Press Statement on Climate Change and Coral Bleaching

Scientific Panel, International Coral Reef Symposium, Bali, October 27, 2000

THE extensive coral bleaching that occurred in 1997-98 has been a source of wide-spread concern among scientists, managers and policy makers. Many of the 1465 papers submitted to the conference concerned key parts of the issues associated with coral bleaching and its association with climate change.

The majority of scientists at the Bali conference agree that climate change is having a significant impact on the world's coral reefs.

Coral bleaching occurs when the symbiotic algae that live in corals become stressed and are expelled. This turns coral white, leaving them in an unhealthy state. Research presented at the conference revealed that corals died in large numbers or were severely compromised after the 1998 bleaching event and that rising sea temperatures have been responsible for recent large scale bleaching and mortality events. Results also showed that this effect was exacerbated by other factors like high light levels and human-related stress.

In Belize, for example, studies have shown that the extent of bleaching and the subsequent death of corals in 1998 was unprecedented in at least the last 3,000 years. This was the subject of a paper by Dr Aronson and colleagues.

"Sea surface temperatures throughout the tropics have shown dramatic increases over the last two decades; as much as half a degree per decade. This is ten times what we are observing globally. As a result, the concern for coral reefs is how much of this increase will continue over the ensuing decades," said Dr Al Strong, team leader in satellite research at the National Oceanic and Atmospheric Administration.

Discussions also highlighted the fact that climate interactions with coral reefs are highly complex and that we need to understand much more than the southern oscillation such as the decade level climate variability. At the same time, as noted by Dr Eakin (NOAA) we have evidence to show similar rates of climate change over geological history and we are able to explain these by natural phenomena. In contrast, the changes we are currently witnessing can only be explained on the basis of human induced impacts.

Similarly, as evidenced in the fossil record, coral reefs have demonstrated recovery from such global scale climatic events historically. However, as noted by Dr Greenstein, Cornell College, this has typically taken between 2 to 100 million years.

Several papers also indicated that increases in sea temperature were not the only concern. A special session within the conference found evidence for a large decrease in coral calcification due the direct influence of carbon dioxide on sea water chemistry. In essence, absorption of carbon dioxide into the oceans increases acidity, which lowers the ability of corals to generate their skeletons.

In view of the multiple issues, it was widely expressed at the conference that coral reefs face a bleak future.

"The fact that all major climate models show that the current increases in sea temperature will continue is a source of major concern. We have insufficient evidence that corals are able acclimate or adapt fast enough to these sorts of changes. This is a clear area for priority research. " said Professor Ove Hoegh-Guldberg, Centre for Marine Studies at the University of Queensland.

In the absence of any clear evidence that acclimation or adaptation will see coral reefs through such future crises, it seems perilous to use this as a reason for little or moderated action.

In the end of his presentation on the 1998 devastating bleaching event in Okinawa, Prof. Yossi Loya, from Tel-Aviv University, Israel, winner of the ISRS year 2000 Darwin Medal, made a call for action: "As a coral reef society, we add our voice to the growing international concern on the issue of global climate change, and call for an effective reduction in greenhouse emissions over the next decade."

Please see next page for list of signatories.

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Response of Coral Reef Builders to Changes in Ocean Chemistry

Joan Kleypas [1] and Chris Langdon [2]

Statement of Issue

GLOBAL climate change and the extensive coral bleaching that occurred in 1997-98 has been a source of wide-spread concern among scientists, managers and policy makers. Research indicates that rising sea temperatures associated with global climate change have been responsible for recent large scale bleaching and mortality events. However, increases in sea temperature are not the only concern to coral reef ecosystems from global climate change. There is also evidence that coral calcification will decline due to the direct influence of carbon dioxide (CO_2) on sea water chemistry. In essence, increased absorption of carbon dioxide into the oceans increases acidity, which lowers the ability of corals to generate their skeletons. The direct impacts of changes in carbon dioxide concentrations and ocean chemistry on coral reef organisms and ecosystems are the focus of current research. Relevant findings presented at the 9th ICRS are discussed below.

State of Knowledge

Increase in CO_2 leads to decrease in calcification

Surface ocean chemistry is changing in response to increased atmospheric CO_2 concentrations, and the magnitude of these changes is larger than that experienced by coral reefs for at least 420,000 years, and probably for many millions of years. The oceans' increased uptake of atmospheric CO_2 leads to the formation of carbonic acid, which lowers both pH and carbonate ion concentration. These changes are highly predictable and have been tracked with ocean measurements for over two decades.

In aquarium and mesocosm studies, both scleractinian corals and coralline algae exhibit an essentially linear decrease in calcification in response to these ocean chemistry changes, and primarily to the carbonate ion concentration. The relative decrease in calcification varies between species, and can be dramatic, with coralline algae generally exhibiting a slightly stronger calcification response (25-44 percent) than corals (19-27 percent) to doubled CO_2 conditions. These experiments have been conducted from hours to years, with no adaptive response indicated among the organisms tested.

Implications for coral reefs

At the organismal scale, it is likely that reduced calcification of corals and algae will be expressed as a decrease in extension rate, reduced density (greater fragility), and/or a change in growth form. Within coral reef communities, reduced calcification translates into reduced competitiveness for space, and because the various coral and algae species are likely to exhibit reduced calcification to different degrees, this will likely lead to shifts in community structure. On a larger scale, coral reefs represent the *net* accumulation of calcium carbonate produced by coral reef communities; while the growth of some reef organisms are contributing calcium carbonate, such as corals and coralline algae, other reef organisms are constantly removing calcium carbonate through bioerosion, such as burrowing organisms. Since $CaCO_3$ removal processes are naturally high, a net reduction in $CaCO_3$ production will result in slower or even negative reef growth.

