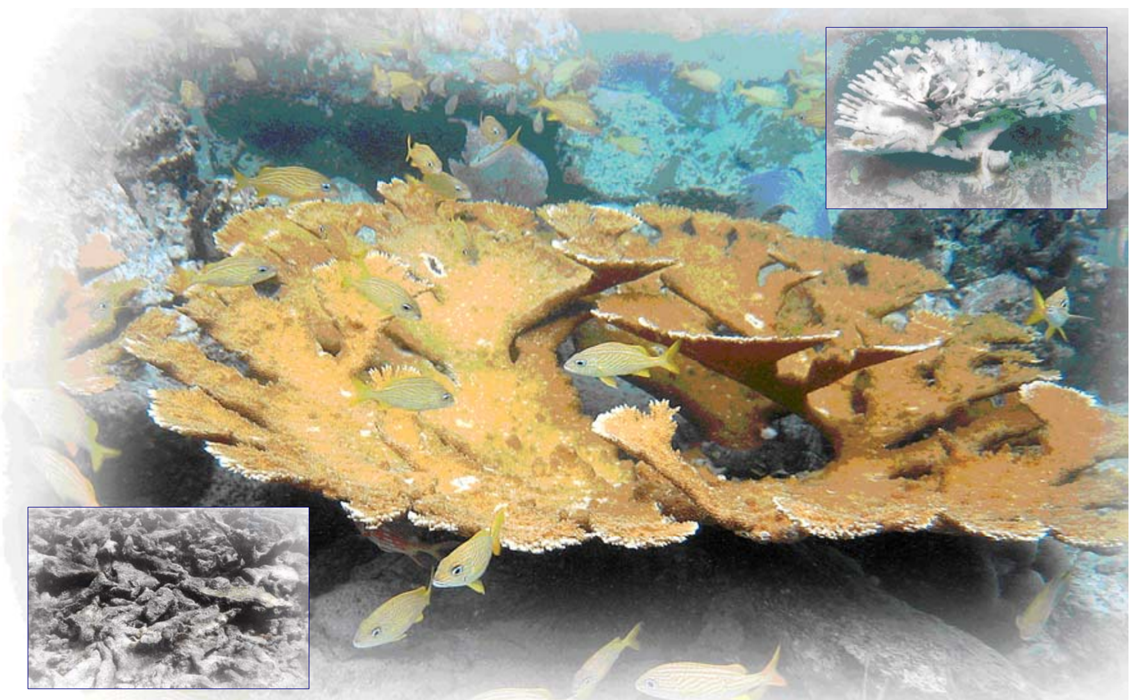
Strategic Science for Coral Ecosystems

2007-2011



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U.S. Department of the Interior
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U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

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Mark D. Myers, Director

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Cover photo: Elkhorn coral (*Acropora palmata*) in the U.S. Virgin Islands, clockwise from top: A growing colony; a bleached colony after the 2005 warm water event; coral rubble damaged by disease and storm waves.

Photo credits (cover and document): G. Brewer, C. Birkeland, J. Brock, M. Field, J. Gardner, R. Halley, C. Rogers, I. Kuffner, S. Ross, K. Sulak, K. Yates

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Executive Summary

Shallow and deep coral ecosystems are being imperiled by a combination of stressors. Climate change, unsustainable fishing practices, and disease are transforming coral communities at regional to global scales. At local levels, excessive amounts of sediments, nutrients, and contaminants are also impacting the many benefits that healthy coral ecosystems provide. This Plan, *Strategic Science for Coral Ecosystems*, describes the information needs of resource managers and summarizes current research being conducted by U.S. Geological Survey (USGS) scientists and partners. It outlines important research actions that need to be undertaken over the next five years to achieve more accurate forecasting of future conditions and develop more effective decision-support tools to adaptively manage coral ecosystems. The overarching outcome of this Plan, if fully implemented, would be in transferring relevant knowledge to decision-makers, enabling them to better protect and sustain coral ecosystem services. These services include sources of food, essential habitat for fisheries and protected species, protection of coastlines from wave damage and erosion, recreation, and cultural values for indigenous communities.

The USGS has a long history of research and monitoring experience in studying ancient and living coral communities and serving many stakeholders. The research actions in this Plan build on the USGS legacy of conducting integrated multidisciplinary science to address complex environmental issues. This Plan is responsive to Federal legislation and authorities and a variety of external and internal drivers that include the President's *Ocean Action Plan*, the recommendations of the Coral Reef Task Force, the information needs of Bureaus in the Department of Interior, the USGS *Bureau Science Strategy* (USGS 2007) and the formal plans of several USGS Programs. To achieve this Plan's desired outcomes will require increased funding and more effective coordination and collaboration among USGS managers and scientists within a national and international framework of partnerships in coral ecosystem science.

As funding permits, USGS coral ecosystem research will focus on three major research Themes and their associated research Actions during the next five years, including:

Theme 1: Reef Structure, Ecological Integrity, and the Role of Marine Reserves

- Explore, discover, map, and characterize shallow deep coral reefs and other sensitive benthic communities.
- Develop and apply geospatial data integration techniques to compare, contrast, and resolve site-scale variability and change in coral ecosystems with landscape-scale heterogeneity and ecological processes.
- Understand the role of physical structure, topographic complexity, and circulation in controlling the biotic organization of shallow and deep reefs.
- Evaluate predator and prey abundances and assess relationships between herbivory, algal cover, and coral recruitment.
- Evaluate community metabolism and calcification, and determine the net ratio of accretion to bio-erosion.
- Assess and monitor the prevalence of disease and reveal disease processes.
- Determine the character of coral-associated microbial communities in shallow and deep systems.
- Determine the nature of disturbances that facilitate establishment of invasive species in relation to the characteristics of the coral community.
- Use genetic, stable isotope, and other techniques to evaluate the pathways and spatial scales that connect shallow and deep reef systems and link marine reserves.

Theme 2: Land-based and Local Impacts

- Determine impacts of land-based sediments on coral reefs, and evaluate how different land uses affect the quantity, rates, and character of sediment delivered to coral reefs.
- Assess the role of sediment and nutrient run-off in causing blooms and/or prolonged growth of benthic algae on coral reefs, and evaluate the interactions of herbivorous species in potentially mediating the spatial and temporal dynamics of the algae.
- Identify the sources, transport pathways, residence times and understand the biological and physiological impacts of contaminants and pollutants on coral ecosystems and their synergistic effects.

Theme 3: Responses to Global Change

- Investigate coral bleaching and recovery, including the synergistic interactions of high water temperatures sunlight, water circulation, microbes, and other environmental variables.
- Investigate the mechanisms of acclimatization and adaptation of corals to high water temperatures and related stressors.
- Evaluate existing and future threats to corals by increased levels of carbon dioxide and increasing acidification of ocean waters.
- Use estimates of expected sea-level rise to model and predict erosion rates, turbidity, and the ability of coral growth to keep pace with rising waters.
- Determine impacts of atmospheric dust on coral reefs.
- Identify paleoecological proxies for coral responses to specific components of climate change.

The Actions, their Implementation, Outcomes, and Measures are listed in a final summary table. Products resulting from this plan will include oral presentations, fact sheets, databases, maps, models, decision-support tools, technical reports, and journal publications.

Purpose and Scope

The purpose of this Plan is to outline a strategy for conducting research on coral ecosystems. This Plan is targeted for a wide audience within the U.S. Geological Survey (USGS), the Department of Interior (DOI), and with other Federal, state, and local government and non-governmental institutions, including scientists, resource managers and decision-makers. Objectives for preparing and sharing this Plan are to 1) better inform existing and prospective stakeholders about coral ecosystem issues, 2) summarize existing USGS activities and capabilities that support coral ecosystem studies, 3) provide a summary of research actions to address priority information needs, and 4) guide the development of implementation plans, detailed work plans, joint research ventures, and budget initiatives.

This is an ambitious Plan, catalyzed in part by the growing recognition that coral ecosystems are now in a crisis of degradation (Pockley 2000) that is projected to increase under current climate models [Intergovernmental Panel on Climate Change (IPCC 2007)]. Enhanced research support for USGS, other DOI Bureaus and collaborating partners is needed to understand the dynamics of coral ecosystems and to apply that knowledge to effective decision-support, adaptive management, and modeling frameworks. Resource managers require information and tools to make wise decisions in their efforts to balance economic growth and ecosystem vitality.

Healthy coral ecosystems provide vital goods and services to the Nation.

This Plan had its origins in three planning meetings, most recently in May 2004. USGS managers and coral researchers from across the Bureau met to describe current research, define the distinctive role that USGS plays in coral ecosystem science, and develop a suite of long-term research goals. Since the May 2004 meeting, key events have transpired that required a refocusing of the proposed strategic approaches. Examples of these recent events include: The release in late 2004 of the President's *Ocean Action Plan*; priorities of the U.S. Coral Reef Task Force (CRTF); increased attention on deepwater corals and marine managed areas, including the designation of new coral reef marine reserves by

Executive Order of the President and the National Park Service; increased attention on global climate change; and unprecedented levels of coral bleaching and disease.

In response to these and other drivers (detailed below), this Plan represents a Bureau-wide, multidisciplinary approach to serve the DOI and to promote the leveraging of resources with other national, regional, and local partners, collaborators, and stakeholders. Priority issues are explained and relevant actions proposed that maximize the use of existing USGS capabilities and anticipated resources. Implementation of this Plan will lead to a better understanding of fundamental physical, chemical and biological processes that structure and control the integrity and viability in coral ecosystems. The resulting research will provide decision-makers with information to understand natural versus anthropogenic change and to deal more effectively with coral degradation. New knowledge and tools well help promote coral resilience and recovery and thereby sustain and restore the many values that healthy coral ecosystems provide.

