this approach as essential to constituting future working groups to enhance the breadth and exposure of their activities.

The topics to be covered by these groups, in more detail than could be done during the Miami workshop, would be:

- Coordinating comparative, long-term environmental monitoring research on coral reefs, to establish local, regional, and global trends of variability and sustainability of coral reefs through time.
- Using corals, coral reef sediments, and fossil reefs as retrospective environmental recorders, to establish the long-term history of environmental variations recorded by coral reefs.
- Using historical records about coral reefs and adjacent waters and land masses as recent retrospective environmental recorders, to assess how anthropogenic or natural variations in the past few decades may be reflected in available, but largely unanalyzed, historical data.
- Developing and employing ecophysiological "probes" and biological markers to detect stress in coral reef organisms, and thereby sharpen our ability to understand and recognize the responses of reef organisms to specific environmental perturbations.
- Assessing the contribution of coral reefs to the biological diversity of the marine environment, and indeed, the biosphere.

2. **We recommend that scientists involved in any program or initiative resulting from the Miami workshop adopt certain conceptual and philosophical approaches to the study of reefs and climate change,** namely:

- Scientists working in the context of this program have a responsibility to interact with environmental resource managers as well as their scientific peers. The study of reefs, or any other ecosystem, in an environmental context represents a challenging intersection of scientific and management questions that requires such interaction.
- A scientifically structured monitoring program is a critically important tool for use in a well designed research program examining change through time — one that involves the constant scrutiny and refinement that can only be provided by scientifically qualified participants. Such environmental monitoring is a logical and necessary component that is neither competitive nor inconsistent with research of the sort discussed here.
- Coordination and comparison among research sites and programs is required in any systematic study of reefs and global environment, and should be part of the planning for such a program. Contrary to some opinions, comparability does not necessarily require common techniques or identical instruments to be used at all sites. In fact, today's changing technology probably makes excessively strict adherence to a single measuring device inadvisable. It is important, however, that data collection protocols and intercalibrations be established so that data can be compared between sites, or between times at the same site.
- Successful extrapolation from existing observational assessments of reef status demands both objectivity and rigor. Since

much of our insight about coral reefs has been collected over a relatively short period of time — what might be termed the SCUBA age of underwater observation — some fraction of our present knowledge is undoubtedly colored by the short period of rigorous underwater observations relative to the time constants of natural variability and reef development.

- Establishing an inventory of reef resources in largely unstudied areas should be a significant part of a study of reefs and global environment. Although coral reef research scientists have been able to learn much about coral reefs in particular geographic areas, vast areas of reefs, especially the abundant and species-rich reefs adjacent to developing nations in Southeast Asia, are largely unstudied; they are potentially stressed by large and rapidly growing human populations.
- Training, especially of young scientists and technical support officers in developing countries, should be an integral part of the future plans for study of reefs and the global environment. Our ignorance about a large fraction of the world's reefs largely reflects the paucity of trained observers in many developing nations.

Additional findings and observations include:

3. **Coral bleaching is just one symptom of a large set of environmental problems confronting coral reefs world-wide.** Observers are noting other signs of stress on coral reefs. In some instances, we can explain the stresses as being due to human activity. All too often, we do not have an explanation. The recommendations we have advanced above will help us to define and understand the effects of human activity on coral reefs and will perhaps help us control or alleviate the impacts of that activity.

4. **Certain key environmental issues, that have substantial ramifications for coral reef and coastal ecosystems, require no further study for development of policy. Action on these issues need not be predicated on the outcomes of any study advocated by our workshop:**

- Widespread degradation of coral reefs and reef fisheries appears to be occurring world-wide principally in areas were development in nearby coastal areas is accelerating. Land-use and human demography have important ramifications regarding the ecological "health" of coral reefs and other coastal ecosystems.
- Human population, the ultimate source of anthropogenic stress on the biosphere or on any individual ecosystem, including coral reefs, is increasing roughly exponentially. Energy consumption, a measure of human impact that includes both population and economic growth, is also likely to increase roughly exponentially in intensity over the next century.

Addressing the proximate causes of anthropogenic environmental stress will be of little long-term benefit if we do not also recognize and control the ultimate sources of that stress.

APPENDIX A

Status of Knowledge on Coral Reefs and Climate Change Issues

To prepare a consensus document on the status of knowledge concerning issues relating to coral reefs and environmental (including climate) change, the organizing committee prepared a draft version of the document presented below and circulated it to the participants for comments or additions before the workshop. A revised version was distributed at the workshop, and further amendments were solicited and received. After incorporating these responses, the document was reviewed for consistency with the reports of the working groups.

The following material is presented as the best available concise summary of community wisdom on the subject of coral reefs and environmental change. The intention is to portray consensus viewpoints or reliable information, not controversial or untested hypotheses. However, we recognize that this knowledge is not static, but will be expanded or supplanted by future research.

I. Climate/Environmental Change

The consensus on climate change used for workshop discussion was based on the published results of the Intergovernmental Panel on Climate Change (IPCC), and includes:

1) an atmospheric composition change equivalent to doubled CO_2 by some time during the middle of the 21st century;

2) a mean global temperature increase of a few degrees (e.g., 1.5-4.5) for a doubling of preindustrial atmospheric CO_2 levels;

3) a latitudinal temperature gradient, with high latitudes warming much more than low latitudes;

4) a resultant sea level rise of 0.5-1.5 m (with present estimates favoring the lower values, at least in the short term);

5) regional changes in cloud patterns, precipitation, and winds.

Although dramatic improvement in the spatial resolution of and agreement between GCM models is unlikely in the near future, significant progress can be anticipated within the next few years. In this context, coral reefs and other marine and terrestrial systems may have specific response characteristics that will allow "fine tuning" of GCMs.

As non-climatic but important interactive factors, we recognize the probability of a significant increase in surface ultraviolet flux due to stratospheric ozone depletion, and the probable steady increase in world population and consequent environmental stress (deliberate coastal modification, marine resource exploitation, land use, waste disposal and pollution, etc.).

Research needs:

1) It is extremely important to address the apparent discrepancy between GCMs that predict a $2xCO_2$ warming of up to 2 degrees in the tropics with paleoclimate formulations that indicate low latitudes were not substantially warmer than present during past Quaternary warm periods. The question of whether future warming will exceed the evolutionary experience of reef organisms and communities will shape other, more specific research agendas.

2) Assuming the possibility of atmospheric warming in the tropics, it is important to be able to put credible limits on the possible amount of SST increase, on either a sustained or transient basis, and to identify (generically or specifically) areas that may not be subject to those limits.

3) Improved predictions of changes in cloudiness, cloud patterns, precipitation, and winds are extremely important assessing the effects of climate change on shallow-water marine environments.

4) Ocean models are being rapidly developed and improved. It is important both to keep the reef research community in contact with the results of those studies and to encourage ocean modelers to address regions and issues of specific interest to questions of reef climate response.

II. Paleoclimate Studies

Retrospective studies based on reef sediments or coral skeletons have direct relevance to establishing baselines for many of the phenomena discussed, and merit detailed consideration. Studies of Holocene and late Pleistocene climate, climate change, and coral reef environments and communities can address several important questions:

1) What aspects of climate can be reliably deduced from skeletal, sedimentary, or paleontological evidence, and with what precision and resolution?

2) How have climates varied in the recent past, what have been the rates and magnitudes of change, and how have reefs and related communities responded to these changes?

3) Can we identify past environments comparable to some or all aspects of the anticipated Greenhouse GCC? If not, can we set limits on how different (in terms of rates of change and absolute values of environmental parameters) present or future climates will be from conditions experienced during the Quaternary?

4) What kind of baseline can be established for trends and variability in late Holocene tropical climates, and what sort of GCC signal could be reliably detected in view of these trends and variabilities?

III. Reef Responses to Environmental Parameters

A. The Physical Environment

1. Parameter: Sea level

Effects: Sea level rise (SLR) may be expected to:

a) Increase coral colonization, calcification, and growth on reef flats and coasts where coral development is currently sea-level limited;

b) Gradually deepen reefs where sediment production and retention are not adequate to keep up with rising sea level;

c) Increase and/or change the patterns of coastal erosion, and affect the distribution of critical intertidal communities such as mangals;

d) Increase water circulation and ventilation in currently restricted environments.

e) Alter recruitment patterns and ecological composition in benthic communities.

f) Modify shallow water habitats.

Sources of variation: Thermal expansion of ocean water; melting of continental ice sheets.

Extent, distribution, variability: Global eustatic rise is predicted (IPCC) to be 8-29 cm by 2030 and 50-150 cm by 2100. Local relative sea levels will also respond to tectonic effects, ocean current and atmospheric pressure shifts, and anthropogenic coastal and near-shore modifications. Local factors may be at least as important as eustasy in the short (few decades) term.

Issues, questions, research needs: Direct, short term effects of SLR appear likely to be positive for reefs if past/present patterns of recruitment and calcification continue. However, the local consequences of reef failure to keep up with SLR may be serious both for reefs and for back-reef shorelines and islands. Therefore, an integrated assessment of the net effect of GCC and other anthropogenic changes on the growth potential of shallow reef communities is important. Indirect effects (via coastal impacts) are more likely to be negative than positive in the short term, but local/regional in nature.

Comments: In view of the climate scenarios adopted we do not consider the issue of sustained or significant reductions in sea level important to address. Estimates of present and recent past SLR are in the range of 1-5 mm/yr; near-term increases will be comparable to slightly larger.

2. Parameter: Temperature

Effects: Unusually elevated water temperature is a stressor that can lead to bleaching of corals (and other zooxanthellate organisms), and may result in death if the "dose" (excess temperature times duration of excursion) is great enough. It may have profound ecological effects on species composition and ecosystem function, and its implications are great on temporal and spatial scales of evolutionary responses. Theoretical and empirical information suggest the possible existence of an absolute temperature upper limit, but conclusive data all point to the importance of relative temperature excursions (temperatures above the normal maximum to which the coral is adapted). Synergism with light exposure has been documented and interactions with other environmental parameters are likely.

