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Climate Change and Interacting Stressors:

Implications for Coral Reef Management in American Samoa

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Climate Change and Interacting Stressors: Implications for Coral Reef Management in American Samoa

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ABSTRACT

Climate variability and change can negatively impact sensitive coral reef ecosystems by altering sea surface temperatures, ocean carbonate concentrations, sea level, storm surges, precipitation patterns, stream flows to the coast, salinity, and pollution loads. This report focuses on the coral reefs of American Samoa as a case study for how managers can approach (1) assessments of reef vulnerabilities to climate change and interacting stressors, (2) identification of adaptive management strategies in response, and (3) integration of management options with existing decision processes and mandates. Large-scale climate stressors are reviewed along with information on localized stressors in American Samoa to assess reef vulnerabilities to climate-related impacts such as coral bleaching. Based on this information, this report presents some adaptive management strategies that could be implemented immediately (e.g., water quality improvements), in the near-term (e.g., enhanced strategic monitoring), and in the long-term (e.g., resilience planning). In each case, management options are considered in a decision making context – i.e., in terms of how such strategies relate to existing plans, processes, and mandates.

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PREFACE

The goal of EPA's Global Change Research Program is to assess the potential implications of climate change for water quality, air quality, human health, and ecosystem health, and to provide decision makers with information and tools for incorporating considerations of climate change into decision making processes. The Ecosystem Focus Area examines the effects of climate change and other interacting stressors on freshwater and coastal ecosystems with the goal of improving society's ability to manage these ecosystems in the context of continuing climate change.

Ecosystems show a variety of responses to climate change, and coral reef ecosystems are especially sensitive. Climate variability and change can either directly or indirectly affect sea surface temperatures, ocean carbonate concentrations, sea level, storm surges, precipitation patterns, stream flows to the coast, salinity, and pollution loads–all of which must be considered in the design of effective strategies for management of coral reefs and their ecosystem services. Yet, current management decisions are often being made without knowledge of sensitivities to climate change and without information on options for best management practices in the context of climate change. Thus, there is an urgent need for studies that link an understanding of climate change effects to management options that are compatible with local decision processes.

This report focuses on the coral reefs of American Samoa as a case study for the development of a general approach for (1) assessing reef vulnerabilities to climate change and interacting stressors, (2) identifying adaptive management strategies in response, and (3) placing management options in the context of existing decision processes and mandates. A review of large-scale climate stressors is combined with information on localized stressors in American Samoa to assess reef vulnerability to climate-related impacts such as coral bleaching. Based on this information, this report presents several adaptive management strategies that could be implemented over immediate, near-term, and longer-term time frames. The report also discusses the importance of considering these options in a decision making context–i.e., identifying how such strategies relate to existing plans, processes, and mandates.

The information presented in this report supports EPA's strategic Goal 4 (Healthy Communities and Ecosystems) as well as the EPA Office of Water's responsibilities under the Clean Water Act to "restore and maintain the chemical, physical and biological integrity of the Nation's waters" and the EPA Office of Research and Development's mission to "provide leadership in addressing emerging environmental issues and in advancing the science and technology of risk assessment and risk management." EPA is also a member of the U.S. Climate Change Science Program (CCSP), which integrates federal research on climate and global change across its thirteen member agencies. This report contributes to two of the CCSP's five major goals: Goal 4, "Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes" and Goal 5, "Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change." Finally, this report responds directly to priority needs of the U.S. Coral Reef Task Force, of which EPA is a member. The USCRTF has named climate change and coral bleaching as a key focal area of concern for coral reef research and management and has called for the development of appropriate management strategies in response.

AUTHORS AND REVIEWERS

The Global Change Research Program in EPA's Office of Research and Development was responsible for preparing this document. Major portions of this report were prepared by TN & Associates, Inc., under EPA Contract No. 68-C-04-004. Jordan West served as the EPA Work Assignment Manager, providing overall direction and coordination of this project, and is a co-author.

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EXECUTIVE SUMMARY

A major goal of this report is to provide the natural resource managers of American Samoa, in particular the Governor's Coral Reef Advisory Group (CRAG), with some management options to help enhance the capacity of local coral reefs to resist the negative effects of climate change. This effort supports the U.S. Environmental Protection Agency's (EPA) Global Change Research Program in its goal to improve scientific capabilities for evaluating the effects of climate change on ecosystems (especially in the context of other local stressors such as water pollution) and develop adaptation strategies. This information is needed because current management decisions are often being made without sufficient information on climate change. American Samoa was chosen for this study due to the interest of local managers in climate change issues and preliminary indications that climate change should be considered an emerging stressor of concern in American Samoa.

A secondary goal of this report is to introduce a simple conceptual model (Figure ES-1) to support managers outside American Samoa in the thought process of planning and conducting similar assessments at their own locations. Section 1 introduces the model as a series of steps in a logical process for (1) assessing those local ecosystem vulnerabilities that potentially occur when climate change and existing local stressors overlap and compound each other, (2) identifying tractable management responses, and (3) evaluating how such responses may be compatible with existing management activities. Section 2 reviews climate variability and change stressors in relation to American Samoa, while Section 3 reviews other (non-climate), local interacting stressors. Section 4 synthesizes scientific information available from the literature on the incidence and degree of reef responses to such stressors in order to assess local reef vulnerabilities. This leads to the examination of potential management strategies and their relation to existing decision-making opportunities in Section 5.

Based on available literature, three local coral reef ecosystem vulnerabilities were identified in American Samoa: (1) climate change alone was determined to be a stressor based on past bleaching events, (2) vulnerabilities could exist due to the combined stresses of poor water quality and climate change, and (3) also of concern, but lacking substantiation, are the potential alterations of cyclones/extreme precipitation events and increases in coral diseases due to climate change.

In order to address the top vulnerabilities to combined climate change and poor water quality stressors, an adaptive management approach is recommended. This approach supports immediate actions by managers based on current knowledge and promotes future refinement as additional information becomes available. Key to adaptive management for climate change is the idea of sustaining ecosystem resilience. Two basics tenets underlie the resilience approach: reduction or elimination of non-climate stresses and protection of adequate and appropriate habitat.

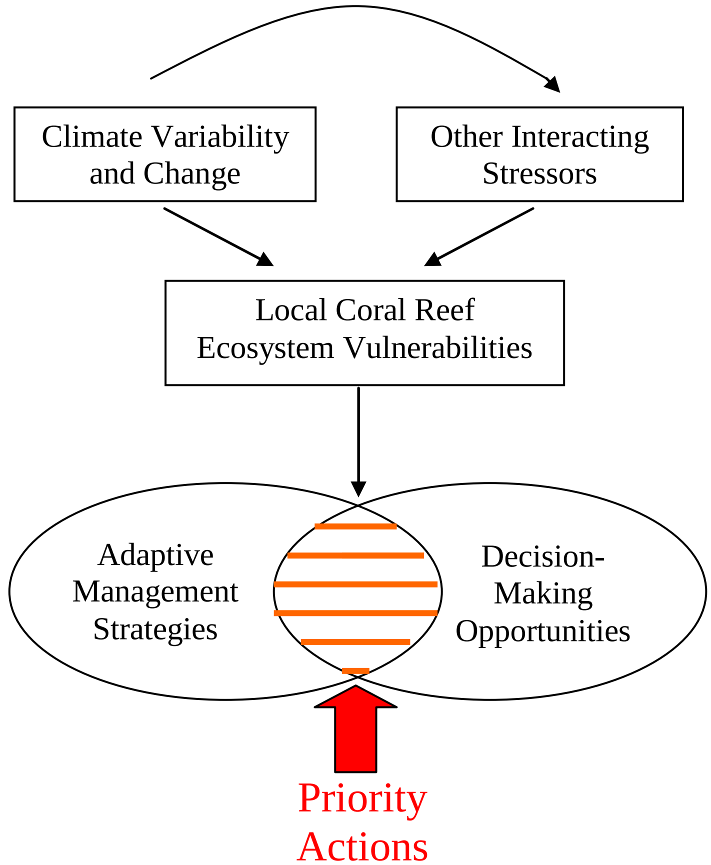


Figure ES-1. Logic diagram for assessment of ecosystem vulnerabilities to climate change and other interacting stressors, and identification of priority management actions.

When the results of the vulnerability assessment are coupled with an adaptive management approach to enhance resilience to climate change, three categories of priority management actions emerge:

1. immediate time frame – implement water quality improvements
2. near-term time frame – develop and implement hypothesis-driven monitoring and research, and
3. long-term time frame – design and implement resilient marine protected area (MPA) networks, with strong village community outreach and involvement.

These priority actions are tailored to ease their integration into existing management projects. With these ideas and the tools provided in the Appendix, management plans may be enhanced by insights into the effects of climate change on this valuable marine resource.

1. INTRODUCTION

1.1. GOAL OF THIS REPORT

Coral reef ecosystems are especially sensitive to changes in climate. Climate variability and change can either directly or indirectly affect sea surface temperatures, ocean carbonate concentrations, sea level, storm surges, precipitation patterns, stream flows to the coast, salinity, and pollution loads–all of which must be considered for the design of effective strategies for management of coral reefs and their ecosystem services. While global-scale stressors such as temperature changes are beyond the control of local reef managers, there are other actions that managers can take to enhance the capacity of natural systems to persist in the face of continued climate variability and change. These actions center on (1) reducing the localized stressors that interact with climate change stressors to compromise the ability of coral reef systems to naturally moderate the effects of climatic perturbations and (2) accounting for patterns of variability in resilience to climate change when planning and managing networks of marine protected areas.