Photo: Chris Langdon

Laboratory facility in Biosphere

Although atmospheric CO_2 had already increased by 25 percent by 1990, and despite the consistent laboratory results showing that calcification of reef builders declines in response to changes in seawater chemistry, coral cores from massive *Porites* colonies (through about 1990) on the Great Barrier Reef do not exhibit an industrial age decrease in calcification. The possible reasons for the laboratory/field mismatch in findings include: (1) massive *Porites* exhibits a smaller calcification response to increased pCO_2; (2) the response is overprinted by some other variable that affects calcification (for example, light and temperature); (3)

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dissolution of $CaCO_3$ sediments provides local buffering of seawater chemistry; and/or (4) some undetected flaw in laboratory studies.

Relevant Actions Being Taken to Address Issue

- As more experiments are conducted on different species and different species assemblages, our knowledge of how specific taxa and coral communities will respond to increased atmospheric CO_2 is improving.
- Although coral and algal calcification appears to behave geochemically (i.e. reflecting surrounding seawater chemistry), physiological studies indicate that the internal biochemistry of these organisms is complex. Several groups have tackled this problem using radioactive tracers to understand how Ca^{2+} and CO_3^{2-} ions are tranported by the organism to the site of calcification.
- $CaCO_3$ saturation state obviously exerts control on coral calcification, but other variables such as light, temperature and nutrients also play a role. Several researchers are attempting to define how these four variables interact to control calcification rate in corals.
- Recent evidence shows that not only will calcification decrease in the future, but dissolution will increase. Quantifying dissolution of carbonate minerals on coral reefs is difficult, but necessary if we are to understand how reef-building processes will change in the future.

Management and Policy Implications

Unlike other major impacts on coral reefs (bleaching, overfishing, etc.), changes in seawater chemistry are truly global in nature, with little evidence of significant regional differences. Future changes in surface seawater carbonate chemistry are directly linked to atmospheric CO_2 concentration, and are therefore highly predictable. In terms of policy, the only perceivable way to stop or reverse the effects of seawater chemistry on corals is to control CO_2 emissions.

In the meantime, managers of our coral reefs may be faced with increasing problems associated with decreased calcification on reefs. Coral communities may experience changes in community structure or a reduced competitiveness with other benthic taxa (both of which will be impossible to attribute to calcification changes alone). Also, unlike the acute effects of coral bleaching, decreases in calcification rate are chronic. These two factors render management difficult, because such effects occur over long time scales and are difficult to measure. As a consequence, reduced calcification on reefs is often not considered an immediate problem, particularly in comparison to mass mortalities associated with coral bleaching. This attitude is understandable, but incomplete in terms of planning for long-term reef survival.

Specific Recommendations for Action

- Reduce other anthropogenic sources of reef stress and degradation.
- Educate reef managers, and also policy makers and the general public about the impacts of changing seawater chemistry on coral reefs; encourage reductions in greenhouse gas emissions.
- Support studies to elucidate: (1) links between coral physiology and calcification; (2) effects of other variables on calcification; (3) species-specific response to seawater chemistry changes; (4) role of dissolution in carbonate budgets on reefs; (5) coral community ecosystem responses to increased atmospheric CO_2.
- Scale up aquarium and mesocosm experiments to field-scale CO_2 "fertilization" experiments. Field experiments will include the effects of natural variability of temperature and light, and will also allow observations of community response.
- Conduct longer term experiments designed to examine coral response to decreased calcification, and how this response is reflected in density, extension, and isotopic composition of growth bands.

Useful References and Resources

This paper is based upon presentations at the 9th International Coral Reef Symposium, Mini-Symposium E1, *Global Climate Change and Coral Reefs: The Science Behind the Prognostications of Gloom*. Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/

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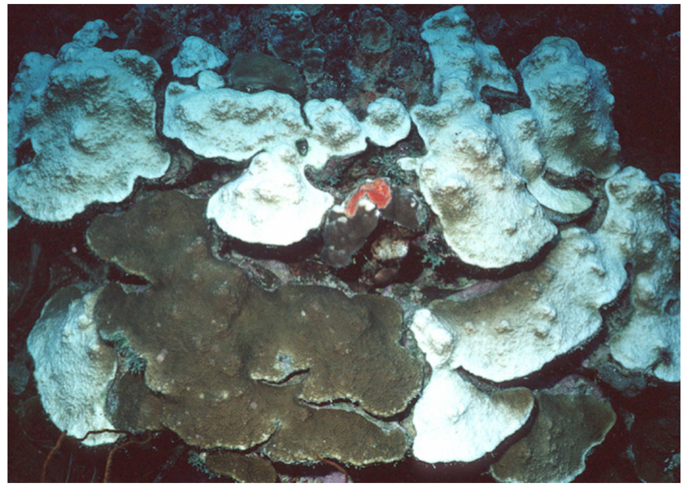
Mechanisms and Causal Factors Associated with Coral Bleaching

Ove Hoegh-Guldberg [1] and William K. Fitt [2]

Statement of Issue

THE global, unprecedented mass coral bleaching and mortality event of 1998 caused an avalanche of new information about the causal factors, molecular mechanisms and ecological outcomes of mass coral bleaching. Coral bleaching occurs when the symbiotic algae that live in corals become stressed and are expelled. This turns the coral white, leaving them in an unhealthy state. Presentations of recent studies at the 9th ICRS, approximately two years after the 1998 bleaching event, reveal a greater understanding of the causes and consequences of mass coral bleaching. This is especially important given the projected scenario of more frequent and greatly more intense episodes of mass bleaching and mortality under global climate change.