Sources of variation: Sea temperature excursions can result from normal climatic variation (e.g., El Niño), local anthropogenic effects (e.g., artificially restricted circulation, thermal effluents), or the regional effects of Global Climate Change. Current GCM results suggest tropical warming may be as high as 2 degrees for doubled CO_2. Even a fraction of this reflected in SST could greatly increase the frequency of damaging temperature excursions.

Extent, distribution, variability: Obvious vulnerable areas include shallow and/or restricted water bodies with high insolation, and regions subject to high natural fluctuation (e.g., El Niño sensitive). With significant low-latitude SST warming, potential vulnerability would be ubiquitous. As with most such climate-driven shifts and variations, specific predictability is poor.

Issues, questions, research needs:

1) Theoretical/model calculations of the maximum SST values to be anticipated, both on average and as transients (see discussion under I above).

2) The nature of physiological, genetic and evolutionary mechanisms of apparent temperature adaptation (or selection), and the basis for differences within and between taxa.

3) Temperature sensitivities (and their mechanisms) of other reef organisms, especially "keystone" taxa.

4) Synergism with other acute and/or chronic stressors.

5) Temperature effects on ecological factors such as rates of reproduction, recruitment, mortality, growth, and dispersal of larvae that influence processes such as succession, competition, predation, and the food web structure.

Comments: Temperature is a key variable: it has demonstrated and putative connections with recent episodes of coral bleaching and mortality, and it has both logical and intuitive connections with GCC.

3. Parameter: Oceanic currents

Effects: Oceanic currents are a primary control on nutrient levels, temperature, etc. by determining intensity and location of upwelling and water mass advection. These water movements have a secondary control on nutrient, sediment and contaminant distributions by interacting with local sources (typically anthropogenic). Currents control the distribution of reefs and competing communities by transporting their propagules, and therefore has ecological, biogeographical and evolutionary implications. They also have significant influence on sediment/coastal dynamics and local relative sea level.

Sources of variation: Climate changes may be responsible for transitions to new quasi-equilibrium patterns of atmospheric and oceanic circulation.

Extent, distribution, variability: Are changes in oceanic circulation patterns predictable with any useful certainty? Extrapolation of recent and intermediate-term past trends offers some limited views, but there is no understanding of their causes or an estimation of the probability of major state transitions, either gradual or abrupt.

Issues, questions, research needs: Continued development of ocean and climate models will, if properly focused, address parts of the problem. Continued or expanded marine paleoclimate studies aimed at determining and explaining patterns and rates of past circulation or related changes can provide major insights. Studies of the resilience of existing coral and related communities to changes in currents (e.g., El Niño) may help with prediction of possible effects. Studies of relationships between larval dispersal and currents are needed.

Comments: As with many major features of the global climate system, variability is at least as important as change in the mean, and even less predictable.

4. Parameter: Storms and wave energy

Effects: Storms provide long-term episodic control of reef community development by catastrophic pruning and/or substrate renewal. They influence community succession and diversity directly at the local level, and indirectly regionally. Wave energy (including direction) operates more or less consistently as a component of winds and surface currents to shape the biological and physical development of reef communities. The upper end of the "normal" wave energy spectrum grades into the range of storm effects, with frequency of occurrence decreasing and becoming more variable as magnitude increases.

Sources of variation: Increases in tropical SST and expansion of the geographic extent of surface water temperatures capable of sustaining tropical storm activity are believed (but not proven) likely to increase the frequency and/or intensity of tropical storms; changes in distribution are likely but less predictable. Wave energy/direction changes will derive from presently unpredictable shifts in atmospheric and oceanic circulation patterns (see discussion above under currents).

Extent, distribution, variability: Increases in storm frequency/intensity are most likely to affect regions currently subject to tropical storms, and their immediately adjacent geographic fringes. Wave energy changes are not readily predictable other than to note that SLR may make local areas currently protected by sea-level reefs somewhat more exposed to wave effects.

Issues, questions, research needs:

1) What are the time constants of reef development that relate to or are potentially controlled by the recurrence intervals of storm events?

2) Do reef communities (at various scales) outside present areas of tropical storms differ significantly (e.g., in structure, diversity, or sensitivity to storm effects) from their counterparts in storm-prone regions, and what may be the effects of extending storm tracks or increasing frequencies?

Comments: Although catastrophic from human viewpoints, storms are a natural phenomenon to which reef systems are adapted. In the context of GCC and environmental change they are probably most important as acute stressors whose direct effects are followed by community recovery or succession that may be controlled by effects of more subtle chronic stressors.

5. Parameter: Ultraviolet light

Effects: UV light imposes physiological stress on shallow-water and intertidal organisms and may also be mutagenic.

Sources of variation: Progressive destruction of the stratospheric ozone layer by atmospheric pollutants is expected to result in global increases in surface UV exposure, modulated by changes in cloud cover.

Extent, distribution, variability: Stratospheric ozone depletions are propagating toward lower latitudes from initial polar effects, and are expected to continue to do so. Variations in this depletion are large-scale, but these variations are not uniform with longitude or in time.

Issues, questions, research needs:

1) Establishment of a good network, integrated in space and time, to make baseline measurements of tropical marine UV levels for characterization and correlation of the apparently inevitable change.

2) Determination of the vulnerabilities (both absolute and relative) to UV increase of shallow water tropical organisms. Information is needed not only on acute stress to the mature organism, but on such life-cycle factors as fertility, larval survival, etc. as well.

Comments: Of all of the potentially synergistic or confounding anthropogenic changes that will interact with GCC or other environmental change, this is one of the most important on a truly global scale. Monitoring is specifically mentioned for UV since, unlike the case of temperature and possibly sea level, prompt action may provide some reasonable estimate of baseline exposures before ozone depletion increases in the tropics.

6. Parameter: Visible light

Effects: Light is required for photosynthesis. On clear days, peak light values at the surface are in excess of photosynthetic requirements in most locations. The water column attenuates light to the extent that photosynthesis and calcification both diminish below depths of a few meters to a very few tens of meters. Increased radiant energy input at the surface may or may not have effects on shallow organisms, and may slightly extend the depth zone of active reef growth. Reduced light penetration, either by changes in water column characteristics or by incident energy changes, can significantly reduce the optimum depth zone for reef/reef organism growth.

Sources of variation: Peak clear-day values of incident light are unlikely to increase due to atmospheric change. However, average input could increase in areas where cloudiness decreases as a result of GCC. Decreased light availability could result from increased cloudiness (considered probable by some climate specialists), atmospheric pollution, or increased turbidity due to either sediment input or in-situ effects of nutrient loading (see discussions below).

Extent, distribution, variability: Although it is thought likely that a warmer world will be a cloudier world, predictability of changes in cloud pattern is currently very weak. See sections on sedimentation, nutrients, and turbidity for discussion of other contributing variables.

Issues, questions, research needs:

1) Although effects and interactions are qualitatively understood, we lack models or empirical studies that would permit us to predict or understand coral and reef community responses, as functions of depth, to changes in mean light level and especially to changes in variance and/or distribution (e.g., seasonal/daily shifts in intensity/duration factors).

2) Differential responses of hard coral and potentially competitive or destructive organisms (algae, soft corals, bioeroders) to changes in light regime are extremely important, implying increased attention to non-coral species and communities.

3) a) Synergism of changing light levels with other (likely coincident) effects such as sedimentation and nutrient loading is potentially important, as is b) synergism of existing light levels with high temperature or salinity stress.

4) Visible light changes in cloud cover due to GCC may lead to changes in light quality. What influences will spectral changes have on organisms including primary producers?

Comments: As with several of the other parameters, systematic differences between coastal and oceanic reefs are probable.

7. Parameter: Sedimentation

Effects: Extremely rapid sedimentation can smother corals and other sedentary reef organisms. Slower but significant rates are known to cause reductions in coral growth rate. Occlusion of hard substrate with soft sediment can reduce coral recruitment. Increased sedimentation is often, if not always, accompanied by elevated turbidity and nutrient levels (discussed below). Among the mechanisms for deleterious effects are choking of feeding mechanisms, sulfide generation, facilitation of bacterial "infections", and increased metabolic expenditure to maintain sediment free tissue.

Sources of variation: Rising sea level will expose coastal and shallow-water sediments to changes in erosional and depositional patterns. Changes in currents, storm frequency or intensity, and precipitation/runoff will probably change sedimentation rates and patterns on a local or regional basis. Non-climate anthropogenic changes in land use (deforestation, agriculture, construction) will also have major local and regional effects.

Extent, distribution, variability: Increased vulnerability as a result of sea level rise will be ubiquitous, with local impacts predictable in part on the basis of the nature and exposure of local soils and sediments. Changes resulting from atmospheric or oceanic circulation pattern changes are probable but unpredictable without better models or actual data on climate change. Non-climatic anthropogenic effects may be predicted to some degree based on geographic trends in population and development.

Effects will be significant only in proximity to land masses; oceanic and atoll reefs may experience redistribution of existing sediments, but lack of sources for a major increase in terrigenous material input.

Issues, questions, research needs: Sedimentation (and related stresses, such as turbidity and nutrient loading) are only occasionally and very locally acute, but its probable general and sustained increase make it important to be able to monitor low-level changes and effects, and to understand its synergism with other chronic and acute stressors.

Comments: See discussions of turbidity and nutrients below.

B. The Chemical Environment

1. Parameter: <u>Carbonate mineral saturation state</u>

Effects: The effects of changes in carbonate saturation state are predicted but not empirically determined:

1) Possible reduction in calcification and/or extension rate of corals and other calcifying organisms.

2) Possible shifts in skeletal chemistry/mineralogy.

3) Possible shifts in sediment/community dominance if thermodynamic preference for mineral deposition affects organismic success.

Sources of variation: CO_2 dissolved in surface ocean waters will equilibrate with increased atmospheric pCO_2 and reduce supersaturation of tropical surface waters with respect to carbonate minerals.