While simple in concept, the above approach can prove difficult to implement in an efficient and effective way. Geographic patterns of climate variability (and their effects on sea surface temperatures, currents, etc.) differ among and within regions, as do the combinations of localized stressors that are unique to any given reef area. Thus, no single management plan will be optimal for all reef systems. Rather, the effectiveness of any reef management strategy will hinge on skillful application of general principles that are used to guide place-based analyses of specific vulnerabilities and to identify priority management responses that are most likely to be effective in that particular reef location. In this report the coral reefs of American Samoa are used as a case study to create simple guidelines for place-based assessment and identification of adaptive management options for coral reef systems.

This report will (1) introduce a simple conceptual model for assessing reef vulnerabilities and potential responses, (2) apply the model to American Samoa's reefs, in particular, and (3) identify priority management actions. The conceptual model will help guide coral reef managers through the thought process of identifying stressors, assessing reef vulnerabilities, and using the information to identify priority management actions that could be incorporated into local management strategies to maximize long term reef resilience in the face of a changing climate. The goal is to provide resource managers in American Samoa with information that supports an informed understanding of collective risks and provides a systematic approach for application of this understanding to management decision processes. To begin, this report presents some background information on American Samoa and its reefs followed by an overview of the conceptual model that will serve as a roadmap for the remainder of the report.

1.2. AMERICAN SAMOA AND ITS CORAL REEFS

The Territory of American Samoa consists of five volcanic islands (Tutuila, Aunu'u, Ofu, Olosega, and Ta'u) and two atolls (Swains Island and Rose Atoll) in the central South Pacific Ocean (Figure 1-1). Tutuila Island is approximately 170°W and 14°S. Surrounding these islands are 296 km^2 of coral reefs that are home to over 890 species of fish, 237 species of algae, 200 species of coral, and many other invertebrates (Waddell, 2005; Wilkinson, 2004). Most reef areas in American Samoa are comprised of fringing reefs that are close to shore (<200 m). Generally, these fringing reefs include a shallow reef flat (0-1 m depth) situated between the shore and outer edge of the reef, where coral tops can be exposed at low tide. The prominent seaward edge of the reef flat is the reef crest, beyond which the reef front or face drops off into deeper water. At most sites, the reef front descends at a slope of 30-90º to a depth of 10-30 m where the reef transitions to a gently sloping sand flat. Well developed lagoons are uncommon in American Samoa (Green, 1996).

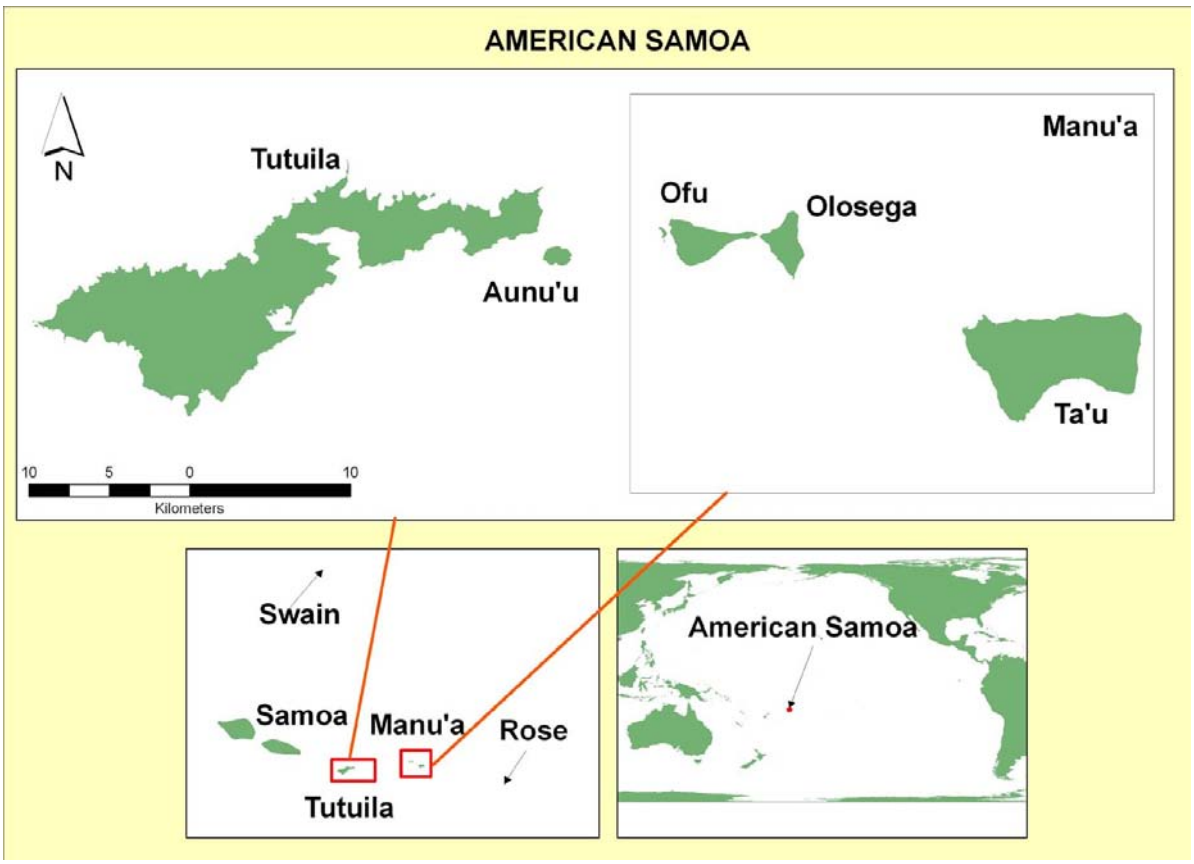


Figure 1-1. Islands of the Territory of American Samoa. Courtesy of Francesca Riolo, Mappamondo GIS.

Nearly 80% of the coral populations in American Samoa are comprised of eight coral genera: *Montipora*, *Porites*, *Acropora*, *Pavona*, *Goniastrea*, *Montastraea*, *Pocillopora*, and *Galaxea* (in decreasing order according to Fisk and Birkeland, 2002). Another 33-54 genera, depending on location, make up the remainder (Fisk and Birkeland, 2002; Maragos et al., 1994). These coral reefs and their biological diversity provide important benefits to the people of both American Samoa and the U.S. mainland. The coral reefs currently support local subsistence and artisanal fisheries, provide coastal protection, and offer recreational opportunities to residents and visitors. There is also great "existence value" placed on coral reefs as unique natural resources by the U.S. public (Heywood, 1995). Combined, these benefits have been economically valued at over $10 million per year for American Samoa (Spurgeon et al., 2004), further underscoring the importance of this resource and the need for careful management.

Coral reefs are unique ecosystems with both biological and geological characteristics. Most reef-building corals consist of tiny animals called polyps that are connected by living tissue and form a surface veneer that covers and builds the colony's shared calcium carbonate skeleton. In fast growing species, a colony's calcium carbonate skeleton can grow several centimeters in a year. Together, a community of coral colonies may build a reef at an average vertical accretion rate of 1-10 millimeters per year (Smith and Buddemeier, 1992).

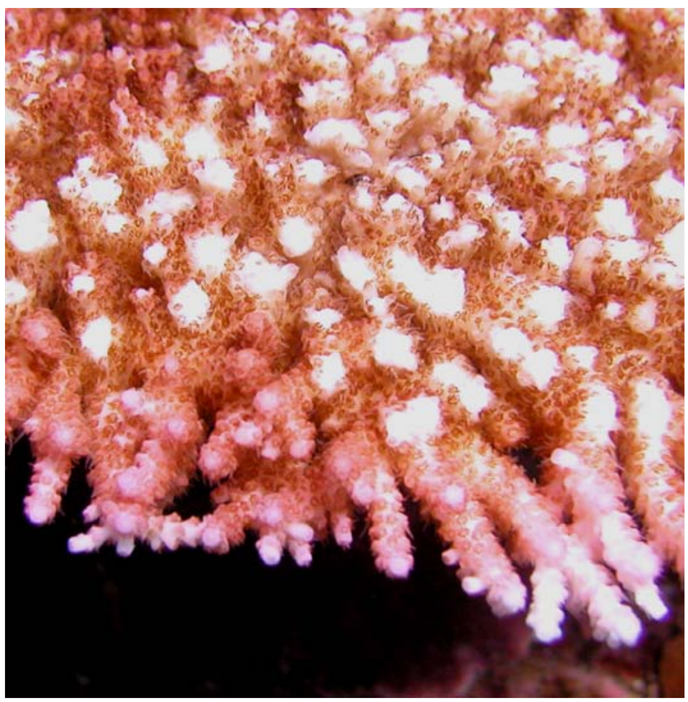
Aerial view of coral reefs in American Samoa. (Photo by Eric Mielbrecht.)

Coral polyps rely on a symbiotic relationship with single-celled microalgae (zooxanthellae) that live in large numbers within their body tissues and give the colonies their many vibrant colors. These zooxanthellae capture solar energy through photosynthesis and create nutrients that are shared with the host coral in exchange for a protected living space and coral nutrients (e.g., nitrogen). Because their primary need is sunlight (and little else), corals are uniquely adapted to shallow, clear, oligotrophic (low nutrient), tropical and subtropical waters

(Buddemeier et al., 2004). This adaptation to stable conditions renders the coral-algal symbiosis vulnerable to acute environmental fluctuations such as climate-related sea surface temperature anomalies. Coral bleaching is one potential result.