Bleaching *Montastraea faveolata*, Caribbean

State of Knowledge

Mechanisms associated with coral bleaching

The evidence that increased sea temperature causes bleaching is indisputable. Evidence presented at the meeting also affirmed this. There is also little doubt now that the advent of coral bleaching is accompanied by an massively increased sensitivity to photoinhibition of the dinoflagellate symbionts of corals and other symbiotic organisms. Beyond this understanding, two main mechanisms are under investigation: (1) that thermal stress during bleaching begins with the collapse of the dark reactions of photosynthesis, and/or (2) that there are other lesion points, some of which lie within the light reactions of photosynthesis. While much support can be found for the former idea (for example, light enhancement of bleaching or the "shade effect"), more work is needed to resolve whether one or both mechanisms are at the heart of thermal mass bleaching.

Causal factors associated with coral bleaching

A large number of studies addressed the causal factors that underpin bleaching responses. Much of this was stimulated by an interest in explaining the variability in response that is commonly seen across a coral reef during a bleaching event. While some symbiotic invertebrates bleach (loss of dinoflagellate pigments and/or cells) in response to elevated water temperatures, the occurrence of bleached and unbleached individuals side by side on affected reefs has driven many to seek additional factors or mechanisms. Observations and experiments over the past few years have indicated that light, ultraviolet radiation (UVR), water flow and feeding status modify the primary effect of elevated temperature.

An important issue was raised by a study that measured key photobiological parameters for 5 years in corals growing in Florida. Even during times of non-bleaching, there are significant variations in cell densities, pigment content and photosynthetic parameters that may ultimately affect the interpretation of the response of corals to thermal or other stresses. Natural seasonal variations in these parameters have to be considered if one is to get a complete picture of how symbiont density and condition change. This background information is critical for a more complete understanding of the mechanisms that underlie mass coral bleaching.

Variation in intrinsic response to thermal stress

As well as the extrinsic factors represented by the physical and biological parameters in the environment, intrinsic factors, such as genotype, may influence the response to thermal stress. Biochemical measures of sensitivity to thermal stress within the light reactions of photosynthesis,

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particularly Photosystem II (PSII), revealed significant and large differences—up to 4 degrees centigrade (°C)—in thermal tolerance between individual colonies. Several studies from Okinawa also showed that differences in the susceptibility to thermal stress of corals matched field results in differences in susceptibility of corals and dinoflagellates during the bleaching event in Okinawa in 1998. In addition, there are differences in the susceptibility to thermal stress of symbiotic dinoflagellates, related to differences in dinoflagellate symbiont type and behaviour. How these mechanisms will affect the responses of reefs is still largely undetermined. It was clear, however, from presentations at the 9th ICRS that support for the idea that bleaching may be adaptive remains very weak at best.

Host physiology (another intrinsic factor) can also have an effect on the outcome of thermal stress. Increased concentrations of host pigments (mycosporine-like amino acids, fluorescent pocilloporins or gfp-like compounds) overlying the symbiotic dinoflagellates appear to be able to reduce photoinhibition and ultimately bleaching. Again, ideas that some corals will do better than others are interesting but does not negate the scale of impacts that are likely to occur as sea temperatures continue to increase. The fact that near complete mortality occurred on a number of coral reefs during 1998 suggests that even the thresholds of individuals that have higher thermal tolerances are also likely to be exceeded.

Subchronic impacts of coral bleaching

A greater understanding of the impacts of mass bleaching of reef organisms is required to properly understand the ecological and socio-economic implications of increased coral bleaching under climate change. While much of the earlier work concentrated on whether corals live or die after a bleaching event, only a few studies have asked the question as to whether the physiology of corals and other symbiotic organisms that do survive is compromised at all. The conference saw several studies that indicate that subchronic impacts are indeed very important.

Many studies indicated that tissue thickness, lipid levels and growth, levels of antioxidants, and reproductive output are all severely inhibited in corals that bleach, but later recover their symbiotic dinoflagellates. Clearly, it is therefore incorrect to assume that the reef has "recovered" if its corals recover their symbiotic algae. The potential error of this conclusion is highlighted by one observation that those corals that bleached in 1998, still had not recovered the reproductive output of unaffected colonies two spawning seasons later.

Recovery following coral bleaching

Surprisingly, there are only a few studies on the ecological processes that occur during the impacts and recovery processes on reefs after mass bleaching events. Results from these studies indicate that: (1) Differences in the extent to which gross photosynthesis (P_g) changed relative to Respiration (R) in macroalgae versus corals may explain why thermally stressed reefs may result in macroalgal-dominated ecosystems; and (2) environmental factors (such as ultraviolet radiation) could have a strong effect on the rate of recovery of bleached corals. The ways reefs and the accretion of reef carbonate changes with time after bleaching events is likely to be important and are being explored.

Implications for Management and Policy

While recent results hint at the importance and the types of factors that have an influence on recovery, the study of reefs after bleaching events clearly needs to be expanded. Questions like the extent of variability in animal and dinoflagellate genotypes that differ in their tolerance to stress needs to be explored rigorously as does the genetic connectivity of reefs. These population genetic aspects are crucial to our ability to develop ecological models of how coral reefs might change in the face of rising thermal stress. Only with this information in hand can we truly understand the implications of climate change for these valued ecosystems.

