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Module 1: Basics of Coral Reefs and Climate Change

Section 1: Global Climate Change

Learning Objectives

By the end of this module you will have:

- ② An update on current scientific knowledge on climate change
- ② An understanding of the causes of mass bleaching
- ② A grounding in bleaching physiology
- ② An understanding of ocean acidification and how it may affect reefs
- ② A background on the emerging connection between climate and coral disease

Background

(<http://www.ncdc.noaa.gov/oa/climate/globalwarming.html>) Human activity has been increasing the concentration of greenhouse gases in the atmosphere (mostly carbon dioxide (CO₂) from combustion of coal, oil, and gas; plus a few other trace gases). There is no scientific debate on this point. Pre-industrial levels of carbon dioxide (prior to the start of the Industrial Revolution) were about 280 parts per million by volume (ppmv), and current levels are greater than 380 ppmv and increasing at a rate of 1.9 ppm yr⁻¹ since 2000. The global concentration of CO₂ in our atmosphere today far exceeds the natural range over the last 650,000 years of 180 to 300 ppmv. According to the IPCC Special Report on Emission Scenarios (SRES), by the end of the 21st century, we could expect to see carbon dioxide concentrations of anywhere from 490 to 1260 ppm (75-350% above the pre-industrial concentration).

Global surface temperatures have increased about 0.74°C (plus or minus 0.18°C) since the late-19th century, and the linear trend for the past 50 years of 0.13°C (plus or minus 0.03°C) per decade is nearly twice that for the past 100 years. The warming has not been globally uniform. Some areas (including parts of the southeastern U.S. and parts of the North Atlantic) have, in fact, cooled slightly over the last century. The recent warmth has been greatest over North America and Eurasia between 40 and 70°N. Lastly, seven of the eight warmest years on record have occurred since 2001 and the 10 warmest years have all occurred since 1995.

Global mean sea level has been rising at an average rate of 1.7 mm/year (plus or minus 0.5mm) over the past 100 years, which is significantly larger than the rate averaged over the last several thousand years. Depending on which greenhouse gas increase scenario is used (high or low) projected sea-level rise in the next 100 years is projected to be anywhere from 0.18 (low greenhouse gas increase) to 0.59 meters for the highest greenhouse gas increase scenario. However, this increase is due mainly to thermal expansion and contributions from melting alpine glaciers, and does not include any

potential contributions from melting ice sheets in Greenland or Antarctica. Larger increases cannot be excluded but our current understanding of ice sheet dynamics renders uncertainties too large to be able to assess the likelihood of large-scale melting of these ice sheets. Healthy coral reefs can probably grow fast enough to keep up with moderate rates of sea level rise. There is some concern that reduced light availability may be a problem, especially for species that grow in deeper areas that may already be light limited. The biggest concern is that other climate factors, especially bleaching and ocean acidification, have been shown to reduce coral growth rates. Slower-growing corals may not be able to keep up with rising sea levels.

(<http://www.pmel.noaa.gov/co2/OA/background.html>) The oceans have absorbed approximately 525 billion tons of carbon dioxide from the atmosphere, or about one third of the anthropogenic carbon emissions released. This absorption has benefited humankind by significantly reducing the greenhouse gas levels in the atmosphere and minimizing some of the impacts of global warming. However, the ocean's uptake of carbon dioxide is having negative impacts on the chemistry and biology of the oceans. Hydrographic surveys and modeling studies have revealed that the chemical changes in seawater resulting from the absorption of carbon dioxide are lowering seawater pH. The pH of ocean surface waters has already decreased by about 0.1 units from an average of about 8.21 to 8.10 since the beginning of the industrial revolution. Estimates of future atmospheric and oceanic carbon dioxide concentrations, based on the Intergovernmental Panel on Climate Change (IPCC) CO₂ emission scenarios and coupled ocean-atmosphere models, suggest that by the middle of this century atmospheric carbon dioxide levels could reach more than 500 ppm, and near the end of the century they could be over 800 ppm. This would result in an additional surface water pH decrease of approximately 0.3 pH units by 2100.