Extent, distribution, variability: Surface ocean effects may be modified by changes in winds, upwelling, etc., but to a good first approximation, the effect can be estimated on a global basis. Smith (unpublished calculations) estimates that tropical saturation states will go from 370% to 270% for aragonite, 560% to 380% for low-Mg calcite, and 290% to 215% for high-Mg calcite for a doubling of atmospheric CO_2 and a 2-3 degree temperature increase.

Issues, questions, research needs:

1) Within the predicted levels, is there an effect of saturation state on the calcification/growth rates of major reef organisms?

2) If the answer is yes, what are the implications for community response to increasing pCO_2 in conjunction with rising sea level and increasing temperatures?

3) Is there a chemical or mineralogical signature in skeletal carbonates that can be related to saturation state (such a signal would have both real-time and paleo applications)?

4) Will change in pCO_2 influence marine photosynthesis?

Comments: In spite of the fact that this is one of the most reliably predictable effects of increasing atmospheric CO_2 of arguable significance to the whole carbon cycle, there are few experimental or theoretical treatments of the subject. It is experimentally straightforward, and could and should be addressed by coordinated field and laboratory studies. The questions relate to all calcifying organisms, but are especially important for corals and calcifying algae.

2. Parameter: <u>Salinity</u>

Sources of variation: Changes in salinity are primarily due to rainfall (and coastal runoff) variation. Local/regional environmental modification will be important in controlling runoff. Increased salinity is a possible side effect of increased evaporation.

Effects: Corals (and other reef organisms) are adapted to oceanic salinities and can tolerate only modest sustained increases or decreases in salinity. Reef organisms will exhibit stress when subjected to transient variation far outside the normal range.

Extent, distribution, variability: High salinity excursions are likely to be locally very important but geographically restricted in extent. In some environments, increased evaporation or altered rainfall patterns may be compensated for by rising sea level (which can improve flushing of enclosed basins). Effects due to changes in ocean circulation patterns will be minor but real. Low salinity extremes will be controlled by climatic variations in rainfall (at present poorly predictable) and by coastal land-use practices that influence runoff. Reefs near land masses may be quite vulnerable to the combination of climate change and local/regional anthropogenic effects, while oceanic reefs are likely to be little affected.

Issues, questions, research needs: Information on salinity stress responses and adaptation rates/mechanisms would be useful, for both corals and other key reef organisms.

Comments: Because of the local nature and the uncertain occurrence of the stress, this is not a relatively high priority. Local anthropogenic modifications to marine circulation and terrestrial runoff are probably more important to impact evaluation.

3. Parameter: <u>Nutrients</u>

Sources of variation: Primary inputs of nutrients are anthropogenic and local/regional in scale. GCC may affect both local and global budgets by changing the frequency/amount of upwelling.

Effects: Phosphate is believed to have a direct effect on coral skeletal development. Nitrate is also a primary control on algal growth, and elevated nitrate concentrations will directly favor more rapidly growing algae. Such conditions may facilitate changes of a reef community from one dominated by corals to one dominated by bioeroders and non-scleractinian benthos. Chronic nutrient stress may prevent coral community recovery from acute stress by favoring competitors of corals. Nutrient concentration may also influence turbidity (see below).

Extent, distribution, variability: At present, acute and major chronic effects are most likely the result of local/regional waste disposal or contamination, fertilizer runoff, or soil erosion. Ocean circulation is significant to the distribution of anthropogenic inputs, but also an important influence on the natural nutrient cycle.

Issues, questions, research needs:

1) Are there direct nutrient stresses on reef organisms, or on the relationship of endosymbiotic algae to their hosts? If so, to what extent are they interactive or synergistic with other stressors?

2) Can we define nutrient levels that apparently place scleractinian communities at a competitive disadvantage, or that represent a threshold for synergism with other environmental stresses at the community level?

3) Are bioerosion processes (grazing and boring) directly or indirectly modified by nutrient changes and how do these processes interact with other stresses?

4) To what extent and at what rate are human activities affecting regional or global (oceanic) budgets of nutrients apart from the issues of GCC? What are the probable consequences of these effects?

Comments: Although not a major climate issue in the strict sense, nutrient loading and contamination of marine waters is global in extent, and is probably one of the most important anthropogenic stresses on reefs. Its assessment in reef environments is complicated by the fact that biotic uptake of nutrients is very efficient, leaving most of the evidence of excess nutrient levels in the biomass and sediments rather than in the more readily measurable water column.

4. Parameter: Toxic/artificial compounds

Sources of variation: Runoff from land use activity is an important source of chemical compounds that pollute coastal waters. The proximity of industrial/agricultural/waste disposal activities to reefs is an obvious consideration in the 'health' of coral reefs. The incorporation of compounds within skeletons and sediments may provide time markers of pollution events and records of biogeochemical processes under stress conditions.

Effects: Not well characterized, but some biocides are known to have deleterious effects on reef organisms.

Extent, distribution, variability: The effects of pollutants are local or regional depending on the extent of agricultural and industrial development. There is no particular GCC correlation.

Issues, questions, research needs: Dose-response characteristics of reef organisms to long-lived and/or widely used biocides or industrial contaminants are not known. Screening is necessary to identify target compounds, and synergism with GCC or other local stresses needs to be assessed.

Comments: Not a GCC issue, but probably one of the more neglected concerns in terms of anthropogenic effects on reef environments.

5. Parameter: Turbidity

Sources of variation: Planktonic and particulate organic material from biological productivity is an important source of turbidity and is related to nutrient loading. The erosion and transportation of sediment is also an important source (see above).

Effects: Turbidity is an important control of light transmission to depth.

Extent, distribution, variability: The causes of turbidity in reef waters are primarily local or regional and do not directly relate to GCC. However, turbidity is likely to correlate with nutrient or salinity effects.

Issues, questions, research needs: Identification of the specific role of turbidity in cases of near-shore environmental degradation.

Comments: Turbidity is only secondarily related to GCC issues, but turbid waters may be an important confounding variable in near-shore coral responses to environmental change.

IV. The Bleaching Question

"Bleaching" is the phenomenon of loss or expulsion of pigmented endosymbiotic algae by corals or other normally symbiotic organisms. It is known to be a stress response, and can be induced by high and low water temperatures, protracted darkness and high fluxes of visible and/or UV light, prolonged aerial exposure, low salinity shock, high sedimentation, and various pollutants. Some work suggests that the production of active oxygen species within the tissues may be related to bleaching induced by high temperatures and light levels, but it is not clear if this represents a mechanism or if other stressors operate in the same fashion. At least in the case of temperature (see discussion above) it appears that stress is not related to absolute temperature as much as to excursions above the normal ambient maximum.

Bleaching is a symptom. It may indicate sublethal stress, with the animals re-acquiring zooxanthellae and recovering. The animals may also survive for protracted periods in a bleached or partially bleached condition.

In cases of severe stress, bleaching typically precedes mortality. Bleached corals are not normally functional, with reduced vitality, increased vulnerability to disease, and little or no calcification, reproductive activity, etc.

Bleaching episodes in reef environments have been reported with increasing frequency and extents over the past decade. The focus of attention has been on temperature as the causative agent; in some cases, especially those related to the 1982-83 El Niño, it is well established that bleaching is correlated with and almost certainly caused by protracted periods of unusually high water temperature. Other episodes have been anecdotally related to elevated temperature, but at least some bleaching occurrences do not appear to be associated with unusual temperatures and there is at least a suggestion that past high temperature events have not always resulted in bleaching.

It has been suggested that coral reefs may be more sensitive indicators of early oceanic warming (or other GCC or anthropogenically-induced deterioration of the marine environment) than direct instrumental measurements. In order to assess the potential validity of that claim and the possible use of coral bleaching as an interpretable environmental bioindicator, a number of questions remain to be answered:

A. An understanding of the mechanism(s) by which stressors induce bleaching and of the nature and extent of synergism between co-occurring stressors is critical (specific aspects are discussed in other sections of this issues list). Subsets of these issues include the basis for differences in sensitivity between and within taxa, the question of adaptation and/or selection in different temperature regimes, and the consistency of response for a given taxon from a given locale (e.g., does sensitivity vary with season, reproductive state, etc.).

B. What is the baseline for assessing frequency and extent of bleaching observations — to what extent did the 1980s have more bleaching and to what extent did they have more observers who were more sensitized to look for and report the phenomenon?

C. What are the calibration factors (and associated uncertainties) by which bleaching observations may be related to both local and regional SST and weather conditions? Are there criteria that can be reliably used to ascribe bleaching to temperature (or any other individual parameter) as a primary cause?

D. What are the consequences to other reef organisms of massive bleaching events that result in extensive death of corals on a reef? Are bioerosion processes enhanced? Are recovery processes diminished? Does the Crown-of-Thorns phenomenon provide a model of such events?

V. Resource Utilization

The preceding sections identified numerous indirect effects of human resource utilization, primarily in terrestrial environments that affect coral reefs. Direct anthropogenic alteration of coral reefs and related communities may also occur as a result of marine resource utilization. Specific examples include:

A. Fisheries — perhaps the most dramatic and important potential effect is the reduction of the herbivorous fish populations to the point where they no longer control the growth of algae. Algal overgrowth of reefs is often taken to indicate nutrient loading; in areas of heavy fishing pressure an alternative explanation is removal of control by grazing. The effects can be the same, and can be strongly reinforcing where both fishing pressures and nutrient inputs are high. Harvesting of reef organisms is not limited to fish; invertebrates are also harvested, both for food and for other markets (e.g., souvenir trade in corals and shells). Fisheries result in direct alteration of community population structure that may change the community response to environmental factors or changes.

B. Mineral exploration and production — In some reef areas, particularly adjacent to low islands, reef limestone is the only economically available construction material, and is quarried directly from the reef. Oil exploration and production in reef areas can result in both direct physical damage and the possibility of chronic or acute oil spills and incidental contamination.

C. Incidental damage — fishing with explosives or other destructive techniques can result in damage more extensive than the removal of the target organisms. In areas of high tourism, including some marine reserves, physical damage from boat anchors, divers, swimmers, waders, etc. may combine with incidental local pollution to place substantial stress on the reef community.