It is also clear that we need to explore the consequences of mass bleaching events. The following questions loom large and are of major importance to both users and managers of coral reefs. Are coral reefs resilient in the face of projected climate change over the next 100 years and how fast will change occur within coral reefs ecosystems if sea temperatures continue to change? Can coral reefs recover and if so, how fast? What will coral reefs look like if coral abundance decreases dramatically over time? Will some corals be more immune than others and hence increase in relative abundance? Will coral reefs erode if corals and their dinoflagellate symbionts are no longer a dominant organism? How much of the present high diversity of coral reefs be lost if coral reefs no longer exist?

Specific Recommendations for Action

An almost universal conclusion of the 9th ICRS was that climate change is a major threat to coral reefs that is already having an unprecedented influence on reef health. The impacts projected suggest that coral reefs will be lost from most regions by the middle of this century if climate change is not slowed. There was little doubt from data presented at the meeting that another degree increase in sea temperature will have dire consequences for coral reefs. While attempts to adapt to changes may represent one response to the projected climate impacts, immediate action must occur on reducing the growth in greenhouse gas emissions if coral reefs are to have any future at all. It is no longer credible to claim that the impacts of climate change generally or specifically (for example, on coral reefs) are debatable.

The reduction in the health and distribution of coral reefs projected under rising sea temperatures has implications for the many industries and societies that depend on coral reefs partly or wholly for livelihoods and income. The reduced productivity and value of coral reefs will mean that societies that depend on coral reefs will have to find alternatives as the climate changes. In some cases, alternatives may exist and these developments (if given time) may occur with minimal disruption to dependent societies. In many other cases, however, it is hard to imagine alternatives for the roles that coral reefs perform. This suggests that there must be an increasing effort placed into understanding how reefs are likely to change and into finding solutions to the decreased ability of tropical coastal regions to support the populations that they currently support. Not to actively meet these challenges will be to ignore a looming problem of a fundamentally huge magnitude.

Responses must encompass both short and long terms. Given the long residence times of most greenhouse gas constituents in the earth's atmosphere, action today will have little benefit for coral reefs over the next 100 years. Sea temperatures are projected to increase by at least 1-3^{o}C by the end of 2100. This suggests that responses that involve socio-economic adaptation to climate change will be crucial in the next 10 to 100 years. Reducing greenhouse gas emissions still are vital however. To state the obvious, coral reefs are ecosystems of enormous value for sustaining (at low cost) millions of people and billion-dollar industries like tourism. Reducing or reversing the rate of increase in greenhouse gases will mean that coral reefs and these inherent benefits have a chance of returning in several hundred year's time. This must be a priority of this current generation.

In considering the shorter term, it is very important to initiate studies and planning of the impacts of climate change on coral reefs. These studies are important if we are to anticipate and implement socio-economic adaptation to climate change. Studies that consider biological, economic and policy responses to sea temperature, reduced

Photo: Andy Bruckner

Coral bleaching is associated with increases in sea temperature. *Agaricia* colony in Caribbean

alkalinity and sea level rise are vital at this point. Only with these fully integrated studies can we have a chance of responding to these extreme challenges to tropical coastal societies and nations.

Useful References and Resources

This paper is based upon presentations at the 9th International Coral Reef Symposium, Mini-Symposia E2a *Global Climate Change and Coral Reefs: Systematics of Bleaching* and A4 *Zooxanthellae in Animal Hosts: A Symposium Honoring the Lifetime Contributions of Len Muscatine and Bob Trench to Algal Symbiosis*. Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/

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Coral Bleaching: Geographical Perspectives

Thomas Spencer [1] and Kristian Teleki [2]

Statement of Issue

THE 1980s marked a clear upturn in the reporting of coral bleaching, with the 1997-98 mass coral bleaching and mortality event as the most extensive and severe on record. Coral bleaching occurs when the symbiotic algae that live in corals become stressed and are expelled. This turns the coral white, leaving them in an unhealthy state.

Coral bleaching causes reduced coral fecundity and, when extreme, losses in reef biodiversity, degradation of biological and physical functions of the reef ecosystem, and impacts on adjacent mangrove and seagrass habitats and resources. These impacts are likely to cascade through the sustainability of local fisheries and the local incomes associated with reef-related activities.

Bleaching incidence statistics have been used as both an early signal of global environmental change in the tropical oceans and an indicator of non-climatic stresses, often human-related, in tropical shallow marine environments. Discussions over the likelihood of near-future bleaching patterns have arisen because the phenomenon under study shows intra- and inter-regional spatial variability at within-reef, between-reef and reef province scales, and temporal variability over decadal time-scales at different sites. Some reefs appear to bleach on a regular annual basis (for example, southern Red Sea) whereas other reefs have only recently recorded extensive bleaching (for example, Belize, western Caribbean Basin).

At the 9th ICRS several critical issues were identified, including whether or not there will be a greater frequency and/or greater magnitude of ocean warming events in the near future and, if so, whether or not corals will be able to adapt — in what ways and how quickly — to such a changed climate regime.

State of Knowledge

Improved information base

The last two decades have seen considerable advances in the understanding and prediction of ocean-atmosphere dynamics. Data on temperature and solar irradiance is now available from *in situ* buoy arrays, space-based remote-sensing satellites, and sparser environmental monitoring at reef sites. At the same time, the application of broadly standardised rapid reef assessment techniques, often co-ordinated through international monitoring programmes, has generated a broad base of coral reef status reports for a large number of reef locations throughout the seas.

Photo: M. Rard/ECOMAR

Bleaching reef at Reunion Island in April, 2001.