Coral bleaching, or the paling of coral tissues, is characterized by *in situ* degradation or loss of the symbiotic zooxanthellae from coral tissues, usually as a stress response (Brown, 1997a). If the zooxanthellae and associated pigments are lost, the white calcium carbonate skeleton is seen through the translucent coral tissue, giving the coral the appearance of having been *bleached*. The coral colony can die if the zooxanthellae association is not quickly re-established (within weeks) (Harriot, 1985). Coral bleaching can be induced in the laboratory or field by high or low temperatures, intense light, absence of light, changes in salinity, infectious disease, or other physical or chemical stresses (Buddemeier et al., 2004; Jokiel, 2004; Hoegh-Guldberg, 1999; Brown, 1997a).

Widespread coral bleaching began to attract global attention after the first, carefully tracked, broad-scale bleaching event that occurred in association with the severe 1982-83 El Niño-Southern Oscillation (ENSO) (Glynn, 1984). The rate of occurrence (annually in some areas) and large scale of mass bleaching events since the early 1980s is in stark contrast to the trend of the first half of the 20th century, during which time bleaching events were localized and linked to local stress events (Glynn, 1993; Jokiel and Coles, 1990; Williams Jr. and Bunkley-Williams, 1990; Goreau, 1964). This increase in the scale of bleaching has led to the suggestion that climate change-related increases in annual sea surface temperatures and occurrences of ENSO conditions may be responsible (Hoegh-Guldberg, 1999; Pittock, 1999). ENSO results in the development of regions of unusually warm water throughout the equatorial Pacific and Indian Oceans. Significant coral bleaching is especially likely when these warming anomalies overlap with seasonal maximum water temperatures. Indeed, coral bleaching correlates with ocean thermal anomalies, and there is substantial evidence that elevated temperatures are the chief cause of large-scale, mass bleaching events (Hoegh-Guldberg, 1999; Brown, 1997a; Glynn, 1993; Williams and Bunkley-Williams, 1990).



A partially bleached *Acropora* coral. The white portions have lost the golden brown algae (zooxanthellae) that normally give the tissues their color. (Photo by Eric Mielbrecht.)

In American Samoa, widespread coral bleaching occurred in 1994, 2002, and 2003 (Hansen et al., in preparation-b; Craig et al., 2005; Wilkinson, 2004; Fisk and Birkeland, 2002; Green, 2002). Unusually high sea surface temperatures (>29.9°C) were recorded in the region during the summer months of those years (Hansen et al., in preparation-b; Goreau and Hayes, 1995). Data from a limited number of monitoring studies have indicated that there was significant variability in bleaching and recovery within and among locations during these events, but an understanding of the reasons for this variability remains incomplete.

Any attempt to understand the effects of climate-related stressors will require consideration of the interaction with localized stressors associated with human activities. Over 95% of American Samoa's roughly 60,000 inhabitants live on Tutuila, the largest island. Its population is growing rapidly and is expected to double in the next 30 years. The steepness and small size of the island force the human population to concentrate on the narrow coastal plains, where heightened development and commercial activity have affected nearby reefs (Craig et al., 2005). For example, industrial and domestic wastes and land development have resulted in water pollution in the form of toxic contaminants, excess nutrients, and sedimentation influxes to coral reef waters (DiDonato and Paselio, 2006).

Fortunately, the traditional Samoan way of life, or *fa'asamoa*, with its strong family and village kinship, promotes sharing and maintaining land, sea, and water resources for the good of the whole community. With this motivation 26.7 km^2 of coral reef areas have been included in marine protected areas (MPAs) in the Territory of American Samoa (about 9% of the total reef area) (Craig et al., 2005; Green, 1997). This includes the National Park of American Samoa, administered by the National Park Service; Fagatele Bay National Marine Sanctuary, administered by the National Oceanic & Atmospheric Administration; The Vaoto Marine Park, administered by the Territorial Government; Rose Atoll National Wildlife Refuge, administered by the U.S. Fish and Wildlife Service; and community-based MPAs, administered by the local village communities with assistance from the Territorial Government (Craig et al., 2005). Additionally, Governor Tauese Sunia furthered this process in 2000 when he pledged that the American Samoa Government would establish no-take areas to protect at least 20% of the surrounding coral reefs by 2010. The resource conservation management processes of existing MPAs in American Samoa are an excellent infrastructure for integrating the adaptation options developed in this report.

1.3. ROADMAP TO THIS REPORT

The goal of this report is to provide the natural resource managers of American Samoa with an assessment process and some basic adaptation options that can be integrated into existing and future management decisions in order to enhance the resilience of coral reefs to climate change impacts. In support of this goal, a simple conceptual model is presented as a structure for the remainder of the report (Figure 1-2).

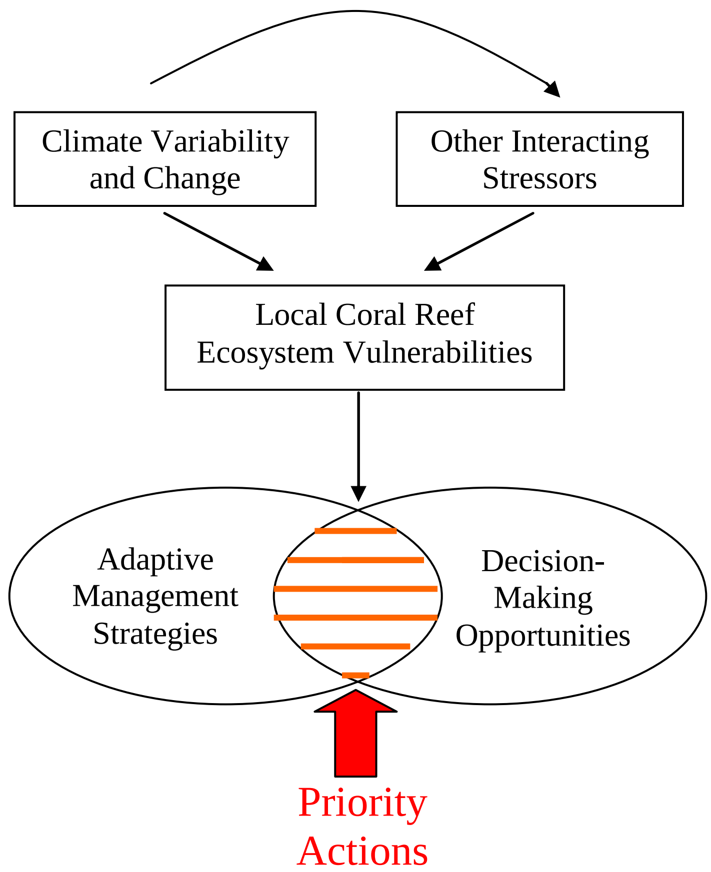


Figure 1-2. Logic diagram for assessment of ecosystem vulnerabilities to climate change and other interacting stressors, and identification of priority management actions.

Section 2 introduces current scientific understanding of the presence and effects of stressors associated with climate variability and change. An account of local stressors that are likely to have the greatest impact on the reefs of American Samoa follows in Section 3. The combined information on stressors–including an analysis of potential interactions among climate and local stressors–is then presented in Section 4 as a means for managers to characterize the vulnerabilities of local reefs in American Samoa to coral bleaching and other climate-related impacts. This includes a summary and review of past coral bleaching events in American Samoa and a discussion of patterns of variability in bleaching and mortality associated with different resilience characteristics.

In Section 5, the results of the vulnerability assessment are used to identify some adaptation options that may be location-specific or specific to a whole region. These options range from uncomplicated actions that could be implemented immediately, to more complex longer-term strategies. In situations where the strategies readily overlap with existing management decision processes in American Samoa, the report identifies certain options as potential candidates for priority actions. Section 6 concludes that, in the future, as the assessment process continues and more information becomes available through continued research, more complex adaptation strategies may be developed, thereby increasing the overlap between available management strategies and the decision-making processes that make them possible. The current aim, then, is to facilitate rapid incorporation of simpler adaptation options into today's management decisions while simultaneously developing a battery of more complex options for integration into future resource management decisions. All are crucial elements of a strategy to help the sensitive coral reef ecosystems of American Samoa maintain long-term resilience in the face of on-going climate variability and change.

2. STRESSORS ASSOCIATED WITH CLIMATE VARIABILITY AND CHANGE

Climate variability and change add a variety of chronic and acute large-scale stresses to coral reefs. Large-scale climate stressors act as an overlay on already-existing local stressors (e.g., disease outbreaks, pollution) and generate layers of interactions that can cause complex reef responses. Climate change occurs on all temporal and spatial scales, from brief but severe storms to multi-seasonal ENSO conditions, decadal droughts, and shifts in temperature and sea level over centuries. In this section, a number of climate-related stressors of particular concern to coral reefs are reviewed.

2.1. CHANGES AND FLUCTUATIONS IN SEA SURFACE TEMPERATURES

The concentration in the atmosphere of carbon dioxide (CO_2), the primary heat trapping gas, has increased during the 20th century and currently is at the highest level of the past 420,000 years (IPCC, 2001b). The Earth's surface temperature has also risen during this time. This trend is projected to continue even if concentrations of heat trapping gases are rapidly stabilized. According to the IPCC (2001b), the global mean surface temperature has increased by 0.6 ± 0.2°C during this period and is projected to rise an additional 1.4-5.8°C during the 21st century (Figure 2-1). To date, no precedent has been found in 10,000 years of paleoclimate data for this rate of warming.