Comments: Resource utilization stresses are population-related, although mediated by a variety of cultural and economic factors. In the near term they are probably more readily identifiable and predictable than climate-induced or other environmental stresses, with which they interact. Identification of baseline or "natural" conditions can be a severe problem, particularly where intensive local fisheries predate scientific observations.

VI. Integrated issues — research and monitoring

Several observations and conclusions seem implicit or explicit in the above summary. These may merit discussion and refinement:

A. Many of the environmental stressors, both GCC-related and of other anthropogenic origins, will primarily affect those reef systems in relatively close proximity to land masses. Although monitoring of such reefs is both logistically simple and very useful, a monitoring or research program that includes oceanic or outer-shelf reefs removed from the complex mixture of near-shore effects will provide better controls for GCC-oriented studies.

B. The known and/or probable synergism of stresses at both the organism and community levels suggests: 1) an emphasis on mechanistic studies of organismic stress responses, since single-parameter input-output studies of responses are of relatively little use in dealing with variable and/or non-linear combinations of effects; and 2) more attention to the robustness of response characteristics across taxa and environments, as generalization from local or species-specific studies is usually difficult and often unproductive.

C. We need more attention to the issues of scale, uncertainty, experimental design, and the limits to knowledge (or limiting uncertainties), particularly in comparing or predicting responses across a wide range of time and space scales.

D. Are there strategies by which instrumental and biological observations can be economically combined in a mixed monitoring network? What are the optimum approaches to designing and validating such a system, and on what time and space scales could it be expected to work?

E. The issues of vulnerability and the impacts of environmental change are implicit in most of the foregoing material. However, second-order effects such as threats to marine biodiversity from large-scale regional change have not been addressed; these could be better formulated on the basis of the proposed improvements in knowledge about both the responses of organisms and communities and the locales or types of environments most subject to extreme stresses.

VII. Communication and Implementation

Although it was not a specified product of the workshop, it is useful to consider the institutional problems. The existence of this workshop (and many others of similar orientation) testifies to a common belief that there are answers to questions or problems that can be developed but that are not forthcoming through the usual channels of scientific research and communication. Government agencies typically have time horizons to short and missions too restrictively defined to address integrated problems of this sort (see W. S. Broecker, 1987, *Nature* 328:123-126). Academic research tends to be too narrowly defined, and the publication of results in the refereed literature tends to be too slow to address effectively to address effectively rapidly developing and broadly interdisciplinary problems such as global change. When one adds in the well-known barriers to institutional coordination and interdisciplinary communication, it is obvious why we do not even know what we know, much less what we might know.

Workshops, commissioned reviews, targeted symposia, etc., are useful ways of assembling information and focusing attention within the existing system. Are there feasible methods of modifying our approaches to facilitate the coordination and communication that should happen but doesn't? Could some sort of structure of committees of review and correspondence be developed and supported without having them turn into political playpens or institutional prizes? Can dissemination of information be broadened and speeded without sacrificing quality or proper credit? The climate community has become reasonably well organized around the issue of GCC — is there the potential for those working in tropical marine science to do likewise?

APPENDIX B

Development of a Monitoring Program: Practical Recommendations

1. ORGANIZATIONAL

Given the urgency of the program, the following timetable was developed for implementation.

YEAR 1

A. Meeting of interested parties representing most/all marine laboratories conducting coral reef research. Election of a committee to handle initial logistical phases of the program, and another to develop methods. Agreement as to participation in further initiatives, and capabilities of existing laboratories assessed.

B. Methods development meeting(s), producing a detailed manual.

C. Letters of agreement from all laboratories.

YEAR 2

A. Data management development.

B. Hands-on methods workshops at the "intensive" sites for all designated participants (i.e. the lead individual from each laboratory who will be responsible for program implementation at his/her site).

C. Installation/calibration of equipment.

D. Establishment of regional committees.

YEAR 3 Program begins!

Among the many issues to be decided are:

A. Sites: Should the two levels of monitoring be based on present capabilities of participating laboratories? Basic monitoring would occur at all (about 30) sites to gather extensive data. These would cover reefs representing diverse conditions and various disturbance levels. At fewer sites (5-10), in addition to basic monitoring data, more intensive information would be gathered. These would presumably be at existing marine labs or MAB sites.

B. Measurements:

Data must be gathered at three spatial scales:

1. Large scale — using satellites, LIDAR aircraft, GIS, oceanographic vessels, etc.

2. Community scale — physical parameters (temperature, salinity, tide, etc.), community structure (via biotic surveys, etc.), community physiology (P/R, etc.), phototransects, etc.

3. Organism/suborganism level — biochemistry, physiology, life histories, etc.

C. Data management:

Frequency of data collection must be feasible yet informative.

Coordinated, centralized, integrated validation, storage, and dissemination of data is central to the program. Development of standardized methods and instrumentation, and increased support for strengthening taxonomic and paleoecological studies will contribute to rational data management.

We estimate $5 million per year during the first two years would cover purchase and installation of equipment, hire and training of technical personnel, and establishment of the data processing center. Thereafter, operation costs will be about $3 million per year (1991 US$ basis), assuming 30 monitoring sites with two full-time technicians each, and a central data repository.

2. SCIENTIFIC

PRIORITIES FOR A MONITORING SYSTEM:

1. **Immediate establishment of a world-wide system** for monitoring physical and biological parameters on coral reefs. Because many aspects of normal reef function are poorly understood, it may be difficult to recognize, much less predict, effects of environmental change. The sooner large-scale, sophisticated, and well-managed monitoring begins, the more of a baseline will be available, and the greater the chances of early detection and understanding of change. Field and laboratory experimentation (including microcosms) and complex computer simulations are valuable approaches to study of contemporary reef function. Field experiments relevant to global change must be coordinated with the monitoring network.

2. **Laboratory and field experiments** to determine responses of model system species to effects of radiation and temperature. Radiation (via changes in cloudiness, turbidity, and ozone) and temperature (via the greenhouse effect) are the most important long-term changes expected as a function of anthropogenic modifications to the environment.

3. **Development of microcosm facilities** for bridging between laboratory and field. Nutrients, among the most important short-term consequences of human activity and population growth, are particularly difficult to manipulate in the field at a scale required to study community level effects.

4. **Increased development and use of complex model simulations** for evaluating physical effects in nearshore tropical environments and biological interactions in high diversity reef communities.

5. **Publication of well illustrated manuals** with workable keys to permit reef scientists and technicians to identify major taxa, particularly for regions

to be intensively studied. This should be backed by systematic research where necessary, for even the best studied of reef organisms are not well categorized systematically.

6. **Accumulation of background information** on physical changes projected for the future, and what happened in the past, as the context for study of effects of environmental change on reefs. Realistic experiments that concentrate on likely changes within the next decade to century require information on magnitude and rate of projected changes; change in variance may be more important in some cases than change in mean. General predictions from modelers currently lack understanding of vital particulars about temperature effects on nearshore tropical environments. This problem of modeling must be coupled with testing through continued monitoring. Knowledge of past biota and conditions is critical to distinguishing potential changes that may have been experienced by reefs in the not-too-distant past from those that have never been experienced. As above, means, variances, and rates of change must be considered. We predict that changes previously survived pose less of a threat. However, since some changes are certainly novel, we cannot assume that a previously survived condition will be equally manageable when combined with novel stresses.

WHERE TO MONITOR: Which reefs should be studied is a compromise between the desire to have broad geographic coverage ("extensive monitoring") and the need for detailed information ("intensive monitoring"). The following criteria are proposed.

I. General Objectives

A. Broad geographic coverage

B. Major reef systems containing important environmental gradients

C. Reefs in extreme habitats of particular interest in the context of local and global environmental change

D. Reefs having between/among them the potential for comparing closely related species or populations

E. Transects across turn-on/turn-off regional gradients

II. Specific Criteria

A. Previous history of study

B. Logistical support

III. Suggestions (* U.S. waters or U.S.-sponsored laboratories)

A. Major reef sites

1. Caribbean

a. island (*U.S.V.I., *Puerto Rico)

b. continental (*Panama, *Belize)

2. Central-West Pacific

a. high island (*Guam, Moorea/Tahiti)

b. atoll (?Enewetak/Marshalls?, Tuamotus)

3. Central/Northern Great Barrier Reef

a. inshore

b. offshore (Lizard Island)

4. South-east Asian fringing reefs

5. Indian Ocean (Seychelles)

B. Reef sites in extreme or isolated environments

1. *Florida Keys (including Dry Tortugas)

2. *Hawaii

3. *Gulf of Mexico (Flower Gardens)

4. *Eastern Pacific

a. upwelling

b. not upwelling

5. Bermuda

6. Red Sea (Eilat, Sharm el Sheikh)

7. Southern Great Barrier Reef (Heron Island)

8. Japan (Okinawa)

9. Western Australia

WHAT TO MONITOR: Understanding the impact of environmental change on coral reefs is an enormous task because of the number of potential factors to be considered. Interactions are critical because the effects of multiple factors are often not additive. Multiple sites and species are critical because communities may differ in their responses, and even the same species at different sites may respond differently, presumably because of evolutionary selection and interactions with different species.

Our choice of physical variables to monitor reflects the consensus that both the long-term effects of climate change and the short-term effects of human activity and population growth must be investigated. Some factors are critical to development of realistic, useful models. Parameters should be measured at least daily (and/or with daily maximum/minimum values) at each location. The anticipated pattern of expected change is noted for each. Experimentals should reflect as well as possible time scales of the expected changes (e.g., pulse perturbation, press manipulations with gradual or sudden onsets). Interactions more numerous and complex than those listed are expected, but constraints on replication and statistical analysis require focus on a limited number of two- or three-way interactions.

The species to be studied at the cell, organismal, and community levels will vary depending on the question, although some should be intensively studied at all levels because of their importance as model systems. A limited number of other species of considerable importance in reef communities should be studied in less detail (e.g., sensitivity to temperature and U.V.). The systematic status of all model system species must be clarified as soon as possible to facilitate interpretation and comparison of results.