The scope of this Plan encompasses shallow and deep coral ecosystems. While distinctions are made between shallow vs. deep/cold coral habitats, these systems provide important ecological services and functions, and they share common threats and research needs. Recommendations in the *Ocean Action Plan* call for research and management actions that are specific to both shallow and deep coral communities. The DOI has significant stewardship responsibilities for managing and conserving shallow and deep coral habitat in areas under its jurisdiction, including parks, refuges, the Outer Continental Shelf (OCS), and the Exclusive Economic Zone (EEZ). USGS serves DOI and the Nation by conducting relevant research, mapping, and monitoring in Federal, State, and international lands and waters.

Need

Coral ecosystems worldwide are in decline. These stressed and threatened habitats include shallow, sunlit (photic) coral reefs in tropical regions as well as deep/cold (aphotic) reef communities where corals sometimes predominate. Coral ecosystems are geological/biological complexes composed of hundreds to thousands of interacting species, providing essential goods and services that contribute $30 billion (Cesar et al. 2003) to economies worldwide. In the broadest sense, coral ecosystems include adjacent seagrass, mangrove, and sand communities that are linked to shallow and deep coral habitats through physical, chemical and biological connections and complex interdependencies. Healthy, productive coral ecosystems are important on local to global scales by providing or promoting:

- The most biologically diverse marine habitats
- Sources of food
- Essential habitat and nurseries for fisheries and protected species
- Protection of coastlines from wave damage and erosion
- Vital functional linkages among terrestrial, estuarine, and marine habitats
- Sand for beaches and construction
- Recreation
- Vibrant coastal economies
- Cultural values for indigenous communities
- Genetic biodiversity for biomedical research and unique bioactive chemicals for pharmaceuticals
- Geochemical and biological archives of ocean change
- Opportunities for scientific exploration, discovery, and education
- A sense of wonder and aesthetic appeal for their beauty and diversity

Hence, the deterioration of coral communities results in significant cultural, recreational, scientific, and economic losses. More than one-fourth of the world's shallow coral reefs have been seriously impaired over the past 25 years. In the Caribbean, roughly two-thirds of reefs are in jeopardy (Burke and Maidens 2005). In 2006, elkhorn and staghorn coral (*Acropora palmata* and *A. cervicornis*, respectively), once abundant throughout Florida and the Caribbean, were listed as Federally threatened species. Recent damage and future threats to coral ecosystems are unprecedented, including:

- Over-fishing, harmful fishing practices, and resulting impacts that cascade through food webs
- Climate change, including sea-level rise, increased water temperatures, and elevated carbon dioxide concentrations (resulting in ocean acidification)
- Pathogens and disease
- Degradation, fragmentation and loss of interdependent wetland and mangrove habitats
- Invasive species
- Storms
- Coastal development, human population pressures and concomitant input of nutrients, contaminants, and sediments
- Mining, dredging, oil and gas drilling
- Ship groundings and anchoring damage

These threats vary in their spatial and temporal extent, but climate change, unsustainable fishing practices, and disease are arguably the most widespread perils to coral ecosystems. From whatever cause, the loss of biodiversity, especially of the major predators and herbivores, is often followed with increased prevalence of algal cover, coral disease, and failure of reefs to recover. While knowledge of coral ecology has advanced significantly over the past few decades, the accelerating declines in the extent, health, and resiliency of coral ecosystems have reached the crisis stage.

White plague disease has caused significant mortality of major reef-building corals in Florida and the Caribbean. USGS and partners in the Coral Disease and Health Consortium are investigating the extent and nature of white plague and other coral diseases (contacts: Caroline Rogers, Thierry Work, Bane Schill, Frank Panek, Leslie Dierauf).

Mandate

The proposed actions presented in this Plan are responsive to Federal legislation and authorities that describe the mission and responsibilities of the DOI and by extension, guide coastal and marine research at the USGS. External guidance to address coral ecosystem issues includes 1) directives in the President's *Ocean Action Plan* and the associated *Ocean Research Priorities Plan*; 2) recommendations of the CRTF (co-chaired by the Secretaries of Interior and Commerce), including the need to inventory, monitor and identify major causes and effects of coral reef degradation; 3) the information needs of the DOI stewards of the Nation's coral resources. These stewards include the National Park Service (NPS), the U.S. Fish and Wildlife Service (FWS), and the Minerals Management Service (MMS) for parks, refuges, submerged and OCS lands under their respective jurisdictions; and 4) other Federal, state, U.S. Territorial and Commonwealth partners who provide reimbursable funding or in-kind services that leverage and expand joint research opportunities.

With the addition of the Exclusive Economic Zone (EEZ) to the United States in 1983, more than half of the U.S. is encompassed by submerged land – some 1.8 billion acres. The extent of U.S. shallow-water coral ecosystems is estimated to be 9.1 million acres (Rohmann et al. 2005). The DOI alone is accountable for more than 3.6 million acres of shallow coral reef habitat through the stewardship responsibilities of the NPS and the FWS. The resource base for deep living corals is even larger. Although deep coral habitats have not been adequately mapped, deep corals are known to occur at locations throughout the EEZ, particularly along offshore banks, seamounts, shelves, and walls where depths change abruptly. About 4800 species of coral are known worldwide, and about 65 percent of the taxa occur at depths in excess of 40 meters (~120 feet). The deepest living known coral was taken at a depth of nearly 6.5 kilometers (~4 miles). It is the MMS that has the regulatory and environmental oversight for leasing submerged lands of the EEZ for all forms of energy (oil, gas, gas hydrates, and wind) development and sand and gravel extraction. As DOI's chief science Bureau, the USGS has a special obligation to serve the information needs of all DOI Bureaus, i.e., including requests to map, characterize, study, and monitor shallow and deep coral ecosystems.

Internal Bureau project planning is, in turn, guided by the Bureau's 2007 *Strategic Science Plan* (USGS 2007) and the goals of several USGS Programs. For coral ecosystem activities described herein, applicable goals include those established by the Coastal and Marine Geology (CMG) Program, including *A Plan for a Comprehensive National Coastal Program*. Other USGS Programs with relevant goals in support of coral ecosystems include the Terrestrial, Freshwater and Marine Ecosystems Program (TFME); Fisheries: Aquatic and Endangered

Resources Program (FAER); Wildlife: Terrestrial and Endangered Resources Program (WTER); Earth Surface Dynamics Program (ESD); and Cooperative Research Unit Program (CRU).

Past and Current USGS Coral Ecosystem Research

USGS scientists have a long history of research and monitoring experience studying ancient and living coral communities in U.S. waters and occasionally in other parts of the world. Reef geology, paleo-history, mapping, and habitat characterization were emphasized in the past. These efforts continue, and in recent years study planning has been more strategically and ecologically focused with an increased emphasis on applied studies and

Some corals on Ofu Island, American Samoa are adapted to temperature extremes. Experiments are underway to evaluate the potential use of such thermally tolerant corals in restoring reefs impacted by climate change (contact: Chuck Birkeland).

experimental protocols. Study oversight has been redefined with more rigorous peer-review and explicit performance measures and outcomes that align with multiple USGS Program goals. The trend is for more integrated, interdisciplinary efforts. Multiple Principal Investigators and outside collaborators are now standard for USGS coral reef and deep reef studies. Advances in technologies for remote sensing, Geographic Information Systems (GIS), in-situ sensors and experimental chambers, submersibles and remotely operated vehicles, biochemistry, molecular biology, physiology, microchemistry, isotopic analysis, and modeling have afforded new opportunities for discovery and understanding. These technological advances are being applied to current USGS research and monitoring efforts related to coral reef ecology, climate change, coral diseases and bleaching, microbial ecology, genetics, physical and chemical oceanography, contaminants, and comprehensive "ridge to reef" watershed issues.

In situ samplers on the island of Molokai measure sediment loads on reefs and other potential stressors in relation to adjacent land use and watershed practices (contact: Mike Field, Pat Chavez, Gordon Tribble, Jon Stock).

Many current USGS coral ecosystem studies are being conducted on submerged lands managed by NPS, MMS, FWS in the Pacific, Gulf of Mexico, and Caribbean. These and related efforts are also geared to address issues that are important to the CRTF and the Local Action Strategies of the States of Hawaii and Florida, the U.S. Territories and Commonwealth Nations, including Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands. One outstanding example of multiple stakeholder participation is an ongoing USGS research partnership in Hawaii, based on the native Hawaiian land unit, the *ahupua'a*, and traditional natural resource management systems that holistically encompass the ecosystem from the high ridges to the near-shore reef (i.e., "ridge-to-reef"). Collaborators include representatives from four USGS Disciplines, the State of Hawaii, FWS, NPS, the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Natural Resources Conservation Service (NRCS), and The Nature Conservancy (TNC). These efforts include research, assessments, and monitoring related to how changes in land-use practices affect land cover and soil retention; surface and ground water studies and resulting changes in sediment load and additions of nutrients and contaminants that are carried to the sea by streams and groundwater discharge; the transport and fate of sediment and other pollutants in the reef environment; and impact on reef health and the relative role of pollutant threats and other natural and human-induced threats to the reef ecology.

In collaboration with the NPS, USGS developed monitoring protocols (in use in the Virgin Islands and Dry Tortugas) that use video cameras, sonar, and GPS to document reef changes and ensure precise and accurate locator information (contact: Caroline Rogers).