Warming of the sea surface parallels past land-surface air temperature changes (Figure 2-2). Sea surface temperatures have increased globally by 0.4-0.8°C since the late 19th century and are projected to increase another 1-2°C by 2100 (IPCC, 2001b). Historically, environments where coral reefs have thrived have had a high degree of temperature stability, and available data indicate that temperatures in tropical oceans have fluctuated less than 2°C over the past 18,000 years (Thunnell et al., 1994). Corals have adapted to this stability and in many locations live close to their upper thermal limits (Goreau, 1992). They can become stressed if exposed to increases in water temperature as little as 1-2°C above average summer maximum temperatures, the result being bleaching and potential mortality (Hoegh-Guldberg, 1999; Brown, 1997a).

Meanwhile, from the 1970s to today, temperature anomalies associated with ENSO events have also been more frequent, persistent, and intense. The El Niño segment of the Southern Oscillation cycle results in the development of regions of unusually warm water throughout the eastern and central equatorial Pacific Ocean. The combination of climate-driven sea surface warming and more frequent and intense ENSO conditions over the past two decades have already resulted in a significant increase in coral bleaching (Wilkinson, 2004; Hoegh-Guldberg, 1999; Brown, 1997a; Glynn, 1993). The most extensive and intense bleaching event to date was in 1997-1998 and coincided with the strongest ENSO disturbance on record (Hoegh-

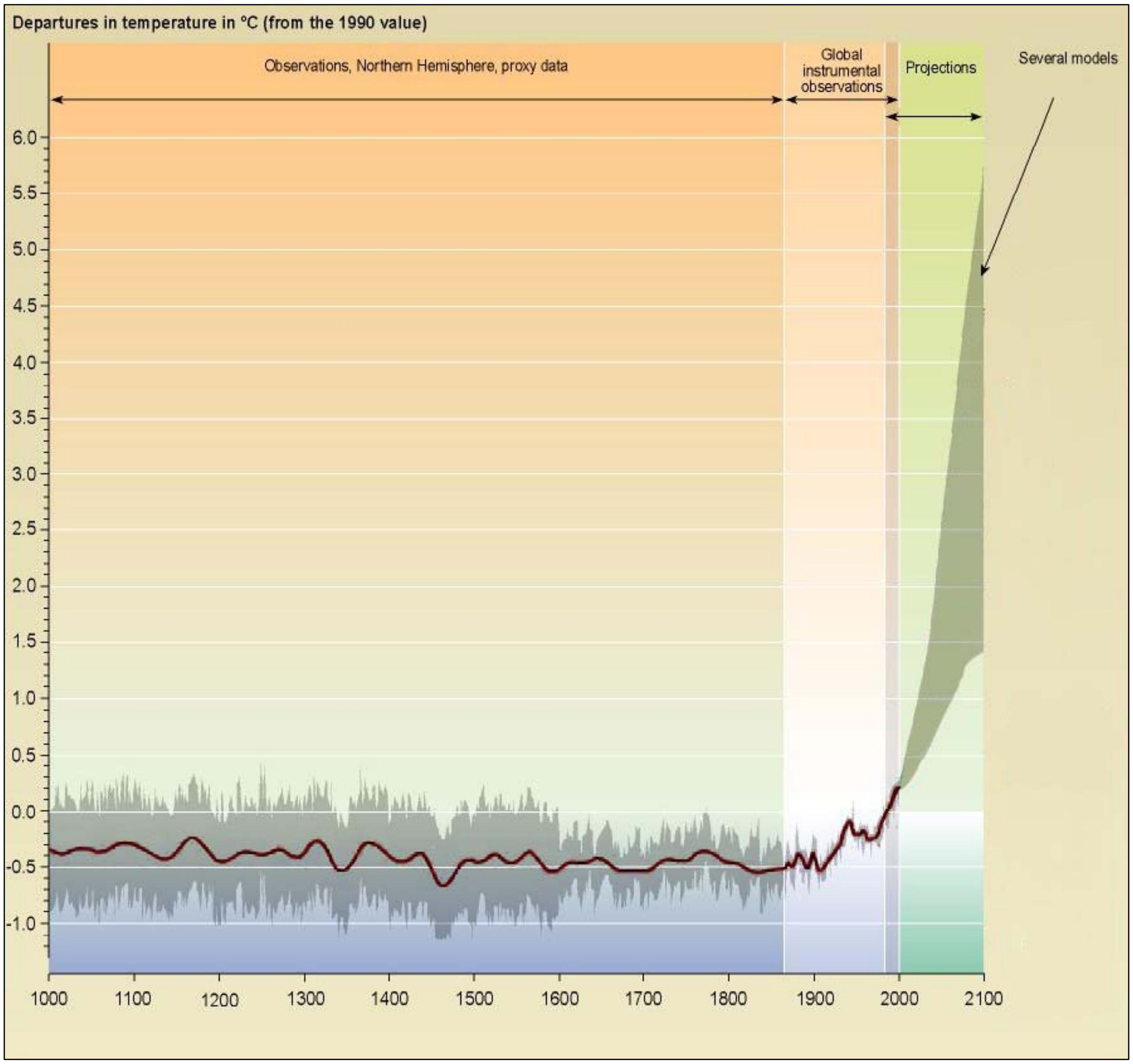


Figure 2-1 Variations of the Earth's average surface temperature (°C) from the year 1000 to 2100. The temperature scale is the departure from the 1990 value. Years 1000-1860 are reconstructed from tree rings, corals, ice cores, and historical records. From 1000-1860, the black line is the 50-year average, and the gray region is the 95% confidence limit. Years 1860-2000 are from instrumental records. From 1860-2000, the black line is the 10-year average. Years 2000-2100 are projections from several model scenarios, with the gray region showing the full range of predictions.

Source: IPCC, 2001a.

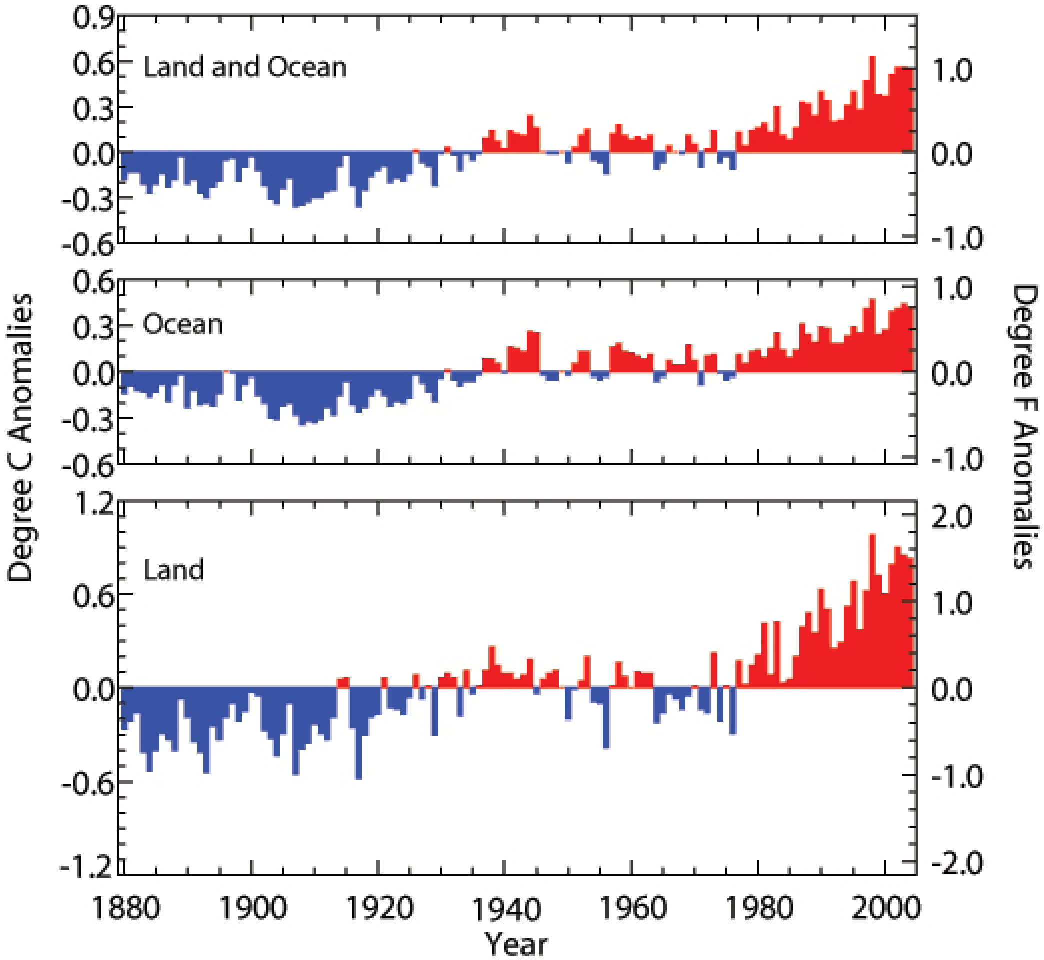


Figure 2-2. Comparison of the variation in the mean land and ocean surface temperatures from years 1880-2000. Temperature scale is the departure from the 1961-1990 mean. Ocean surface temperatures closely parallel global surface temperatures, although with reduced amplitude.

Source: National Climate Data Center, 2005.

Guldberg, 1999). Wide-scale bleaching also occurred during the ENSO events of 1982-1983 and 1987-1988 (Hoegh-Guldberg, 1999).

While climate model projections show little change or only a small increase in amplitude for ENSO events over the next 100 years, there is evidence that a gradual shift to more consistent ENSO-like conditions will occur and that La Niña conditions (the cooler segment of the Southern Oscillation cycle) will become increasingly unusual (IPCC, 2001b). In addition, climate change is expected to cause greater extremes in drought and heavy rainfall during ENSO events (IPCC, 2001b) and has already begun to heighten cyclone intensity (Emanuel, 2005). These affects are discussed further in Section 2.2.