I. Physical factors

A. In isolation —

1. Temperature — of near-surface air, and of sea at surface and to 100 m depth. Over the short term, increased variability likely to be more important than gradual mean increase. Proposed research: monitoring (including comparing sites with different temperature regimes); transplants of organisms within regions between sites of different temperature regimes (e.g., within Red Sea or within Eastern Pacific); laboratory tests of temperature sensitivities (to both variation and mean increase).

2. Sea level (including vertical geodetic stability and tides). Predicted rise of little effect over the short term, except on reef flats where negative effects of extreme low tides may be mitigated. Proposed research: monitoring.

3. Rainfall and/or runoff (fresh water), sedimentation, and turbidity. Changing mean and variance expected. Will be influenced by other climate changes (e.g. storms). Proposed research: monitoring at several depths (in situ and remote sensing); laboratory and microcosm studies; field transplants.

4. Salinity. Local changes only, due to factors such as runoff and upwelling. Proposed research: monitoring at several depths.

5. CO_2. Predicted gradual increase; tropics not likely to differ from other sites. Proposed research: laboratory and microcosm experiments to determine effects on zooxanthellae, other algae, and corals.

6. Solar radiation — incident U.V. and visible, absorbed surface radiation. Increased U.V. via ozone depletion, plus changes in visible light due to changed cloud patterns and turbidity of water are predicted. Proposed research: urgent need for monitoring in tropics using scanning spectroradiometer (290-750 nm) at water depths to 5% visible light; laboratory experiments using both acute and gradual exposures. Note that availability of instrumentation is currently a problem for the critical 290-300 nm region.

7. Nutrient levels (including nitrogen, phosphorus, total inorganic carbon, and iron). Changing mean and variance anticipated due to increased human activities, although perhaps some upwelling changes. Proposed research: monitoring (water quality, remote sensing, community changes, depth profiles); microcosm experiments to examine competition between coral and algae; where possible (enclosed lagoons and tidal flats), field manipulations.

8. Barometric and near-surface vapor pressure. Changed variability likely as storm tracks shift. Proposed research: monitoring.

9. Wind and current speed and direction, wave climate, storms. No major trends expected over the next decade, although increased variance likely in context of mean temperature increase. Proposed research: monitoring; monitor recovery of storm-damaged reefs on fine spatial scales; computer simulation important because experimental simulation usually impossible.

10. Toxic pollutants and artificial substances. Mean and perhaps variance likely to change. Already present due to human activities and may continue to increase. Proposed research: monitoring at several depths; laboratory sensitivity studies.

B. Especially important interactions —

1. Temperature + light + nutrients

2. Temperature + nutrients + biological interactions

3. Temperature + light + pollutants

4. Storms + nutrients (study opportunistically)

II. Biological factors

A. Model systems —

1. Indicator species (with special sensitivity to temperature, nutrients, toxic pollutants, U.V., etc., or changes therein)

2. Species with broad geographic ranges (even if species complexes, these have enormous potential in comparative studies aimed at detecting evolutionary responses to various environmental regimes)

3. Ecologically key species

4. "Lab rats" for studies of physiology and cell biology

5. Species of paleontological importance

B. Other important species —

1. Representatives of major morphological categories of corals (branching, massive, and weedy)

2. Important competitors of corals (especially algae and alcyonarians)

3. Important predators of corals and algal grazers

4. Commercially important species. Overfishing and related activities have modified biological interactions and changed relative abundances of reef organisms, and will continue to do so. Research should consist of monitoring abundance and distribution of reef organisms at all trophic levels; field manipulations of important predators, competitors, grazers, symbionts, and bioeroders on reefs; microcosms and complex computer simulations of interactions.

C. Water column characteristics —

1. Phytoplankton (chlorophyll) concentration

2. Zooplankton concentration

D. Anatomy and physiology of the benthos —

1. Living coral cover

2. Community structure (by some relatively simple measure — e.g., species diversity)

3. Community P/R ratios

4. Calcification/bioerosion ratios

5. Settlement/colonization rates

E. Individual coral colonies

1. Growth rate

2. Calcification rate

3. Photosynthetic parameters, including zooxanthellae/chlorophyll density

4. P/R ratios

5. Reproductive activity

6. Infestation with parasites, commensals, bioeroders

THE VALUE OF REMOTE SENSING: Because most coral reefs are distant from sophisticated laboratories, they are ideal candidates for remote sensing — especially for techniques that employ optical sensors about environmental effects of global climate change. It is imperative that we begin now to develop technology and research strategies for assessment of coral reef biomass and measurement of growth using these optical sensors.

Optical remote sensing uses active (LIDAR) or passive (wavelength scanners) instrumentation. Both systems have been used to study the characteristics of vegetation, but both have limitations as to areal coverage and/or detection specificity. LIDAR should be able to measure the fluorescences characteristic of most corals. Sun-induced fluorescence of zooxanthellae also could be measured. Reflectance (spectral) through radiometry or from a pulsed laser at the appropriate wavelengths would allow measurement of chlorophyll as well as water clarity. Coral photosynthesis and photosynthetic efficiency can be estimated using other techniques. A study of the fluorescence signals from chlorophyll and accessory pigments could be used as a diagnostic to measure algal invasion after a bleaching event.

Although satellite remote sensing techniques are useful to monitor changes in many large ecological systems, resolution of these data is such that current remote sensing of coral reefs should be by high-resolution airborne systems and associated ground truthing, which are able to produce pixel sizes equivalent to the scale of coral colonies. Of particular use will be the definition of spectral signatures over wavelengths ranging from UV through visible to at least the near-IR. Data already at hand indicate that in near-IR wavelengths, different species of corals may show small variations in spectral signatures. Signatures change as corals undergo stress. Expansion of this type of work will allow researchers to gather data at scales needed to discern regional to global scale changes in coral reef ecosystems.

Complementing visible wavelength observations are reflected IR and emitted IR. Reflected IR provides high definition of land-sea boundaries, and assists in quantification of areal mapping. Emitted IR, particularly multispectral sensing, provides temperature information at the scale of interest to the local patchiness that may be typical on coral reefs. Here again, aircraft observations will probably provide data at the scale required, with less atmospheric influence from the lower altitudes and therefore of higher accuracy.

Other techniques may be useful in monitoring coral reefs. HF coastal radar provides high resolution maps of sea surface current vectors at 1-2 km resolution and at 3 hour time steps; typically 100x100 square kilometers of coverage from two HF stations is possible. Synthetic Aperature Radar (SAR) or Side-Looking Airborne Radar (SLAR) can also provide information on currents and internal waves that may affect circulation around coral reefs; both SLAR and SAR can be obtained from aircraft, but SAR at 25 m pixel resolution is available from satellite. Scatterometer data from either aircraft or satellite can provide detailed information on wind stress vectors in and around coral reefs, which is valuable in data assimilation modeling of the currents and wave energy that may affect a particular reef.

THE ROLE OF EXPERIMENTATION: The effects of environmental change on reefs must be studied at several levels. Central is the individual. In some cases we may need information on physiology and cell biology of the response, particularly to clarify future research directions. Interactions between individuals eventually translate into a community response. Different methods are appropriate to each hierarchical level. All can be studied as part of, or in conjunction with, monitoring.

I. Cell biology

laboratory experiments[1]

II. Physiology

laboratory experiments[1]

III. Individual growth, reproduction, mortality

laboratory[1] or microcosm[2] experiments (depending on scale)

field monitoring[3]

IV. Community structure

microcosms[2] (especially for competition, e.g., algae vs. corals)

theoretical modeling[4]

field monitoring and field experiments[3]

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[1] Methodologies for laboratory experiments are generally well established.

[2] Microcosms, especially those with adequate replication, have been underutilized because of capital expense, but represent the method of choice for a number of critical experiments.

[3] In addition to good management and very long-term support for manpower, field monitoring requires good design based on maximizing statistical power. Properly designed observations can test hypotheses that are, in some cases, without alternative because of the large scale of the processes involved. Tropical marine field facilities are currently limited in number, but the technology exists, and such facilities should be a top priority.

[4] Theoretical modeling requires access to advanced computers and programming expertise, which are scarce resources.

APPENDIX C

Written Materials Submitted to the Workshop*

Achituv, Y. and Dubinsky, Z., "Carbon Budgets in Marine, Mutualistic Associations between Microalgae and Cnidarians," *Comparative Physiology,* 1990, vol. 5, pp. 36-48.

Ben-Zion, M., Achituv, Y., Stambler, N. and Dubinsky, Z., "A Photographic, Computerized Method for Measurements of Surface Area in Millepora," *Symbiosis,* 10(1991)115-121.

Buddemeier, R.W. and Hopley, D., "Turn-ons and Turn-offs: Causes and Mechanisms of the Initiation and Termination of Coral Reef Growth," Proceedings of the 6th International Coral Reef Symposium, Australia, 1988, Vol.1, pp.253-261.

Bunkley-Williams, L. and Williams, E.H., "Global Assaults on Coral Reefs," *Natural History,* 4/90, pp.47-54.

Caribbean Coral Reef Ecosystems Program (CCRE), Program description and published contributions. Carrie Bow Cay, Belize, National Museum of Natural History, Smithsonian Institution.

Connell, J.H., "Detecting trends due to Global Climatic Change in populations and communities on coral reefs," June 1991 (4 page handout).

D'Elia, C.F. and Taylor, P.R., "Disturbances in Coral Reefs: Lessons from *Diadema* Mass Mortality and Coral Bleaching," *Mar.Technol.Soc.Oceans* '88 Proc.: 3:803-807.

Done, T.J., "Use of matrix model to assess effects of coral bleaching on coral community calcification, " June 1991 (1 page handout).

Dubinsky, Z., "Establishment of a Global, Long-term Research and Monitoring Network to follow Climate Change and Anthropogenic Input Effects on Coral-Reef Ecosystems, " June 1991 (6-page handout).

Dubinsky, Z., "The Functional and Optical Absorption Cross-Sections of Phytoplankton Photosynthesis, " 12 pages.