This improved information base has proved particularly useful in assessing the onset, development and recovery of corals from ocean warming events that have a global footprint. In particular, NOAA/NESDIS satellite-derived sea surface temperatures (SST) 'hotspot' maps have been successful in identifying broad regions where SSTs exceed long-term mean maximum summer month SSTs, thus predicting areas likely (but not certain) to experience coral bleaching. At the same time, the spread of Internet postings of bleaching reports from the field has both tested and extended these remotely derived predictions.

Triggers for bleaching events

Bleaching events appear to relate to seasonal fluctuations in photosynthetic efficiency and densities of the photosynthesising symbiotic alga, the zooxanthellae, within

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coral tissues. Coral bleaching is species specific, and probably relates also to variations in stress resistance within the poorly understood different types of zooxanthellae. While the key trigger appears to be the amplitude and duration of temperature excursions, high irradiance acts as a further trigger for bleaching. Associated climatological and oceanographic changes result in variations in sea surface state, short-term changes in sea level and varying cyclone incidence which act in synergy with the prime triggers. The sequencing of high temperature / irradiance events may reduce coral susceptibility.

High spatial variability in bleaching
Coral bleaching shows high spatial variability at a number of scales – from the colony (variation between different surfaces on the same colony and with colony size), within individual reefs (by depth, between windward and leeward reefs, and in relation to localised upwelling) and between reef systems (inner vs. outer shelf vs. oceanic reefs, in relation to wave exposure, current patterns and regional upwelling processes).

While coral bleaching is related to the warm phase (that is, "El Niño") of the El Niño Southern Oscillation events (ENSO), this relationship is not simple and requires incorporation of a wider range of climatological and oceanographic factors. For example, climatological factors such as cloud cover characteristics at times of high SSTs, and oceanographic factors such as operation of the Indian Ocean dipole oscillation need to be considered. ENSO events themselves vary in terms of their strength and mode of development and nest within longer term climatic patterns, such as the Pacific Decadal Oscillation.

The complexities of both the dynamics of environmental forcing factors and responses at coral colony to reef system scales have implications for the prediction of likely future impacts on reefs of ocean warming.

Relevant Actions Being Taken to Address Issue

- Improvements in the resolution of satellite monitoring of SSTs, from 50 km (AVHRR) to 9 km (Pathfinder) offers the possibility of beginning to establish better linkages between broad scale patterns in the movement of water masses and reef responses at specific field sites. (please visit http://podaac.jpl.nasa.gov/)
- Careful measurements of SSTs, irradiance, water level fluctuations and other environmental parameters, including the role of the sequencing of events, are being taken to better understand environmental triggers for bleaching episodes.
- A focus on the genetic diversity of zooxanthellae populations and their dynamics will allow a better understanding of zooxanthellae – coral interactions under temperature and irradiance stresses.
- Construction of better linkages between coral reef biology and oceanographic processes are underway to better define coral reef recovery and recruitment dynamics.

Management and Policy Implications

Managers and policy makers need to be aware of the issues that surround the explanation of variable bleaching impacts over time and space, including the inherent uncertainties involved. Knowledge of the geographical variation in bleaching impacts and particularly in the location of surviving coral 'refugia' has implications for the re-seeding of damaged reefs, and hence in regional schemes for the conservation and protection of key reef sites. Geographic areas which are known not to bleach, or to regularly survive bleaching, should be afforded increased protection from other human-induced sources of stress. The potential for a greater frequency and/or greater magnitude of bleaching events in the near-future, although not certain, nevertheless requires the development of planned responses to bleaching episodes now which will be robust enough to deal with future scenarios.

Specific Recommendations for Action

- Attempt to reduce human-induced sources of reef stress and degradation so that reefs are better able to deal with high SST / high irradiance events.
- Develop a better knowledge of the connectivity of reef systems to better understanding processes of coral recruitment and reef recovery after bleaching, including a better appreciation of the time scales necessary for regeneration.
- Communicate the natural dynamic of reef systems ('the shifting baseline'), including the importance of sequencing of bleaching impacts with other environmental perturbations.
- Communicate the spatial variability of bleaching impacts and reef recovery processes to enable the development of site specific, rather than standardised, management plans for reef rehabilitation.

Useful References and Resources

This paper is based upon presentations at the 9th International Coral Reef Symposium, Mini-Symposia E2b *Global Climate Change and Coral Reefs: Bleaching Status of Reefs*. Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/ and at: www.uncwil.edu/isrs/

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NOAA/NESDIS satellite-derived sea surface temperatures (SST) 'hotspot' maps. Web site: www.coralreef.noaa.gov/ and click on link to "Coral Bleaching Hotspots."

Coral Reef Watch Web site that lists reports from field on bleaching: http://orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html

Socio-Economic and Management Implications of Mass Coral Bleaching

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Statement of Issue

THE socio-economic impacts of mass coral bleaching are known in theory, based on the observed consequences from other causes of reef degradation, and include tourism and fisheries in the short term with additional losses to coastal protection and other "services" over time. Studies undertaken in response to the 1997-98 bleaching event provide the first empirical documentation and estimates of these impacts, allowing us to refine our understanding and to better plan effective responses.

The studies presented at the 9th ICRS underscore the potential for well-implemented responses to reduce the extent to which socio-economic losses are felt by coastal communities. For example, one study reports a difference of approximately US$ 7 billion in economic loss for the Indian Ocean region between an optimistic estimate that assumes coral reef recovery (US$ 608 million) versus a pessimistic estimate that assumes no reef recovery ($8.26 billion). Clearly, there is a real opportunity to mitigate expected socio-economic impacts from bleaching, if response measures can be effective in promoting coral recovery.