The first quantitative coral reef study transects in the Pacific were established in American Samoa in 1917. These reefs have high species diversity and other unique characteristics that are currently being studied by USGS and collaborators. The relatively pristine reefs of Samoa's Ofu Lagoon provide an excellent field laboratory for research on global climate change, coral reef resilience, and primary mechanisms driving changes on coral reefs. About 80 species of reef-building scleractinian corals appear to live well in Ofu Lagoon although the water temperatures frequently reach 35.5° C and the temperatures often fluctuate by 6.5° C daily. This site is providing an exceptional opportunity to examine coral adaptation, the mechanisms for acclimatization by coral, and the possible factors in the physical environment that can ameliorate the stress to coral of especially warm seawater.

USGS field work is sometimes linked to laboratory investigations of coral physiology, coral genetics, and coral microbes. For example, scientists at the USGS Leetown Science Center (LSC) use a re-circulating sea water system and associated aquaria (microcosms) to maintain a variety of coral reef plants and animals. The facility is useful for designing experimental manipulations that test coral stressors and for conducting research on coral disease where pathogens are isolated. LSC also has state-of-the-art genetics facilities that allow for efficient, high throughput analyses of corals for examining population genetic structure (e.g., extent of gene flow between reefs) and genomics (e.g., the study of functional genes that may act in response to stressors). Microbiologists at the USGS Florida Integrated Science Center in St. Petersburg are studying bacteria, archaea, and fungi, using both standard culture and molecular techniques, and their ecological role in shallow and deep systems.

USGS has recently (2006) signed a Cooperative Agreement with the University of the Virgin Islands to enhance the Virgin Islands Environmental Resource Station (VIERS), which is located on NPS lands on St. John, U.S. Virgin Islands. USGS has a long history of research and monitoring partnerships with the NPS on St. John. The USGS/NPS long-term coral reef monitoring project in the Virgin Islands has proved vital in providing quantitative information on the 2005 coral bleaching and disease event and in evaluating subsequent recovery of the reef community. A refurbished VIERS will provide important research support services for the ongoing studies of coral bleaching and disease, including dive operations, laboratory and office space, boats, and equipment storage. The Cooperative Agreement complements a Memorandum of Understanding between USGS and the NPS that was signed in 2006 to promote joint collaborations between scientists and resource managers on St. John and throughout the southeast U.S.

The USGS is also a partner in the Palmyra Research Consortium, a new research entity including Federal partners and eight universities on the FWS Palmyra Marine and Atoll Refuge. Palmyra is a resource that can be used to address a variety of research objectives that may not be possible elsewhere. Palmyra Atoll lies at an oceanographic crossroad in the Pacific Ocean, and as such can be explored relative to its role as a center for larval recruits and larval dispersal to other Pacific reefs. Palmyra reefs are not significantly affected by local human impacts and serve as a natural laboratory to explore the effects of local to global natural variability of oceanic, atmospheric, and biologic processes on reefs, as well as any human-induced processes of global change. Understanding the effects of natural variability in Palmyra reefs will be transferable to other locations more impacted by human activities and help distinguish the effects of natural variability from local human-induced threats.

USGS scientists were co-investigators in the discovery of novel, deep (photic) coral communities at Florida's Pulley Ridge and led to its designation as a protected area by the Gulf of Mexico Fishery Management Council. Efforts to understand deep coral ecosystems and address the information needs of the MMS and the Fishery Management Councils requires special tools and techniques. High resolution multi-beam mappers, seismic survey gear, submersibles, Remotely Operated Vehicles (ROVs), video and digital still cameras, and innovative collection devices are being used by USGS scientists and collaborators to characterize coral and chemosynthetic ecosystems in depths to 3000 meters. Mapping and related ecological studies of deep coral (*Lophelia*) communities on the Gulf of Mexico continental slope are providing MMS with the information necessary to protect these uncommon habitats from potential impacts of deep water oil and gas development and from potential deep trawling for fishes.

A Long-Term Vision

An overarching vision of this Plan is to describe the geological and historical framework of ancient and living coral communities and develop a more complete understanding of the physical, chemical, and biological processes – both natural and anthropogenic – that now control or influence the structure, function, and ecological relationships within those communities. USGS will study coral ecosystems in the context of understanding linkages and interactions, at various spatial and temporal scales, with surrounding landscapes and "seascapes," including adjacent terrestrial, estuarine, and marine systems. USGS will use this knowledge to inform partners and stakeholders and work collectively to develop and provide decision-support tools and techniques that will promote adaptive approaches to ecosystem-based management and models to forecast change.

Fundamental to achieving this vision is more effective coordination, collaboration, and integration within the coral research and management communities, including other Federal, state, territorial, and local governmental, non-governmental organizations, and international partners. These efforts will begin from within USGS by engaging USGS Regional Ocean Science Teams with the responsibility to work with scientists and USGS Program Coordinators to help frame priority issues, identify research opportunities, and promote budget initiatives. These Teams will help connect Science Centers, Regions, Program Coordinators and external stakeholders and through consensus building, identify and realize common goals. Connections with external stakeholders will be facilitated by active USGS participation on key Federal ocean commissions and working groups, including for example, the Joint Subcommittee on Ocean Science and Technology (JSOST), Subcommittee for Integrated Management of Ocean Resources (SIMOR), the CRTF, and DOI teams. Substantive progress in achieving the vision requires enhanced, stable funding with more effective leveraging of resources across USGS Programs and among participating stakeholders. USGS must expand its scientific and technical workforce while making significant investments in the infrastructure that is necessary for research excellence. USGS scientists must have access to modern facilities and equipment that enable new ideas and methods to be tested, results confirmed, products produced efficiently, and broadly disseminated. Strategically located marine laboratories, experimental aquaria, access to ships, boats, and field equipment, and the means for scientists to be adequately supported at remote field locations are vital to state-of-the-art data collection, analysis, interpretation, and reporting. The step-wise design and conduct of the comprehensive suite of the coral reef research activities outlined below will not be possible by depending on existing USGS resources. USGS will continue to rely on the expertise of other Federal and academic collaborators. Large ships and expensive equipment will be leased, rented, or shared. Nevertheless, an enhanced cadre of dedicated, permanent USGS

Remote sensing techniques, including hyper-spectral LIDAR, are used to map and characterize reef and seagrass habitats and determine the degree to which these tools can provide rapid assessments of the communities' health (contact John Brock; Pat Chavez, Dave Zawada).

scientists is required to provide intellectual leadership and to maintain the long-term vision of service to the DOI and our Nation. A realistic approach, using existing personnel, capabilities, facilities, and current levels of reimbursable funding, is proposed for Fiscal Years (FYs) 2007 and 2008. However, significantly increased levels of new base funding are required, beginning in FY 2009, to adequately address and answer the urgent and complex questions related to declining coral ecosystem health.

To achieve the goals of this Plan, an enhanced, long-term research effort, as outlined below, will require additional investments in personnel, technologies, and equipment. With an increase in available resources, many of the Actions outlined below can be completed within a 5-year time frame. Other Actions may require a decade or more to complete. Definitive, relevant information that addresses these Actions will come as incremental steps toward a full understanding of change and resiliency in coral ecosystems. These efforts will lead to decision-support tools and increasingly accurate models, providing marine resource managers with more effective means to prescribe safeguards, mitigate impacts, and sustain coral reef ecosystems for the many valued goods and services that they provide.

A Five-Year Strategy

USGS coral ecosystems research will focus on three major research "Themes" during the next five years, including:

- Theme 1: Reef Structure, Ecological Integrity, and the Role of Marine Reserves
- Theme 2: Land-based and Local Impacts
- Theme 3: Responses to Global Change

These research Themes are interrelated and collectively will explain the history, composition, and natural processes of coral reefs; clarify what and how anthropogenic-induced changes occur; and describe specific management options that would help sustain and conserve natural processes and associated goods and services.

The issues, actions, and recommendations described below are fully compatible with guidance provided by the CRTF, the President's *Ocean Action Plan* and associated *Ocean Research Priorities Plan*, and the other primary drivers of USGS coral ecosystem research as mentioned above under "Mandate."

This Plan is structured with a synoptic statement of the problem and need for each Theme. Each Theme has a primary "Objective, followed by "Actions," including both current and proposed study topics of high priority. The "Explanations" provide brief descriptions of each Action. A final Table (1) lists the Actions, with corresponding descriptions of "Implementations," "Outcomes," and "Measures."

Theme 1: Reef Structure, Ecological Integrity, and the Role of Marine Reserves

Coral ecosystems exist as complex habitat mosaics (e.g., reef, seagrass, mangrove, sand), with dynamic biotic and abiotic connections and dependencies that encompass multiple spatial and temporal scales. Scientists are challenged to describe these relationships and understand how and why ecosystem components and processes change, either naturally or as influenced by humans. Resource mangers, in turn, must use decision-support tools that weigh ecological, social, and economic factors and move beyond simply identifying symptoms of coral reef stress and monitoring losses, to actually addressing the underlying causes of coral ecosystem degradation. Many coral reef communities now fail to recover after natural or human disturbances end or are removed. It is possible that unidentified stressors or mechanisms exist or that fundamental components or processes have been eliminated or altered, thereby preventing a return to their previous states of ecosystem structure (spatial distribution of species assemblages) and function (biotic and geochemical processes and species interactions) when these systems were first studied decades ago. Evidence suggests that only healthy coral communities have the structures and functions, i.e., ecological integrity, to provide the raw materials (component parts) and mechanisms that are necessary for reefs to recover. Many coral reef scientists believe that the integrity of coral ecosystems has been lost primarily from direct and indirect effects of over-fishing. Hence, to tease out the underlying causes of coral degradation, experiments are needed that compare and contrast ecological integrity in fished and unfished (marine reserve) areas. When fishing stops, changes in fish populations are relatively predictable; however, it is not clear how changes in fish trophic groups affect benthic resources. Deep coral communities that, to date, have not been fished remain relatively pristine. It is vital that remote or uncommon ecosystems are found, explored, and characterized before uncertain, future impacts threaten our ability to understand their fundamental integrity.