Dubinsky, Z., Falkowski, P.G., Porter, J.W. and Muscatine, L., "Absorption and utilization of radiant energy by light- and shade-adapted colonies of the hermatypic coral *Stylophora pistillata,*" *Proc.R.Soc.Lond.* B222, 203-214 (1984).

Dubinsky, Z., Stambler, N., Ben-Zion, M., McCloskey, L.R., Muscatine, L. and Falkowski, P.G., "The effect of external nutrient resources on the optical properties and photosynthetic efficiency of *Stylophora pistillata,*" *Proc.R.Soc.Lond.* B239, 231-246 (1990).

*Unless noted with the citation, authors' addresses and can be found on the list of participants, in the Introduction. Please contact the authors for copies of submissions.

Due to the copyright laws, certain articles could not be copied and sent to those who requested them. Please contact the authors directly.

Dunbar, R., Wellington, G., "Climate Change, Bleaching and Long-term Coral Growth Records, " June 1991 (2 page handout).

Dunbar, R.B., Wellington, G.M., Colgan, M.W. and Glynn P.W., "Eastern Tropical Pacific Corals Monitor Low Latitude Climate of the Past 400 Years," *Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, April 1990*, J.L. Betancourt and V.L. Tharp, eds.,1991, California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

Elms, J.D., "Sea Surface Temperature Trends in the Caribbean Sea and Gulf of Mexico, 1950-1989, " June 17, 1991 (9 pages).

Enfield, D.B. and Cid S., Luis, "Low-Frequency Changes in El Nino/Southern Oscillation," February 1991, 17 pages (resubmitted to *Journal of Climate* for publication)

Enfield, D.B., "El Niño, Past and Present," *Reviews of Geophysics*, 27, 1/February 1989, pp. 159-187.

Glynn, P.W., "Coral Reef Bleaching in the 1980s and Possible Connections with Global Warming," *Trends Ecol.&Evol.* Vol.6, no. 6, June 1991.

Glynn, P.W. and Colgan, M.W., "Defense of Corals and Enhancement of Coral Diversity by Territorial Damselfishes," 7 pages.

Glynn, P.W., "Predation on Coral Reefs: Some Key Processes, Concepts and Research Directions," Sixth International Coral Reef Symposium, August 1988.

Glynn, P.W., Cortes, J., Guzman, H.M. and Richmond, R.H., "El Niño (1982-1983) Associated Coral Mortality and Relationship to Sea Surface Temperature Deviations in the Tropical Eastern Pacific, " 7 pages.

Glynn, P.W., "El Ni~o-Southern Oscillation 1982-1983: Nearshore Population, Community, and Ecosystem Responses," *Ann. Rev. Ecol. Syst.* 1988, 19:309-45.

Glynn, P.W., "Coral Mortality and Disturbances to Coral Reefs in the Tropical Eastern Pacific, Global Ecological Consequences of the 1982-83 El Niño-Southern Oscillation" P.W. Glynn, ed., Elsevier Oceanography Series. (1989).

Glynn, P.W. and de Weerdt, W.H., "Elimination of Two Reef-Building Hydrocorals from the Eastern Pacific Following the 1982-83 El Niño Warming Event, " *Science*, Vol. 252 , 1991 (in press).

Glynn, P.W. and D'Croz, L., "Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality," *Coral Reefs* (1990) 8:181-191.

Goreau, T.J., Hayes, R.L., Clark, J.W., Basta, D.J. and Robertson, C.N., "Elevated Satellite Sea Surface Temperatures Correlate with Caribbean Coral Reef Bleaching, " NOAA Technical Report N.O.S. #137:1-60 (1991) (in press).

Goreau - Global Coral Reef Alliance, 324 N. Bedford Road, Chappaqua, NY 10514 or Hayes - Department of Anatomy, Howard University, Washington, D.C. 20059

Halley, R.B. and Hudson, J.H., "Sea Temperature and Coral Bleaching in the Florida Keys: No Relation to Global Warming...Yet," 1991 (1 page summary).

Hallock-Muller, P., "Why are nutrients Killing Florida's Coral Reefs so Difficult to Measure?", June 1991 (10 page handout).

Hardy, J. and Gucinski, H., "Stratospheric Ozone Depletion: Implications for Marine Ecosystems," *Oceanography*, November 1989, pp. 18-21.

Hardy - Huxley College of Environmental Studies, Western Washington University, Bellingham, WA 98225.

Hudson, J.H., Halley, R.B., Joseph, A.J., Lidz, B.H., and Schroeder, D., "Long-Term Thermograph Records from the Upper Florida Keys, Comparison Between Sites, " 1991, 116 pages.

IPCC Scientific Assessment-Climate Change, Executive Summary, 2 pages.

Johnson, H.P., Wilson, J.C. and Strickland, R., "New Hard-Rock Drill Successful in Deep Sea Test," *Sea Technology*, December 1990, pp. 43-46.

Johnson - School of Oceanography, University of Washington, Seattle, WA 98195.

Johnson, H.P., "Next Generation of Seafloor Samplers," *EOS*, vol. 72, no. 7, February 12, 1991.

Kinsey, D.W., and other authors, series of articles from *Search*, Vol. 22, No. 4, June 1991.

Kinsey, D.W. and Hopley, D., "The significance of coral reefs as global carbon sinks-response to Greenhouse," *Palaeogeography, Palaeoclimatology, Palaeoecology* (Global and Planetary Change Section), 89 (1991) 363-377., Elsevier Science Publishers, Amsterdam.

Klein, R., Loya, Y., Gvirtzman, G., Isdale, P.J. and Susic, M., "Seasonal Rainfall in the Sinai Desert during the late Quaternary inferred from fluorescent bands in fossil corals," *Nature* (Int'l), Vol. 345, No. 6271, pp. 145-147, May 10, 1990.

Knowlton, N., Weil, E., Weigt, L.A. and Guzman, H.M., "Sibling Species in Montastraea Annularis, Coral Bleaching, and the Coral Climate Record," (in review for *Science*) June 1991 (3 page handout based on 24 page manuscript submitted).

Lesser, M.P., Stochaj, W.R., Tapley, D.W. and Shick, J.M., "Bleaching in coral reef anthozans: effects of irradiance, ultraviolet radiation, and temperature on the activities of protective enzymes against active oxygen," *Coral Reefs* (1990) 8:225-232.

Loya, Y., "Changes in Red Sea Coral Community Structure: A Long-Term Case History Study," *The Earth in Transition, Patterns and Processes of Biotic Impoverishment*, G.M. Woodwell, ed., 1986, pp. 369-384.

Maul, G., "Implications of Climate Changes in the Wider Caribbean Region," available from: Caribbean Environment Programme UNEP, 14-20 Port Royal Street, Kingston, Jamaica, CEP Technical Report No. 3, 1989.

Maul, G., "Temperature and Sea Level Change," June 1991, 38 pages.

Mearns, L.O., "Analysis of Increases in Sea Surface Temperature Extremes with Global Warming," June 14, 1991, 15 pages (Draft).

Ogden, J.C., Information Sheets on SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape) and CARICOMP (Caribbean Coastal Marine Productivity).

Ogden - Florida Institute of Oceanography, 830 First Street South, St. Petersburg, FL 33701.

Quinn, W.H., "Southern Oscillation-Related Climatic Changes, " June 1991, 3 page handout.

Reaka, M.L., "The Ecology and Evolution of High Biodiversity on Coral Reefs" and "Bioerosion and Its Significance on Coral Reefs," June 1991 (1 page handouts).

Reaka - Department of Zoology, University of Maryland, College Park, MD 20742.

Rowan, R., "Taxonomic Issues in Algal-Animal Symbioses," June 1991 (3 page handout).

Santavy, D.L., "Issue Paper: Microbiological Considerations - Microbial Ecology of the Bacterial Flora Naturally associated with Coral and the Microbiological Processes involved in Coral Bleaching," June 1991.

Savina, L.A. and Sebens, K.,"Short and Long Term Recovery from Bleaching - A Comparison of Naturally Occurring and Laboratory Induced Bleaching," June 1991 (1 page handout).

Sebens - Northeastern University Marine Science Center, Nahant, MA 01908

Shen, G.T., "Utility of trace element geochemistry in reconstructing environmental change in coral reefs," June 16, 1991, Draft Statement, 5 pages.

Shick, J.M. and Lesser, M.P., "An Overview of Photooxidative Stress and Defenses against It in Coral Reef Symbioses," June 1991 (15 page handout).

Shick, J.M., Lesser, M.P. and Stochaj, W.R."Ultraviolet Radiation and Photooxidative Stress in Zooxanthellate Anthozoa: the Sea Anemone *Phyllodisius semoni* and the Octocoval *Clavalaria* sp., " *Symbiosis* 10 1991 pp. 145-173.

Smith, S.V., "Climate Change, Carbonate Mineral Saturation State, and Coral Reef Calcification," June 5, 1991, 7 page handout.

Topinka, J.A., Bellows, W. Korjeff, Yentsch, C.S., Characterization of marine macroalgae by fluorescence signatures, Int. J. Remote Sensing, 1990, Vol. 11, No. 12, 2329-2335.

Ware, J.R., Smith, S.V. and Reaka-Kudla, M.L., "Coral Reefs: Sources or Sinks of Atmospheric CO_2?" manuscript submitted to *Coral Reefs*, 22 pages

Ware, J. and Reaka-Kudla, M., "The Suitability of Coral Bleaching as a Detection Mechanism of Global Temperature Change," June 1991 (9 page handout).

Ware - Atlantic Research Corporation, 1375 Piccard Drive, Rockville, MD 20850.

Wellington, G.M. and Gleason, D.F., "Potential Effects of Increased Levels of Ultraviolet Light on Reef-Building Corals," June 1991 (4 page handout).

Williams, E.H. and Bunkley-Williams, L., "The World-wide Coral Reef Bleaching Cycle and Related Sources of Coral Moratality," Atoll Research Bulletin No. 335, National Museum of Natural History, Smithsonian Institution, January 1990.