In American Samoa, there has been a trend of increasing average sea surface temperatures since 1982 according to satellite measurements (Figure 2-3), with the warmest seasons occurring in 1994, 2002, and 2003. These warm periods coincided with ENSO-related Pacific Ocean conditions in 2002/2003. However, sea surface temperatures were not abnormally elevated in American Samoa during the other strong ENSO years of 1983 and 1997/98. American Samoa appears to be located far enough West and South in the central Pacific Ocean to not be consistently influenced by the ENSO cycle.

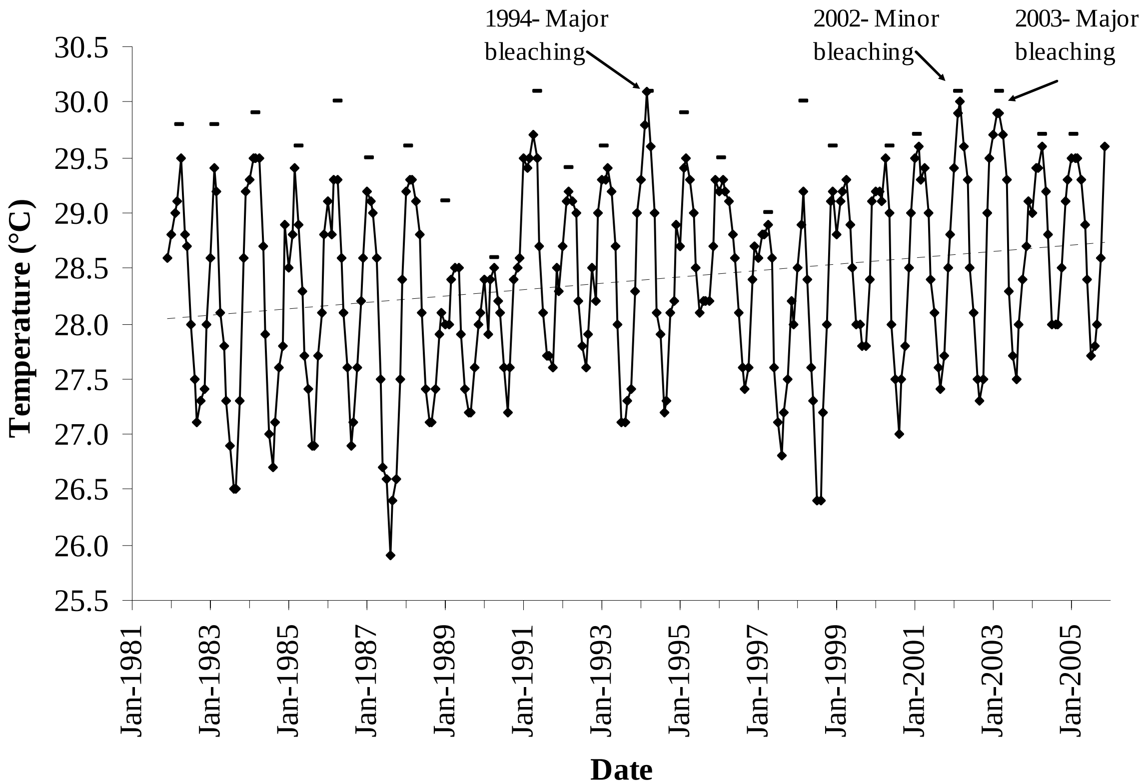
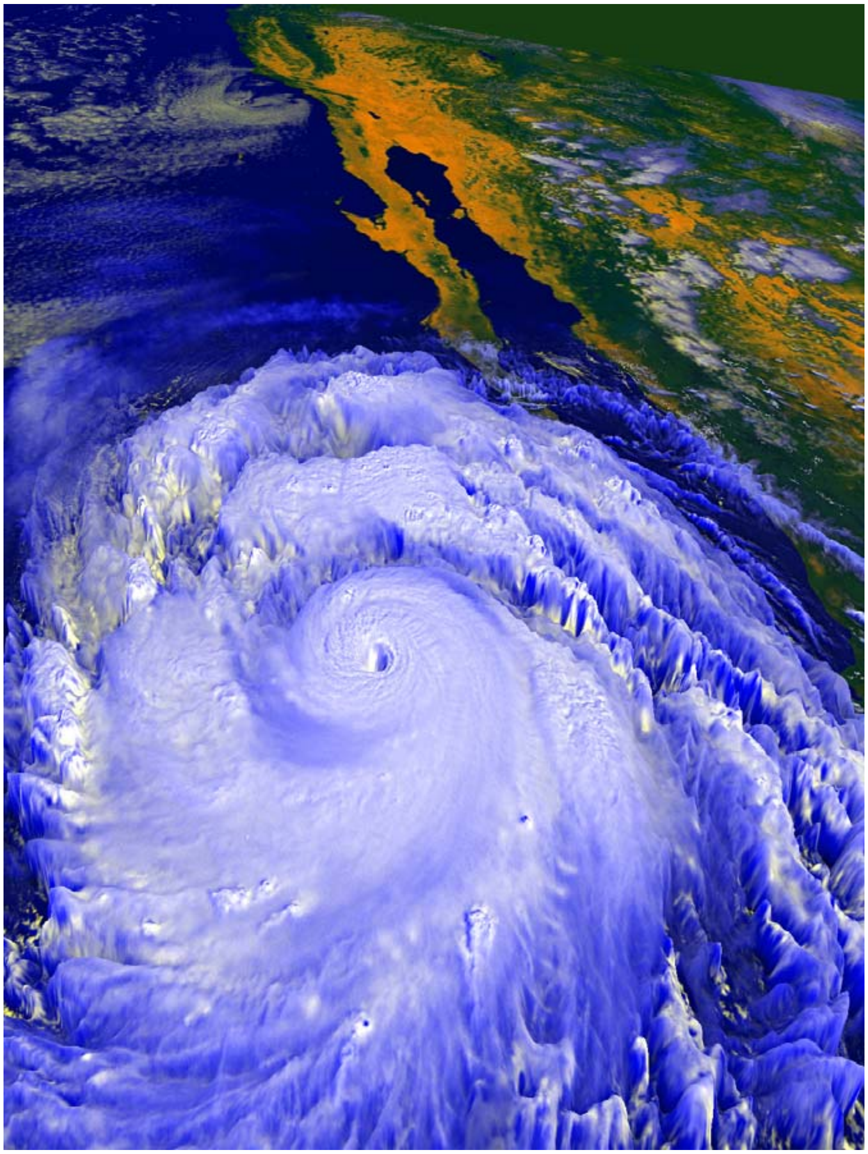


Figure 2-3. Monthly mean sea surface temperatures in the vicinity of Tutuila Island, American Samoa. Points are monthly means, bars above are maximum mean weekly temperature for the year. Trend-line shows a long-term temperature increase of ~0.28°C per 10 years. Temperature data are from the Reynolds/National Centers for Environmental Prediction integrated satellite and *in situ* sea surface temperature databases.

Source: NASA Jet Propulsion Laboratory, 2005.

2.2. CHANGES AND FLUCTUATIONS IN WEATHER PATTERNS

Cyclones are a regular feature of many tropical regions. Although they can be quite damaging to coral reefs and surrounding ecosystems, healthy reef systems have thus far been able to recover from their intermittent, acute effects. Recent scientific study has shown that cyclone intensity has increased over the last 30 years in some regions (Emanuel, 2005). Projections show that cyclones are expected to be more intense (5-10% increase in peak wind) in the future, with greater associated precipitation (20-30% increase) (Emanuel, 2005; Trenberth, 2005; IPCC, 2001a). There has been no evidence or prediction of changes in cyclone frequency, tracks, or areas of formation.



Hurricane Linda (1997), an example of a Pacific cyclone. (Photo courtesy of the National Aeronautics and Space Administration [NASA].)

Overall, global average precipitation is projected to increase in the future (IPCC, 2001b). Geographic and temporal patterns of precipitation are also likely to change, with greater extremes in localized events such as intense downpours. During the 20th century, precipitation increased over the tropical oceans and land areas. This trend is expected to continue along with increasing frequency and intensity of rainfall events. One of the larger increases in mean precipitation is expected in the tropical oceans, with the equatorial Pacific Ocean seeing a greater than 20% change under some modeling scenarios (IPCC, 2001b). American Samoa is situated just south of this region and is expected to see a mean increase in precipitation of approximately 5% in the next century (IPCC, 2001b). Increasing precipitation can cause a variety of impacts on coral reefs, including greater transport of land-based sediments, nutrients, and contaminants along with extension of low-salinity plumes in the vicinity of streams and rivers. Stress-related mortality events for coral reefs are more possible with the increasing frequency and intensity of these events (McCarthy et al., 2001).

From 1981 to 2005 American Samoa has been impacted by six tropical cyclones: Esau in 1981, Tusi in 1987, Ofa in 1990, Val in 1991, Heta in 2004, and Olaf in 2005. The strongest and most damaging in recent history were Ofa and Val, which were both category 4 cyclones (Green, 2002). There has been at least one recent extreme rain event that caused widespread flash floods and mudslides. It occurred on May 18-19, 2003 and was called the Pago Pago/Fagatogo flood. Approximately 25–40 cm of rain fell in approximately 24 hours (Brakenridge et al., 2003).