Objective of Theme 1: Understand the physical, chemical, and biological processes that control the integrity of coral ecosystems, and apply that knowledge to decision-support tools that encompass ecological, social, and economic factors and thereby promote effective management and sustain coral ecosystem resources.

Action 1-1: Explore, discover, map and characterize shallow and deep coral habitats and other sensitive benthic communities.

Explanation: Comprehensive efforts to map, inventory, and describe benthic habitats are essential for developing science-based predictive models and decision-support tools. Geospatial and related environmental information are vital to characterizing coastal and offshore resources, documenting human influences and landscape change, and establishing the context for integrated assessments and systems models. Geologic and seabed mapping and seamless topographic/bathymetric elevation models are fundamental for revealing watershed to coastal to offshore linkages and potential ecological relationships. Light Detection and Ranging (LIDAR), hyperspectral sensors, satellite, precision bathymetry, seismic methods and other remote sensing technologies will continue to provide invaluable tools for discovering and characterizing shallow and deep reefs. Explorations using submersibles and Remotely Operated Vehicles (ROVs) have led to the discovery of *Lophelia pertusa*, a deep water (200-2000 meters) coral that forms dense colonies and extensive reef habitat for fishes and invertebrates in the Gulf of Mexico and along the Atlantic OCS. At even greater depths (400 to 3000 meters in the Gulf of Mexico), rare chemosynthetic communities have also been found in association with seeps of methane and

The distribution, structure, and function of deep coral communities, some dominated by Lophelia and Oculina, are being studied, including their role as fish habitats, their food web interactions and pelagic linkages (contacts Ken Sulak, Steve Ross, Kathy Scanlon, Amanda Demopoulos).

hydrogen sulfide. The same geological features that make the Gulf of Mexico an important source of petroleum are the reason that seeps and associated chemosynthetic communities exists, and links between seep environments and coral mounds have been described. USGS has partnered with MMS, NOAA, the University of North Carolina, and other universities to develop information about the biology and ecology of Lophelia reefs and deep chemosynthetic communities.

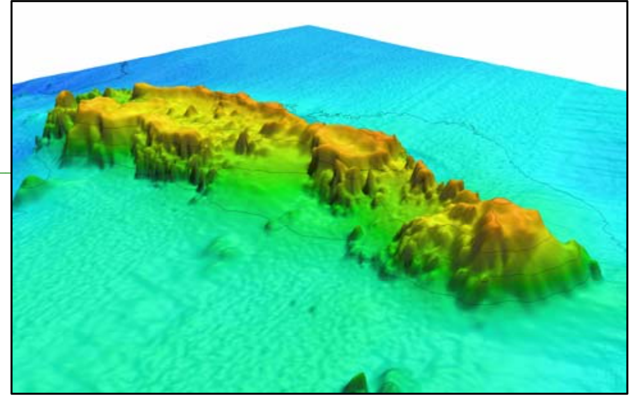
Action 1-2: Develop and apply geospatial data integration techniques to compare, contrast and resolve site-scale variability and change in coral ecosystems with landscape-scale heterogeneity and ecological processes.

Explanation: Landscape (or "seascape") approaches are needed to deal with the spatial and temporal complexities of coral reef dynamics. Existing physical, chemical, and biological datasets should be compiled to build powerful methods to examine spatial heterogeneity and temporal patterns of distribution, abundance, and health of corals and other key plant and animal species in shallow reef communities.

Remote sensing data and ongoing process studies must be integrated to evaluate quantitative relationships and help define data gaps. Geospatial techniques, associated statistics and modeling can be used to define ecotopes, and evaluate connectivity among networks of reefs, seagrasses, and mangroves. GIS tools should be adapted and applied to important and specific coral reef management questions; for example, relating to the function of marine reserves, impacts of fishing and other anthropogenic stressors, transport and retention of fish and invertebrate larvae (propagules), influence of land-uses in adjacent watersheds, and natural (storm) disturbance. These tools and techniques should also be applied to tackle environmental threats and conservation issues for the elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*) (the only corals listed as "threatened" under the Endangered Species Act), relating to bleaching, disease, resistance, resilience, and recovery. Areas with high biological diversity or ecological significance - so-called "hot spots"- should be identified and evaluated in the context of landscape processes.

Action 1-3: Understand the role of physical structure, topographic complexity, and circulation in controlling the biotic organization of shallow and deep reefs.

Explanation: Scientists have a poor understanding of how the geological characteristics and three-dimensional complexity of hard substrates influences their suitability for coral settlement, survival, and growth. Topographic complexity is generally believed to increase the habitat "choices" that are available for settlement by coral larvae. Following disturbances such as hurricanes, crown-of-thorns outbreaks, and increased bio-erosion resulting from eutrophication, the topographic complexity of reef structure characteristically decreases. Deep corals and the three-dimensional structure of deep reefs, which are likely centuries old, are susceptible to damage from bottom trawling and oil and gas activities; recovery will likely be slow. Reduced topographic complexity provides fewer refuges for fishes, and fewer fishes may result in a decrease in community resilience. Thus, topographic complexity of reef sites in relation to density, biomass, and diversity must be determined. If correlations between rugosity and community structure are revealed, managers may be able to use remotely sensed LIDAR data, high resolution multibeam bathymetry, and laser line scanning to predict habitat quality, coral reef viability, and other characteristics that are indicative of reef health.



Precision bathymetry and habitat mapping are crucial for biological investigations and for managing and protecting sensitive benthic communities such as this "Pinnacles" site in the Gulf of Mexico (contacts: Page Valentine, Brad Butman, Lawrence Poppe, Jane Denny, Walter Barnhardt, Dave Twichell, Guy Cochrane, Jane Reid, Pete Dartnell, Curt Storlazzi, Roberto Anima).

Action 1-4: Evaluate predator and prey abundances and assess relationships between herbivory, algal cover, and coral recruitment.

Explanation: The ratio of predators to prey in terms of population size, recruitment potential, and space are critical factors in community integrity. When herbivores are limited by natural factors such as reef topography for shelter or by human activities such as overfishing, then the herbivores are unable to control the increase of algae. Conversely, when a disturbance reduces the prey population more than the predators, the prey continue to decrease in a positive feedback process until the prey become locally extinct. On the other hand, high intensity of predation or grazing pressure can prevent the establishment of invasive alien species and preempt the defensive morphological and chemical traits of algae. Studies should determine the thresholds in relative abundances of predators and prey, including grazers and algae, at which positive feedback mechanisms switch directions. The inhibitory role of cyanobacteria and nuisance algae in the settlement and recruitment survival of coral requires further investigation.

The disappearance of urchins may be related to the overgrowth of algae on many reefs. Interactions among corals, algae and urchins are being evaluated in the field and with controlled laboratory experiments (contact: Ilsa Kuffner).

Action 1-5: Evaluate community metabolism and calcification, and determine the net ratio of accretion to bio-erosion.

Explanation: Coral reefs are believed to exhibit similar rates of community metabolism and reef calcification independent of latitude and longitude. Atlantic coral reefs are similar to Pacific coral reefs in regard to these ecosystem processes and these fundamental processes are standard from the equator to perhaps 34°N. There is ultimately a latitudinal limit, but we should determine coral growth and metabolic rates inside and outside reserves. One operational quantitative index of reef "health" or ecological integrity is the ratio of accretion to bio-erosion. A hypothesis is that healthy, diverse reefs with substantial stocks of fishes and living coral cover will show net accretion while over-fished reefs will show net bio-erosion.

The SHARQ® (Submersible Habitat for Analyzing Reef Quality) experimental chamber is used to measure reef calcification, photosynthesis, respiration, and other process studies of reef communities (contacts: Bob Halley, Kim Yates).

Further, reef ecosystems in effectively enforced no-take reserves should show net accretion and areas outside reserves will show net bio-erosion. These hypotheses require investigation because the role of herbivory in bio-erosion is complex. Predation on corals provides access to coral skeletons for bio-eroders; but by grazing on algae, herbivores may facilitate the dominance of living cover of coral and crustose coralline algae. The strategy will be to define an index of reef health ranging from topographically complex reefs to less complex reefs.

Action 1-6: Assess and monitor the prevalence of disease and reveal disease processes.

Explanation: Observations of the diversity and extent of coral diseases have increased off Florida and the Caribbean over the past two decades. We lack understanding of the underlying mechanisms of coral pathologies, which inhibits our ability to manage the growing coral health problems. Coral bleaching and disease prevalence require close observations coupled with research on pathogenicity and etiology. The use of genetic markers for analysis of healthy and diseased corals should be further explored, focusing on the development of strain-specific probes for identification of resistant clones of corals to disease. An effort is needed to survey and record the distribution of wide-spread coral diseases in the Caribbean, but also in Hawaii and in the tropical Pacific before diseases become prevalent. Such efforts will add to our body of knowledge so that an increase in disease prevalence in the future can be addressed with some understanding of the physical and/or biological factors that facilitated the increase.

Bacteria, archaea cyanobacteria, fungi, and viruses are natural components of reefs, and certain microorganisms are vital to coral health. USGS is studying the ecological function of these microbes as well as their role as disease agents (contacts: Chris Kellogg, John Lisle, Bane Schill).

Action 1-7: Determine the character of coral-associated microbial communities in shallow and deep systems.