When CO₂ reacts with seawater, the reduction in seawater pH also reduces the availability of carbonate ions, which play an important role in shell formation for a number of marine organisms such as corals, marine plankton, and shellfish. This phenomenon, which is commonly called "ocean acidification," could have profound impacts on some of the most fundamental biological and geochemical processes of the sea in coming decades. Some of the smaller calcifying organisms are important food sources for higher marine organisms. Declining coral reefs due to increases in temperature and decreases in carbonate ion would have negative impacts on tourism and fisheries. Abundance of commercially important shellfish species may also decline and negative impacts on finfish may occur. This rapidly emerging scientific issue and possible ecological impacts have raised serious concerns across the scientific and fisheries resource management communities.

Worksheet or Activity

Discussion: What indications of Climate Change have you observed in your region?

What habitats do you manage that are susceptible to Climate Change?



On-the-Web

Intergovernmental Panel on Climate Change
<http://www.ipcc.ch/>

NOAA “Frequently Asked Questions” on climate change
<http://www.ncdc.noaa.gov/oa/climate/globalwarming.html>

NOAA background on Ocean Acidification
<http://www.pmel.noaa.gov/co2/OA/background.html>

NOAA ocean acidification tutorial
http://coralreefwatch.noaa.gov/satellite/oa/description/oaps_intro_oa.html

Sea Level Rise explorer in Google Maps
<http://www.globalwarmingart.com/wiki/Special:SeaLevel>



Publications and References

Blanchon, P. A. Eisenhauer, J. Fietzke, and V. Liebetrau. 2009. Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. *Nature* 458: 881-884.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi and M.E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318(5857): 1737-1742.

IPCC 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate

Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Raupach, M.R., G. Marland, P. Ciais, C. Le Quere, J.G. Canadell, G. Klepper, and C.B. Field. 2007. Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National Academy of Science (PNAS)* 104(24):10288-102093.

Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, United Kingdom, 712 pp.

Slides

Section 2: Rising Temperature, Mass Coral Bleaching & Bleaching Weather

Learning Objectives

By the end of this module you will have:

- 🌐 A background in rising sea surface temperatures around the world
- 🌐 An understanding of the connection between environmental conditions and coral bleaching
- 🌐 An understanding of the weather conditions that can lead to bleaching

Background

The number of regions reporting mass coral bleaching has increased substantially in recent years. The implications of mass bleaching received global attention in 1997–98, when increased sea surface temperatures associated with El Niño resulted in extensive bleaching of the world’s reefs. Prior to this event, coral bleaching was often considered a local problem—someone else’s problem—resulting from localized stresses. The event of 1997–98 distinguished mass coral bleaching from localized events by the global extent of its impacts across reefs and reef regions of different condition, composition, and geography. It is attributed to causing mass mortalities of corals to many reef regions, in total ‘destroying’ an estimated 16 per cent of the world’s reefs. This event fuelled scientific curiosity about the causes of mass bleaching events and the implications of these events for future coral reef condition.

Using satellite data over the last 20 years, warming in most tropical areas is easily seen. Unfortunately, these warming trends are expected to continue into the future. Comparisons of expected sea temperature increases with bleaching thresholds suggest that the frequency and severity of mass bleaching events will increase, as the temperature is likely to rise faster than coral reef ecosystems can to adjust. This implies that, should tropical seas continue to warm, coral reef ecosystems are likely to undergo significant changes. These changes include losses to biological diversity and coral cover as well as economic losses to the fisheries and tourism sectors.

Sea temperature is the most reliable predictor of the occurrence and severity of large-scale coral bleaching events. An understanding of the factors that influence sea temperature can help managers predict the risk and severity of a bleaching event. Reef managers may get a very useful indication of whether their region is likely to experience increased heating in coming months based on climate predictions. Longer-term predictions, such as seasonal weather forecasts, can be used to assess the probability of weather conditions that contribute to increasing sea temperatures occurring over timescales of weeks to months. Shorter-term predictions, such as weekly weather

forecasts, indicate whether sea temperatures will increase or decrease in coming days and weeks.

Our understanding of mass bleaching suggests that the future condition of coral reefs will be largely influenced by two factors: (1) the rate and extent of sea temperature increases; and (2) the resilience of coral reef ecosystems. The rate and extent of warming will determine the window of opportunity for reefs to adjust through acclimatization, adaptation, and other ecological shifts. For example, fewer and less intense temperature anomalies will reduce the frequency and severity of bleaching events, and slower rates of warming will allow more time for reefs to recover between events that do occur. These relationships mean that the effectiveness of broader efforts to address the rate and extent of warming will have significant implications for local management initiatives. However, such efforts are largely a matter for national and international policy. The focus of this workshop is to consider strategies local coral reef managers can implement to reduce the impacts of mass bleaching events and to restore and maintain the natural resilience of coral reefs to climate change.