2.3. OCEAN CHEMISTRY

Surface seawater CO_2 concentrations are predominately driven by atmospheric CO_2 levels. As CO_2 dissolves in seawater, the pH of the seawater decreases, shifting the relative concentrations of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions. Many reef building organisms use the calcium (Ca^{2+}) and CO_3^{2-} ions in seawater to build calcium carbonate ($CaCO_3$) skeletons. The reduction of either component can affect the rate or quality of skeletal deposition (Kleypas et al., 1999). Ca^{2+} is very abundant in seawater and is not affected by climate change; however, CO_3^{2-} is much less abundant, such that even a small decrease in seawater pH caused by increasing atmospheric CO_2 will substantially decrease its concentration, reducing the calcification rates of reef building organisms (Buddemeier et al., 2004).

In laboratory experiments, a doubling of atmospheric CO_2 (a level expected to be reached in nature before 2100, if current rates of increase continue) (IPCC, 2001b) caused coral calcification rates to decrease by 11-37% (McCarthy et al., 2001; Kleypas et al., 1999). Such reductions in calcification rates in nature would mean that corals would build their skeletons more slowly and/or less densely. Less dense skeletons could be more easily broken during storm events or other physical impacts. In general, reef structures can only grow and persist when $CaCO_3$ deposition rates exceed (or at least equal) erosion rates. Given this, the possibility of significantly slowed reef-building–or even a complete reversal and loss of reef structures–becomes a concern.

American Samoa is in a region of the tropical Pacific Ocean where calcification rates are projected to decrease with climate change over time, but not as rapidly as at higher latitudes (Kleypas et al., 1999). Calcification rates in American Samoa may have already decreased approximately 10% from rates prior to industrial revolution (1880). Rates may decrease an additional 10-20% by the year 2100, based on model projections (Kleypas et al., 1999).

2.4. SEA LEVEL RISE

Global average sea level has risen between 0.1 and 0.2 meters in the 20th century, according to long-term tide gauge data from locations in Northern Europe (IPCC, 2001a). During the 21st century, the sea level is expected to rise another 0.09-0.88 meters, primarily due to thermal expansion and the melting of glaciers and ice shelves (IPCC, 2001a). This translates to an average annual rise of 0.9–8.8 mm a year, a rate that is within the ability of most healthy reefs to match through growth (Smith and Buddemeier, 1992). However, growth rates in some areas may be slowed enough by chronic stresses and changes in ocean chemistry (see Section 2.3) to cause deeper reefs to fall below available light depth limits (Buddemeier et al., 2004). Historically, South Pacific sea level rise has been consistent with the global average, and this trend is expected to continue (McCarthy et al., 2001). Therefore, future sea-level rise in American Samoa is likely to be in the range of 0.09-0.88 meters over the next century.

2.5. INDIRECT EFFECTS OF CLIMATE CHANGE ON ULTRAVIOLET (UV) RADIATION STRESS

UV-related stress is an important concern for coral reefs because it can exacerbate coral bleaching, irrespective of water temperatures (Gleason and Wellington, 1993; Lesser et al., 1990). Conditions that result in elevated levels of visible and UV light may be indirectly compounded by climate variability and change (Zepp, 2003; Hoegh-Guldberg, 1999). The penetration of UV radiation in the water column varies by location. It ranges from meters in coastal regions to tens of meters in the open ocean and changes over time at a given location (Zepp, 2003). Variability in the amount of UV-absorbing organic matter in the water column, which is primarily responsible for UV attenuation, accounts for these differences in UV penetration. During times of exceptionally calm and clear water conditions (such as ENSO conditions, which are likely to increase in frequency and duration in the next 100 years [IPCC, 2001b]), greater penetration of UV radiation increases the potential for UV-exacerbated coral bleaching (Zepp, 2003; Gleason and Wellington, 1993). There has been little evidence that climate change directly influences the intensity of solar radiation reaching the Earth's surface, except possibly by large-scale changes in cloud cover.

Preliminary findings from a recent study in American Samoa show that water above the fringing reef face at several locations on Tutuila Island is quite transparent to UV light. Attenuation of UV light in near-shore American Samoa water was less than measured in coral reef areas of the Florida Keys (Hansen et al., in preparation-b). Information on variability over time and analysis of the potential ramifications for coral reefs in American Samoa are not yet available.

3. STRESSORS ASSOCIATED WITH LOCAL ACTIVITIES AND EVENTS

In addition to stressors associated with large-scale climate variability and change, a wide variety of additional stressors result from localized human activities. These activities range from acute disturbances (e.g., sedimentation stress associated with coastal development activities) to chronic disturbances (e.g., nutrient stress associated with ongoing agricultural activities). Coral reefs are less likely to recover if stresses increase in number and severity (Buddemeier et al., 2004; Hoegh-Guldberg, 1999). When combined with large-scale climate stressors, the effects of local stressors may be exacerbated. This section provides a brief overview of common local stressors of concern for coral reefs. Details of how local stressors in American Samoa may interact with climate stressors to generate particular patterns of reef vulnerability will be discussed in Section 4.

3.1. POOR WATER QUALITY

Corals thrive in the clear, nutrient-poor, and uncontaminated waters of tropical marine environments. Inputs of excessive nutrients, contaminants, and particulates from land-based sources can harm corals directly by interfering with biochemical and reproductive processes or indirectly by reducing light availability for photosynthesis and promoting the growth of phytoplankton, macroalgae, sponges, and ascidians (all of which can out-compete corals for space) (Fabricius, 2005; Brown, 1997a; Hubbard, 1997).

The various forms of excess nutrient loading caused by human activity generally result in local, chronic stress. Incompletely treated sewage, agricultural fertilizers, animal wastes, and increased terrestrial runoff due to land disturbances are all common sources of excess N and P in marine systems. Furthermore, nutrient pollution can increase exponentially in developing countries with rapid population growth (Wilkinson, 1996).

The impacts of excessive nutrients due to sewage input have been clearly documented in a case study of Kaneohe Bay, Hawaii (reviewed in Brown, 1997b). Coral reefs in Kaneohe Bay were exposed to high amounts of nutrient-rich sewage from 1963–1977, which caused considerable changes in the reef community structure. A successional shift occurred when a species of green algae (which flourished in the nutrient-rich water) smothered existing corals and led to domination of the site by particle feeders such as zoanthids, sponges, and barnacles. Three years after the relocation of the sewage outfall, the particle feeders had disappeared. Within six years, the algal community had declined and a high number of coral recruits were seen over the reefs (Brown, 1997b).

Contaminants are toxic or bioactive man-made chemicals that have found their way onto coral reefs as part of waste streams discharged to the ocean, as accidental spills, as a result of use of antifouling biocides, or as components of terrestrial runoff (Buddemeier et al., 2004). They include oil and fuels, insecticides, herbicides, heavy metals, and other industrial and household chemicals. Fuel or other chemical spills can be common near busy harbors or industrial areas. Runoff containing insecticides and herbicides can be common in reefs adjacent to agricultural fields. Storm water runoff from urban and suburban regions can be another route of contaminant input. Such contaminants can cause a range of sublethal to lethal effects on corals (Haynes and Johnson, 2000).

A 1974-75 study of chronically oil-polluted reefs in close proximity to an oil terminal in the northern Gulf of Eilat in the Red Sea showed higher coral mortality rates, smaller numbers of breeding colonies, and lower coral larvae settlement rates when compared to a control reef nearby (Loya, 2004). Local laboratory studies supported these field observations (Loya, 2004). Studies on the Great Barrier Reef have shown that contaminants such as heavy metals and pesticides have been making their way into reef organisms from terrestrial sources. These contaminants alter reproductive success and interfere with photosynthesis and may pose a threat to Great Barrier Reef coral communities if toxic concentrations are reached (Haynes and Johnson, 2000).

Terrestrial runoff also often contains sediment that increases turbidity and reduces available light for photosynthetic activity on the reef. High sedimentation rates can kill coral tissue within a period of a few days (Fabricius, 2005). Lower sedimentation rates reduce photosynthetic yields, increase relative respiration rates, and increase carbon losses through greater mucus output (Riegl and Brancha, 1995). Sediment accumulation can also inhibit the establishment of new coral colonies by covering suitable settlement surfaces. Because sediment can become repeatedly re-suspended when the water is disturbed, its effects can be widespread in space and time (Buddemeier et al., 2004).

A sediment plume caused by terrestrial runoff. (Photo courtesy of the National Oceanic and Atmospheric Administration [NOAA].)

Unchecked erosion caused by dredging, construction activities, agriculture, logging, dumping, mining, and land reclamation, can all result in increased sedimentation and elevated turbidity. Extensive nearby dredging has reduced coral cover and diversity at sites in Thailand

and Bermuda (Cook et al., 1996; Brown et al., 1990). Logging, together with poor agricultural practices in Southeast Asia and changes in agricultural methods in Australia, have threatened adjacent coral reefs by vastly increasing sediment delivery to the near-shore environment in both places (Buddemeier et al., 2004). Coral communities adjacent to areas of enhanced erosion or where re-suspension of sediments is common will probably continue to experience increasing chronic stress with periodically-intense acute episodes. Climate variability and change may magnify this chronic stress and increase the frequency of acute events in some places through increased precipitation or intensity of rain events (Hubbard, 1997).