Explanation: Coral-associated bacteria are distinct from those in the water column, and the microbial communities appear to be species-specific in regards to the coral host. There are also differences in bacterial community compositions between bleached and normal corals in the Caribbean. The resilience of the reef community may be related to whether the bacterial community associated with a coral colony changes in response to temperature stress or other environmental factors. Differences in the bacterial community are apparent between healthy and diseased corals, and between diseased and apparently healthy tissues a distance from disease lesions. This indicates that the coral-associated microbes respond to organism-level changes, and may be good indicators of stress or physiological changes in the coral before they are visibly evident. Because the "normal" microbiota is thought to help protect coral from pathogenic organisms (either by niche occupation or production of antibiotics), a change in the microbial community composition may compromise the coral's resistance to disease. An understanding of the coral-associated microbial communities, including associated bacteriophages, is essential to an understanding of coral community resilience, ecological integrity, and potential for disease control. Molecular, genetic, and genomic techniques hold great promise for understanding the vital role that microbes play in coral health.

Action 1-8: Determine the nature of disturbances that facilitate establishment of invasive species in relation to the characteristics of the coral community.

Explanation: Habitat alteration and loss of ecological integrity are the main factors facilitating invasion by alien species. Introductions may be intentional, as releases from the aquarium trade, or passive, e.g., from ships' ballast water. Alien marine species may have a difficult time becoming established in coral reef communities with high biodiversity, but such relationships have not been rigorously tested. Once invasion is facilitated by human activities, generalized foreign invaders are likely to become incumbent and

USGS and DOI partners are evaluating the role and function of fully protected (no fishing) marine reserves and their value in conserving marine biodiversity and maintaining normal ecosystem functions (contacts: Caroline Rogers, Chuck Birkeland)

nearly impossible to remove. Hawaiian reefs have been particularly prone to invasions, in some cases with significant ecological impacts. For example, food consumption by a single introduced species of grouper (roi) was determined to be an important factor shaping reef fish communities on the Island of Hawaii. It is important to determine the nature of disturbances hat most effectively facilitate the establishment of alien species and the characteristics of coral reef communities that tend to repel invaders. It is also important to determine the harmful or benign nature of invaders so that managers can assess the potential severity of the problem once the invasive species is recognized. In some cases, marine invaders may have significant public heath implications. One example is the invasive gastropod, *Melanoides*, found in Biscayne Bay, Florida, which harbors liver and lung flukes that may pose a threat to humans.

Action 1-9: Use genetic, stable isotope, and other techniques to evaluate the circulation pathways and spatial scales that may connect shallow and deep reef systems and link marine reserves.

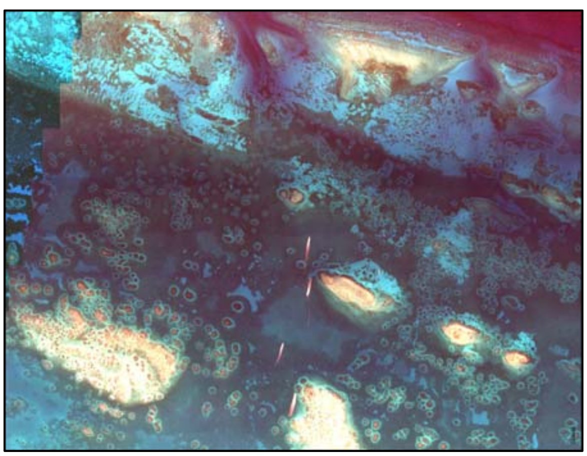
Genetic and molecular techniques are providing new information on coral reproduction, geographic affinities, and the role of sub-lethal environmental stressors on sea grasses and shallow and deep corals (contacts: Tim King, Cheryl Morrison, Bane Schill, Jim Murray).

Explanation: While many marine organisms have planktonic larval stages that can be dispersed over large distances, evidence indicates that dispersal of most larvae of reef-associated animals is on the order of tens of kilometers rather than hundreds of kilometers. An understanding of how currents and circulation patterns transport larvae (in horizontal, vertical, and temporal dimensions) over large and small-scales is vital information. Linkages (connectivity) among reefs are an important factor to consider in locating marine reserves and in evaluating recovery potentials of damaged systems. Finding and reserving sources of genetic material has a high priority. Analytical approaches are needed to determine the degree of speciation and fine-scale genetic structure of reef organisms. Sources of replenishment for bleached and disease corals in the Caribbean and Florida must be determined. Ongoing genetic studies of the deepwater coral *Lophelia* and associated invertebrates are important to understanding reproductive connectivity among deep reef sites in the Gulf of Mexico and their ability to recover from disturbances by oil and gas activities and bottom trawling. USGS has partnered with MMS and NOAA to broaden the scope of *Lophelia* reef studies from the Gulf of Mexico to the South Atlantic coast. The hypothetical relationship of Palmyra as the source for the coral reef biota of the eastern tropical Pacific Faunal Province is especially important to verify because the eastern tropical Pacific is particularly prone to extinctions.

Theme 2: Land-based and Local Impacts

Sediment, nutrients, and contaminants from a variety of land-based activities may adversely impact coral reef ecosystems. Other sources include ship discharges, oil spills, and natural hydrocarbon seepage. Compelling evidence indicates that pollutant and contaminant sources have increased globally as a result of human population pressures. Excess nitrogen, phosphorus, dissolved organic carbon, and iron fosters algal growth that may be detrimental to coral settlement and growth; these nutrients may cause bacterial overgrowth and result in coral disease and mortality. Mercury, cadmium, copper, zinc, vanadium, various hydrocarbons, pesticides, personal care products, antimicrobials, and pharmaceuticals that are present in wastewaters are potential toxicants to marine organisms. These pollutants may be transported in surface water runoff, groundwater seepage, and atmospheric deposition. Strategies to address these issues include a combination of laboratory experiments, field studies, and "ridge-to-reef" monitoring strategies and integrated research.

Objective of Theme 2: Understand the origin, fate, and effects of local and land-based physical, biological, and chemical stressors to shallow coral reef communities, determine their individual and collective effects, and provide managers with the knowledge and tools to predict, prevent, and mitigate any detrimental impacts to shallow coral ecosystems.



Measurements and modeling of surface and groundwater flux and associated contaminants in Biscayne Bay National Park and adjacent areas are being conducted to uncover possible linkages to coral and seagrass losses (contacts: Chris Langevin, Bob Halley, Lynn Wingard, Pam Scholfeld)

Action 2-1: Determine impacts of land-based sediments on coral reefs, and evaluate how different land uses affect the quantity, rates, and character of sediment delivered to coral reefs.

Explanation: Terrigenous sediment runoff and deposition on coral reefs may significantly impact coral health by inhibiting sunlight and photosynthesis, smothering and abrading coral, preventing coral recruitment, and promoting growth of algae. System-level studies are needed that combine information on watershed characteristics and terrigenous sediment deposits, surface-and groundwater-flow, transport and fate of sediment and other pollutants in the reef environment, and their impact on reef ecology.

Multidisciplinary "ridge-to-reef" investigations in Hawaii use an holistic watershed approach to understand land-use practices, sediment and contaminant flux, and their impacts on reef communities (Contacts: Mike Field, Curt Storlazzi, Eric Grossman, Susan Cochran, Ann Gibbs).

Improved GIS tools and modeling techniques can provide resource managers the ability to predict and evaluate runoff and sedimentation rates and impacts with various land-use and mitigation scenarios. Multi-partner, "ridge-to-reef" investigations are well-developed in Hawaii. The term "ridge-to-reef" implies the connectivity of terrestrial, freshwater, and marine habitats (from mountain ridges to coral reefs). It is the recognition that the health of coastal ecosystems may be strongly influenced by land-use practices in adjacent watersheds, and that multidisciplinary, integrated studies are required to understand the processes, both natural and anthropogenic, that impact reefs.

Action 2-2: Assess the role of sediment and nutrient run-off in causing blooms and/or prolonged growth of benthic algae on coral reefs, and evaluate the interactions of herbivorous species in potentially mediating the spatial and temporal dynamics of the algae.

Explanation: In tropical and subtropical waters worldwide, there have been significant declines in coral cover and an increase in algal cover on reefs. A decrease in live coral cover, followed by the proliferation of macroalgae (termed a phase shift) is widely recognized as indicative of coral reef decline. Coral recruitment is poor in reef areas that are blanketed with algae and cyanobacteria and algae. There may be correlations between introduced sediments, nutrient levels, cyanobacteria and algae, together with complex interactions of the kinds and numbers of invertebrate and fish grazers and their respective diets.

Action 2-3: Identify the sources. transport pathways, residence times, and understand the biological and physiological impacts of contaminants and pollutants on coral ecosystems and their synergistic effects.

Explanation: The effects of contaminants and pollutants on coral reefs at the molecular, cellular, organism, population, and system levels are essentially unknown. Objectives should include understanding at what concentrations suspect chemicals or chemical combinations impair coral growth, immune response and reproduction or interfere with the ability of coral larvae to successfully settle and survive. Functional genomic studies can address what biochemical pathways are active under basal and stressed conditions. Groundwater-carried pollutants have been implicated in the decline of reefs in some areas, including those in Biscayne Bay, but recent sampling and modeling results do not implicate subsurface flows as contributing significant levels of pollutants to the Bay's nearshore areas. Atmospheric deposition of contaminants over large geographical areas may be deleteriously affecting benthic and planktonic marine organisms. Stable and radiogenic isotope studies can identify nutrient sources and pathways.

Theme 3: Responses to Global Change

Global change is causing fundamental, potentially irreversible alterations in the setting in which coral reefs thrive. Researchers are showing that increases in water temperature, ultraviolet radiation, carbon dioxide, atmospheric deposition, and the rate of sea-level rise will have progressively adverse effects on coral ecosystems. The consequences will be unprecedented. The development of tools to predict coral ecosystem responses to environmental change and identification of features that impart resistance and resilience of coral communities are vital for managers to plan strategies to protect coral resources.