Williams, E.H., Caribbean Coordinator, Department of Marine Sciences, University of Puerto Rico

- Marine Ecological Disturbance Information Center, Summary 8, June 15, 1991

- Marine Ecological Disturbance Information Center, Summary 7, February 10, 1991

- Publications of the Caribbean Aquatic Animal Health Project (list)

Ad Hoc Plenary Talks, June 19, 1991

Connell, J., "Detection of significant trends in populations on reefs and attribution to global climate change"

Dubinsky, Z., "A biological rationale for monitoring strategies"

Hallock-Muller, P., "CZCS scenes of fluvial chlorophyll plumes and their ranges through the Caribbean and Atlantic"

Hopley, D., "Paleo-oceanographic records in *Porites* cores"

Jackson, J., "Pleistocene Caribbean coral reefs"

Knowlton, N., "Sibling species in the 'lab rats' of coral research — implications for environmental bioassays, ecological moinitoring and reconstructing the past"

Loya, Y., "Climate change and coral reef communities of the Sinai"

Maul, G., "Observations of temperature and sea level change during the last 100 years"

Mearns, L., "Predicted changes in sea surface temperature extremes in the tropics under global warming"

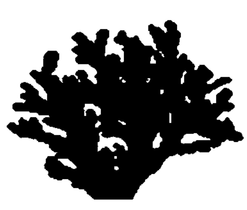
Quinn, W., "Southern Oscillation-related climatic changes"

Santavy, D., "Importance of the microbial communities as a response measure to ecosystem stress"

Smith, S., "The role of coral reefs in global carbon fluxes"

Wicklund, R., "Temperature Spike and observed coral bleaching, summer 1990"

Yentsch, C., "Potential and present practices for remote sensing of coral reefs"



APPENDIX D

Abstracts of Invited Plenary Talks

Coral Reefs, Climate, and Environmental Change

Robert W. Buddemeier
Kansas Geological Survey

In order to discuss relationships between environmental — or climate — change and organism or ecosystem responses, we need to define some terms and address issues of scale. Environmental change is what is experienced at the local level; its causes may be local and unique, local and part of a larger pattern of trends ("Global Change" — for example, large-scale increases in waste dumping or UV exposure), or the result of large scale systematic changes (Global Climate Change, or GCC). It is important to note that local changes resulting from GCC are not necessarily consistent or monotonic; some areas may become cooler even in a world that is warmer on the average.

Many definitions of climate are possible, but for the purposes of quantitative prediction, climate is defined in terms of quantitative measurements of primary physical and chemical variables over multi-decade and global or large-region averages, with associated statistics. To be relevant to climate issues, biological responses must be explainable or calibrated in these same terms. This is complicated by scale mismatches — organisms and communities function at a very local level, while the concept of "climate" has an intrinsically larger scale, with severe limitations on deterministic links to short-term or small-scale observations.

In addition to problems of scale, efforts to use bioindicators must contend with natural variability and fundamental uncertainty about models and predictions. It has been suggested that coral bleaching increased substantially in the Caribbean in the 1980s, that this was the result of elevated temperatures, and that this in turn might indicate the advent of the greenhouse effect. Both the definition of climate and a review of instrumental temperature records indicate that a decade of regional observations falls far short of the time and space scales necessary to define or detect a climate trend. Furthermore, offshore water temperature data indicate that any modest warming trend in the shallow water during the 1980s was superimposed on a 40-year cooling trend for the region as a whole. Although climate models predict a modest tropical warming as a result of the greenhouse effect, paleoclimate data from past (6 ka, 125 ka) warm periods hint at cooler tropics. With judicious choice of conceptual model, any temperature trend can be interpreted as evidence of GCC.

As a factor in global carbon budgets we must recognize that coral reefs are insignificant on time scales relevant to GCC; their CO_2 fluxes are trivial compared to anthropogenic releases. However, their responses to climate change are interesting for several reasons. Although reefs would appear particularly vulnerable to climate change because of their restriction to warm, shallow marine environments, present community structures and inventories of organisms appear to have undergone little change through the repeated climate and sea level cycles of the Quaternary period. Detailed knowledge on shorter time scales is limited to the very few decades of intensive observations in the post-SCUBA era, but chemical and physical records of reef environments contained in annual skeletal growth bands have the potential to extend retrospective studies to time scales of centuries. Environmental response characteristics on all scales are relevant to the potential use of reef communities or individual taxa as real-time indicators of environmental stress. Equally important is the opportunity to use environmental change as a large-scale experimental probe to test hypotheses about organism and ecosystem responses and their mechanisms.

Environmental factors that favor or stress reef ecosystems are well known; Table 1 lists the stressors, subdivided according to whether increases in stress over the next few decades are more likely to result from changing climate or from other anthropogenic environmental alterations.

Table 1: Dominant Sources of Near-Term Coral Reef Stresses

Climate	*Other*
Sea level rise**	Ultraviolet light**
CO_2 changes**	Nutrients(*?)
Temperature change*	Sedimentation
Visible light	Turbidity
Current/storm change	Toxics
(Fresh water)	Resource use
	(Fresh water)

** global, trends monotonic
* global mean trends monotonic, significant spatial/temporal exceptions

In order to assess relative importance or sensitivity, these same stressors may be categorized by their primary pathway or mechanism of delivery to the local reef environment. This list is given in Table 2; although not extremely rigorous, it provides a basis for identifying signal amplification possibilities.

Table 2: Dominant Pathways of Stress Delivery

Atmospheric	*Hydrographic*	*Hydrologic*
		Freshwater
Temperature	Sea level	Nutrients
UV light	Currents	Sedimentation
Visible light	Storms/waves	Toxics
CO_2 change		Turbidity

From the standpoints of sensitivity, vulnerability, and monitoring, marginal environments are particularly sensitive to change because of their steep gradients and physical constraints. Coastal zones are a particularly good example of such environments, and a large fraction of the world's coral reefs occur within coastal zones or their physical extensions, enclosed and/or shallow basins or shelf environments. In such locales the hydrologic pathway has a particularly high signal amplification because changes are integrated over very large land areas and focused (e.g., through runoff) onto the narrow coastal zone. It is important to note that the stressors delivered via the hydrologic pathway are generally those in the "other" (non-GCC) source category.

This analysis leads to the conclusion that reefs in proximity to land masses or in relatively shallow or enclosed basins will be particularly sensitive (or vulnerable) to the effects of environmental change, but will have a low specificity for climatic variables. In the near term, the suggestion is strong that local and regional effects of population growth, land use, etc., will have more effect on reefs than the more distributed and gradual climatic changes. Oceanic reefs are probably more sensitive to the truly climatic component of environmental change and could serve as control sites for studies in the more complex nearshore environment. Specific stress responses could be investigated on a local basis, but problems of scale and variability would require extensive networks of long-term observations if signal detection or "average" response determination were desired.

Coral Bleaching: A Cell Biological Perspective

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From a cell biological perspective, coral bleaching (i.e. loss of zooxanthellae) may be viewed generally as a problem in the regulatory biology of algae-invertebrate symbiosis.

The population density of zooxanthellae in reef-building corals is often constant and predictable within a species. It may be regulated before or after the the zooxanthellae undergo mitosis. Premitotic regulation may be achieved by nutrient limitation or selective release of zooxanthellae metabolites. Postmitotic regulation may be result from digestion or release of excess zooxanthellae. Population density may also be deregulated. For example, sustained exposure to inorganic nutrients causes a dramatic increase in zooxanthellae population density ("up regulation"). In contrast, temperature extremes, low salinity, and ultraviolet radiation cause release of zooxanthellae ("down regulation"). Coral bleaching may then be viewed as a problem in down regulation of population density of zooxanthellae. The cell biologist asks "What are the signal transduction phenomena associated with down regulation of population density of zooxanthellae?" To answer this question, a case study of bleaching in the tropical sea anemone *Aiptasia pulchella* and selected reef corals is described. In this study we examine bleaching in response to low and high temperature.

When the tropical sea anemones *Aiptasia pulchella* and *A. pallida* are exposed briefly to subnormal temperatures (i.e. cold-shocked), and then rewarmed to ambient temperatures, they release substantial numbers of zooxanthellae. Release varies with cold shock temperature and duration. A four-hour cold shock at 4° evokes release of 40 - 55% of the zooxanthellae after 12 hours, and in some cases up to 97% in 72 hours. As shock temperature increases to about 16°C., fewer zooxanthellae are released. Above about 16°C, and up to 28°C, the response is similar to that of unshocked controls. Release is greater at 4° and 10° if the duration of exposure is extended up to about 7 - 8 hours. Longer cold shock duration elicits no additional release. Rewarming to at least 17 . 5°C. is essential for evoking maximum release. Eleven species of scleractinian corals from the Seychelles Islands, St. Croix, and Hawaii also released zooxanthellae after a four-hour cold shock between 12° and 18°C. Release at 12° ranged from about 20 to 75% after 12 hours, depending on species, geographic location, duration of cold shock. Similarly, at elevated temperatures (32°C.), a seven hour exposure is sufficient to evoke release of zooxanthellae.

The mode of release is unique. The sea anemone *A. pulchella* and the coral *Pocillopora damicornis* release whole endoderm cells with their zooxanthellae. The phenomenon is interpreted as the result of cell adhesion dysfunction brought on by the temperature extremes.

How might temperature extremes evoke cell adhesion dysfunction? We hypothesize that temperature perturbations cause membrane thermotropic effects in host cells. This leads to failure of ion pumps and then passive flux of ions. Calcium influx is known to cause collapse of elements of the cytoskeleton, and concomitant dysfunction of cell adhesion molecules. In preliminary tests of this hypothesis, we have observed release of host cells at normal maintenance temperatures with pharmacological agents that elevate intracellular calcium ion concentration.

Systems Level Management, Monitoring, and Research: The Australian Perspective on Environmental Change

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It is clear that coral bleaching and Greenhouse are now inextricably entwined, at least in the popular media. Much of my talk will relate to this relationship, examine the present status of its credibility, and more importantly will consider the overall status of reef health.

