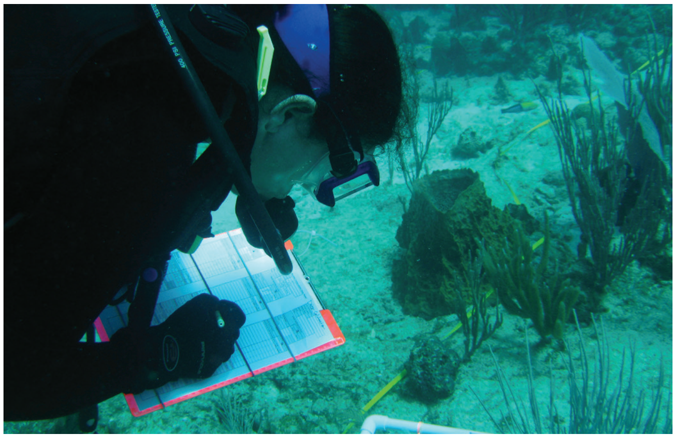
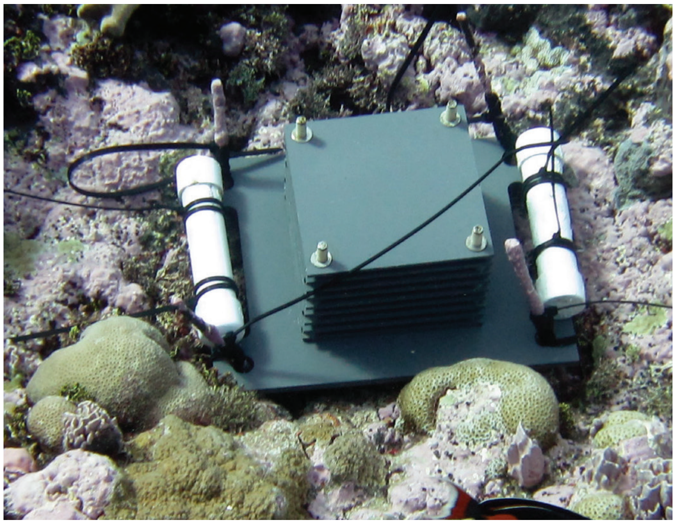
NOAA Coral Reef Conservation Program

National Coral Reef Monitoring Plan





2014

NOAA Coral Reef Conservation Program
National Coral Reef Monitoring Plan

This report was made possible through funding support from NOAA's Coral Reef Conservation Program. For more information about this document, or to request a copy, please email *coralreef@noaa.gov*, or visit *www.coralreef.noaa.gov*, or fax your request to (301) 713-4389.

NOAA Coral Program (2014). *National Coral Reef Monitoring Plan.* Silver Spring, MD, NOAA Coral Reef Conservation Program.

Written by the National Coral Reef Monitoring Plan (NCRMP) Working Group:

Rusty Brainard, Chris Caldow, Mark Eakin, Steve Gittings, Dwight Gledhill, Ron Hill, Chris Jeffrey, Jocelyn Karazsia, Randy Kosaki, Christy Loper, Derek Manzello, Margaret Miller, Greg Piniak, Bob Schroeder, Jennifer Schull, Bernardo Vargas-Angel, and Ivor Williams.

Editor: Jessica Morgan

With contributions from NOAA scientists:

Stewart Allen, Tim Battista, Laurie Bauer, Jeremiah Blondeau, Jim Bohnsack, Renee Carlton, Billy Causey, John Christensen, Randy Clark, Alicia Clarke, Scott Crosson, Gerry Davis, Annette DesRochers, Maria Dillard, Amanda Dillon, John Dunne, Kim Edwards, Peter Edwards, Ian Enochs, Marie Ferguson, Theresa Goedeke, Jamie Gove, Ian Hartwell, Jim Hendee, Scott Heron, Susie Holst, Brittany Huntington, Jack Javech, Danielle Jayewardene, Michael Jepson, Libby Jewett, Matt Kendall, Bill Kiene, Steve Kolinski, Bob Leeworthy, Arielle Levine, Gang Liu, Susan Lovelace, David McClellan, Tom McGrath, Mark Monaco, Jessica Morgan, Lindsay Morrison, Tony Pait, Britt Parker, Linwood Pendleton, Noah Pomeroy, Anita Pritchett, Tauna Rankin, Jacqueline Rauenzahn, Cristi Richards, Kim Roberson, Ben Ruttenberg, Kelley Sage, Gabe Sataloff, Heidi Schuttenberg, William Skirving, Al Strong, Adrienne Sutton, Dione Swanson, Mitchell Tartt, Steven Thur, Molly Timmers, Amanda Toperoff, Oliver Vetter, Shay Viehman, Jenny Waddell, Kevin Wong, and Chip Young.

And additional contributions from federal, state, and academic scientists:

Tom Adam, Andreas Andersson, Marlin Atkinson, Jerry Ault, Marilyn Brandt, Eric Brown, David Bryan, Bob Carpenter, Mark Chiappone, Tim Clark, Anne Cohen, Mike Colella, Eric De Carlo, Bill Fisher, Gary Green, Jean Kenyon, Ilsa Kuffner, Chris Langdon, Steven Miller, Matt Patterson, Nichole Price, Leanne Rutten, Stuart Sandin, Brice Semmens, Steve Smith, Bronte Tilbrook, Rob Waara, Kim Yates, and Brian Zgliczynski.

Front cover photo credits: NOAA (top left, top center, top right, middle center, bottom center), Malinda M. Vagasky Photography (middle left), Frank Mancini (bottom left), Sanya DuPlessis (bottom right).

Contents

Acknowledgments:

The NOAA Coral Reef Conservation Program would like to thank the NCRMP Working Group and those NOAA, federal, state, and academic scientists who provided valuable input during the development, review, and refinement processes for their contributions—the commitment, time, and effort brought to this enterprise are greatly appreciated. In particular, the program would like to acknowledge the detailed technical review provided by ten anonymous external scientific experts. Special thanks to Jessica Morgan and Anita Pritchett for coordination; Susie Holst, Ethan Lucas, Carl Nim, and Tauna Rankin for program integration; and Chris Ellis for meeting facilitation.

Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program is investing approximately $4.5 million of its annual operating budget to support a *National Coral Reef Monitoring Plan* (NCRMP) for biological, physical, and socioeconomic monitoring throughout the U.S. Pacific, Atlantic, and Caribbean coral reef areas. The overarching goal of this effort is to collect the information needed to gauge changing conditions of U.S. coral reef ecosystems, which are among the most biologically diverse and economically valuable ecosystems on earth, providing billions of dollars in food, jobs, recreational opportunities, coastal protection, and other important services.

This publication defines the national monitoring effort, which will provide a consistent flow of information about the status and trends of environmental conditions, living reef resources, and the people and processes that interact with coral reef ecosystems. Results will be reported through a periodic national-level status and trends report. Data will be used to help evaluate the efficacy of place-based investments in coral reef conservation, which in turn will ensure that the Coral Program's goals and objectives are achieved, and that U.S. coral reef ecosystems—and the communities that depend on them—benefit from conservation activities.

The effort builds upon a decade of work supported by the national Coral Program, including research and monitoring under the umbrella of the Coral Reef Ecosystem Integrated Observing System (CREIOS), reporting efforts such as *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States*, and outcomes from the program's external review. The NCRMP provides a strategic framework for the Coral Program's long-term domestic contribution to the larger CREIOS.

The focus is on four monitoring themes: benthic community structure, fish community structure, climate impacts, and socioeconomic condition. A wide range of potential indicators were considered and measured against program objectives, budget constraints, and logistics—fifteen key indicators were selected for the NCRMP.

Benthic and fish monitoring will be conducted using a diver-based stratified random-sampling design throughout shallow water coral reefs. Carbonate chemistry water sampling will be conducted at a subset of the biological sampling areas, while a smaller number of fixed stations will have variable configurations of instrumentation, including ocean acidification monitoring buoys at six locations. Satellite monitoring of regional thermal stress will complement *in situ* measurements of ocean temperature. Socioeconomic monitoring will be conducted using human dimension surveys of a random sample of residents every three to four years.

The Coral Program will continue to support monitoring activities that are conducted at smaller scales and designed to address specific management questions. The NCRMP purposefully seeks opportunities to work with partners to enhance the value of joint observations and maximize the value of conservation activities.

Overview

Table 1. NCRMP general themes and core indicators recommended by the Working Group and committed to implementation by the NOAA Coral Reef Conservation Program. * indicates Tier 2 (Important) indicators included in the NCRMP via partnership with the NOAA Ocean Acidification Program.

Monitoring Themes	Tier 1 (Critical) Indicators
Biological	
• **Coral and Benthos**	• Coral abundance and size structure • Coral condition (bleaching and disease incidence, mortality) • Benthic percent cover • Benthic key species • Rugosity
• **Reef Fish**	• Fish abundance and size structure • Fish diversity • Fish key species
Climate	
• **Thermal Stress**	• Temperature/thermal stress • Vertical thermal structure
• **Ocean Acidification**	• Carbonate chemistry
• **Ecological Impacts***	• Coral growth rate* • Bioerosion rate* • Community structure* (cryptofauna diversity)
Socioeconomics	• Knowledge, attitudes, and perceptions of coral reefs and management strategies • Participation in coral reef activities • Population changes and distribution • Economic dependence on coral reefs

Introduction

Coral reefs provide nearly $30 billion in net benefits in goods and services to world economies each year, including tourism, fisheries, and coastal protection (Cesar *et al.* 2003), and an estimated $3.4 billion annually in total economic value to the U.S. (Brander and van Beukering 2013). The Coral Reef Conservation Act of 2000 (CRCA 2000) authorizes a national program that includes "monitoring [and] assessment . . . that benefit the understanding, sustainable use, and long-term conservation of coral reefs and coral reef ecosystems." Since 2001, the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program (Coral Program) has produced sound scientific information on coral reef ecosystems under the broad category of "Assess and Characterize U.S. Coral Reefs." In 2003, the Coral Program defined a Coral Reef Ecosystem Integrated Observing System (CREIOS) to provide a diverse suite of long-term ecological and environmental observations over a broad range of spatial and temporal scales (Hoeke *et al.* 2009; Morgan *et al.* 2010).

In 2007, the Coral Program convened an external review (NOAA Coral Program 2007) to evaluate the success of the Coral Program and provide guidance to improve the program. Recommendations included: focus the program's goals, emphasize management-relevant science, and emphasize place-based management. In response to the external review, in 2008 the Coral Program developed a *Roadmap for the Future* (NOAA Coral Program 2008) to define new priorities and national-level responsibilities. This led to, in 2009, the Coral Program defining new goals and objectives (NOAA Coral Program 2009) to address three priority threats: climate change, fishing, and land-based sources of pollution.

The program then convened two regional CREIOS workshops (Morgan and Waddell 2009) to assess monitoring needs with local management entities in the U.S. Pacific and U.S. Atlantic and Caribbean. Recommendations included the need to increase management-scale mapping and monitoring, technical capacity within jurisdictions, communication of scientific information, and dissemination of NOAA data. Finally, the Coral Program engaged a consultant to evaluate existing mapping, monitoring, and assessment activities—the *Boreman Report* (Boreman 2009)—that recommended the program develop a national plan for monitoring the status and trends of coral reef ecosystems and reorient the "State of the Reefs" assessments (e.g., Waddell and Clarke 2008).

Building on these strategic planning efforts, in 2010 the Coral Program began developing a *National Coral Reef Monitoring Plan* (NCRMP). According to the decisions of the program's Senior Management Council (SMC), approximately $4.5 million will be set aside annually for sustained national-level monitoring, including data collection, analyses, dissemination, annual reporting, and coordination. Non-NCRMP monitoring, including external cooperative agreements to states and territories, will also continue to be funded. To guide this process, the Coral Program assembled a working group of NOAA scientists and managers with expertise on coral reef ecosystems from nine different offices and science centers across four NOAA line offices (National Environmental Satellite, Data, and Information Service [NESDIS], National

Marine Fisheries Service [NMFS], National Ocean Service [NOS], and Office of Oceanic and Atmospheric Research [OAR]) in the U.S. Pacific and Atlantic and Caribbean regions (see the appendix for contributors). The charge to the working group was to:

- develop unified monitoring questions and goals
- develop a long-term monitoring plan within a constrained budget of approximately $4.5 million per year
- identify core indicators within four general themes: coral/benthos, fish, climate, and people
- develop monitoring approaches consistent within jurisdictions and comparable across regions
- develop an approach for a national-level status and trends assessment report

The working group convened nine workshops during 2010-2013 to develop and refine the approaches detailed in this document. The draft *National Coral Reef Monitoring Plan* was submitted for technical review by anonymous scientific experts, and for review and comment by state and territory partners. The working group then revised this document to address reviewers' comments, and to incorporate new guidance, approaches, and the outcomes of various workshops convened to address specific aspects of the plan. The results of these strategic planning efforts and workshops are summarized in this final *National Coral Reef Monitoring Plan*, which is intended to guide the NOAA Coral Reef Conservation Program, and its implementing partners, in adaptive planning and implementation—and represents the program's long-term contribution to CREIOS.