Objective of Theme 3: Understand, quantify, and model how climate change will transform the structure of coral communities and the biogeochemical processes associated with reef health and productivity (calcification, photosynthesis, respiration, recruitment), and evaluate where and how habitat characteristics, genetic adaptations, and coral-associated microbes may influence coral's tolerance and resilience to environmental change.

Action 3-1: Investigate coral bleaching and recovery, including the synergistic interactions of high water temperatures sunlight, water circulation, microbes, and other environmental variables.

Explanation: Although some of the direct effects of climate change are well established (e.g., high water temperatures can result in coral bleaching), the mechanisms and synergistic effects are poorly understood. Coral bleaching, for example, is only partially predictable, because other factors such as light intensity, turbidity, water motion, algal symbionts, and bacterial populations interact with temperature. The idea that corals can "swap out" symbionts should be addressed in the context of coral bleaching. We have insufficient understanding of physiological tolerance, acclimatization, and adaptation of coral reef communities to a host of environmental parameters associated with global change.

Action 3-2: Investigate the mechanisms of acclimatization and adaptation of corals to high water temperatures and related stressors.

Explanation: Coral bleaching most often occurs when corals are subjected to water temperatures 1-2 degrees greater than is "typical" for their seasonal maximum. Nevertheless, some corals appear to resist bleaching at high temperature at the same time that other colonies of the same species bleach at

NPS/USGS long-term coral monitoring data proved invaluable in monitoring the nature and extent of the 2005 coral bleaching event in the Virgin Islands National Park. The degree of recovery is still being evaluated (contact: Caroline Rogers).

lower temperature just a few meters away. The physiologic, genetic, and microbiologic factors that allow some corals to survive high temperature must be determined. An examination of the genetic structure and microbes of coral populations in American Samoa is testing the hypothesis that the populations in a back-reef moat, living in stressful, high-temperature conditions, differ in genetic markers and microbes from populations of the same species a few tens of meters away on the fore-reef slope. Whether populations only tens of meters apart can differ in adaptation to local conditions is a fundamental question for coral reef managers faced with limited options in dealing with climate change impacts. If some coral populations are found that are adapted to high seawater temperatures, these populations should be given highest priority for conservation and management.

The ability of coral polyps to metabolize calcium and create their hard skeletons may be severely compromised as the ocean becomes more acidic (contacts: Kim Yates, Lisa Robbins, Bob Halley).

Action 3-3: Evaluate existing and future threats to corals from increased levels of carbon dioxide and increasing acidification of ocean waters.

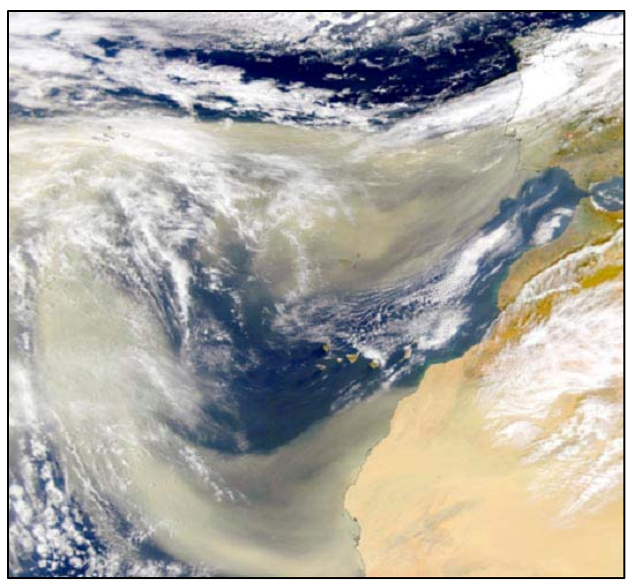
Explanation: Acidification occurs when the oceans absorb excess carbon dioxide from the atmosphere, decreasing the pH and the availability of carbonate ions that are needed to combine with calcium ions to form calcium carbonate. Decreased availability of carbonate ions makes it more difficult for calcifying organisms to form their shells, tests, and skeletons. Measurements to-date have focused on a few members of the reef community and have not considered other potentially significant physical-chemical interactions. Strategies should include the following: determining how higher pCO_2 will effect other members of the coral reef community; measuring community photosynthesis at higher pCO_2; clarifying the relation between calcification and photosynthesis at higher pCO_2; and determining biologically mediated interactions between sediments and pore fluid and elevated CO_2.

Action 3.4: Use estimates of expected sea-level rise to model and predict erosion rates, turbidity, and the ability of coral growth to keep pace with rising waters.

Explanation: The scientific community has largely ignored the effect of forecasted, higher-than-present sea levels and accelerating rates of rise on framework reefs. Rapid rise of sea-level may outpace coral growth rates. In some cases, rising sea levels may actually benefit some very shallow reefs. This action will require supporting research to model wave energy and island erosion at different reef flat depths, predict rates of sediment yield and flux, and document reefs experiencing different rates of relative sea-level rise. Questions that need to be addressed include:

- How will water circulation change across the reef system as sea-level increases over the next century?
- What impact will changes in wave dynamics have on reef processes?
- How will the reef respond to circulation and wave energy changes?
- What is the character of the feedback between reef change and hydrodynamic energy?
- What will be the net effect of changes in sea-level on sediment production, resuspension, and transport of pollutants, nutrients, and larvae?
- How will the sediment cycle change?
- Will there be more or less sediment derived from the adjacent watershed and coastal plain? What will be its fate, i.e., longer or shorter residence times?
- Will sea-level rise affect reefs through erosion of materials stored in adjacent coastal plains and stream deltas?

Action 3.5: Determine impacts of atmospheric dust on coral reefs.

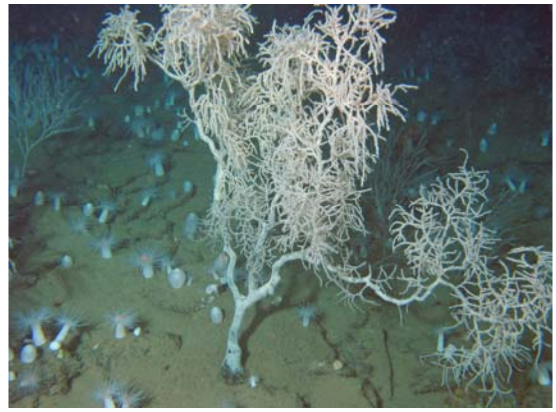


Possible linkages between reef degradation and the contaminants and pathogens associated with African and Asian dust events are being investigated in the Caribbean and Hawaii (contacts: Ginger Garrison, Dale Griffin).

Explanation: Fine dust particles eroded from the world's great deserts, along with associated nutrients, chemical contaminants, and microbes, are transported through the atmosphere and deposited on the surface of the earth and ocean, sometimes thousands of miles from their sources. Global ocean-atmosphere systems, regional meteorology, local surface conditions, and human activities are the major drivers controlling the quantities of dust and contaminants lifted into the atmosphere and the distance the dust is transported. Climate change is expected to increase the amounts of dust transported in the future. Atmospheric deposition of dust has been shown to trigger Harmful Algal Blooms (HABs) in the Gulf of Mexico and off the coast of China. Direct and indirect evidence indicate that deposition of these materials to the sea surface can expose coral reef communities to toxic chemicals, bioavailable nutrients, and microorganisms. Field studies have determined potential sources of dust, evaluated variability in transport, and quantified dust characteristics, including chemical contaminants, and microorganisms. Major concerns include: The effects of dust-derived nutrients on reef microbe pathogenicity; the effect of atmospheric pollution and ocean acidification on contaminant bioavailability and mobility; and the effects of chemical contaminants on photic zone organisms (phytoplankton), coral spawn, and coral reproduction and immune function. Controlled laboratory exposure experiments are needed to isolate and confirm detrimental effects of dust components to coral reef organisms. While dust has been implicated in one octocoral (soft coral) disease, scleractinian (stony/reef-building) corals require testing. Geographic analysis of the contaminant load in coral reef organisms at dust impacted and unimpacted sites is needed.

Action 3-6: Identify paleoecological proxies for coral responses to specific components of climate change.

Explanation: The fossil record contains information relevant to today's coral reef crisis. The chemistry that is encapsulated in the growth bands or segments of shallow and deep-water corals may allow reconstruction of the paleo-ecology, including the high-resolution history of climate change. Carbon, nitrogen, sulfur isotopes, and metal in the annual growth rings of deep-water corals (some living specimens are 2000 years-old) reflect fluxes that are related to environmental change. Similarly, benthic foraminifera may be used to evaluate both current geochemical and morphological studies and past environments through geochemical and morphological studies.



This deep water black coral (Antipatharian), photographed from a submersible in the Gulf of Mexico, is at least several hundred years old. The annual growth bands in such coral may hold incomparable data on ocean chemical and climate history (contacts: Chuck Holmes, Steve Ross, Ken Sulak).

Products

All USGS studies that are conducted under this Plan will be required to develop and communicate data, results, interpretations, and recommendations under strict requirements for quality assurance/quality control and data management. The highest standards of peer and policy review will be maintained as prescribed by USGS *Fundamental Science Practices*. The aim is to communicate sound, objective study results to a variety of audiences with different levels of scientific and technical knowledge, including the public, legislators, resource managers, and scientists. Specific products that can be expected are detailed in Table 1 and include:

- Oral presentations for partners, conferences, and symposia
- Fact sheets
- Databases
- Maps and GIS data layers
- Models
- Decision-support tools
- Technical reports formatted to meet the specific needs of DOI partners and reimbursable contracts
- Journal publications

References Cited

Burke, L., and J. Maidens 2005. Reefs at Risk in the Caribbean. World Resources Institute, Washington D.C. 80 pp. (*http://www.wri.org/biodiv/pubs_description.cfm?pid=3944*)

Cesar, H., L. Burke and L. Pet Soede. 2003. Economics of worldwide coral reef degradation. WWF-Netherlands and ICRAN. 24 pp.