Worksheet or Activity

Discussion: Have you witnessed mass bleaching on the reefs in your region?
What were the long terms impacts/recovery in your area?



On-the-Web

Encyclopedia of Earth article on corals and climate change

http://www.eoearth.org/article/Coral_reefs_and_climate_change



Publications and References

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi and M.E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318(5857): 1737-1742.

Marshall P.A. and Schuttenberg, H.Z. 2006. *A Reef Manager's Guide to Coral Bleaching*. Great Barrier Reef Marine Park Authority, Australia.

http://www.coris.noaa.gov/activities/reef_managers_guide/welcome.html

Wilkinson, C., Souter, D. 2008. *Status of Caribbean coral reefs after bleaching and hurricanes in 2005*. Global Coral Reef Monitoring Network, and Reef and Rainforest

Research Centre, Townsville, 152 p.
http://www.coris.noaa.gov/activities/caribbean_rpt/

Slides

Section 3: Delving Deeper into Bleaching Physiology

Learning Objectives

By the end of this module you will have:

- 🌐 A deeper understanding of the mechanisms that cause coral bleaching
- 🌐 A background in how light and temperature combine to cause bleaching
- 🌐 An understanding of how this knowledge can help predict when and where bleaching may occur.

Background

It is often stated that high water temperatures “cause” coral bleaching. That is not strictly true, when you look more closely at the mechanisms within the coral itself.

It’s important to remember that corals host symbiotic algae within their cells, called zooxanthellae. These algal cells photosynthesize just like any plant, and the compounds they produce are a crucial energy source for the coral animals. Within the zooxanthellae there is a complex chemical “machinery” that carries out photosynthesis—pigments that absorb light energy from the sun, and a series of proteins and enzymes that convert the solar energy into sugars/carbohydrates that the plant (and its coral host) can use. During the highest-light periods of even a normal day, the system will be overwhelmed with too much solar energy coming in through the pigments. This excess energy is turned into oxygen free radicals, dangerous compounds that damage the photosynthesis machinery and other crucial parts of the cell. The zooxanthellae have another complex system whose job it is to repair this normal light damage. On normal days, all of the damage from excess light can be repaired.

Unfortunately, stressfully warm temperatures will disrupt the balance of damage and repair. The exact mechanism is not yet known, but the overall result is that the zooxanthellae cannot fully repair the daily light damage from the oxygen free radicals. If these conditions continue over several days or weeks, serious consequences will result. The coral can digest or expel the harmful zooxanthellae, so that they will not be further damaged. Since most of the color of a coral colony comes from the zooxanthellae, the coral will then appear pale or white (“bleached”).

The worst-case scenario is that the stressful conditions are so severe and long-lasting that the coral colony dies. Without its main food source, the coral may starve to death. The oxygen free radicals from the zooxanthellae and the stress from expelling the symbiotic cells may damage the coral’s tissues enough to cause it to die. However, if the stressful light and temperature conditions abate, the coral will be able to recover. The animal will repopulate its tissues with zooxanthellae cells, either from the water column or from reproduction of the few algae cells that remain in the coral tissue. Even if the bleaching doesn’t kill the coral, there are long-term consequences from the stress

of a bleaching event: drastically slowed growth rate, failure to reproduce that year, and higher susceptibility to coral disease infections.

It is clear that bleaching is caused by a combination of strong sunlight and warm temperatures. Clear skies, low wind, neap tides, and reduced sediment can quickly lead to very high light conditions for the corals. Many of those same factors also cause warming at the ocean surface, of course, which sets up the ideal conditions for coral bleaching.



Publications and References

Dove, SG and O Hoegh-Guldberg. 2006. The cell physiology of coral bleaching. In *Coral Reefs & Climate Change: Science and Management*. JT Phinney, W Skirving, J Kleypas & O Hoegh-Guldberg, eds. American Geophysical Union. pp 1–18.

Woolridge, S.A. 2009. Water Quality and coral bleaching thresholds: Formalizing the linkage for the inshore reefs of the Great Barrier Reef, Australia. *Marine Pollution Bulletin* 58:745-751.