Geographic Coverage

The NCRMP is limited to shallow water coral reef ecosystems in the following Coral Program priority geographic areas (Miller *et al.* 2011):

- American Sāmoa (AS)
- Commonwealth of the Northern Mariana Islands (CNMI)
- Guam
- Hawai'i (HI), including the Main Hawaiian Islands (MHI) and the Northwestern Hawaiian Islands (NWHI)
- Florida (FL), including Martin County through Dry Tortugas
- Flower Garden Banks (FGB)
- Pacific Remote Island Areas (PRIA), including Wake, Johnston, Palmyra, and Kingman Atolls and Howland, Baker, and Jarvis Islands
- Puerto Rico (PR)
- U.S. Virgin Islands (USVI)

While the Coral Program's geographic and depth priorities include mesophotic reefs ("hermatypic, zooxanthellate corals to the depth of light limitation"), NCRMP monitoring will focus primarily on depth strata within 0 to 30 meters because of the higher logistical and financial costs associated with monitoring beyond these depths. Similarly, while the impacts of land-based sources of pollution (LBSP) are acknowledged to be significant in certain areas and instances, efforts to monitor water quality indicators would be cost-prohibitive and are deemed outside the scope of the NCRMP.

Purpose

The working group developed the *National Coral Reef Monitoring Plan* to support conservation of the nation's coral reef ecosystems through documenting and understanding the status and trends of core indicators (Table 1). The NCRMP details a long-term approach to provide an ecosystem perspective via monitoring climate, fish, benthic, and socioeconomic variables in a consistent and integrated manner. The NCRMP is intended to coordinate various Coral Program biological, physical, and human dimensions activities into a cohesive NOAA-wide effort. Through the implementation of the NCRMP, NOAA will be able to clearly and concisely communicate results of national-scale monitoring to national, state, and territorial policy makers, resource managers, and the public on a periodic basis.

Indicators

The Coral Program's national status and trends monitoring focuses on four priority themes:

- benthic communities (emphasizing corals)
- reef-associated fish communities
- climate change (thermal stress and ocean acidification)
- human dimensions related to perceptions of, and interactions with, coral reef ecosystems

The working group reached consensus on the key monitoring questions for the NCRMP to address to support conservation of the nation's coral reef ecosystems:

1. What is the *status* of U.S. coral reef ecosystems?
    a. What is the status of coral reef biota?
    b. What is the status of human knowledge, attitudes, and perceptions regarding the importance and uses of coral reefs?

2. What are the *trends* in conditions of U.S. coral reef ecosystems?
    a. How is the community structure of coral reef biota changing over time?
    b. How are temperature and carbonate chemistry in waters surrounding coral reefs changing over time?
    c. How are human uses of, interactions with, and dependence on coral reefs changing over time?

The working group identified a comprehensive list of indicators (Table 2) based on extant coral reef monitoring programs worldwide, as well as processes or indicators that are necessary for or contribute to coral reef ecosystem function. The group then prioritized the list into "tiers" based on criteria ranging from effectiveness for determining status and identifying trends to cost-effectiveness within budget limitations. The working group reached consensus on an annual budget of approximately $4.5 million to address the monitoring questions and Tier 1 critical indicators within the Coral Program's geographic priority areas. Data on indicators outside of Tier 1 may be acquired via partnerships, or through the NCRMP if minimal additional effort is required. Where possible, NCRMP surveys will record supplementary data to allow for quantification or estimation of those additional indicators.

Table 2. Prioritized indicators for all themes considered by the Working Group for inclusion in NCRMP.

Theme	Tier 1 Indicators – Critical	Tier 2 – Important	Tier 3 – Informative
Benthos/ Coral	• Abundance and size structure • Coral condition (e.g., bleaching, disease) • Percent cover of benthic organisms/substrate • Key benthic/coral species • Benthic/coral diversity • Rugosity	• Growth rate • Bioerosion rate	• Reproduction • Recruitment • Mortality • Metabolic performance • Microbial communities • Non-indigenous species • Protected species
Fish	• Abundance and size structure • Fish diversity • Key fish species		• Reproduction • Population fecundity • Recruitment • Distribution • Trophic structure • Non-indigenous species • Protected species
Climate	• Temperature/thermal stress • Vertical thermal structure • Carbonate chemistry	• Insolation • Wave energy • Hydrodynamics	• Nutrients/productivity • Meteorology • Impacts of global change
People	• Knowledge, attitudes, and perceptions of coral reefs and management strategies • Participation in coral reef activities • Economic dependence on coral reefs • Population changes and distribution	• Land use • Land cover	• Economic value

The working group recommended sound scientific approaches for meeting Tier 1 requirements, but acknowledged that logistical considerations, particularly between the Atlantic/Caribbean and Pacific basins, may require some differences in specific methods—indeed, the charge to the working group included the guidance that "monitoring approaches [be] **consistent** within jurisdictions and **comparable** across regions." This is interpreted to require methodological consistency within a jurisdiction over time, but allows limited differences across regions and jurisdictions, *where necessary*. Therefore, for each indicator (and see Table 6), specific approaches are detailed where they vary due to funding or logistics considerations between the Atlantic/Caribbean, which is conducted biennially via small boat operations, and the Pacific, which is conducted triennially via ocean-going NOAA ship operations.

Partnerships

The NCRMP welcomes opportunities to work with partners to leverage and optimize our ability to effectively monitor the status and trends of the nation's coral reef ecosystems. The Coral Program will also continue to support monitoring outside of the NCRMP. These monitoring activities are generally at smaller scales, address more direct management needs, or may address different questions than national-level status and trends monitoring. Grants to external partners in seven U.S. jurisdictions with coral reefs have funded local monitoring for more than a decade and will continue. While jurisdictional monitoring programs can benefit from the context that the NCRMP can provide, there is no requirement that local methods change to meet NCRMP objectives. The program will also continue to support monitoring by NOAA principal investigators using internal Coral Program funds to address targeted management effectiveness questions, such as the efficacy of marine protected areas (MPAs) or the impacts of watershed restoration work upland of priority reefs.

Partnerships with the state or territory governments of Florida, Puerto Rico, the U.S. Virgin Islands, Hawai'i, American Sāmoa, Guam, and the Commonwealth of the Northern Mariana Islands, as well as federal agencies (including U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service, U.S. Geological Survey, and U.S. National Park Service) and academic institutions (including Nova Southeastern University, University of Hawai'i, University of Miami, University of Puerto Rico, and University of the Virgin Islands) will continue to provide valuable monitoring data (particularly at various long-term fixed-site locations), logistical support for field operations, scientific research, and statistical analyses that will contribute to NCRMP implementation and status and trends assessments.

A partnership with the NOAA Ocean Acidification Program (OAP) and Pacific Marine Environmental Laboratory (PMEL) will support the NCRMP's Tier 1 carbonate chemistry measurements in Coral Program priority areas within OAP's existing efforts, as well as support both programs' scientific goals regarding ocean acidification (Feely *et al.* 2010; Gledhill and Tomczuk 2012). This partnership effectively extends the NCRMP's footprint to include indicators of ecological responses of coral reef ecosystems to ocean acidification (e.g., changes to coral reef carbonate budgets, coral growth rates, bioerosion, framework integrity) which were initially ranked as non-critical indicators given budget limitations (Tables 1 and 2). These important (Tier 2) and informative (Tier 3) indicators include: targeted benthic community characterization, fine-scale rugosity assessments, indices of cryptic biodiversity, coral coring, and crustose coralline algae recruitment and accretion rate monitoring.

A partnership with the NOAA Pacific Islands Fisheries Science Center (PIFSC) provides support for complementary Reef Fish Survey (RFS) cruises in the Pacific, rotating through populated portions of each archipelago in sync with Pacific NCRMP schedules, and using the same survey methods, design, target domain, data management, and survey personnel as are employed for the fish portion of Pacific NCRMP cruises. For those populated islands, this partnership will approximately triple the number of fish survey sites that can be achieved by the NCRMP alone.

Partnerships with the NOAA Office of National Marine Sanctuaries (ONMS), including the Florida Keys National Marine Sanctuary (FKNMS), Flower Garden Banks National Marine Sanctuary (FGBNMS), National Marine Sanctuary of American Sāmoa (NMSAS), and the Papahānaumokuākea Marine National Monument (PMNM), support NCRMP biological and climate monitoring in various ways, including sharing vessels and staff members. NCRMP teams will continue to work closely with ONMS personnel to ensure that this monitoring meets management needs for coral reef ecosystem data, and to increase efficient and effective cost-sharing and resource leveraging to extend the NCRMP investment.

Partnerships with the NOAA Integrated Ocean Observing System Program (IOOS) and regional associations, including the Caribbean Regional Association for Coastal Ocean Observing (CaRA), Gulf of Mexico Coastal Ocean Observing System (GCOOS), Pacific Islands Ocean Observing System (PacIOOS), and the Southeast Coastal Ocean Observing Regional Association (SECOORA), will support data dissemination and delivery, data standards, and *in situ* instrumentation at NCRMP climate stations.

NCRMP scientific and technical staff members are supported by the NOAA Coral Reef Conservation Program and Offices across NOAA including: NESDIS Center for Satellite Applications and Research (STAR), NMFS Coral Reef Ecosystem Division (CRED), Pacific Islands Regional Office (PIRO), and Southeast Fisheries Science Center (SEFSC), NOS National Centers for Coastal Ocean Science (NCCOS) Center for Coastal Monitoring and Assessment (CCMA) and Hollings Marine Laboratory (HML), and OAR Atlantic Oceanographic and Meteorological Laboratory (AOML). Support for data stewardship is provided by the NESDIS National Oceanographic Data Center (NODC) Coral Reef Information System (CoRIS), and support for NOAA ship operations is provided by the Office of Marine and Aviation Operations (OMAO).

NCRMP and CREIOS

Since its inception in 2001, the Coral Program has invested in monitoring activities that contribute to the CREIOS goals of understanding the condition and health of, and processes influencing, coral reef ecosystems, and assisting stakeholders in making improved and timely ecosystem-based management decisions to conserve coral reefs (Hoeke *et al.* 2009; Morgan *et al.* 2010). The NCRMP provides a strategic framework for the program's long-term, domestic contribution to the larger CREIOS, which also includes near-real-time components such as the Integrated Coral Observing Network (ICON) and Coral Reef Watch (CRW), as well as local-level state and territory monitoring, and international partnerships.

Goals and Implementation

The goals of NCRMP monitoring are to:

- develop consistent and comparable methods and standard operating procedures (SOPs), which detail specific field, laboratory, and/or analytical procedures and best practices, for all indicators (with periodic updates to reflect new technologies or logistical considerations)
- develop and maintain strong partnerships with federal, state/territory, and academic partners
- collect scientifically sound, geographically comprehensive biological, climate, and socioeconomic data in U.S. coral reef areas
- deliver high-quality data, data products, and tools to the coral reef conservation community
- provide context for interpreting results of localized monitoring
- provide periodic assessments of the status and trends of the nation's coral reef ecosystems

NCRMP implementation began in FY13 with five implementation teams (Biological-Atlantic, Biological-Pacific, Climate-*in situ*, Climate-Satellite, and Socioeconomic) conducting field work (summarized in Table 6), developing methods and protocols, and engaging with partners and stakeholders to refine NCRMP operations and analyses. Major accomplishments of FY13 included:

- benthic and fish survey missions in the U.S. Virgin Islands, Flower Garden Banks, and Main Hawaiian Islands
- climate instrumentation deployment/retrieval missions and/or carbonate chemistry data collection missions in the U.S. Virgin Islands, Florida, Flower Garden Banks, Main Hawaiian Islands, and Northwestern Hawaiian Islands
- site survey missions for new climate fixed sites in Saipan, CNMI, and St. Croix, USVI
- new benthic protocols, socioeconomic survey modules, high-resolution satellite sea surface temperature data, and data synthesis approaches
- new data management tools and data stewardship policies

The Coral Program expects the specific details of NCRMP activities to continue to evolve during the first three years (FY13-15) as we evaluate new methods, protocols, and data management tools, as well as engage new partners and work in new locations across the U.S. Atlantic/Caribbean and Pacific. In the future, as new technologies become available, and as resources and partnerships change, NCRMP implementation may adaptively change as well.

Biological Monitoring

Reef calcifiers (such as corals, crustose coralline algae, calcified macroalgae, and foraminifera), gorgonians, and certain sponges provide architectural complexity and critical structure for reef fishes and other benthic organisms that comprise coral reef diversity. Reef fish populations can be depleted by human activities such as fishing, and by habitat degradation from factors such as LBSP and climate change impacts. Management efforts to sustain or rebuild coral reef fish populations, or to sustain fisheries yields, have been widely implemented (e.g., marine managed areas, catch limits, size restrictions) and require ongoing data collection and analysis to assess their efficacy and advise adaptive management. NCRMP monitoring of coral reef ecosystems will focus on status and changes in the benthic community, with emphasis on the structure-forming corals, and on the assemblages of reef fishes that utilize the coral reef environment. NCRMP biological monitoring is intended to address a broad range of needs for NOAA and for the wider management and science community while staying within the required funding constraints.