Photo: Coastal Resources Center, URI

Fishing for bait in Indonesia

State of Knowledge

Fisheries

The precarious dependence of subsistence fishers on reef-dependent fisheries throughout tropical developing nations emphasizes the potential for serious socio-economic consequences to result from mass coral bleaching. The vulnerability of these communities to such consequences, including malnutrition, was highlighted, given the few alternative livelihoods available in many instances, notably for island communities. However, the effects of the mass coral bleaching of 1997-98 on fishing communities in Bolinao (Pangasinan), the Philippines and in the Indian Ocean region, at this stage, are subtle if observable at all.

The composition and health of coral reef ecosystems are important factors in determining the structure of reef-dependent fisheries through the food and habitat "services" reefs provide. Temperature-induced bleaching which affects the condition and diversity of coral reef ecosystems is expected to simultaneously affect reef fish populations, reducing abundance and changing composition and distribution. Population reductions are predicted for species that inhabit reefs for at least part of their life cycle or prey on reef fish. Changes in fish abundance may vary by species, shifting the composition of reef fish populations toward herbivores. Such a shift could negatively impact fishers, as herbivores are lower in value than other species.

Two studies described minor increases in herbivores as expected, but the causality between coral bleaching and these observations is currently vague. One reason for this uncertainty, as well as the lack of other observable impacts, may be that coral bleaching is one of many stresses cumulatively impacting reef ecosystems. When bleaching is superimposed on reefs that are already over-fished, reductions in overall reef fish populations will not be observable since herbivores dominated the fishery prior to

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the bleaching event. It is also suggested that impacts occurring at small spatial or temporal scales may have been masked by fishers changing their fishing habits and patterns. Or the answer may simply be one of time scale, and the impacts to fisheries may become more pronounced once the structure of bleached reefs is further eroded.

Tourism

In the short term, the most dramatic socio-economic impacts from the 1997-98 mass bleaching event are the estimated losses to reef-dependent tourism. These losses were studied in the three diving destinations of Palau; El Nido (Palawan), the Philippines; and the Indian Ocean region, and include:

- US $3-4.6 million financial losses in Zanzibar and US $ 13-20 million in Mombasa (Westmacott et al.),
- US$ 3 million and US$ .02 million financial losses in the Maldives and Sri Lanka respectively (Wetsmacott et al.),
- US$ 15 million loss in net revenue to the Philippine economy (Cesar et al.),
- and losses to the diving industry in Palau of approximately US $350,000 each year following the bleaching event (Graham et al.).

These estimates are potential losses resulting from coral bleaching, and in some instances such as East Africa, have not been demonstrated as actual losses in practice. The manifestation of these losses are multi-dimensional and include a) impacts on tourist destination choice, which results in lost visitation and therefore a total loss of tourism revenue, b) impacts on choice of activities pursued, which may cause reduced coral reef-related revenue, and c) reductions in tourist satisfaction of the diving experience as a result of degraded reef conditions.

Understanding the influence reef degradation has on diver decision-making is also important to predicting the economic impact of bleaching events. It is related first to tourist knowledge of the marine environment and coral bleaching and subsequently to the influence this understanding wields on consumer choice and satisfaction. Each of the studies reported relatively low tourist awareness of coral bleaching, at typically 25-50 percent of the respondents surveyed. Low awareness among survey respondents may be because study surveys were undertaken in areas that were heavily bleached and knowledgeable divers had already exercised their decision to go elsewhere. However, of those that were aware of coral bleaching, relatively high percentages (approximately 75 percent) testified that coral bleaching either had negatively impacted their overall dive experience or would impact their destination choice. This strong relationship was true in cases of direct questioning about coral bleaching; more indirect approaches attempting to link bleaching impacts with willingness to pay were less clear in suggesting how reef degradation impacts consumer welfare. These results indicate that increased public awareness about coral bleaching in the future may create a more discerning dive consumer, increasing the influence of coral reef condition in destination and activity choices, as well as overall satisfaction.

Implications for Management and Policy

There are two key factors limiting the development of responses to mass coral bleaching. The first is the major issue of global climate change as a causal factor. The second is the lack of scientific answers to important management questions. While these challenges should be accounted for in a strategic response to mass coral bleaching, neither global warming nor uncertainty should preclude some sort of earnest response. Managers can begin by implementing known approaches to foster coral resiliency and recovery in damaged coral reefs. The elements of any management approach should include the following guiding principles:

- Mass coral bleaching is one of a number of stresses that cumulatively threaten coral reef ecosystems and must be addressed within this larger context.
- Management can be undertaken in the absence of complete scientific understanding of the specific causes and consequences of mass coral bleaching and should be implemented adaptively.
- Management should aim to create situations that maximize the potential for coral reef resiliency to mass bleaching and recovery after these events.
- Management-oriented research is needed to elucidate the conditions that bolster coral resiliency and promote recovery as well as to refine predictions on the extent and implications of future events.
- Ultimately, responding to mass coral bleaching will include addressing global climate change through reductions in CO_2 emissions.

Recommendations for Action

Management responses can generally be divided into strategies directed toward coral reef ecosystems, and strategies directed exclusively toward mitigating the socioeconomic impacts of mass bleaching on coastal communities. To address the ecological issues, the principle articulated here—that management should aim to create situations that foster coral resiliency and recovery—suggests two strategies. The first strategy is to implement responses that generally promote coral health. This recommendation recognizes that bleaching is one of many stressors with the potential to impact coral reefs. It is possible that healthier reefs will be less vulnerable to mortality from bleaching. However, this assumption needs to be further investigated by the research community since the more pristine reefs in the Indian Ocean were the worst affected by the 1998 mass coral bleaching event.