IPCC 2007. Climate change 2007: The Physical Science Basis. Summary for Policymakers. Intergovernmental Panel on Climate Change, Geneva, 18 pp.

Pockley, P. 2000: Global Warming Identified as Main Threat to Coral Reefs. Nature, 407 (6807), 932.

Rohmann, S., J. Hayes, R. Newhall, M. Monaco, and Grigg, R. 2005. The area of potential shallow-water tropical and subtropical coal ecosystems in the United States. Coral Reefs 24(3):370-383.

USGS. 2007. Facing Tomorrow's Challenges: USGS Science in the Coming Decade, U.S. Geological Survey, Reston, VA. 93 pp.

TABLE 1. ACTIONS, THEIR IMPLEMENTATION, OUTCOMES, AND MEASURES

Long-Term Goals: Describe the geological and historical framework of ancient and living coral communities and develop a more complete understanding of the processes – both natural and anthropogenic – that control or influence the structure, function, and ecological relationships within those communities. Use this new knowledge to inform partners and stakeholders and work collectively to develop accurate models to forecast change and promote adaptive approaches to ecosystem-based management.

Objective 1: Understand the physical, chemical, and biological processes that control the integrity of coral ecosystems, and apply that knowledge to decision support tools that encompass ecological, social, and economic factors and thereby promote effective management and sustain coral ecosystem resources.

Actions	Implementation	Outcomes	Measures
1.1 Explore, discover, map and characterize shallow and deep coral and other sensitive benthic communities.	As funding permits, CMG will continue partnerships with the NPS, FWS, and NOAA in mapping shallow coastal parks, refuges, and sanctuaries. TFME will support MMS with information needed to understand and protect deep water systems. USGS will partner with MMS-contracted academics and NOAA to study Gulf of Mexico (GOM) chemosynthetic communities in Fiscal Years (FYs) 2007-2008. USGS participation in a new GOM *Lophelia* study will be conducted in collaboration with the MMS in FY 2008-2011.	Baseline information on the status and trends of coral communities are used by managers to make decisions that lead to habitat protections and enhance ecosystem-based management strategies. NPS, MMS, FWS, NOAA, and states directly benefit from these efforts.	Accurate, detailed map sets, data layers, and reports are delivered to partners.
1.2 Develop and apply geospatial data integration techniques to compare, contrast, and resolve site-scale variability and change in coral ecosystems with landscape-scale heterogeneity and ecological processes.	Ongoing research and monitoring efforts should be enhanced through new budget initiatives. New efforts should focus on expanding information in Hawaii and the greater Pacific and focus on Florida and Caribbean sites recently designated as marine reserves. Incorporation of long-term data sets, available from the NPS, USGS, NOAA, and several universities, should be a primary goal. Support is expected to continue from TFME and CMG. Anticipated FY 2007-2009 funding from the USGS ER State Partnership Program (SPP) and DOI Landscape (DOI Lands) Initiative will be used to catalyze these efforts.	Decision-makers use information to develop criteria for designating and managing marine reserves effectively in an adaptive management framework. Management of coastal parks and refuges in the U.S. Virgin Islands, Florida, Hawaii and the greater Pacific benefit directly.	Geo-referenced data sets and associated reports are delivered to partners on the spatial and temporal scales of variability and change in coral ecosystems as they relate to natural and human impacts.
1.3 Understand the role of physical structure, topographic complexity, and circulation in controlling the biotic organization of	Recent studies in Biscayne Bay should be expanded to the Pacific, Florida, and Caribbean on how geology, topography, and circulation interact to influence the structure reef communities. Secure, long-term funding is required and must be leveraged with partners and collaborators, including the CMG, NPS, NOAA, and universities. New	Knowledge of physical-biotic linkages leads to improved decision support and successful restoration strategies. Resource management	Reports and models are produced and delivered to stakeholders that define how the biotic attributes of healthy reefs are influenced by

shallow and deep reefs.	GOM *Lophelia* studies proposed by MMS to begin in FY 2008 with USGS participation, may provide the opportunity to study relationships of how geology and bottom currents relate to deep coral colony formation, growth, and stability.	decisions by MMS, NPS, and NOAA are enhanced.	foundational geologic structures and small-scale circulation patterns.
1.4 Evaluate predator and prey abundances and assess relationships between herbivory, algal cover, and coral recruitment.	With continued support from TFME and CMG, USGS scientists will partner with NPS, FWS, NOAA, states, and numerous academics to resolve relevant issues related to the food web dynamics of coral communities. New funding would allow enhanced efforts in Hawaii, American Samoa, Florida and the U.S. Virgin Islands. New, comparative studies in marine reserves, including Palmyra Atoll, are needed to evaluate the role of unfished systems in maintaining complex food web structures.	Informed resource managers stipulate measures to protect keystone species, leading to reef recovery and stability.	Definitive guidance documents are delivered that explain the role of predator and prey species in maintaining reef health.
1.5 Evaluate community metabolism and calcification, and determine the net ratio of accretion to bio-erosion.	Shallow marine reserves in Florida, Caribbean, Hawaii, Samoa, and Palmyra Atoll can serve as natural laboratories and control sites for the necessary experimental protocols, which should utilize the SHARQ (Submersible Habitat for Analyzing Reef Quality), other quantitative tools, and real-time sensors. New funding, beginning in FY 2009, is required to build on existing efforts and lead to successful outcomes.	Analytical tools are used to inform management decisions, leading to improved restoration and conservation strategies.	Quantitative measures of reef growth and productivity are developed and used widely as reliable indicators of reef health.
1.6 Assess and monitor the prevalence of disease and reveal disease processes.	Shallow reefs in the U.S. Virgin Islands, Puerto Rico and Florida afford ample opportunities to explore coral disease questions, but new funding is required to deal with the complexity of disease issues. Hawaii and Pacific Islands should be monitored in anticipation of future disease outbreaks. Rigorous monitoring must be matched with field and laboratory research. Coral "lab rat" species need to be cultured for disease studies. The idea of harvesting coral specimens for experimental purposes from offshore oil and gas platforms should be explored in cooperation with the MMS. Self-contained experimental sea water systems and aquaria, e.g., at the USGS Leetown Science Center (LSC), should be promoted for developing and holding corals for disease challenge studies and for genomic studies of gene expression in healthy and diseased specimens. USGS scientists from the National Wildlife Health Center (Madison and Honolulu) should work in close partnerships with NOAA and academic investigators. The TFME, FAER and WTER Programs should support these efforts with funding from successful FY 2009 budget initiatives.	Managers use coral disease information to evaluate the origin of land, water, and air-borne pathogens and stressors, and they implement effective mitigation practices that reduce and eliminate disease in coral communities.	Fundamental information on coral pathologies are discovered and communicated. Databases of diseases and their attributes, locations, prevalence, diagnostics, and disease agents are made available to compare with corresponding information on coastal water quality.
1.7 Determine the character of coral-associated microbial communities in shallow and deep systems.	Ongoing studies at shallow (American Samoa, Florida) and deep (Gulf of Mexico, Alaska) are currently being funded by the TFME and CMG Programs and from various reimbursable sources; these important efforts should be more strongly supported in future years with new funding. Additional investigations on the ecology of microbes that are associated with *Lophelia* are expected to be supported by TFME Program funds from FY 2008-FY 2011.	New knowledge, coupled with near real-time monitoring of bacterial symbionts and pathogens, lead to rapid diagnoses of coral health and incipient coral disease. Potential mitigation strategies	Syntheses of information on coral-microbe associations and relationships of coral condition to genetically differentiated variability in microbial communities are widely distributed to stakeholders.

		are weighed and used effectively by managers to protect coral resources.	
1.8 Determine the nature of disturbances that facilitate establishment of invasive species in relation to the characteristics of the coral ecosystem.	Invasives species threats warrant additional funding support beginning in FY 2009. USGS scientists are encouraged to link ongoing and proposed coral ecology studies, as necessary, with complementary investigations of invasive species and to seek reimbursable funds from partners and collaborators.	Enhanced models provide managers with forecasting tools to predict invasion routes and candidate species. Destructive invasions are prevented or curtailed.	Meta-analysis techniques and models are developed that reveal definitive insights on processes that lead to the spread of invasives and those reef conditions that facilitate the establishment of invasives.
1.9 Use genetic, stable isotope, and other techniques to evaluate the circulation pathways and spatial scales that connect shallow and deep reef systems and link marine reserves.	The SPP and DOI Lands Initiative for FY 2007-FY 2009 may provide USGS scientists and collaborators with seed money to evaluate connectivity among coral reef communities in and around marine reserves in the U.S. Virgin Islands and/or Dry Tortugas. These investigations are expected to attract complementary support from the NPS, NOAA, and several universities. The TFME is expected to participate with MMS in FYs 2008-2011 in studying deep *Lophelia* communities in the GOM, including resolving issues of reef connectivity. To achieve the desired outcomes, new funding sources are needed, beginning in FY 2009.	Informed managers from NPS, FWS, MMS, and states use modeling tools to designate and fully protect critical (source) populations of corals, and other keystone invertebrates and fishes.	Databases and models on circulation patterns, coral genetics, and habitat affinities are delivered to decision-makers that accurately portray physical and biological connectivity among various coral communities.
Objective 2: Understand the origin, fate, and effects of local and land-based physical, biological, and chemical stressors to shallow coral reef communities, determine their individual and collective effects, and provide managers with the knowledge and tools to predict, prevent, and mitigate any detrimental impacts to shallow coral ecosystems.			
Actions	**Implementation**	**Outcomes**	**Measures**
2.1 Determine impacts of land-based sediments on coral reefs, and evaluate how different land uses affect the quantity, rates, and character of sediment delivered to coral reefs.	Land-use practices that are adjacent to Hawaii's coral reefs afford the appropriate setting for monitoring, field experiments, and associated laboratory studies to test the impacts of sediments on coral ecosystems. Ongoing efforts have focused on "ridge-to-reef" processes on Molokai, which can serve as a model for studies in the U.S. Virgin Islands as well as the other main Hawaiian Islands. The establishment of a relatively natural reference site (e.g., the NPS's Kipahulu watershed) could serve as a control area for "ridge-to-reef" efforts, including impact studies of land use and restoration strategies. CMG support for these research and monitoring efforts is expected to continue through FY 2011, with support from NPS, the State of Hawaii, and NOAA.	GIS models and other forecasting tools provide land-use planners with impact scenarios and lead to management options for improving water quality guidelines that afford protections to reef resources and local economies.	Assessments of different land use practices are conveyed to resource managers that describe and model the quantity, rates and character of sediment delivered to the reefs define linkages between pollutant and nutrient levels in the watershed and on adjacent reefs.
2.2 Assess the role of sediment and nutrient run-off in causing blooms and/or	Field work and mesocosm experiments that address this Action have been supported by the CMG and TFME Programs. Additional support is needed to quantify and model relationships of sediment inputs, nutrient	Resolution of issues in Hawaii and the U.S. Virgin Islands support of the needs of the	Presentations and reports are delivered that describe and rank stressors and impacts and