For the benthic component, priority will be given to scleractinian coral population structure and benthic cover. For coral species that are listed or may be listed under the *U.S. Endangered Species Act* (ESA 2002), the NCRMP will contribute coarse presence/absence data, but fulfilling the additional requirements for monitoring and status assessment under ESA is outside the scope of the NCRMP.

For the fish component, not all taxa will be equally targeted. For some groups of fishes—cryptic, nocturnal, schooling pelagic and semi-pelagic species (e.g., scad)—the NCRMP will record data when they are encountered during surveys, but survey designs will not be optimized for them. While the working group recognizes that species-specific coral reef fish information is highly useful for jurisdictional and federal fisheries management, achieving species-specific population information, especially for rare or patchily distributed species, may require more intense sampling than is feasible within the NCRMP alone.

Survey Design

The overall NCRMP survey design is optimized for the scale of the NCRMP reporting units (typically island or sub-island scale), rather than providing comprehensive information at single site or small-scale local spatial scales. The target domain for the NCRMP is reef habitats shallower than 30 m within the NOAA Coral Program geographic priority areas. The working group has adopted the general principle of geographically comprehensive monitoring, i.e., that the broad goal is spreading sampling effort widely across reefs within each jurisdiction, rather than focusing effort at “representative” stations, given concerns that identifying such stations is an inherently subjective and unreliable process (Rodgers *et al.* 2010).

The most appropriate means to ensure that biological survey data are representative of the target domain is to randomize site locations within that domain. Data quality will generally be optimized (e.g., variance minimized) by stratification of the target domain. Depending on the quality and extent of available bathymetry and habitat, the working group has chosen to stratify using combinations of depth (e.g., shallow, medium, deep), reef zone (forereef, backreef, etc.), habitat type (e.g., spur and groove, colonized pavement), and management zone (e.g., MPA, no-take area, etc.). Thus, optimum stratification schemes will vary among reporting units. The working group therefore recommends that a stratified random design be adopted for biological monitoring, but leaves development and subsequent fine-tuning of stratification schemes to the NCRMP biological monitoring implementation teams (including NOAA scientists and external partners) in each jurisdiction.

NCRMP biological sampling involves gathering data from multiple sites in each jurisdiction. Resulting data have value at a number of scales:

1. **Jurisdictional Scale** (e.g., Guam, U.S. Virgin Islands)**:** This is the highest level of reporting. NOAA Coral Program annual data reports will be developed per jurisdiction. Jurisdictions generally include at least several hundred km of coastline where reefs are found, and typically encompass large variations in anthropogenic pressure and reef condition. Therefore, although NCRMP data will be reported at a jurisdictional scale, NCRMP monitoring designs will also generate useful data at smaller, more ecologically similar, and more management-relevant scales.

2. **Sub-Jurisdiction (reporting unit) Scale** (e.g., Upper Keys/Middle Keys/Lower Keys, by island within the Main Hawaiian Islands, see Table 3)**:** Sub-jurisdictions are regions within jurisdictions, which will generally be the minimum reporting units for NCRMP data, i.e., they are spatial units that are small enough to have ecological and management-relevant meaning, but large enough that the NCRMP can sample each reporting unit with sufficient levels of replication to generate acceptable levels of data quality (e.g., coefficient of variation within target limits).

3. **Site Scale:** Individual "sites" are randomized survey locations sampled by a team of divers, generally in the course of a single dive. Single sites may be sub-sampled (e.g., there may be replicate surveys, transects, quadrats, or other measures at a single site). Site-level data are estimated values that typically represent less than an hour's effort over a few hundred square meters. While it might be meaningful to represent site-level data in plots of data from multiple sites (e.g., bubble plots), survey data generally have limited value at the site scale, and will be pooled up at higher scales to become useful for broad-scale monitoring purposes.

Collecting biota and habitat data from the same sample sites greatly increases the scope for interpreting fish and benthic survey data. Fish, benthic, and other surveys will be co-located where feasible, or at least surveyed in an integrated way to allow for analysis at higher spatial scales. Benthic cover and fish surveys will normally be co-located, but the more intensive coral demographic surveys, which may require additional time and effort to conduct, will not be performed at all fish survey sites because the variance structure of the (sessile) benthos is likely lower than that of (mobile) fish, therefore similar levels of precision can be reached with less effort (Smith *et al.* 2011).

Table 3. Sub-jurisdictions within the ten Coral Program priority geographic areas constitute the minimum reporting units for NCRMP biological monitoring.

Geographic Reporting Units for Biological Monitoring			
Florida	• Dry Tortugas • Lower Keys • Middle Keys • Upper Keys • Mainland Southeast FL	**American Sāmoa**	• Tutuila • Ofu and Olosega • Ta'ū • Swains • Rose Atoll
Puerto Rico	• South and West PR • North and East PR • Western Islands • Eastern Islands	**Main Hawaiian Islands**	• Oah'u • Kaua'i • Maui • Moloka'i • Lāna'i • Hawai'i • Ni'ihau and Lehua
U.S. Virgin Islands	• St. Thomas • St. Croix • St. John	**Northwestern Hawaiian Islands**	• Pearl and Hermes Atoll • Midway Atoll • Kure Atoll • Laysan • Lisianski • Maro Reef • French Frigate Shoals
Flower Garden Banks	• East Bank • West Bank	**Mariana Archipelago (Guam and the Commonwealth of the Northern Mariana Islands)**	• Guam • Rota • Tinian and Aguijan • Saipan • Sarigan, Guguan and Alamagan • Pagan • Agrihan • Asuncion • Maug • Urracas
		Pacific Remote Island Areas	• Johnston Atoll • Wake Atoll • Howland • Baker • Jarvis • Palmyra Atoll • Kingman Atoll

A critical question for the NCRMP is the amount of effort necessary to generate meaningful and useful coral reef monitoring data at the scale of a national program. As a basis for estimating necessary effort (replication), the working group has used precision (measured as the coefficient of variation [CV = SE/mean]) as the core measure of data quality. CV is a useful measure of data quality because it is a scale and unit independent measure, and because it can be directly related to confidence intervals (for other than very small samples, the 95% confidence interval is ~± 2 CV). Values of CV vary depending on the parameter of interest, survey method, inherent variability of the sample area, level of survey effort, optimization of the survey design, and observers' experience, skill, and training.

Coral and Benthos Monitoring

Coral abundance, size structure, condition, and diversity

The density and size-frequency distribution of corals provides valuable insights into the demography and space utilization of the selected species in the context of their geographical and environmental range. For example, the relative proportion of small and large colonies in a particular species reflects effective juvenile recruitment and colony longevity, while the most frequent colony size indicates the relative impact of total and partial mortality (Bak and Meesters 1998), as well as physical forcing factors (Gove *et al.* 2013). Size-frequency has been used to assess the impacts of bleaching, predation, and tropical cyclones (Done and Potts 1992; Mumby 1999; Gove *et al.* 2013), and may be particularly useful for assessing success of juvenile corals. Size-frequency distributions should change in predictable ways as reefs degrade (Bak and Meesters 1999), and populations in marginal habitats tend to have lower abundance and consequently larger coefficients of variation (Vermeij and Bak 2000). Species size-frequency distribution characteristics can be quantified mathematically (skewness, mode, coefficient of variation, etc.), allowing detection of change over time and comparison of different populations, provided sampling effort generates robust distributions.

Over the last three decades, coral bleaching and disease outbreaks have resulted in global reductions in coral reef diversity and resilience. As such, assessments of coral condition are an indicator of coral health and have the potential to identify possible causes of changes in benthic community structure. Bleaching and disease are generally estimated via prevalence (i.e., percent of colonies exhibiting a particular condition), which depends on reliable quantifications of counts (occurrences) of individual colonies within their respective taxonomic units (species/genera), and assessment of the health condition of the individual colonies (disease/non-diseased, bleached/non-bleached). Typical assessments further specify the type of lesion/disease (Rogers *et al.* 1994; Bruckner 2002; Raymundo *et al.* 2008), but data on lesion extent, severity, photographic records, and biological tissue sampling are also valuable.

The working group recommended that coral population structure (size-frequency and colony density) be derived from *in situ* coral demographic surveys along belt transects that systematically assess a predetermined and replicable reef area, e.g., Smith *et al.* 2011. In the Atlantic/Caribbean, coral colonies in belt transects will be scored for recent mortality and bleaching. In the Pacific, for coral colonies in paired transects will be scored for mortality and bleaching, with additional information on predation and disease.

The *NOAA Next Generation Strategic Plan* (NOAA 2010) and the *U.S. National Ocean Policy* (CEQ 2010) both identified the protection and maintenance of marine diversity as a key element within their programmatic goals and objectives. Diversity measures, combining species richness and evenness, are often used to characterize parts of coral reef ecosystems, but traditional observations do not easily capture the full range of taxonomic diversity on a reef or genotypic diversity within a species. At present, coarse richness and diversity measures for fish and corals and some sampling of cryptic diversity will form the basis of NCRMP diversity assessments.

Benthic percent cover

Benthic cover data are derived from counts (occurrences) of biotic and abiotic elements occupying the benthos, and each element is tallied and recorded to a predetermined level of taxonomic or functional resolution. Typically, the type of substrate (e.g., pavement, dead coral skeletons, rubble, sand) is also recorded. Many coral reefs have a small percentage of cover by scleractinian corals so other benthic components are more important to characterizing benthic communities and habitat. Percent cover of non-coral benthos is the focus in this sampling approach, especially different functional groups of algae, including turfs, macroalgae and crustose coralline algae and other invertebrates (gorgonians and sponges). Changes in cover can reflect the integrated effects of a set of environmental and disturbance regimes that characterize each reef system (Rogers *et al.* 1994; Jokiel *et al.* 2005; Gove *et al.* 2013). Where the total percent of live coral is very low (generally ≤ 10%), it becomes more difficult to detect changes in abundance or composition of the community.

The working group recommended coral point-based methods, co-located with fish survey sites, as the preferred approach to derive estimates of percent benthic cover. In the Atlantic/Caribbean, a line point intercept (LPI) method will be used for benthic cover, which involves tallying the benthic elements that fall under specified intervals either along transects of predetermined length (e.g., Smith *et al.* 2011). In the Pacific, benthic cover is derived from point counts on sequential photoquadrat images of the benthos acquired along paired transects.

Benthic key species and rugosity

"Key" benthic species are those that can have profound ecological effects on reef communities (*e.g.*, the Indo-Pacific corallivorous crown-of-thorns-starfish *Acanthaster planci*; the Atlantic/Caribbean sea urchin *Diadema antillarum*). In the Atlantic/Caribbean, fine-scale benthic transects capture density and distribution data. In the Pacific, the towed-diver protocol (Kenyon *et al.* 2006; Brainard *et al.* 2008) provides incidence of key species, percent benthic composition (i.e., live coral, crustose coralline algae, macroalgae, and hard substrate), and the percentage of pale and fully bleached coral cover.

Rugosity is a measure of habitat topographic complexity, the three-dimensionality of the coral reef benthic substrate (i.e., physical relief, void space, or bathymetry diversity). Rugosity is often quantified using small-scale *in situ* methods, but the increasing availability of geo-rectified bathymetry allows for the possibility of computer-based calculations at greater spatial scales. Coarse-scale rugosity data (Brandt *et al.* 2009) will be visually estimated, and useful as an explanatory variable for fish at co-located sites; fine-scale rugosity data from digital imagery will be collected at the climate Class III stations.

Reef Fish Monitoring

Fish abundance, size structure, and diversity

NCRMP fish surveys will gather data on the number and size of reef fishes within sample units at the lowest feasible taxonomic resolution (typically species level). This abundance data can be converted to a range of diversity indicators, including richness per sample unit, as well as calculated diversity and evenness measures. Similarly, assuming the dimensions of survey units are known, information on size and numbers allows for the calculation of density and biomass per taxon or functional group, with biomass estimated using species-specific length-to-weight conversion parameters available from a range of published and Web-based sources (e.g., FishBase 2000; Kulbicki *et al.* 2005). For "fish abundance and size," the working group set a minimum data quality of CV of 20% (i.e., 95% CI of 40%) for biomass of four groupings: 'all herbivorous fishes,' 'all piscivorous fishes,' 'all reef fishes combined,' and parrotfishes. That level of data quality will scale up to a minimum CV of ≤ 10% at the jurisdictional level.

In the U.S. Virgin Islands and Puerto Rico, belt transects are conducted. In the Pacific and in Florida, stationary point count (SPC) fish survey methods (Bohnsack and Bannerot 1986; Ault *et al.* 2006; Smith *et al.* 2006; Brandt *et al.* 2009; Richards *et al.* 2011; Williams *et al.* 2011), will be used. Both diver-based survey methods provide the abundance, size, and species of reef fishes.

Fish key species

"Key species" for this purpose are species of particular management concern because they are:

- *keystone species* (species and groups of species that have ecosystem significance disproportionate to their density)
- *indicator species* (e.g., fishing impacts can be clearly reflected in the status of relatively large-bodied and slow-growing target species)
- *species of particular biodiversity interest* (e.g., the bumphead parrotfish, *Bolbometopon muricatum*)

For Pacific jurisdictions, key species of concern for the NCRMP are sharks, large-bodied jacks, the humphead wrasse, and the bumphead parrotfish, and the primary survey method used for those will be the towed-diver survey (TDS) method (Richards *et al.* 2011), which involves a pair of divers being towed behind a small boat, with one diver quantifying fish populations and the other quantifying the benthos. Key Atlantic/Caribbean fish species include Nassau and goliath groupers, large-bodied parrotfishes (i.e., rainbow [*Scarus guacamaia*], blue [*S. coeruleus*] and midnight [*S. coelestinus*]), and sharks.