On this occasion I will be concentrating on presenting the perspective of the agency responsible for the management of the world's largest, multi-use, protected marine area, not the perspective of a coral reef scientist which is the role in which many of you have known me for so long.

Greenhouse:

- Greenhouse is characterised by a greater level of uncertainty and higher levels of opposed viewpoints than most global environmental issues. The more we find out the greater the uncertainties seem to become.
- Bob Buddemeier (Reef Encounters, 1990) has suggested that we currently seem to have the greatest separation between the political and public push for something to be done, and technical scepticism about the details and realities.
- Many postulated scenarios for Greenhouse have become enshrined as hard predictions which some of us in government planning have had to live with, simply because there is nothing more definitive to displace them.
- It was concluded by the Inter-Governmental Panel on Climate Change (1990 Overview) that: "Unequivocal detection of enhanced Greenhouse is not likely for a decade or more."
- The confused situation is typified by the Male Declaration (1989) made by policy setters from small states in which it was concluded that "small states should take adequate measures to protect vulnerable natural ecosystems such as coral reefs and mangroves" — I suggest that there are few measures indeed that can be taken on the basis of our present knowledge and we certainly do not know the time frame within which to take them.

The Great Barrier Reef Marine Park:

The GRBRMPark is not a national park in the conventional sense. Rather it is a large piece of submerged territory which is managed by the Federal Government, assisted by the State of Queensland, for balanced, sustainable multiple use. It is 350,000 km^2 in extent; includes essentially all of the eastern continental shelf north of 23°N; contains nearly 3000 separate reefs, 120 vegetated islands of reefal origin, and 600 high islands; has the largest tidal regine of any reef system (spring tidal range from 3 m to 6 m); has typically strong currents and wind fields, and the associated frequently rough conditions; has never been the site for significant subsistence use by man; and is adjacent to a large continent and subjected to all its natural and anthropogenic inputs. The GBRMP has a high profile on the world scene but in actual fact contains only about 3% of the actual reef area of the world (compare with the Caribbean which has about 9%).

The commercial value (without multipliers) of the GBR Region is approximately $1000 million, with $300-400 million from offshore and island tourism and recreation, $100-200 million from commercial fishing, and the majority of the remainder from onshore tourism.

Management of the GBRMP is primarily by zoning for preferred patterns of use. This overall strategy is combined with special management plans for areas requiring specific attention, and a permit system for all commercial users. The principal vehicle for implementation and achieving compliance is education, and the GBRMPAuthority spends much of its effort and budget in working with user groups and the general public to achieve this. However, enforcement is used as a last resort when clearly necessary.

Environmental Problems in the GBR:

The environmental problems with which the Authority has to cope, in order of probable long term significance:

- **PERCEPTIONS.** Public opinion and the opinions of specific interest groups almost certainly pose the greatest "environmental" problem for the GBRMPA. This situation is greatly aggravated by the fact that such perceptions are so often very poorly supported in fact. The vicarious users (media exposure only) constitute perhaps the biggest "lobby" group, and the least balanced in overall understanding.
- Nutrient build-up — agricultural practice and urban development/sewage

- Effects of all forms of fishing
- Crown of thorns starfish
- Effects of tourism

It should be noted particularly that I have not included either coral bleaching or Greenhouse.

Reef Health:

Are the GBR reefs sick today? Are the world's reefs sick today? — are they "running a temperature"? Are reefs well enough to respond to a rising Greenhouse sea level? — and what can we do about it anyway?

There is certainly a growing body of opinion that reefs are generally showing signs of growing stress. It is, however, a still a strong tendency of many scientists to resist these "conclusions." As it becomes more fashionable to seek environmental problems, it is obvious that we will find them — or more importantly, report them. Thus the search for "signs" is, by its very nature, self-fulfilling. The considerable division of opinion on reef health is just as marked in Australia as elsewhere, with well established reef scientists covering the whole spectrum of opinion.

Probably the most universally invoked stress for reef systems of the world is nutrient build up in inshore waters attributable to anthropogenic sources. This has received considerable attention in the GBR, Florida, and the Caribbean. Yet it is probably the most tenuously based of our serious concerns. Such stress is likely to be even more severe throughout much of the 50% of the world's reefs occurring in SE Asia but unfortunately the hard evidence is very poorly documented for that region. Even more uncertain is the likelihood of Greenhouse enhancement of nutrient build-up. Opinion is extremely divided on whether significantly increased run-off will be of other than very localised significance along tropical coasts.

The Specific Matter of Bleaching:

Particularly because of Peter Glynn's work with bleaching in Pacific Panama and elsewhere, it is clear that bleaching can result from elevated temperature, and that this may result from el Niño events. But does this have anything to do with climate change? Is bleaching really getting more common or are we just much more aware of it because of the efforts of such dedicated information collation networks as that of Bert Williams? How many of the bleaching events reported really correlate with elevated temperature? — and if they do, what reasons do we have to correlate those particular warm water events with overall global warming?

We know that reefs in many parts of the world tolerate very elevated temperatures for considerable periods of the year without bleaching. eg Arabian Gulf, 36-39°; One Tree Is. GBR, 33°+ every midsummer daytime low tide on the reef flat (in the same place that also tolerates 16-19° on winter night low tides). We probably assume that this is because of adaptation of the species present to these unusual conditions over very extended time. How abrupt, and more importantly how patchy or localised will Greenhouse temperatures be? Jokiel and Coles suggest that 50 yr or so will not be long enough for such adaptation. But is 50-yr the time scale for significant global change?

I suggest that we simply do not know how patchy temperature increases will be, and we certainly know too little yet to predict the probability of generalised coral bleaching resulting from temperature increase whether or not caused by global warming.

Is temperature the most common cause of bleaching? Certainly, the southern GBR has long experienced bleaching from extreme low temperature in winter. Low salinity on the inner reef tract in the GBR resulting from floods from hurricane deluges causes spectacular bleaching. This bleaching could easily and mistakenly be attributed to high temperature a few days later when the flood plume has cleared and hot, still monsoonal conditions have reestablished.

Storms and Runoff:

Increased storminess and runoff are one of the possible changes to be expected during Greenhouse climate change. The acute effects of these occurrences are obvious and quite well understood. Also we know that recovery can be vigorous and rapid in the best circumstances. But what if this damage occurs on reefs already "sick" (i.e. subjected to appreciable chronic anthropogenic stresses such as nutrient buildup and/or sediment runoff)? We can then confidently predict a much less optimistic scenario. Will storms and runoff really increase appreciably in the tropics during Greenhouse? On the basis of present prediction, this seems only marginally likely on a global scale, though it might be considerable in particular localised areas.

Stress Response:

It is important always to bear in mind the subtle and synergistic ways in which stresses affect reef systems. Chronic stresses may be tolerated for very long periods of time with little outward sign. Acute events cause obvious death and destruction but, in isolation, are likely to be followed by quite rapid recovery. However, where an acute event occurs in the presence of pre-existing and previously tolerated chronic stresses, there may be an almost complete failure to recover to the status of a normal reef ecosystem.

Greenhouse Summary:

Overall, it is my personal opinion that reefs will prove to be "well" enough to cope with Greenhouse changes, averaged out over the whole of the world's reefs. I believe that sea level rise will prove beneficial, temperature increases will be tolerated and adapted to, and that storminess will not increase to the level of becoming intolerable. The totally unanswered, and perhaps unanswerable, questions concern the extent to which we may expect local, extreme, and intolerable anomalies in the overall climate change pattern.

The Great Barrier Reef Marine Park Authority Position:

We presently believe that the issue most likely to prove of greatest consequence to the long term health of the GBR in the foreseeable future is that of nutrient build-up. This is not because of any total confidence that there is conclusive evidence, but because of the very well established perception that there is a problem, and consequently a pressing need for its resolution. We believe that this stress, if proven to be real, is on a time scale which makes overall climate change of distinctly secondary significance to the Reef.

What we need to know as soon as possible is:

- What levels of nutrients and resulting plankton etc are present?
- What are the trends in these levels?
- Are these levels and trends directly anthropogenic?
- What are the likely effects of nutrient input on reefs?
- Are these effects already in evidence in the GBR?

Obviously, there is some knowledge from Australia and elsewhere about each of these issues. However, it is hopelessly inadequate. Initiatives are being taken in Australia and we do see some hope for our information base in the reasonably near future:

- Public awareness of a problem has greatly increased
- The farming sector is reacting with positive concern
- The "Decade of Land Care" is serving as a very good umbrella
- The Queensland Dept. of Primary Industries has initiated coordination of research effort considering agricultural runoff
- There is considerable concern from the agricultural chemicals industries
- The GBRMPA has in place useful but still inadequate R&M programs
- The GBRMPA has effective controls by permit on direct discharges

What is the Immediate Need?:

There is an immediate and urgent need for the GBRMPA and the coral reef communities of the world to initiate comprehensive, long-term programs of research to consider responses and trends in coral reefs to all aspects of environmental change and anthropogenic influence, both long and short term. It is totally unnecessary, and in fact very unwise to focus primarily on coral bleaching or long term climate change.

What we need is:

- MONITORING, AND MORE MONITORING!
  - on all spatial scales
  - on all time scales
  - and with very long term commitment

In my opinion, the commitment to such monitoring programs can only be at a government/government agency level as no individual scientist or arguably any university is in a position to consider or administer such commitment. Notwithstanding the implied departure from the conventional principal investigator/peer review system, such global environmental monitoring effort must have the support of the significant scientists in the coral reef sciences. Ultimately the scientific community as a whole must benefit from the existence of the resulting long term data base. There is no other way we can ever expect really to come to grips with the impact of environmental variability, climate change, or, in fact, the global significance of coral bleaching, than to have data extensive in time and space.

The Present Miami Workshop:

It is my hope to gain from this meeting a better perspective of the current global status of reef problems; information which will be of value to me in helping to formulate management and research strategies for the Great Barrier Reef Marine Park; and a commitment from the participants to the need for long term, world-wide monitoring programs focussed on all aspects of coral reefs in the context of environmental change.