prolonged growth of benthic algae on coral reefs, and evaluate the interactions of herbivorous species in potentially mediating the spatial and temporal dynamics of the algae.	loads, growth of benthic algae, and grazing pressures of herbivores, with comparison between reef communities in Hawaii and the U.S. Virgin Islands.	CRTF Local Action Strategies. The knowledge gained and applied ensures that coastal resources are protected.	explain linkages and processes between run-off and resulting influences on algae growth and herbivore abundance.
2.3 Identify the sources, transport pathways, residence times and understand the biological and physiological impacts of contaminants and pollutants on coral ecosystems and their synergistic effects.	Monitoring and research in Biscayne Bay, the Florida Keys, the U.S. Virgin Islands, Hawaii, and elsewhere have received insufficient support to tease-out the complex nature of the multiple, potentially confounding environmental factors, that may influence coral health. New funding initiative are required that are aligned with USGS and partner programs to conduct controlled laboratory, microcosm, and field experiments with standard and modified ecotoxicological methods.	Models and decision-support tools provide land managers with a holistic "ridge-to-reef" perspective that is applied successfully to ecosystem-based management and effective mitigation of contaminant and pollutant sources.	Reports are provided to stakeholders that fully document the transport and fate of fine-grained material and associated chemicals. Site-specific studies lead to an evolution from conceptual to 2-D and 3-D models of sediment, contaminant, and pollutant dynamics.

Objective 3: Understand, quantify, and model how climate change will transform the structure of coral communities and the biogeochemical processes associated with reef health and productivity (calcification, photosynthesis, respiration, recruitment), and evaluate where and how habitat characteristics, genetic adaptations, and coral-associated microbes may influence coral's tolerance and resilience to environmental change.

Actions	Implementation	Outcomes	Measures
3.1 Investigate coral bleaching and recovery, including the synergistic interactions of high water temperatures, sunlight, water circulation, microbes, and other environmental variables.	Long-term monitoring and research partnerships in the U.S. Virgin Islands involving USGS, NPS, NOAA, and several universities proved vital after the 2005 bleaching event to evaluate losses and subsequent disease and/or recovery. In partnership with NPS, NOAA and university collaborators, USGS scientists need to expand the scope of these studies with new funds beginning in FY 2009 to further understand the mechanisms involved. Enhanced monitoring is needed, including in situ sensors that will better analyze environmental factors associated with variable bleaching and recovery over both small and large spatial scales. Future bleaching events should be anticipated with carefully planned, hypothesis-driven, experimental protocols.	Accurate models forecast impacts to coral parks, refuges, and sanctuaries and help evaluate management options and potentials for recovery and restoration.	Research and monitoring in the Pacific, Caribbean, and Florida provide the necessary databases, assessments, and evaluations of coral ecosystem status and projected trends in light of projected climate change.
3.2 Investigate the mechanisms of acclimatization and adaptation of corals to high water temperatures and related stressors.	Additional laboratory studies, including physiological tests, microbial and genetic analyses of corals from American Samoa and the U.S. Virgin Islands are needed to address questions about coral acclimatization and adaptation. The TFME and ESD Programs and USGS partners should collaborate to fund these additional studies with budget initiatives and new funding in FY 2009.	Managers possess the knowledge for critical habitat designations and for sustaining and transplanting corals that are tolerant to the projected extremes of climate change.	Reports and publications are delivered that answer questions about the ability of some coral species and communities to tolerate and adapt to high water temperatures and associated stressors.

3.3 Evaluate existing and future threats to corals from increased levels of carbon dioxide and increasing acidification of ocean waters.	These studies are beginning in FY 2007 with seed funding from the CMG Program. The CMG, ESD, and TFME Programs should work together proactively to provide support for these studies with new funds beginning in FYs 2009 by assisting USGS scientists in establishing and extending Federal and university collaborations.	Decision-makers have sufficient science-based information and decision-support tools that are necessary to accurately model future environmental scenarios and thereby minimize coral degradation caused by the decreasing pH of ocean waters.	Technical papers and models are completed that describe coral biology and population dynamics as influenced by ocean acidification.
3.4 Use estimates of expected sea-level rise to model and predict erosion rates, turbidity, and the ability of coral growth to keep pace with rising waters.	This Action is being partly addressed with ongoing USGS research collaborations in Hawaii that are supported primarily by CMG. The strategy is focused on three components: 1) recent reef history as a guide to the future behavior; 2) the effect of sea-level rise on transport dynamics; and 3) the effect of sea-level rise on sediment yield to reefs. Enhancement of this research with new funding will lead directly to: conceptual models; site-specific studies of the likely changes in turbidity and circulation that will result from modest and extreme sea-level rises; and working 2-D and 3-D models that will enable managers to work with USGS scientists to better understand and predict change. Substantive increases in budgetary resources are needed to expand these studies to other islands and coasts that are vulnerable to sea-level rise.	Models provide land resource managers with tools to anticipate change. Effective decisions are made relating reef response and human adaptation to rising sea levels.	Publications and space-based models are developed that help visualize, prioritize, and weigh various inundation, erosion, and turbidity scenarios as threats to living resources, human health and infrastructure.
3.5 Determine impacts of atmospheric dust on coral reefs.	Collaborations and partnerships have been established with other Federal agencies (NPS. FWS, NOAA, EPA), state and U.S. Territorial agencies, universities NGOs, and international government agencies. Collection and analysis of atmospheric dust should continue at selected monitoring sites in the Caribbean and in the dust source region, with funding from ESD, CMG, and CONT. New funding is needed for laboratory experiments that challenge selected marine organisms and their associated microbiological communities with realistic exposure levels of dust, known dust-associated pathogens and contaminants. Sub-lethal, physiological and molecular effects should be investigated using corals, their associated zooxanthaellae and microbial symbionts.	Information drives management and regulatory recommendations and decisions related to dust control in source regions and mitigations in impacted areas.	Presentations and reports are communicated that provide comprehensive analyses of dust sources, components, variability, and impacts to coral communities.
3.6 Identify paleoecological proxies for coral responses to specific components of climate change.	If the analysis of preliminary data from deep Atlantic coral specimens looks promising, limited funds should be made available by the ESD and CMG Programs to test deep corals collected from the Gulf of Mexico during upcoming (TFME Program-funded) cruises of the GOM Chemosynthetic Communities Study (FY 2007) and proposed *Lophelia* investigations (FYs 2008-2011). If these efforts look promising in FY 2008, new funding should be found in FY 2009 to support an expansion of the research to other deep and shallow coral sites.	Reconstruction and modeling of past ocean temperatures and associated ocean conditions are use to develop credible forecasting scenarios that are used by decision-makers in establishing U.S. climate change policies.	Technical reports and publications are transmitted that describe and quantify paleo-ecological events in the ocean's temperature and geochemical history as recorded in the growth bands of selected coral species.

Glossary

CMG	USGS Coastal and Marine Geology Program
CONT	USGS Contaminant Biology Program
CRTF	Coral Reef Task Force
CRU	USGS Cooperative Research Unit Program
DOI	Department of Interior
EPA	U.S. Environmental Protection Agency
EEZ	Exclusive Economic Zone
ESD	USGS Earth Surface Dynamics Program
FAER	USGS Fisheries: Aquatic and Endangered Species Program
FWS	U.S. Fish and Wildlife Service
GOM	Gulf of Mexico
JSOST	Joint Subcommittee on Ocean Science and Technology
LSC	USGS Leetown Science Center
LIDAR	Light Detection and Ranging
MMS	U.S. Minerals Management Service
NRCS	Natural Resources Conservation Service
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
NPS	National Park Service
PES	USGS Priority Ecosystems Study Program
ROV	Remotely Operated Vehicle
SHARQ	Submersible Habitat for Analyzing Reef Quality
SIMOR	Subcommittee for Integrated Management of Ocean Resources
SPP	USGS Eastern Region State Partnership Program
TFME	USGS Terrestrial Freshwater and Marine Ecology Program
TNC	The Nature Conservancy
USGS	U.S. Geological Survey
VIERS	Virgin Islands Environmental Resource Station
WTER	USGS Wildlife: Terrestrial and Endangered Species Program