Climate Monitoring

Rising ocean temperatures and ocean acidification are expected to have profound influences on the nation's coral reef ecosystems over the coming years and decades. By altering the fundamental physical and chemical environment within which coral reef organisms reside, long-term changes in climate will likely affect vital physiological processes and ecological function of coral reefs. Increases in ocean temperatures have already negatively impacted coral reefs globally through widespread mass coral bleaching, enhanced disease outbreaks, and resultant mortality (Williams and Bunkley-Williams 1990; Wilkinson and Souter 2008; Eakin *et al.* 2009; Eakin *et al.* 2010). Furthermore, a mounting number of studies suggest that changes in ocean chemistry in direct response to rising levels of atmospheric CO_2 (ocean acidification) could significantly impact coral reef ecosystems over the next several decades (Langdon and Atkinson 2005; Kleypas *et al.* 2006; Hoegh-Guldberg *et al.* 2007; Ricke *et al.* 2013).

Status and trends in ocean temperature (thermal stress) and carbonate chemistry (ocean acidification) were adopted by the NCRMP working group as Tier 1 indicators based on the expectation that changes over time in these two indicators will cause the most significant synoptic impacts to coral reef ecosystems and their ability to deliver essential ecosystem goods and services at regional, national, and global scales. Monitoring these parameters will be achieved through a synthesis of remotely-sensed, moored, and discrete observations that will provide regional sea surface temperature patterns, *in situ* vertical thermal structure, and carbonate chemistry observations. These Tier 1 observations will be supplemented with a set of low-cost targeted and repeated ecological observations at key climate and ocean acidification monitoring sites. Collectively, these thermal stress and ocean acidification monitoring observations will provide information essential to tracking the impacts of climate change within the nation's coral reef ecosystems, and will serve as critical validation datasets to ongoing climate and ocean acidification risk/vulnerability modeling both within and external to NOAA.

Thermal Stress

Ocean temperatures have increased globally over the last century and have directly resulted in the loss of significant coral reef resources (Parry *et al.* 2007). Globally, thermal stress events in coral reef areas are becoming increasingly common and more severe (Baker *et al.* 2008; Eakin *et al.* 2009; Strong *et al.* 2009) and have directly resulted in mass coral bleaching and mortality (Wilkinson 2000; Eakin *et al.* 2010). Anomalously warm summer (and winter) temperatures have also been correlated with more frequent and severe coral disease outbreaks (Bruno *et al.* 2007; Heron *et al.* 2010). Within coral reef environments, water temperatures exhibit spatial and temporal variability through complex and dynamic physical oceanographic processes (e.g., Leichter *et al.* 1996), including surface heat and buoyancy fluxes, and current-topographic interactions (Gove *et al.* 2006; Leichter *et al.* 2012). Analyses of existing time-series data comparing surface and subsurface *in situ* temperatures from around the U.S. Pacific reveals that most reef systems are characterized by a highly complex and variable thermal structure, both within island-reef systems (Gove *et al.* 2006) and across regional scales, on diurnal to interannual time scales.

Sea surface temperature (SST) is a simple observation that is common to most existing *in situ* coral reef observing platforms and available through satellite remote-sensing. However, temperature at the sea surface alone is insufficient to discern the full thermal complexities of the nation's reefs, and conversely subsurface temperature variability can rarely be captured solely with surface observations. Understanding this variance is important in identifying potential localized bleaching refugia that may be important to coral reef resilience to climate change (Karnauskas and Cohen 2012). Elucidation of thermal structure confers insight into water movement patterns that directly influence the physical and chemical setting of coral reefs.

Satellite-based observations will serve as the primary means of monitoring regional SST and estimates of surface thermal stress for all the nation's coral reefs. Data from NOAA operational satellites provide SST, from which coral bleaching degree heating weeks are derived (Liu *et al.* 2006; NOAA Coral Reef Watch 2011; Liu *et al.* 2013) and provide estimates of thermal stress in coral reef areas (NOAA Coral Reef Watch 2008). Vertical thermal structure will be monitored using *in situ* subsurface temperature recorders deployed at representative sites at four depths in each of the sub-jurisdictions where NCRMP biological monitoring will occur.

Ocean Acidification

The persistence of coral reefs under continued ocean acidification remains a primary concern as an increasing number of studies have measured reduced rates of calcification for many species of reef-building organisms (e.g., Leclercq *et al.* 2002; Marubini *et al.* 2003; Ohde and Hossain 2004; Langdon and Atkinson 2005; Anthony *et al.* 2008). Ocean acidification may also increase dissolution of reef sediments that often contain appreciable amounts of more soluble carbonate minerals (Morse *et al.* 2006), and may enhance bioerosion of corals and reef frameworks (Tribollet *et al.* 2009; Wisshak *et al.* 2012). Bioerosion and dissolution of reef carbonates may outpace carbonate production in some reef habitats by 2030 (Yates and Halley 2006; Ricke *et al.* 2013). Furthermore, current-day areas where upwelling causes chemistries analogous to future conditions (i.e., a tripling of atmospheric CO_2) exhibit poorly cemented and highly bioeroded coral reefs (Manzello *et al.* 2008). Such effects would likely compromise reef framework integrity and resilience in the face of other acute and chronic stresses, such as coral bleaching, diseases, potential increases in storm intensity, and rising sea level (e.g., Silverman *et al.* 2009). Other modes of expected impact include a potential lowering of the thermal thresholds for bleaching (Anthony *et al.* 2008) and impairment of early life stages of corals including reduced fertilization success, reduced larval settlement, and reduced growth and survival rates of newly settled corals (Cohen and Holcomb 2009; Albright *et al.* 2010; Morita *et al.* 2010; Suwa *et al.* 2010). Direct impacts of ocean acidification on coral growth and fitness, in combination with largely unknown potential impacts on non-calcareous competing functional groups, may profoundly affect the basic ecological interactions structuring coral reef ecosystems.

Ecological Impacts

Understanding ecological responses of marine ecosystems is needed to serve as the basis for testing the validity of climate model predictions and experimentally-derived assumptions about the impacts of climate change and ocean acidification on the natural environment. To date, most climate change research targeting biological impacts has focused on laboratory response experiments rather than examining these impacts *in situ*. The Coral Program's partnership with the NOAA Ocean Acidification Program provides an opportunity to sustain long-term *in situ* monitoring of ecological responses to climate change, and allows investigation of the relationships between biological response variables (calcification and bioerosion rates, biodiversity, and community composition) to both physical and chemical processes.

Climate Stations

The NCRMP climate monitoring strategy includes fine temporal-resolution monitoring with moored instruments at fixed time-series sites in both the U.S. Atlantic/Caribbean and Pacific basins, complemented by broadly-distributed water sampling surveys nested within the NCRMP biological surveys within each of the sub-jurisdictions. There are four classes of NCRMP climate stations (Table 4): Class 0 represents water sampling conducted at a subset of the random stratified sites monitored by the biological teams; Classes I, II, and III represent fixed sites exhibiting an increasingly comprehensive suite of observations at increasingly fewer locations.

Table 4. Summary of the parameters and instrumentation deployed at each type (Class) of NCRMP climate monitoring station.

Climate Monitoring Stations		**Parameters**										**Instrumentation**						
	Type	**Physical environment:** Temperature	Salinity	Dissolved oxygen	Rugosity	**Carbonate chemistry:** DIC and Total Alkalinity (TA)	pCO_2 and pH	**Ecological impacts:** Coral growth rates	Calcification rates	Bioerosion rates	Community structure	**STRs:** Subsurface temperature recorder arrays	**Automated water samplers**	**ADCPs:** Acoustic Doppler Current Profilers *(Pacific only)*	**MapCO$_2$:** Moored autonomous pCO_2 buoys	**CAUs:** Calcification accretion units	**BMUs:** Bioerosion monitoring units	**ARMS:** Autonomous reef monitoring structures
Class 0	random	•	•			•												
Class I	fixed	•										•						
Class II	fixed	•	•			•		•	•	•	•		•	•		•	•	•
Class III	fixed	•	•	•	•	•	•	•	•	•	•				•	•	•	•

Vertical thermal structure

Observations at Class I stations provide the widest distribution of fixed sites measuring changes in vertical thermal structure (for computing thermal stress) within the NCRMP. Near-surface (1 m) temperatures will be the uppermost of the vertical temperature profiles, and other monitoring platforms such as the Class III buoys contain SST recorders. Subsurface temperature recorders (STR) will be attached to the reef substrate at four depths at locations (primary exposures of seas and currents) around most islands or atolls. Island size and proximity will be evaluated for instrumentation requirements (i.e., small islands and islands within close proximity may require less instrumentation while especially large islands, island chains, or mainland areas may require more). Each STR array will be deployed for 2-3 years, after which they will be recovered, data downloaded, and processed. The three ICON pylons within the Atlantic/Caribbean will be leveraged to provide additional temperature monitoring, thereby extending existing long-term temperature records and providing validation to remotely-sensed products.

Carbonate chemistry

Discrete carbonate chemistry water sampling at a subset of the biological monitoring sites (Class 0 stations) will provide important linkages needed to establish broad-scale spatial and temporal relationships between key biological indicators (e.g., coral cover and benthic composition) and the corresponding climate observations (thermal stress and saturation state) at regional and sub-jurisdictional scales. Carbonate chemistry water samples will be collected according to best practices (Dickson *et al.* 2007) in concert with subsurface temperature and salinity measurements at a subset of locations nested within the random stratified benthic and fish monitoring surveys. All collected samples will be processed for dissolved inorganic carbon (DIC) and total alkalinity (TA). These spatially distributed water samples will be complemented by fine-temporal-resolution observations of key physical and chemical indicators at the fixed climate change and ocean acidification monitoring sites (Class I, II, and III).

Diel variability in carbonate chemistry can be significant depending on water residence time, benthic community productivity, and local carbon cycling considerations. To better constrain the diel ranges in aragonite saturation state, automated benthic water samplers will be deployed, when possible, at many of the Class II stations. The systems will autonomously collect water samples every 2-4 hours over the duration of up to two diel cycles (24 to 48 hours). Together with water temperature and salinity from co-deployed conductivity-temperature-depth (CTD) casts, and in some locations near-reef current information collected from Acoustic Doppler Current Profilers, diel ranges in aragonite saturation state will be derived from post-recovery analysis of *in situ* total alkalinity and total dissolved inorganic carbon.

The spatiotemporal variability of carbonate chemistry is inherently complex, and a direct function of the interaction between physical forcing (meteorology, oceanography) and diurnally-varying reef metabolism (Manzello 2010a). As such, the near-reef seawater CO_2 system varies with temperature, salinity, tidal state, water mass residence time, light intensity, as well as the benthic community's integrated rates of organic (photosynthesis, respiration) and inorganic (calcification, dissolution) carbon metabolism. The high variability in carbonate chemistry experienced within most reef systems precludes the utility of solely obtaining discrete observations for the purpose of establishing the rate and magnitude of changes in carbonate mineral saturation state (a key indicator of interest with regard to ocean acidification).

Moored Autonomous pCO_2 (MApCO_2) buoys deployed at six Class III stations (three within each ocean basin) will provide autonomous real-time carbon dioxide aqueous partial pressure ($pCO_{2,aq}$), carbon dioxide atmospheric partial pressure ($pCO_{2,atm}$), pH, atmospheric pressure, air temperature, salinity, dissolved oxygen (DO), and relative humidity. Discrete and automated remote sampling conducted at Class III sites will be used to devise algorithms to estimate carbonate mineral saturation state from autonomous observations of $pCO_{2,sw}$, salinity, and temperature, and allow for extrapolation of information collected at the Class III monitoring sites to wider areas within the jurisdiction or basin based upon the discrete sampling (Class 0 sites). This approach of fine temporal-resolution time-series sampling nested within broad spatial surveys is similar to that of other NOAA ocean acidification monitoring efforts within coastal environments, providing an internally consistent and logical extension of the NOAA-wide monitoring effort.

Both the thermal (ocean warming) and chemical (ocean acidification) ramifications of global climate change have the potential to push the calcium carbonate budget of coral reefs into a state of net erosion (Manzello *et al.* 2008; Manzello 2010b). Consequently, the architectural complexity of reefs is likely to continue to deteriorate as it has broadly in the Atlantic/Caribbean (Alvarez-Filip *et al.* 2009). It is thus important to monitor these changes given their potential to impact reef structure. To measure these changes, fine-scale observations of rugosity using side-scan and/or multi-beam sonar will provide more habitat characterization information at each Class III station (Costa *et al.* 2009). High-resolution acoustic data will be collected using a small-boat-based multi-beam system to collect fine-scale bathymetry and backscatter and map fine-scale rugosity. These data will be post-processed to produce finalized mosaics of the bathymetry, backscatter, and derivative layers (e.g., rugosity, slope, fractals).