Photo: Coastal Resources Center, URI
Tourist resort in Indonesia

The second strategy is to identify and pursue responses that are specific to bleaching. Opportunities for bleaching-specific responses need to take into consideration variations in local conditions. These options might include, for example, adjusting fisheries management on bleached reefs to protect species population composition and species that are useful in maintaining coral health during bleaching events (that is, herbivores that scrape algae off dead coral maintaining suitable surfaces for coral larvae recruitment). Tourism destinations will vary to the extent that they are impacted by coral bleaching – ecologically, economically and in their ability to mitigate the impacts of bleaching through diversification. Being able to predict a destination's resiliency in spite of degraded reef conditions will provide a rationale for planning emergency assistance. The degree to which tourism will be impacted is related to the ability of a destination to maintain its status and reputation even in the face of reef degradation, by promoting other unrelated attractions. Impacts to the diving industry can be mitigated by diverting divers' attention to other focal points such as wrecks or, perhaps, by involving divers in coral bleaching monitoring as an attraction. However, such diversification is not inevitable and may not be easy. For example, although resorts in El Nido, Philippines have been shifting market segments from divers to honeymooners in response to reef degradation, a notable loss is nonetheless observable, estimated at US$ 1.5 million annually.

Management, research and policy responses to mass coral bleaching will be most effective when coordinated. Such coordination needs an appropriate framework - such as Integrated Coastal Management (ICM) - to operate in. ICM is appropriate as it incorporates adaptive management, has the capacity to address the multiple stressors which cumulatively impact reef condition, and has already been promoted as the recommended response to related issues, including global climate change and coral reef management.

ICM planning should begin by focusing on general coral reef management, which considers the multitude of stressors that cumulatively have the potential to impact reef condition. Essentially, it involves identifying reefs and the circumstances that currently threaten reef condition or have the potential to do so. Based on the threats identified, strategies are implemented to address both stressors that impact reefs directly, for example, destructive fishing or anchor damage from diving boats, and indirectly, such as sedimentation or pollution. These strategies can include land-use and fishing regulations, zoning schemes including MPAs, and passive or active rehabilitation of damaged corals. Additionally, general reef management should include monitoring protocols to keep a pulse on reef health, and public education initiatives to create and maintain a constituency for reef management and conservation.

One of the threats that needs to be considered during the ICM planning stage is coral bleaching. The bleaching consideration should be superimposed on the composite picture already established for the reefs being managed. Based on our current understanding of coral bleaching, predictions should be made about the likely impacts of future events under optimistic, average, and pessimistic scenarios. Key questions that need to be addressed in the assessment are:

- Which reefs are most and least likely to be impacted by coral bleaching?
- Are the reefs expected to be more resilient "source" or "sink" reefs?
- Are "source" reefs that are expected to be resilient currently threatened by another anthropogenic stress that can be addressed by management actions now? What actions are required?
- What are the likely impacts to diving destinations in the area being managed?
- To what extent will these destinations and diving operations be able to diversify to maintain their reputation and status should local reefs become degraded?
- How will reductions in catch affect local fishers, including subsistence fishers?
- To what extent are opportunities for alternative or supplemental livelihood available to fishers should the fishery collapse as a result of coral bleaching?

Contingency plans can then be prepared to most efficiently respond to likely or catastrophic impacts. Contingency plans should include emergency response protocols for both research and management. The research protocol should establish a procedure for documenting the severity, extent, and recovery from the bleaching event in detail so that the experience can be incorporated into future management efforts. The management protocol should be prepared to offer emergency assistance to fishers – especially subsistence fishers – and tourism operators that are unable to avoid losses due to coral bleaching. Management protocols should include a procedure for reviewing and responding to scientific assessment of the bleaching event as it becomes available. Such review may suggest creating or revising MPA boundaries to protect resilient source reefs from other anthropogenic stresses, facilitating post-bleaching recovery.

Contingency plans should also include non-emergency responses that can be implemented either prior to or following bleaching events, such as:

- Diversification of local tourism industries and/or opportunities available to fishers.
- Public education on mass bleaching to help prepare communities for bleaching events and create a constituency for climate change.
- Briefing government representatives on the implications of mass coral bleaching locally, so that these considerations can be voiced in international forums.
- Assessing the feasibility, cost and likely success of coral reef restoration or rehabilitation.

Implementation of ICM planning and response recommendations is most needed in tropical developing nations that host most of the world's reefs. Policymakers need to address the gap in required funding and human capacity that is often in short supply in these countries. Since tropical developing nations are most likely to be affected by mass coral bleaching and are also the least responsible for global warming, appropriate policies should be established to compensate for this inequity through the provision of assistance.

Funding and human capacity must be made available at a local level to implement management, monitoring, and, when necessary, rapid response. Rapid response assessments of bleaching will be most useful to management efforts when they are comparable, meaning that assessments must be standardized and funding must be available to implement these efforts in a timely manner. Standardization requires adopting a monitoring protocol, establishing training programs on the selected technique, and facilitating access to expert advice for less experienced researchers.

Evaluation is both the basis for genuine adaptive management, and a forum where cohesion between research, management, and policy communities can significantly enhance the effectiveness of response. Adjustments to mass coral bleaching response strategies should reflect the best scientific information. More informed predictions as to the severity and extent of future mass bleaching events will assist the policy community in its difficult work. There are already good examples of evaluation studies at both the global scale and the regional scale. The next step is to translate this new information into strong policies.