Slides

Section 4: Ocean Acidification

Learning Objectives

By the end of this module you will have:

- 🌐 An understanding of the chemistry behind ocean acidification
- 🌐 Current scientific knowledge on what the future will bring
- 🌐 Background on how acidification affects coral reefs

Background

The global oceans are the largest natural reservoir for the excess CO₂ in the atmosphere, absorbing approximately one-third of the CO₂ from human activities each year. As a result, dissolved CO₂ in the surface ocean will likely double over its pre-industrial value by the middle of this century, representing perhaps the most dramatic change in ocean chemistry in over 20 million years.

As CO₂ reacts with seawater it forms carbonic acid, causing a reduction in pH. Seawater is naturally buffered against these pH changes, but the buffering process consumes carbonate ions. Carbonate ion is an essential ingredient in the creation of calcium carbonate (CaCO₃) shells and skeletons produced by many marine organisms.

Reef-building corals construct intricate three-dimensional frameworks by calcification (biological precipitation of CaCO₃). In order for the reef to grow over time, corals must produce CaCO₃ faster than the natural reef removal processes (dissolution, storm export, and bioerosion). Studies of CaCO₃ budgets on coral reefs suggest that these building and erosion processes are nearly balanced at most modern reefs, and net reef accretion is small. Many experiments show a reduced rate of calcification as a consequence of ocean acidification. Laboratory studies have examined the effects on many types of corals and coralline algae, revealing a range of responses from a 3% to 60% decline in calcification rate for a doubling of atmospheric CO₂. Recent field studies have also shown declines in coral calcification rates at the Great Barrier Reef, the Arabian Gulf, and Bermuda. These slower growth rates are probably caused, at least in part, by ocean acidification. Thus, a primary threat of ocean acidification is the potential to compromise the ability for reefs to maintain a positive net accretion, thereby resulting in the loss of habitat and coastal protection. This effect is particularly critical because of sea level rise.

Recent work has also shown secondary effects that suggest there is still a lot to learn about how acidification affects coral reefs. A recent lab study shows that lower pH increases a coral's susceptibility to bleaching. Other potential effects include a reduced capacity to tolerate ultraviolet radiation, and increased bioerosion rates.



On-the-Web

Encyclopedia of Earth article:

http://www.eoearth.org/article/Ocean_acidification

Tutorial on OA and coral reefs, from NOAA Coral Reef Watch:

http://coralreefwatch.noaa.gov/satellite/oa/description/oaps_intro_oa.html

Wikipedia entry:

http://en.wikipedia.org/wiki/Ocean_acidification

Scientific information from a global network of researchers:

<http://ocean-acidification.net/>



Publications and References

Feely R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero. 2004. Impact of anthropogenic CO₂ on the CaCO₃ system in the oceans. *Science* 305: 362-366.

Langdon C. and M. J. Atkinson. 2005. Effect of elevated pCO₂ on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. *Journal of Geophysical Research* 110 (C09S07).

Sabine C. L., R. A. Feely, et al. 2004. The oceanic sink for anthropogenic CO₂. *Science* 305: 367-371.

Slides

Section 5: Global Climate Change and Coral Disease

Learning Objectives

By the end of this module you will have:

- ② An understanding of hypotheses regarding the increase in disease prevalence worldwide
- ② An update on current scientific knowledge on coral diseases
- ② A background on the emerging connection between climate and coral disease
- ② An understanding of the challenges to managing coral diseases
- ② A grounding in field assessment of diseases and other known impacts to corals

Background

Disease is a part of all natural systems. However, when a disease increases in spatial or temporal extent or in its capacity to cause mortality, it can become problematic, necessitating active management. Disease of corals and other reef animals is an emerging issue in marine science and management. Because corals provide the living and self-repairing foundation for reef communities, diseases that cause significant mortality to the primary reef building species are of major concern. This concern is based on evidence that diseases are apparently having greater impacts than before, and at a time when reefs are subjected to increasing threats despite global management efforts. This increase is thought to be brought about by a number of drivers, several of which have an anthropogenic link: 1) degradation of nearshore water quality that stresses benthic organisms and may lower their immunodefense capabilities, or expose them to elevated concentrations of pathogens (e.g., white pox disease of *Acropora palmata* in the Caribbean, caused by a sewage-associated bacterium *Serratia marcescens*); 2) increases in species introductions from shipping and the aquarium trade; 3) extension of the geographic range of pathogenic or parasitic species as a result of warming coastal water (e.g., *Perkinsus marinus*, the protist that causes the disease “dermo” in oysters); 4) introduction of novel pathogens to naïve hosts (e.g., *Aspergillus sydowii*, a soil fungus that causes aspergillois in Caribbean sea fans); and 5) a change in the virulence or infectiousness of a pathogen as a result of a change in its environment (e.g., *A. sydowii* becomes more virulent in slightly warmer water).