Ecological impacts: Coral growth rates, bioerosion rates, and community structure

The benthic community directly surrounding each Class II and Class III site will be characterized and mapped at the beginning and end of each deployment to measure coral and algal cover and benthic community structure using photo quadrats and image analysis. This is necessary to interpret and eventually model carbonate dynamics given that the community structure of benthic organisms (e.g., proportion and types of calcifiers *vs*. non-calcifiers) exerts a strong influence on the reefal water chemistry (e.g., Gattuso *et al.* 1997). Coral cores will be collected and processed to assess historical extension and calcification rates of massive reef-building corals (primarily *Porites* spp. in the Pacific and the *Orbicella* [formerly *Montastraea*] spp. complex in the Atlantic).

Laboratory experiments have shown that crustose coralline algae (CCA), which are important calcifiers and well-known substrata for successful settlement of coral larvae, are particularly sensitive to ocean acidification (Gherardi and Bosence 2001; Webster *et al.* 2006; Kuffner *et al.*

2008). Their abundance, therefore, can be inherently linked to the resilience of coral reefs. As such, it is important to monitor long-term trends in the recruitment potential and accretion of CCA as they provide an index of reef resilience and may be first responders to ocean acidification. Calcification accretion units (CAUs), settling plates onto which CCA recruit, will be deployed at the fixed Class II and III monitoring sites to systematically monitor broad-scale spatial patterns of rates of net CCA recruitment and accretion. After recovery, each plate will be photographed and the net weight of accumulated calcium carbonate measured. CAU deployments and recoveries, processing, and analysis will be repeated at the Class II and Class III fixed sites at 2- to 3-year intervals to monitor changes over time.

The formation of reef habitat and its persistence is a function of additive calcification and the subtractive process of erosion. Biological erosion (bioerosion) is a complex process involving a diverse suite of taxa utilizing numerous behaviors and methods of reef substrate removal. Recent evidence suggests that the rate at which many of these taxa erode reef habitat may be accelerated by ocean acidification (e.g., Tribollet *et al.* 2009; Wisshak *et al.* 2012). This represents a direct mechanism by which ocean acidification will lead to reef degradation and the loss of ecosystem services. Bioerosion monitoring units (BMUs), blocks of calcium carbonate, will be deployed at fixed Class II and III monitoring sites to systematically detect changes in the broad-scale spatial patterns of net reef bioerosion rates. Before deployment, BMUs are scanned using a high-resolution computed tomography (micro-CT) to assess coral block density. After recovery, they are scanned again to quantify the loss of material due to biological, chemical, and physical processes. BMU deployments and recoveries, processing, and analysis will be repeated at Class II and Class III sites at 2- to 3-year intervals to monitor changes over time.

Marine biodiversity is predicted to be indirectly impacted by climate change and ocean acidification (Worm *et al.* 2006; Riebesell 2008) due to alterations in community structure, functionality, relationships among organisms, and the anticipated increases in species extinctions and invasion (Ives and Carpenter 2007; Cheung *et al.* 2009). Much of the biomass and most of the diversity of coral reef ecosystems lies within the complex architecture of the reef matrix (Ginsburg 1983; Small *et al.* 1998; Knowlton *et al.* 2010). This community of organisms is collectively known as the cryptobiota (Macintyre *et al.* 1982), some of which may be vulnerable to acute direct impacts, such as habitat degradation, and chronic indirect impacts, such as climate change and ocean acidification. Autonomous Reef Monitoring Structures (ARMS), comprised of stacked polyvinyl chloride (PVC) plates onto which cryptic marine invertebrates recruit and colonize, will be deployed at each fixed Class II and Class III station to monitor long-term trends of invertebrate diversity in response to global environmental changes. As such, they will improve the ability of the NCRMP to monitor and relate the diversity and abundance of the cryptobiota with reef ecosystem processes and function. Upon recovery, each ARMS unit will be disassembled plate by plate and photographed, and the motile fraction sieved into four size fractions for taxonomic and molecular processing. ARMS deployments and recoveries, processing, and analysis will be repeated at Class II and Class III fixed sites at 2- to 3-year intervals to monitor changes over time.

Socioeconomic Monitoring

One of the recommendations of the 2007 external review was the need to increase the Coral Program's social science portfolio and use social science strategically to improve coral reef management by engaging local communities and better assessing the social and economic consequences of management policies, interventions, and activities on those communities. Coral reefs contribute significant economic value to the U.S. public, and consideration of the economic value of coral reefs should lead to more efficient decision-making that balances development and conservation as well as raising awareness and building public support for the protection of this valuable natural resource (NOAA Coral Program 2013). In 2010, the *Coral Reef Conservation Program Social Science Strategy* (Loper *et al.* 2010) was approved by the program's Senior Management Council. Development of national-level social science indicators, collected through triennial jurisdictional surveys, constitutes two of the top three priorities under the *Social Science Strategy*, with the third calling for an increase in social science capacity within the program.

Including socioeconomic indicators in the NCRMP represents a strong step forward for the Coral Program, which has recognized the need to integrate socioeconomic factors with our suite of biophysical indictors. Integration of socioeconomic factors will strengthen our national monitoring and improve the program's ability to explain how coral reef ecosystems and coral reef management strategies are perceived by the public -- issues of utmost interest to our partners, resource managers, and policy makers. The socioeconomic component of the NCRMP will gather and monitor a collection of socioeconomic variables, including human population demographics in coral reef areas, human use of coral reef resources, as well as knowledge, attitudes, and perceptions of coral reefs and coral reef management. The Coral Program will use this information for research and to improve the results of programs designed to protect coral reefs.

The overall approach of the socioeconomic monitoring component is to employ indicators to assess the state of a jurisdiction, including information about the population, social and economic structure, impacts of society on coral reefs, and contributions of healthy corals to nearby residents. The indicators were developed in consultation with stakeholders, partners and other scientists and will be measured through surveys of residents in the U.S. coral reef jurisdictions and the collection of existing socioeconomic data from secondary sources such as the U.S. Census and local government agencies. The NCRMP national socioeconomic indicators are:

1. Participation in reef activities
2. Perceived resource condition
3. Attitudes toward coral reef management strategies and enforcement
4. Awareness and knowledge of reefs
5. Human population changes near coral reefs
6. Economic impact of coral reef fishing to jurisdiction

7. Economic impact of dive/snorkel tourism to jurisdiction
8. Community well-being
9. Cultural importance of reefs
10. Participation in behaviors that may improve coral reef health
11. Physical infrastructure
12. Awareness of coral reef rules and regulations
13. Governance

Knowledge, attitudes, and perceptions

Resident surveys will take place in each jurisdiction every 3 or 4 years. The potential respondent universe for this study is adults, eighteen years or older, who live near, and may use, coral reefs affected by activities related to the NOAA's Coral Reef Conservation Program. Jurisdictional surveys will gather longitudinal information from residents in Florida, U.S. Virgin Islands, Puerto Rico, Hawai'i, American Sāmoa, Guam, and the Commonwealth of the Northern Mariana Islands. The NCRMP overall focuses on the Coral Program's geographic priority areas; however, as some of those areas are uninhabited, socioeconomic indicators will be collected from only the inhabited areas (Table 5). Each survey will have one set of questions that is the same for all locations, as well as selected jurisdiction specific questions relevant to local management needs. In general, we will collect data using a variety of modes as appropriate to the culture, including telephone-administered surveys, in-person household surveys, mail surveys, and Internet-based surveys.

Table 5. Socioeconomic monitoring locations within the seven inhabited Coral Program priority geographic areas analogous to the biological monitoring reporting units.

Geographic Reporting Units for Socioeconomic Monitoring	
American Sāmoa	Islands of Tutuila, Ta'u, Olosega, Ofu, and Aunu'u
CNMI	Islands of Saipan, Tinian and Rota only
Guam	Entire island of Guam
Hawai'i	Islands of Oah'u, Kaua'I, Maui, Moloka'I, Lāna'i, Hawai'i only
Florida	Martin, Palm Beach, Broward, Miami-Dade, and Monroe Counties only
Puerto Rico	Puerto Rico, Vieques, Culebra Islands
USVI	St. Croix, St. Thomas, and St. John

The survey data collection is focused on the following indicators:

- Participation in reef activities (including snorkeling, diving, fishing, harvesting)
- Perceived resource condition
- Attitudes toward coral reef management strategies and enforcement
- Awareness and knowledge of coral reefs
- Cultural importance of reefs
- Participation in behaviors that may improve coral reef health

Information will be collected in the means most efficient and effective in each jurisdiction, generally following the Total Design Method (TDM) as described by Dillman for mail, telephone, and Internet surveys (Dillman 1978; Dillman 2007). Statistically representative samples of individuals from each coral reef jurisdiction, with a 95% confidence level, will be collected once every 3 or 4 years. Sample size may need to be adjusted to ensure representative coverage of cultural groups. Where feasible, indicators reported at the sub-jurisdictional scale will be reported alongside biological indicators collected at the same scale. Efforts will be made to ensure sufficiently robust sample size to allow for reporting of socioeconomic indicators at appropriate sub-jurisdictional scales.

Population changes and economic dependence

Human demographic information will be derived from U.S. Census data and population estimates for all coral reef jurisdictions to provide information on human population change near coral reefs. (refer to the previously published *Baseline Report of U.S. Territories and Counties Adjacent to Coral Reef Habitats*, Crossett *et al.* 2008). For Florida, this will include Monroe, Dade, Broward, Palm Beach, and Martin Counties only. For all other states and territories, the entire jurisdiction will be included.

Additional socioeconomic data on community well-being and physical infrastructure will be compiled for each jurisdiction from secondary data sources like the U.S. Census Bureau and local government agencies. These data will be collected and analyzed at the jurisdiction level.

Indicators of economic impacts of coral reef resources that will be tracked through the NCRMP include the following:

- Economic impact of coral reef fishing to jurisdiction
- Economic impact of dive/snorkel tourism to jurisdiction
- Awareness of coral reef rules and regulations
- Governance

These indicators will be collected using a combination of both survey and secondary data.

Data, Documentation, and Reporting

NCRMP activities will generate a broad range of biological, physical, chemical, and socioeconomic data that will be highly valuable to the coral reef conservation community. The NCRMP is committed to making data and data products publically available in a timely and user-friendly format to a wide variety of audiences. NCRMP data reporting will follow data stewardship and dissemination guidelines recommended by the NOAA Environmental Data Management Committee (EDMC).

An annual NCRMP report will be completed within one year of the end of each year's monitoring activities, following quality control and data synthesis, and will report on observations at the jurisdiction level.

NCRMP data, data products, SOPs, cruise reports, and annual reports will be archived at the NOAA National Data Centers (NNDCs) via the Coral Reef Information System (CoRIS), and made publically available through a Coral Program website. International Organization for Standardization (ISO) compliant metadata will accompany all NCRMP data sets. NCRMP data will be available for free to the public and the scientific community in the belief that their wide dissemination will lead to greater understanding and new scientific insights, and it is anticipated that many single and cross-disciplinary peer-reviewed publications will result from the NCRMP data.

Ultimately, NCRMP data will be used to generate a periodic national-level report on the status and trends of U.S. coral reefs. This report will assimilate and synthesize the data products from NCRMP monitoring activities to tell the story of how the condition of the nation's reefs is changing over time. The primary audience for this report is intended to be Congress and other high-level decision makers. A relatively short document will replace the Coral Program's previous major monitoring report, *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States* (Waddell and Clarke 2008), in an effort to more clearly and succinctly disseminate status and trends of U.S. coral reefs as a whole.

The final format of the national-level report will be determined with the assistance of NOAA and/or partner communications and messaging staff members. Indicators would be presented by sub-jurisdictional reporting unit, jurisdiction, as well as rolled up by basin (Pacific and Atlantic/Caribbean), and finally summarized at a national level. Key findings, additional information, and case studies will augment the status and trends reporting tools.