The quality of the offshore waters around American Samoa is generally considered to be good (Craig et al., 2005). However, near-shore and stream water quality is quite variable, with some areas exhibiting poor water quality (e.g., Pago Pago Harbor) (Craig et al., 2005; ASEPA, 2004; Green et al., 1996). Water pollution in American Samoa is primarily from non-point sources in the form of excessive nutrient and bacteria loading and excessive erosion and sediment runoff during storm events (DiDonato and Paselio, in review; ASEPA, 2004). Generally, poor water quality in streams or at the shoreline (measured as nutrient or bacteria content) correlates well with human population density, and even more so near areas not serviced by the municipal sewage treatment system (DiDonato and Paselio, in review). Past dredging and filling operations for road construction and other near-shore construction projects have also impacted coral reefs in Pago Pago Harbor and other areas around Tutuila Island (Cornish and DiDonato, 2004; Green et al., 1996; Dahl, 1981; Dahl and Lamberts, 1977).

3.2. DISEASES AND OPPORTUNISTIC SPECIES

Outbreaks of coral diseases and pressures from opportunistic marine organisms represent additional potentially-escalating sources of both acute and chronic stresses for coral reefs. Coral diseases (i.e., any impairment of vital bodily functions) can be caused by pathogens and parasites, or by abiotic stresses including excessive water-born nutrients (Bruno et al., 2003). Corals do possess a variety of defense mechanisms that protect them from invasion by pathogens. However, these defenses can be weakened by chronic environmental stresses and can lead to the emergence of latent infections (Bruno et al., 2003; Peters, 1997).

Coral reef diseases in the Caribbean were first reported during the mid-1970s. The first major coral mortality in the greater region was caused by white plague disease, which appeared in Florida in 1975. This was followed by two acute Caribbean-wide epizootic events that changed the structure and morphology of shallow water coral reef communities in the early 1980s. The first, major mortality event was the die-off of the black sea urchin (*Diadema sp.*) due to an unknown pathogen. Second, and even more significant, was the die-off of the dominant acroporid corals due to white band disease, which resulted in major losses of coral cover, spatial heterogeneity, and reef biodiversity (Weil, 2004). Other diseases have also endangered the future integrity of many coral reef communities in the Caribbean by their widespread chronic persistence (reviewed in Weil, 2004).

Relatively little is currently known about coral diseases on Indo-Pacific reefs. Either disease is less prevalent, or disease distribution and abundance has been underestimated due to a lack of study (Willis et al., 2004). Preliminary results from recent surveys for coral disease in American Samoa show that diseases are present in American Samoa, but the effects are minimal compared to the large scale epizootic events that have taken place in the Caribbean (Aeby, 2005).

The crown-of-thorns starfish (COTS), *Acanthaster planci*, whose juveniles and adults feed directly upon corals, is an opportunistic species that can devastate large areas of reef if a population outbreak occurs. The starfish is a natural inhabitant of Indo-Pacific reefs, and populations are normally low (6 to 20/km^2). However, where population outbreaks occur, densities can exceed 500/km^2 with resulting coral mortality of up to 99% in extreme cases (Brown, 1997b; Zann, 1992). There is no simple condition that leads to the dramatic variation in COTS populations or the ensuing widespread coral destruction that has been observed (Brown, 1997b; Zann, 1992).

Crown-of-Thorns Starfish (COTS). (Photo courtesy of Lara Hansen.)

COTS population outbreaks in American Samoa have been infrequent but highly damaging to some coral communities around Tutuila Island. The only documented outbreak began in 1977 and remained active until 1980, when live coral became limited (Zann, 1992). Coral mortality in Fagatele Bay on Tutuila Island was estimated to be 95% (Green, 2002; Zann, 1992).

3.3. OVER-FISHING AND RESOURCE EXTRACTION

Over-harvesting of reef resources can create myriad stresses that are often difficult to avoid. Coral reef systems have long been a resource for food, but other organisms of many types are also taken as souvenirs or decorations or for the aquarium trade (Buddemeier et al., 2004; Wilkinson, 1996). Over-fishing, or the unsustainable fishing or collection of particular organisms, is a chronic problem worldwide and has impacted the entire marine ecosystem (Pandolfi et al., 2003; Jackson et al., 2001). Coral reefs are highly productive systems but have low net productivity that can not sustain heavy fishing pressures. Over-fished reef communities often decline rapidly due to shifts in ecosystem dynamics. For example, herbivores play an important role in the competitive balance between coral and macroalgae on the reef, so over-fishing or even light fishing of herbivorous fish or invertebrates can lead to enhanced macroalgae growth and concomitant loss of coral cover (Wilkinson, 1996). The methods used in fishing and gathering reef organisms can also have destructive effects through removal of target species. Dynamite fishing and the use of toxic chemicals to take fish result in destruction of non-target organisms, as do net fishing, gleaning, and physical impacts from boat anchoring. The chronic and wide-ranging nature of such over-fishing stresses can contribute to a hampered ability of coral reefs to recover from other acute, harmful events (Wilkinson, 1996).

3.4. CONCLUSIONS

The emerging challenge for successful coral reef resource management lies in understanding how stressors associated with large-scale climate variability and change will add to, modify, or act synergistically with the localized non-climate stressors described above. For example, coral diseases may increase rapidly with increasing sea surface temperatures (Harvell et al., 2002; McCarthy et al., 2001). Also, coastal population growth and an ever-increasing dependence on fertilizers and pesticides for agriculture–coupled with a greater frequency of extreme rain events in the tropics–may amplify nutrient and contaminant pollution in terrestrial runoff as well as sediment deposition. The next section highlights an assessment of the particular combinations of climate and non-climate stressors most likely to be of greatest concern for causing vulnerabilities to the reefs of American Samoa.

4. VULNERABILITIES OF AMERICAN SAMOA'S REEFS TO INTERACTING STRESSORS

4.1. APPROACH

An assessment of local coral reef ecosystem vulnerabilities in the face of combined climate change and local stressors is central to the conceptual model presented in Figure ES-1. Here, climate and local stressors specific to the coral reefs of American Samoa are reviewed, with special attention given to collective interactions. The vulnerabilities that emerge from this assessment are candidates for priority action by local resource managers and stakeholders.

While the original intent of this vulnerability assessment was to be as specific as possible with regard to particular locations and conditions around American Samoa, in reality the ability to be specific is limited by a lack of available information. The examples presented come from a limited collection of studies, most of which were not originally designed to address climate change questions or effects of local stressors. They are general resource monitoring projects, hypothesis-driven studies of limited scope, or qualitative observations made by credible scientists and local agency personnel. Gaps in available information are often large due to the infrequency or inconsistency of these reports. However limited, the best available information is presented here, and the data gaps that have emerged are addressed with the goal of validating and expanding these findings in the future.

One dataset that is repeatedly referred to in this assessment comes from the only island-wide, long-term, and systematic coral monitoring project available for American Samoa. These data are contained in a series of reports by Birkeland et al. (2002; 1987), Green (2002; 1996), Green and Hunter (1998), Green et al. (1999), and Fisk and Birkeland (2002) (which have been recently summarized by Birkeland et al., 2004). Figure 4-1 is derived from Birkeland et al. (2004) and indicates trends in the mean percent coral cover determined from surveys at five locations in 1982, 1985, 1988, 1995, 1998, and 2001. This figure is based on summarized data and not a re-analysis of raw data. A subset of transect locations most consistently surveyed were chosen; however, the researchers involved and methods used vary between dates. Also, coral reefs are inherently heterogeneous, which leads to naturally high variability over time and between locations. Therefore, this figure is used to illustrate trends and may not accurately reflect island-wide conditions.

The method used in this assessment involved the superimposition of information regarding coral bleaching and local stressors (e.g., water quality, coral disease) over these long term coral population trends for the purpose of evaluating potential vulnerabilities. Evidence of potential vulnerabilities emerged where: (1) a single stress was extreme; (2) stresses overlapped in time and location; or (3) stresses occurred in rapid succession.

Identification of vulnerabilities to multiple stressors is a necessary first step toward understanding and supporting overall reef resilience. Holling (1973) first characterized

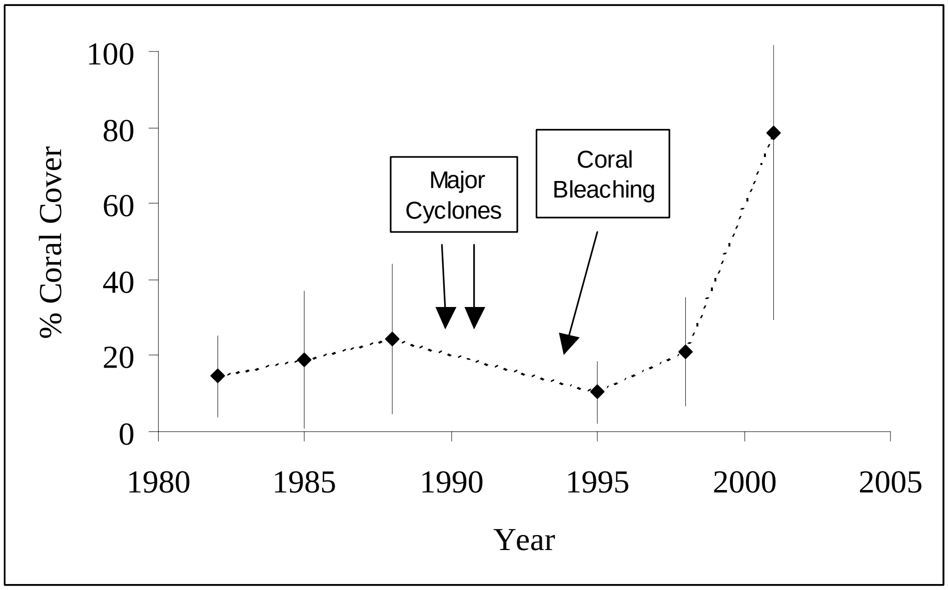


Figure 4-1. Trends in coral populations, 1982-2001. The approximate dates of major acute stresses have been indicated. Mean percent coral cover for reef slope surveys was calculated for Cape Larsen, Fagasa Bay, Masefau Bay, Rainmaker Hotel, and Fagatele Bay survey sites (2-3 m and 6 m survey depths combined). The 1982 point does not include Fagatele Bay (both depths). The 1998 point does not include Fagasa Bay (6 m), Masefau Bay (6 m), or Rainmaker Hotel (2-3 m). Error bars are ± 1 SD calculated between sites.