It would be helpful to understand how certain key concepts are currently used and defined. As managers, understanding these key concepts will contribute greatly to creating a global body of reef workers who are all “speaking the same language”.

Disease – any impairment that interferes with normal function.

Infectious disease – disease caused by a transmissible agent, such as a bacterium or virus.

Non-infectious disease – disease caused by a non-infectious agent such as a toxin, congenital defect, or environmental stress.

Pathogen – any disease-producing agent; usually a microorganism such as a bacterium, virus or protist.

Outbreak – occurrence of disease at a rate above what is expected in a given population.

Prevalence – the number of disease cases among individuals in a population or area at a given point in time.

Incidence – a change in the number of disease cases within a population or area between two points in time.

Because the science of coral disease is very new, limited empirical evidence exists for a link with climate change. However, several recent key studies have reported compelling associations between elevated sea surface temperature and increased prevalence of white syndrome, bacterial bleaching and black band disease in the Indo-Pacific. In laboratory experiments, black band disease progressed faster within a sick coral, and was transmitted more rapidly between corals, in warmer water. Warmer temperatures have been demonstrated to increase the virulence of the bacterium *Vibrio shiloi* which causes bleaching in *Pocillopora damicornis*. In the Caribbean, disease outbreaks, particularly yellow band disease, have been observed to follow major bleaching episodes, killing corals that survive and apparently recover from bleaching. Extensive work with aspergillosis in sea fans has shown that the host gorgonian (*Ventalina* spp.) has reduced defensive chemistry, while the fungal pathogen (*Aspergillus sydowii*) shows increased virulence, at warmer temperatures. These lines of evidence suggest that disease impacts are likely to increase with rising ocean surface temperatures. However, other consequences of climate change such as rising sea level, which may increase the depth at which many coral communities exist, and ocean acidification, which may have impacts on coral health other than calcification rates, remain unstudied at present.

Coral disease is, therefore, both a new source of coral mortality and reef decline, and a consequence of reef degradation from other stressors. As a developing science, it is challenged by the rather urgent need for management tools which currently do not exist, or have not been adequately tested. In other words, we must, as managers and scientists, develop and test management tools for diseases with inadequate scientific knowledge of how these diseases are operating. We know much about human disease, less about disease in domesticated vertebrate animals and cultured plants, still less about diseases of wildlife, and almost nothing, in comparison, of diseases in lower invertebrates. Our management strategies of diseases for humans and domesticated animals and plants--culling, quarantine, vaccination, and education--are difficult or impossible to apply to a coral reef, with the exception of education. But, whom do we educate and what do we communicate? How do we manage the spread of disease and minimize mortality? Current thinking is that the best proactive management tool for coral disease may simply be to improve and protect water quality and ecosystem function to facilitate the coral's natural immunodefense mechanisms and optimize

resilience. At present, this is chiefly accomplished via establishing and enhancing Marine Protected Areas (MPAs). A growing body of evidence is pointing to a number of ancillary benefits of MPA establishment aside from fishery protection and coral health is one such benefit. However, additional tools will undoubtedly be needed, particularly in cases of disease outbreaks where active response may be needed to mitigate impacts and promote recovery.

Worksheet or Activity

Discussion: What coral diseases and other impacts to coral have you seen in your region? Are there any signs that you have not seen before (i.e., potential new or emerging diseases)? Are there signs that appear to be more common or frequent than before? Do you notice any signs of disease that occur more or less frequently in different seasons (i.e., rainy vs. dry; cool vs. warm)?



On-the-Web

Intergovernmental Panel on Climate Change
<http://www.ipcc.ch/>

NOAA “Frequently Asked Questions” on climate change
<http://www.ncdc.noaa.gov/oa/climate/globalwarming.html>

Coral Reef Targeted Research and Capacity Building for Management
<http://www.gefcoral.org>



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Sutherland KP, Porter JW, Torres C (2004) Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals. *Marine Ecology Progress Series* 266:273-302

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