Appendices

Acronyms

ADCP	Acoustic Doppler Current Profiler
ARMS	Autonomous Reef Monitoring Structures
AS	American Sāmoa
AVHRR	Advanced Very High Resolution Radiometer
BMU	Bioerosion Monitoring Unit
CaRA	Caribbean Regional Association for Coastal Ocean Observing
CAU	Calcification Accretion Unit
CCA	Crustose Coralline Algae
CI	Confidence Interval
CNMI	Commonwealth of the Northern Mariana Islands
CO_2	Carbon Dioxide
CoRIS	NOAA NESDIS NODC Coral Reef Information System
CRCP	Coral Reef Conservation Program
CREIOS	NOAA Coral Reef Ecosystem Integrated Observing System
CTD	Conductivity-Temperature-Depth
CV	Coefficient of Variation
DHW	Degree Heating Week
DIC	Dissolved Inorganic Carbon
DO	Dissolved Oxygen
ESA	Endangered Species Act
FGB	Flower Garden Banks
FGBNMS	Flower Garden Banks National Marine Sanctuary
FKNMS	Florida Keys National Marine Sanctuary
FL	Florida
GCOOS	Gulf of Mexico Coastal Ocean Observing System
HI	Hawaiʻi
ICON	NOAA Integrated Coral Observing Network
IOOS	NOAA Integrated Ocean Observing System Program
ISO	International Organization for Standardization
LBSP	Land-based Sources of Pollution
LPI	Line Point Intercept
$MApCO_2$	Moored Autonomous pCO_2 Buoy
MHI	Main Hawaiian Islands
MPA	Marine Protected Area
NCRMP	National Coral Reef Monitoring Plan
NESDIS	NOAA National Environmental Satellite, Data, and Information Service
NMFS	NOAA National Marine Fisheries Service
NMSAS	National Marine Sanctuary of American Sāmoa
NNDC	NOAA National Data Centers
NOAA	U.S. National Oceanic and Atmospheric Administration
NODC	NOAA NESDIS National Oceanographic Data Center
NOS	NOAA National Ocean Service
NWHI	Northwestern Hawaiian Islands
OAP	NOAA Ocean Acidification Program
OAR	NOAA Office of Oceanic and Atmospheric Research
ONMS	NOAA NOS Office of National Marine Sanctuaries
PacIOOS	Pacific Islands Ocean Observing System

$pCO_{2,aq}$	Seawater Carbon Dioxide Partial Pressure
$pCO_{2,atm}$	Atmospheric Carbon Dioxide Partial Pressure
PIFSC	NOAA NMFS Pacific Islands Fisheries Science Center
PMNM	Papahānaumokuākea Marine National Monument
POES	Polar Operational Environmental Satellite
PR	Puerto Rico
PRIA	Pacific Remote Island Areas
PVC	Polyvinyl Chloride
RFS	Reef Fish Survey
SE	Standard Error
SECOORA	Southeast Coastal Ocean Observing Regional Association
SMC	NOAA CRCP Senior Management Council
SOP	Standard Operating Procedure
SPC	Stationary Point Count
SST	Sea Surface Temperature
STR	Subsurface Temperature Recorder
TA	Total Alkalinity
TDM	Total Design Method
TDS	Towed-diver Survey
U.S.	United States of America
USVI	U.S. Virgin Islands

Contributors

Contributors to this document include:

- * NCRMP Working Group Members,
- ^ NCRMP Writing Team Members,
- # NCRMP Implementation Team Members,
- & NCRMP Coordination and Integration Team Members, and

participants of the following workshops:

1. NCRMP 1st Workshop, Silver Spring, MD, November 15-18, 2010
2. NCRMP 2nd Workshop, Silver Spring, MD, April 5-8, 2011
3. NCRMP 3rd Workshop, Key West, FL, September 13-14, 2011
4. NCRMP 1st Benthic Methods Workshop, Silver Spring, MD, June 5-6, 2012
5. NCRMP Socioeconomic Indicators Workshop, Charleston, SC, June 13-15, 2012
6. NCRMP Fish Biomass Metrics Workshop, San Diego, CA, August 6-10, 2012
7. Coral Reef Ocean Acidification Monitoring Portfolio Workshop, Dania Beach, FL, August. 28-29, 2012
8. NCRMP Atlantic Biological Data Management Workshop, Miami, FL, January 29-31, 2013
9. NCRMP 2nd Benthic Methods Workshop, Broad Key, FL, April 9-11, 2013

Tom Adam	Florida International University	8
Stewart Allen	NOAA NMFS Pacific Islands Fisheries Science Center	5
Andreas Andersson	University of San Diego, Scripps Institution of Oceanography	7
Marlin Atkinson	University of Hawai'i at Manoa, School of Ocean Earth Science and Technology	7
Jerry Ault	University of Miami, Rosenstiel School of Marine and Atmospheric Science	8

Tim Battista	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	^
Laurie Bauer	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	#9
Jeremiah Blondeau	NOAA NMFS Southeast Fisheries Science Center	#89
Jim Bohnsack	NOAA NMFS Southeast Fisheries Science Center	#38
Rusty Brainard	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	*^##&1237
Marilyn Brandt	University of the Virgin Islands	9
Eric Brown	U.S. National Park Service	4
David Bryan	University of Miami, Rosenstiel School of Marine and Atmospheric Science	8
Chris Caldow	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	*^#123
Renee Carlton	NOAA OAR Atlantic Oceanographic and Meteorological Laboratory	#78
Bob Carpenter	California State University, Northridge	7
Billy Causey	NOAA NOS Office of National Marine Sanctuaries	3
Mark Chiappone	Nova Southeastern University, Oceanographic Center	489
John Christensen	NOAA NOS Coral Reef Conservation Program	^&3457
Randy Clark	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	^#&89
Tim Clark	U.S. National Park Service	4
Alicia Clarke	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	^#
Anne Cohen	Woods Hole Oceanographic Institution	7
Mike Colella	State of Florida Fish and Wildlife Service	9
Scott Crosson	NOAA NMFS Southeast Fisheries Science Center	5
Gerry Davis	NOAA NMFS Pacific Islands Regional Office	3
Eric De Carlo	University of Hawai'i at Manoa, School of Ocean Earth Science and Technology	7
Annette DesRochers	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	#
Maria Dillard	NOAA NOS National Centers for Coastal Ocean Science, Hollings Marine Laboratory	^#5
Amanda Dillon	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^
John Dunne	NOAA OAR Geophysical Fluid Dynamics Laboratory	7
Mark Eakin	NOAA NESDIS Center for Satellite Applications and Research, Coral Reef Watch	*^#123
Kim Edwards	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	#9
Peter Edwards	NOAA NOS Coral Reef Conservation Program	^#35
Ian Enochs	NOAA OAR Atlantic Oceanographic and Meteorological Laboratory	^#79
Marie Ferguson	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	##
Bill Fisher	U.S. Environmental Protection Agency	4
Steve Gittings	NOAA NOS Office of National Marine Sanctuaries	*^234
Dwight Gledhill	NOAA OAR Ocean Acidification Program	*^&1237

Theresa Goedeke	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	^5
Jamie Gove	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^#&
Gary Green	University of Georgia, Warnell School of Forestry and Natural Resources	5
Ian Hartwell	NOAA NOS National Centers for Coastal Ocean Science, Coastal Ocean Assessments, Status, and Trends Branch	^
Jim Hendee	NOAA OAR Atlantic Oceanographic and Meteorological Laboratory	37
Scott Heron	NOAA NESDIS Center for Satellite Applications and Research, Coral Reef Watch	^#
Ron Hill	NOAA NMFS Southeast Fisheries Science Center, Galveston Laboratory	*^12
Susie Holst	NOAA NOS Coral Reef Conservation Program	&125
Brittany Huntington	NOAA NMFS Southeast Fisheries Science Center	4
Jack Javech	NOAA NMFS Southeast Fisheries Science Center	#9
Danielle Jayewardene	NOAA NMFS Pacific Islands Regional Office	*^1
Chris Jeffrey	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	*^#24
Michael Jepson	NOAA NMFS Southeast Regional Office, Economics Branch	5
Libby Jewett	NOAA OAR Ocean Acidification Program	&7
Jocelyn Karazsia	NOAA NMFS Southeast Regional Office	*^12
Matt Kendall	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	^#6
Jean Kenyon	U.S. Fish and Wildlife Service	4
Bill Kiene	NOAA NOS Office of National Marine Sanctuaries	*^1
Steve Kolinski	NOAA NMFS Pacific Islands Regional Office	^
Randy Kosaki	NOAA NOS Papahānaumokuākea Marine National Monument	*^12
Ilsa Kuffner	U.S. Geological Survey	7
Chris Langdon	University of Miami, Rosenstiel School of Marine and Atmospheric Science	7
Bob Leeworthy	NOAA NOS Office of National Marine Sanctuaries	5
Arielle Levine	NOAA NMFS Pacific Islands Regional Office	^#5
Gang Liu	NOAA NESDIS Center for Satellite Applications and Research, Coral Reef Watch	^#
Christy Loper	NOAA NOS Coral Reef Conservation Program	*^125
Susan Lovelace	NOAA NOS National Centers for Coastal Ocean Science, Hollings Marine Laboratory	^#5
Derek Manzello	NOAA OAR Atlantic Oceanographic and Meteorological Laboratory	*^#&1278
David McClellan	NOAA NMFS Southeast Fisheries Science Center	#89
Tom McGrath	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	#8
Margaret Miller	NOAA NMFS Southeast Fisheries Science Center	*^#24789
Steven Miller	Nova Southeastern University, Oceanographic Center	8
Mark Monaco	NOAA NOS National Centers for Coastal Ocean Science	#3
Jessica Morgan	NOAA NOS Coral Reef Conservation Program	^&123478
Lindsay Morrison	NOAA NMFS Southeast Fisheries Science Center	#9
Tony Pait	NOAA NOS National Centers for Coastal Ocean Science	^

Britt Parker	NOAA NOS Coral Reef Conservation Program	3
Matt Patterson	U.S. National Park Service	4
Linwood Pendleton	NOAA PPI Office of Program Planning and Integration	5
Greg Piniak	NOAA NOS National Centers for Coastal Ocean Science	*^12345
Noah Pomeroy	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	#
Nichole Price	University of San Diego, Scripps Institution of Oceanography	7
Anita Pritchett	NOAA NMFS Coral Reef Conservation Program	^&1234
Tauna Rankin	NOAA NMFS Coral Reef Conservation Program	1
Jacqueline Rauenzahn	NOAA NESDIS Center for Satellite Applications and Research, Coral Reef Watch	^#
Cristi Richards	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^#
Kim Roberson	NOAA NOS National Centers for Coastal Ocean Science, Biogeography Branch	^#9
Leanne Rutten	Nova Southeastern University, Oceanographic Center	89
Ben Ruttenberg	NOAA NMFS Southeast Fisheries Science Center	^36
Kelley Sage	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	##&
Stuart Sandin	University of San Diego, Scripps Institution of Oceanography	6
Gabe Sataloff	NOAA NOS Coastal Services Center	5
Bob Schroeder	NOAA NMFS Pacific Islands Regional Office	*^2
Jennifer Schull	NOAA NMFS Southeast Fisheries Science Center	*^#&1289
Heidi Schuttenberg	NOAA NOS Papahānaumokuākea Marine National Monument	^
Brice Semmens	University of San Diego, Scripps Institution of Oceanography	6
William Skirving	NOAA NESDIS Center for Satellite Applications and Research, Coral Reef Watch	^#
Steve Smith	University of Miami, Rosenstiel School of Marine and Atmospheric Science	8
Al Strong	NOAA NESDIS Center for Satellite Applications and Research, Coral Reef Watch	*^
Adrienne Sutton	NOAA OAR Pacific Marine Environmental Laboratory	7
Dione Swanson	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^#4
Mitchell Tartt	NOAA NOS Office of National Marine Sanctuaries	*^
Steve Thur	NOAA NOS Coral Reef Conservation Program	5
Bronte Tilbrook	Commonwealth Scientific and Industrial Research Organisation (Australia)	7
Molly Timmers	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^#7
Amanda Toperoff	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^#
Bernardo Vargas-Angel	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	*^#&24
Oliver Vetter	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	#
Shay Viehman	NOAA NOS National Centers for Coastal Ocean Science	#9
Rob Waara	U.S. National Park Service	9
Jenny Waddell	NOAA NOS Coral Reef Conservation Program	&

Ivor Williams	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	*^#&1236
Kevin Wong	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^#&
Kim Yates	U.S. Geological Survey	7
Chip Young	NOAA NMFS Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division	^#7
Brian Zgliczynski	University of San Diego, Scripps Institution of Oceanography	6

References

Albright, R., B. Mason, M. Miller and C. Langdon (2010). "Ocean acidification compromises recruitment success of the threatened Caribbean coral *Acropora palmata*." *Proceedings of the National Academy of Sciences* **107**(47): 20400-20404.

Alvarez-Filip, L., N. K. Dulvy, J. A. Gill, I. M. Côté and A. R. Watkinson (2009). "Flattening of Caribbean coral reefs: region-wide declines in architectural complexity." *Proceedings of the Royal Society B: Biological Sciences* **276**(1669): 3019-3025.

Anthony, K. R. N., D. I. Kline, G. Diaz-Pulido, S. Dove and O. Hoegh-Guldberg (2008). "Ocean acidification causes bleaching and productivity loss in coral reef builders." *Proceedings of the National Academy of Sciences* **105**(45): 17442-17446.

Ault, J. S., S. G. Smith, J. A. Bohnsack, J. G. Luo, D. E. Harper and D. B. McClellan (2006). "Building sustainable fisheries in Florida's coral reef ecosystem: Positive signs in the Dry Tortugas." *Bulletin of Marine Science* **78**(3): 633-654.

Bak, R. P. M. and E. H. Meesters (1998). "Coral population structure: the hidden information of colony size-frequency distributions." *Marine Ecology Progress Series* **162**: 301-306.

Bak, R. P. M. and E. H. Meesters (1999). "Population structure as a response of coral communities to global change." *American Zoologist* **39**(1): 56-65.

Baker, A. C., P. W. Glynn and B. Riegl (2008). "Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook " *Estuarine, Coastal and Shelf Science* **80**(4): 435-471.

Bohnsack, J. A. and S. P. Bannerot (1986). A stationary visual census technique for quantitatively assessing community structure of coral reef fishes. NOAA Technical Report NMFS 41, NOAA National Marine Fisheries Service, 15 pp.