Conclusions

The extensive coral mortality caused by the 1997-98 mass coral bleaching event raised serious concern over the ecological and socioeconomic implications of bleaching events, the expected severity and frequency of future events, and the future of coral reefs. Three years after this event a preliminary picture of its impacts is coming into focus that underscores the necessity for management, policy, and research responses to mass bleaching. The ecological impacts of mass coral bleaching have been demonstrated to be severe, with massive losses in coral cover and diversity, as well as in other coral reef-associated organisms. These losses occurred from local to oceanic scales, and with the increasing frequency and severity of ENSO events driven by global climate change, the degradation of coral reefs due to mass coral bleaching can only be expected to increase. Economic losses to reef-dependent tourism are the most significant economic impacts observed thus far. However, the potential for serious socioeconomic impacts to reef-dependent fishing communities as degraded reefs continue to erode justifies critical concern and attention.

Effective responses to mass coral bleaching are hampered by scientific uncertainty, our inability to respond to global climate change in the short term, and insufficient financial and human resources. However, these challenges cannot justify inaction. Rather they underscore the primacy of developing adaptive strategies and capacity so that countries and communities are prepared for future mass bleaching events. Responses should reflect that mass bleaching is one of many stressors cumulatively affecting coral reef communities and begin by implementing actions that promote coral health generally. Mass bleaching is one of these stressors and necessitates identifying and planning for the expected ecological and socioeconomic impacts from future events. Effectively implementing adaptive management will require support from both the research and policy communities to provide the technical information and financial and human resources needed for success. The policy community faces two great challenges. First, to commit the resources needed for successful implementation of coral reef management in the developing nations that host most of the world's coral reefs. Second, to address global climate change through reductions in CO_2. Mass bleaching creates a broad constituency and justifies efforts to address global warming, as it foreshadows the potentially larger impacts to come about through unabated global warming.

Photo: Coastal Resources Center, URI

Child fishing in North Sulawesi, Indonesia. The future of millions of people depend upon healthy reefs and oceans

Useful References and Resources

This paper is based upon presentations at the 9th International Coral Reef Symposium, Mini-Symposia E4 *Global Climate Change and Coral Reefs: Coral Bleaching: Assessing and Linking Ecological and Socio-Economic Impacts, Future Trends and Mitigation Planning.* Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/

Schuttenberg, H.Z., ed. 2001. *Coral Bleaching: Causes, Consequences and Response.* Selected Papers presented at the 9th International coral Reef Symposium on *Coral Bleaching: Assessing and Linking Ecological and Socioeconomic Impacts, Future trends and Mitigation Planning.* Coastal Management Report #2230. ISBN # 1-885454-40-6. Coastal Resources Center, University of Rhode Island, Narragansett, RI, USA.

Wilkinson C., Linden O., Cesar H., Hodgson G., Rubens J., Strong AE. (1999). "Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: An ENSO impact and a warning of future change?" *Ambio*, 28 (2): 188-196.

Westmacott S., Teleki KA, Wells, S. and West, J. 2000. *Management of bleached and severely damaged reefs.* IUCN Cambridge, U.K. vii + 36 pp. ISBN 2-8317-0545-2. This document is available on the Web in English, French, Spanish, Portuguese, Bahasa Indonesian, and Kiswahili, at: www.iucn.org/places/usa/literature.html

Hoegh-Guldberg, Ove. (1999). *Climate Change, Coral Bleaching and the Future of the Worlds Coral Reefs.* Greenpeace, at: http://www.greenpeaceusa.org/media/publications/coral_bleachingtext.html

The International Coral Reef Initiative (ICRI), Web site: www.icriforum.org

Web Links

Please note that some web site URL's listed in the report have been updated since publication.

Organizations

- Conservation International
- International Society for Reef Studies
- US Agency for International Development
- World Resources Institute

Introduction

- 9th International Coral Reef Symposium
- International Coral Reef Initiative

Global Status of Coral Reefs

- Global Coral Reef Monitoring Network
- ReefBase
- Reef Check

State of Research Knowledge

- Australian Institute of Marine Science – Reef monitoring methods
- Coral reef degradation in the Indian Ocean
- National Invasive Species Council
- UNEP Caribbean Environment Programme – Land-Based Sources of Marine Pollution
- University of Hawaii – Marine invasions in Hawaii
- Workshop: Coral Reefs and Global Change: Adaptation, acclimation or extinction?
- World Conservation Monitoring Center – Coral diseases data

Resource Management

- Damage Assessment and Restoration Program
- Florida Keys National Marine Sanctuary
- Great Barrier Reef Marine Park Authority
- Marine Affairs Research and Education
- National Center for Ecological Analysis and Synthesis

Socio-Economics and Capacity-Building

- SeaWeb

Trade and Management

- CITES – Convention on International Trade in Endangered Species of Wild Flora and Fauna
- Marine Aquarium Council
- Secretariat for the Pacific Community
- TRAFFIC – WWF/IUCN Wildlife Trade Monitoring Programme
- UNEP-World Conservation Monitoring Centre
- US Coral Reef Task Force
- The WorldFish Center (formerly ICLARM)

Assessment and Monitoring

- Marine Programme, World Conservation Monitoring Centre
- UNEP Convention on Biological Diversity
- US EPA's Coral Reef Protection site
- West Hawaii Aquarium Project
- Workshop: Quantitative Underwater Ecological Survey Techniques

Global Climate Change and Coral Reefs

- Biosphere 2 Coral Reef
- Coral Reef Watch
- Global Coral Reef Monitoring Network
- Global Ocean Data Analysis Project
- International Coral Reef Action Network
- International Coral Reef Initiative
- NOAA Coral Bleaching Hotspots
- Reef Education Network