Boreman, J. (2009). An Evaluation of the Mapping, Monitoring, and Assessment Activities of NOAA's Coral Reef Conservation Program. Durham, NC, Boreman Consulting, 98 pp.

Brainard, R. E., J. Asher, J. Gove, J. Helyer, J. Kenyon, F. Mancini, J. Miller, S. Myhre, M. Nadon, J. Rooney, R. Schroeder, E. Smith, B. Vargas-Angel, S. Vogt, P. Vroom, S. Balwani, S. Ferguson, R. Hoeke, M. Lammers, E. Lundblad, R. Moffitt, M. Timmers, O. Vetter, P. Craig and J. Maragos [Eds.] (2008). Coral Reef Ecosystem Monitoring Report for American Samoa: 2002 – 2006. Honolulu, HI, NOAA NMFS Pacific Islands Fisheries Science Center Coral Reef Ecosystem Division, 510 pp.

Brander, L. and P. van Beukering (2013). The Total Economic Value of U.S. Coral Reefs: A Review of the Literature. Silver Spring, MD, NOAA Coral Reef Conservation Program.

Brandt, M. E., N. Zurcher, A. Acosta, J. S. Ault, J. A. Bohnsack, M. W. Feeley, D. E. Harper, J. H. Hunt, T. Kellison, D. B. McClellan, M. E. Patterson and S. G. Smith (2009). A cooperative multi-agency reef fish monitoring protocol for the Florida Keys coral reef ecosystem. Natural Resource Report NPS/SFCN/NRR-2009/150, Fort Collins, Colorado, National Park Service.

Bruckner, A. W. (2002). Priorities for effective management of coral diseases. NOAA Technical Memorandum NMFS-OPR-22, NOAA, 54 pp.

Bruno, J. F., E. R. Selig, K. S. Casey, C. A. Page, B. L. Willis, C. D. Harvell, H. Sweatman and A. M. Melendy (2007). "Thermal Stress and Coral Cover as Drivers of Coral Disease Outbreaks." *PLoS Biology* **5**(6): e124.

CEQ (2010). Final Recommendations of the Interagency Ocean Policy Task Force. Council on Environmental Quality, 96 pp.

Cesar, H., L. Burke and L. Pet-Soede (2003). The economics of worldwide coral reef degradation. Cesar Environmental Economics Consulting and WWF-Netherlands, Arnhem and Zeist, The Netherlands.
Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson and D. Pauly (2009). "Projecting global marine biodiversity impacts under climate change scenarios." *Fish and Fisheries* **10**(3): 235-251.
Cohen, A. and M. Holcomb (2009). "Why Corals Care About Ocean Acidification: Uncovering the Mechanism." *Oceanography* **22**(4): 118.
Costa, B. M., L. J. Bauer, T. A. Battista, P. W. Mueller and M. E. Monaco (2009). Moderate-depth benthic habitats of St. John, US Virgin Islands. NOAA Technical Memorandum NOS NCCOS 105, Silver Spring, MD, NOAA NCCOS, 57 pp.
CRCA (2000). Coral Reef Conservation Act of 2000. P.L. 106-562; 16 U.S.C. 6401 et seq.
Crossett, K. M., C. G. Clement and S. O. Rohmann (2008). Demographic Baseline Report of U.S. Territories and Counties Adjacent to Coral Reef Habitats. NOAA, National Ocean Service, Special Projects, 65 pp.
Dickson, A. G., S. L. Sabine and J. R. Christian [Eds.] (2007). Guide to best practices for ocean CO_2 measurements. PICES Special Publication, 191 pp.
Dillman, D. A. (1978). Mail and telephone surveys: The total design method. New York, Wiley-Interscience.
Dillman, D. A. (2007). Mail and Internet Surveys: the Tailored Design Method, 2nd Edition. Hoboken, New Jersey, Wiley and Sons.
Done, T. J. and D. C. Potts (1992). "Influences of habitat and natural disturbances on contributions of massive *Porites* corals to reef communities." *Marine Biology* **114**(3): 479-493.
Eakin, C. M., J. M. Lough and S. F. Heron (2009). Climate variability and change: monitoring data and evidence for increased coral bleaching stress. *In* Van Oppen, M. H. and J. M. Lough [Eds.], Coral Bleaching: Patterns, processes, causes and consequences. Berlin, Springer, p. 41-67.
Eakin, C. M., J. A. Morgan, S. F. Heron, T. B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, E. Bartels, C. Bastidas, C. Bouchon, M. Brandt, A. W. Bruckner, L. Bunkley-Williams, A. Cameron, B. D. Causey, M. Chiappone, T. R. L. Christensen, M. J. C. Crabbe, O. Day, E. de la Guardia, G. Díaz-Pulido, D. DiResta, D. L. Gil-Agudelo, D. S. Gilliam, R. N. Ginsburg, S. Gore, H. M. Guzmán, J. C. Hendee, E. A. Hernández-Delgado, E. Husain, C. F. G. Jeffrey, R. J. Jones, E. Jordán-Dahlgren, L. S. Kaufman, D. I. Kline, P. A. Kramer, J. C. Lang, D. Lirman, J. Mallela, C. Manfrino, J.-P. Maréchal, K. Marks, J. Mihaly, W. J. Miller, E. M. Mueller, E. M. Muller, C. A. Orozco Toro, H. A. Oxenford, D. Ponce-Taylor, N. Quinn, K. B. Ritchie, S. Rodríguez, A. R. Ramírez, S. Romano, J. F. Samhouri, J. A. Sánchez, G. P. Schmahl, B. V. Shank, W. J. Skirving, S. C. C. Steiner, E. Villamizar, S. M. Walsh, C. Walter, E. Weil, E. H. Williams, K. W. Roberson and Y. Yusuf (2010). "Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005." *PLoS ONE* **5**(11): e13969.
ESA (2002). Endangered Species Act of 1973 (Amended). PL 93-205 as amended by 107-136.
Feely, R. A., R. Wanninkhof, J. Stein, M. F. Sigler, E. Jewett, F. Arzayus and D. K. Gledhill (2010). NOAA Ocean and Great Lakes Acidification Research Plan. NOAA Special Report, NOAA Ocean Acidification Steering Committee, 143 pp.
FishBase (2000). "FishBase" from http://www.fishbase.org/home.htm.
Gattuso, J. P., C. Payri, M. Pichon, B. Delesalle and M. Frankignoulle (1997). "Primary production, calcification and air-sea CO_2 fluxes of a macro-algal-dominated coral reef community (Moorea, French Polynesia)." *Journal of Phycology* **33**(5): 729-738.
Gherardi, D. F. M. and D. W. J. Bosence (2001). "Composition and community structure of the coralline algal reefs from Atol das Rocas, South Atlantic, Brazil." *Coral Reefs* **19**(3): 205-219.
Ginsburg, R. N. (1983). Geological and biological roles of cavities in coral reefs. *In* Barnes, D. J. [Ed.], Perspective on coral reefs. Manuka, ACT, Australia, Brian Clouston Publisher, p. 148-153.
Gledhill, D. K. and J. D. Tomczuk [Eds.] (2012). NOAA Coral Reef Conservation Program Ocean Acidification Science Plan Fiscal Years 2012 - 2016. Silver Spring, MD, NOAA Technical Memorandum CRCP 18, NOAA Coral Reef Conservation Program, 32 pp.
Gove, J. M., M. A. Merrifield and R. E. Brainard (2006). "Temporal variability of current-driven upwelling at Jarvis Island." *Journal of Geophysical Research* **111**(C12): C12011.
Gove, J. M., G. J. Williams, M. A. McManus, S. F. Heron, S. A. Sandin, O. J. Vetter and D. G. Foley (2013). "Quantifying Climatological Ranges and Anomalies for Pacific Coral Reef Ecosystems." *PLoS ONE* **8**(4): e61974.
Heron, S. F., B. L. Willis, W. J. Skirving, C. M. Eakin, C. A. Page and I. R. Miller (2010). "Summer Hot Snaps and Winter Conditions: Modelling White Syndrome Outbreaks on Great Barrier Reef Corals." *PLoS ONE* **5**(8): e12210.

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.

Hoeke, R. K., J. M. Gove, E. Smith, P. Fisher-Pool, M. Lammers, D. Merritt, O. J. Vetter, C. W. Young, K. B. Wong and R. E. Brainard (2009). "Coral reef ecosystem integrated observing system: *In situ* oceanographic observations at the US Pacific islands and atolls." *Journal of Operational Oceanography* **2**(2): 3-14(12).

Ives, A. P. and S. R. Carpenter (2007). "Stability and Diversity of Ecosystems." *Science* **317**(5834): 58-62.

Jokiel, P. L., K. S. Rodgers, E. K. Brown, J. C. Kenyon, G. Aeby, W. R. Smith and F. Farrell (2005). Comparison of methods used to estimate coral cover in the Hawaiian Islands. NOAA/NOS/NWHI Coral Reef Ecosystem Reserve.

Karnauskas, K. B. and A. L. Cohen (2012). "Equatorial refuge amid tropical warming." *Nature Clim. Change* **2**(7): 530-534.

Kenyon, J. C., R. E. Brainard, R. K. Hoeke, F. A. Parrish and C. B. Wilkinson (2006). "Towed-diver surveys, a method for mesoscale spatial assessment of benthic reef habitat: A case study at Midway Atoll in the Hawaiian archipelago." *Coastal Management* **34**(3): 339-349.

Kleypas, J. A., R. A. Feely, V. J. Fabry, C. Langdon, C. L. Sabine and L. L. Robbins (2006). Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research. St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey, 88 pp.

Knowlton, N., R. E. Brainard, M. J. Caley, R. Fisher, M. Moews and L. Plaisance (2010). Coral Reef Biodiversity. *In* McIntyre, A. D. [Ed.], Life in the world's oceans: diversity, distribution, and abundance, Blackwell Publishing Ltd, p. 65-78.

Kuffner, I. B., A. J. Andersson, P. L. Jokiel, K. S. Rodgers and F. T. Mackenzie (2008). "Decreased abundance of crustose coralline algae due to ocean acidification." *Nature Geoscience* **1**(2): 114-117.

Kulbicki, M., N. Guillemot and M. Amand (2005). "A general approach to length-weight relationships for New Caledonian lagoon fishes." *Cybium* **29**(3): 235-252.

Langdon, C. and M. J. Atkinson (2005). "Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment." *Journal of Geophysical Research* **110**: C09S07.

Leclercq, N., J.-P. Gattuso and J. Jaubert (2002). "Primary production, respiration, and calcification of a coral reef mesocosm under increased CO_2 partial pressure." *Limnology and Oceanography* **47**(2): 558-564.

Leichter, J. J., M. D. Stokes, J. L. Hench, J. Witting and L. Washburn (2012). "The island-scale internal wave climate of Moorea, French Polynesia." *Journal of Geophysical Research: Oceans* **117**(C6): C06008.

Leichter, J. J., S. R. Wing, S. L. Miller and M. W. Denny (1996). "Pulsed delivery of subthermocline water to Conch Reef (Florida Keys) by internal tidal bores." *Limnology and Oceanography* **41**(7): 1490-1501.

Liu, G., J. L. Rauenzahn, S. F. Heron, C. M. Eakin, W. J. Skirving, T. R. L. Christensen, A. E. Strong and J. Li (2013). NOAA Coral Reef Watch 50 km Satellite Sea Surface Temperature-Based Decision Support System for Coral Bleaching Management. NOAA Technical Report NESDIS 143, College Park, MD, NOAA/NESDIS, 33 pp.

Liu, G., A. E. Strong, W. J. Skirving and L. F. Arzayus (2006). "Overview of NOAA Coral Reef Watch Program's near-real-time satellite global coral bleaching monitoring activities." *Proceedings of the 10th International Coral Reef Symposium, Okinawa*: 1783-1793.

Loper, C., A. Levine, J. Agar, M. Hamnett, V. R. Leeworthy, M. Valdes-Pizzini and K. Wallmo (2010). NOAA Coral Reef Conservation Program Social Science Strategy: 2010-2015.

Macintyre, I. G., K. Rutzler, J. N. Norris and K. Fauchald (1982). "A submarine cave near Columbus Cay, Belize: a bizarre cryptic habitat." *Smithsonian Contributions to the Marine Sciences* **12**: 12-141.

Manzello, D. P. (2010a). "Coral growth with thermal stress and ocean acidification: lessons from the eastern tropical Pacific." *Coral Reefs* **29**(3): 749-758.

Manzello, D. P. (2010b). "Ocean acidification hotspots: Spatiotemporal dynamics of the seawater CO_2 system of eastern Pacific coral reefs." *Limnology and Oceanography* **55**(1): 239-248.

Manzello, D. P., J. A. Kleypas, D. A. Budd, C. M. Eakin, P. W. Glynn and C. Langdon (2008). "Poorly cemented coral reefs of the eastern tropical Pacific: Possible insights into reef development in a high-CO_2 world." *Proceedings of the National Academy of Sciences* **105**(30): 10450-10455.

Marubini, F., C. Ferrier–Pages and J. P. Cuif (2003). "Suppression of skeletal growth in scleractinian corals by decreasing ambient carbonate-ion concentration: a cross-family comparison." *Proceedings of the Royal Society of London. Series B: Biological Sciences* **270**(1511): 179-184.

Miller, J., T. Battista, A. Pritchett, S. Rohmann and J. Rooney (2011). Coral Reef Conservation Program Mapping Achievements and Unmet Needs. Silver Spring, MD, NOAA Coral Reef Conservation Program, 68 pp.

Morgan, J. A., C. M. Eakin, R. E. Brainard, D. W. Collins, J. C. Hendee and M. E. Monaco (2010). NOAA Coral Reef Ecosystem Integrated Observing System (CREIOS): A collaborative ecosystem-based observing system. *In*, Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Annex), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Morgan, J. A. and J. E. Waddell [Eds.] (2009). NOAA Coral Reef Ecosystem Integrated Observing System (CREIOS) Workshops Report. Silver Spring, MD, NOAA Technical Memorandum CRCP 9, NOAA Coral Reef Conservation Program, 68 pp.

Morita, M., R. Suwa, A. Iguchi, M. Nakamura, K. Shimada, K. Sakai and A. Suzuki (2010). "Ocean acidification reduces sperm flagellar motility in broadcast spawning reef invertebrates." *Zygote* **18**: 103-107.

Morse, J. W., A. J. Andersson and F. T. Mackenzie (2006). "Initial responses of carbonate-rich shelf sediments to rising atmospheric pCO_2 and "ocean acidification": Role of high Mg-calcites." *Geochimica et Cosmochimica Acta* **70**(23): 5814-5830.

Mumby, P. J. (1999). "Bleaching and hurricane disturbances to populations of coral recruits in Belize." *Marine Ecology Progress Series* **190**: 27-35.

NOAA (2010). NOAA's Next Generation Strategic Plan. NOAA, 40 pp.

NOAA Coral Program (2007). "External Program Review" from http://coralreef.noaa.gov/aboutcrcp/strategy/reprioritization/exreview/.

NOAA Coral Program (2008). Roadmap for the Future: A Plan for Developing CRCP Direction Through 2015. Silver Spring, MD, NOAA Coral Reef Conservation Program, 15 pp.

NOAA Coral Program (2009). NOAA Coral Reef Conservation Program Goals & Objectives 2010-2015. Silver Spring, MD, NOAA Coral Reef Conservation Program, 40 pp.

NOAA Coral Program (2013). Summary Report, The Economic Value of U.S. Coral Reefs. Silver Spring, MD, NOAA Coral Reef Conservation Program.

NOAA Coral Reef Watch (2008). "Methodology of NOAA Coral Reef Watch Satellite Coral Bleaching Monitoring Products" from http://coralreefwatch.noaa.gov/satellite/methodology/methodology.html.

NOAA Coral Reef Watch (2011). "NOAA Coral Reef Watch Product Overview" from http://coralreefwatch.noaa.gov/satellite/product_overview.html.

Ohde, S. and M. M. M. Hossain (2004). "Effect of $CaCO_3$ (aragonite) saturation state of seawater on calcification of *Porites* coral." *Geochemical Journal* **38**: 613-621.

Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson [Eds.] (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge, UK, Cambridge University Press, 976 pp.

Raymundo, L. J., C. S. Couch and C. D. Harvell (2008). Coral disease handbook: guidelines for assessment, monitoring and management. Melbourne, Australia, Currie Communications, 98 pp.

Richards, B. L., I. D. Williams, M. O. Nadon and B. J. Zgliczynski (2011). "A towed-diver survey method for mesoscale fishery-independent assessment of large-bodied reef fishes." *Bulletin of Marine Science* **87**(1): 55-74.

Ricke, K. L., J. C. Orr, K. Schneider and K. Caldeira (2013). "Risks to coral reefs from ocean carbonate chemistry changes in recent earth system model projections." *Environmental Research Letters* **8**(3): 034003.

Riebesell, U. (2008). "Climate change: Acid test for marine biodiversity." *Nature* **454**(7200): 46-47.

Rodgers, K. S., P. L. Jokiel, C. E. Bird and E. K. Brown (2010). "Quantifying the condition of Hawaiian coral reefs." *Aquatic Conservation-Marine and Freshwater Ecosystems* **20**(1): 93-105.

Rogers, C. S., G. Garrison, R. Grober and Z. M. Franke (1994). Coral reef monitoring manual for the Caribbean and western Atlantic. National Park Service, Virgin Islands National Park.

Silverman, J., B. Lazar, L. Cao, K. Caldeira and J. Erez (2009). "Coral reefs may start dissolving when atmospheric CO_2 doubles." *Geophysical Research Letters* **36**: L05606.

Small, A. M., W. H. Adey and D. Spoon (1998). "Are current estimates of coral reef biodiversity too low? The view through the window of a microcosm." *Atoll Research Bulletin* **458**: 1-20

Smith, J. E., M. Shaw, R. A. Edwards, D. Obura, O. Pantos, E. Sala, S. A. Sandin, S. Smriga, M. Hatay and F. L. Rohwer (2006). "Indirect effects of algae on coral: algae-mediated, microbe-induced coral mortality." *Ecology Letters* **9**(7): 835-845.

Smith, S., D. Swanson, M. Chiappone, S. Miller and J. Ault (2011). "Probability sampling of stony coral populations in the Florida Keys." *Environmental Monitoring and Assessment*: 1-18.

Strong, A. E., G. Liu, C. M. Eakin, T. R. L. Christensen, W. J. Skirving, D. K. Gledhill, S. F. Heron and J. A. Morgan (2009). "Implications for our coral reefs in a changing climate over the next few decades." *Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida, 7-11 July 2008*: 1324-1328.

Suwa, R., M. Nakamura, M. Morita, K. Shimada, A. Iguchi, K. Sakai and A. Suzuki (2010). "Effects of acidified seawater on early life stages of scleractinian corals (Genus *Acropora*)." *Fisheries Science* **76**(1): 93-99.

Tribollet, A., C. Godinot, M. Atkinson and C. Langdon (2009). "Effects of elevated pCO2 on dissolution of coral carbonates by microbial euendoliths." *Global Biogeochemical Cycles* **23**(3): GB3008.

Vermeij, M. J. A. and R. P. M. Bak (2000). "Inferring demographic processes from population size structure in corals." *Proceedings 9th International Coral Reef Symposium* **1**: 589-594.

Waddell, J. E. and A. M. Clarke [Eds.] (2008). The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. Silver Spring, MD, NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, 569 pp.

Webster, J. M., D. A. Clague, J. C. Braga, H. Spalding, W. Renema, C. Kelley, B. Applegate, J. R. Smith, C. K. Paull, J. G. Moore and D. Potts (2006). "Drowned coralline algal dominated deposits off Lanai, Hawaii; carbonate accretion and vertical tectonics over the last 30 ka." *Marine Geology* **225**(1–4): 223-246.

Wilkinson, C. and D. Souter [Eds.] (2008). Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, 152 pp.

Wilkinson, C. R. (2000). Status of Coral Reefs of the World: 2000. Townsville, Australia, Australian Institute of Marine Science, 363 pp.

Williams, E. H. and L. Bunkley-Williams (1990). "The world-wide coral reef bleaching cycle and related sources of coral mortality." *Atoll Research Bulletin* **335**: 330-338.

Williams, I. D., B. L. Richards, S. A. Sandin, J. K. Baum, R. E. Schroeder, M. O. Nadon, B. J. Zgliczynski, P. Craig, J. L. McIlwain and R. E. Brainard (2011). "Differences in Reef Fish Assemblages between Populated and Remote Reefs Spanning Multiple Archipelagos Across the Central and Western Pacific." *Journal of Marine Biology* **2011**(Article ID 826234): (14 pages).

Wisshak, M., C. H. L. Schönberg, A. Form and A. Freiwald (2012). "Ocean Acidification Accelerates Reef Bioerosion." *PLoS ONE* **7**(9): e45124.

Worm, B., E. B. Barbier, N. Beaumont, J. E. Duffy, C. Folke, B. S. Halpern, J. B. C. Jackson, H. K. Lotze, F. Micheli, S. R. Palumbi, E. Sala, K. A. Selkoe, J. J. Stachowicz and R. Watson (2006). "Impacts of biodiversity loss on ocean ecosystem services." *Science* **314**(5800): 787-790.

Yates, K. K. and R. B. Halley (2006). "CO_3^{2-} concentration and pCO_2 thresholds for calcification and dissolution on the Molokai reef flat, Hawaii." *Biogeosciences* **3**(3): 357-369.

Table 6. Summary of NCRMP monitoring themes, indicators and measured parameters, methods, and implementation approaches. ^{A} Atlantic, ^{P} Pacific, * planned.

Theme	Indicator / Parameter	Method	Spatial Approach	Temporal Approach
Biological • **Benthos**	• Coral abundance, size, species, and condition (bleaching, mortality, disease^{P})	• 10mx1m coral demographic transects^{A} • paired 18m coral demographic transects^{P}	Stratified random sampling optimized for commercially and ecologically important fish and coral species in shallow (0-30 m) hard bottom areas. Strata include depth, habitat type, and management zone.	Surveys conducted every 2^{A} or 3^{P} years, all surveys generally conducted within the same 3-month season
	• Benthic percent cover	• 20m line point intercept (LPI) transect^{A} • paired 15m photoquadrat transects^{P}		
	• Benthic key species (presence/absence)	• 25mx2m key species transects^{A} • 200mx10m towed-diver survey^{P}		
	• Rugosity	• visual estimation of surface relief coverage		
• **Fish**	• Fish abundance, size, and species	• paired 15m-diameter stationary point count (SPC) surveys^{AP} • 25mx4m,15min timed transects^{A}		
	• Fish key species (presence/absence)	• ~2000mx10m towed-diver survey^{P}/see above^{A}		
Climate • **Thermal stress**	• Temperature/thermal stress: sea surface temperature (SST)	• coral bleaching HotSpots and degree heating weeks (DHWs) derived from satellite SST	Global POES/AVHRR 50-km resolution Global Geo-Polar blended 5-km resolution	Derived twice-weekly Derived daily
	• Vertical thermal structure	• subsurface temperature recorder (STRs) arrays of Sea-Bird sensors at ~1, 5, 15, 25 m	Class I. Fixed sites (n=27^{A}, 119^{P}) at primary exposures of seas and currents	Instruments retrieved every 2^{A} or 3^{P} years
• **Ocean acidification**	• Carbonate chemistry: dissolved inorganic carbon (DIC), total alkalinity (TA) • Water temperature, salinity, currents^{P}	• discrete water sampling • subsurface temperature and salinity • diurnal cycle water sampling • subsurface temperature and salinity • Acoustic Doppler Current Profiler (ADCP)^{P}	Class 0. Stratified random sites (n=150^{A}, 450^{P}) Class II. Fixed sites (n=6^{A}, 14^{P})	Sampling conducted every 2^{A} or 3^{P} years Diurnal sampling for 48 hours every 2^{A} or 3^{P} years
	• Carbonate chemistry: carbon dioxide aqueous partial pressure ($pCO_{2,aq}$), carbon dioxide atmospheric partial pressure ($pCO_{2,atm}$), pH • Atmospheric pressure, air and water temperature, salinity, dissolved oxygen (DO), relative humidity, fine-scale rugosity	• moored autonomous pCO_2 (MApCO_2) telemetered surface buoys include *sui generis*, LI-COR, Sea-Bird, Aanderaa, and Sunburst sensors • subsurface temperature and salinity • bi-weekly water sampling^{A} • 50m^2 photoquad^{P}/landscape mosaic^{A}	Class III. Fixed sites (n=3^{A}, 3^{P}): • La Parguera, PR • Cheeca Rocks, Islamorada, FL • Flower Garden Banks* • Kāne'ohe Bay, HI • Saipan, CNMI* • Aunu'u, American Sāmoa*	Buoy data retrieved every 3 hours.
• **Ecological impacts**	• Coral growth and calcification rates	• cores of massive reef-building corals	Class II and III. Fixed sites (n=30^{A}, 300^{P})	Instruments retrieved and surveys conducted every 2^{A} or 3^{P} years
	• Bioerosion: net community calcification rates, net reef bioerosion rates	• calcification accretion units (CAUs) • bioerosion monitoring units (BMUs) • community census of bioeroders		
	• Community structure	• Autonomous Reef Monitoring Structures (ARMS)		
Socioeconomic	• Knowledge, attitudes, and perceptions • Participation in coral reef activities	• resident telephone, in-person, mail, or Internet surveys	Random sampling of residents of inhabited islands/counties in direct proximity to coral reefs, data aggregated to jurisdiction level	Surveys conducted every 3 to 4 years, secondary data compiled and analyzed for the same 3 to 4 year period
	• Population changes and distribution • Economic dependence on coral reefs	• synthesis and analysis of secondary data from public sources (e.g., U.S. Census Bureau)		

www.coralreef.noaa.gov

U.S. Department of Commerce,
National Oceanic and Atmospheric Administration,
NOAA Coral Reef Conservation Program,
1305 East-West Highway, Silver Spring, MD 20910
phone: 301-713-3155 | fax: 301-713-4389 | coralreef@noaa.gov