Source: Birkeland et al., 2004.

ecological resilience - as the ability of ecological systems to absorb changes of state variables, driving variables, and parameters, and still persist. Since then, usage of the term has expanded to include the speed of return of a system to equilibrium after a disturbance, as well as the magnitude of disturbance that can be absorbed by the system before it shifts from one stable state to another (Gunderson, 2000; Nystrom et al., 2000). Thus, ecosystem *phase shifts*–dramatic shifts in community structure from one stable equilibrium to another–are probable when resilience is low.

In the case of coral reefs, resilience to coral bleaching is dependent upon a combination of factors: coral resistance to bleaching, coral survival during bleaching, and reef recovery after bleaching-related mortalities have occurred (West et al., 2005). Reefs that are under chronic or acute stress from a variety of local sources are likely to have a reduced capacity to remain resilient in the face of large-scale temperature anomalies that trigger bleaching events. Indeed, there have been multiple instances in which coral bleaching is believed to have contributed to a phase shift from a community dominated by reef-building organisms to one dominated by non-reef-building organisms such as fleshy algae and soft corals (Ostrander et al., 2000; Done, 1999).

The followings sub-sections review accounts of climate change-related impacts on coral communities in American Samoa and infer the likely compounding role of local or regional stresses that may overlap or occur in rapid succession with climate stress. In each case, a qualitative assessment of coral reef ecosystem vulnerability and resilience to climate change-related impacts is provided.

4.2. VULNERABILITIES TO CLIMATE CHANGE AND INTERACTING LOCAL STRESSORS

4.2.1. Climate Change: Sea Surface Temperatures

There is considerable and growing evidence that the coral communities of American Samoa are susceptible to periodic extremes in sea surface temperatures associated with climate change. In American Samoa, coral bleaching becomes theoretically probable when local sea surface temperatures exceed 30.3°C, one degree above the local mean maximum sea surface temperature (NOAA Coral Reef Watch, 2005). Local reports of coral bleaching correlate well with regional sea surface temperatures near this threshold in 1994, 2002, and 2003 (see Section 2.1 and Figure 2-3).

The most extensive and best documented coral bleaching events in American Samoa occurred in 1994, 2002, and 2003. Bleaching that occurred in 1994 was described by Goreau and Hayes (1995) as part of a coral bleaching study in the South Pacific Ocean. In 2002, coral bleaching was quantified by both Fisk and Birkeland (2002), and Green (2002). Hansen et al. (in preparation-b), in a specific study of bleaching variability on Tutuila Island, quantified coral bleaching during its height in 2003. Together, these studies provide the most rigorous information available on local coral reef responses to elevated sea surface temperatures.

In 1994, coral bleaching around Tutuila Island occurred in 40% of colonies, according to semi-quantitative surveys (Goreau and Hayes, 1995) at six sites (Table 4-1). This is the greatest proportion of coral bleaching damage recorded on the outer reef in American Samoa to date. It was also the greatest proportion of bleaching observed in the Goreau study, which also included reefs in French Polynesia and the Cook Islands. Locations around Tutuila Island with a large proportion of observed bleaching damage (approximately 50%) were Masefau Bay, Atauloma/Afao Bay, and Faga'alu Bay (Goreau and Hayes, 1995) (Table 4-1, Figure 4-2).

Coral bleaching in 2002 was sporadic and less prevalent in American Samoa when compared to 1994 and 2003 (Table 4-1). Two parallel studies recorded coral bleaching as part of general benthic organism monitoring at 11 similar sites (three additional sites were surveyed by Green) in March of 2002 on Tutuila Island (Figure 4-2) (Fisk and Birkeland, 2002; Green, 2002). Fisk & Birkeland (2002) found bleaching to be variable, with a combined frequency of 2.3% of

Table 4-1. Summary of coral bleaching surveys on Tutuila Island

Date	Source	Number of sites	Mean percent of colonies bleached, (min-max)	Bleaching-sensitive species (proportion bleached)
1994 (August)	Goreau & Hayes (1995)	6	40%	*Porites, Montipora, Diploastrea, Acropora, Pocillopora, Merulina, Pachyseris, Gardinoseris, Astreopora, Montastrea curta, Pavona, Favia, Favites, Sarcophyton*
2002 (March)	Fisk & Birkeland (2002)	11	2.3% (0.4-9%)	*Montastraea curta* (57-71%) *Porites lichen.* (15-33%)
2002 (March)	Green (2002)	14	Low, 1-10% (none to 1-10%)	*Montastraea curta* (50% *Porites sp.* *Acropora sp.*(10-50%) *Pocillopora sp.*(10-30%)
2003 (February)	Hansen et al. (in preparation)	7	10.4% (6-23%)	*Acropora sp.* (>30%) *Pocillopora sp.* (>30%)

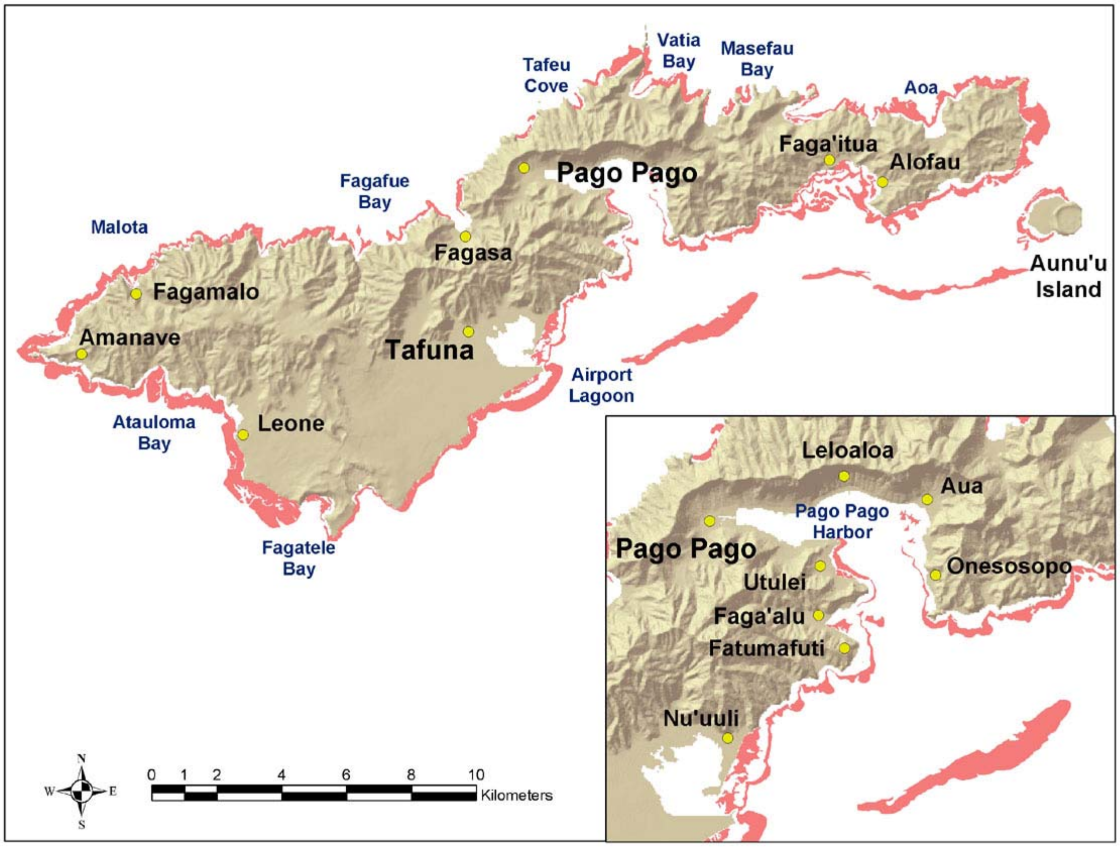


Figure 4-2. Locations on Tutuila Island where studies have been conducted. Embayments or nearby villages are named. Major fringing and offshore reef formations are indicated in pink. Courtesy of Dan Catanzaro, T N & Associates, Inc.

coral colonies bleached at the Tutuila Island sites (10 m depth). Bleaching was greatest at Fagatele Bay (9%); however, five of the 11 sites showed no bleaching. Green (2002) determined coral bleaching to be low (1-10% of corals) using a semi-quantitative method to survey a wider area and depth range than that surveyed by Fisk and Birkeland (Table 4-1). Again, bleaching was variable, with moderate (10-30%) bleaching observed at Fagafue and Fagasa on the north side of Tutuila Island (Figure 4-2). Both of these studies documented great variability in bleaching susceptibility between genera, with bleaching of up to 71% of individuals of some genera (Table 4-1) (Fisk and Birkeland, 2002; Green, 2002).

The 2003 bleaching event was quantified during its peak in February and March. The proportion of bleached colonies was reported to be 10.4%, based on preliminary data from seven sites around Tutuila Island (Table 4-1) (Hansen et al., in preparation-b). Preliminary findings show that bleaching was greatest in Vatia Bay on the north side of Tutuila Island (Figure 4-2), with 23% of surveyed colonies bleached. Overall, bleaching was most common in plate and branching Acroporids and branching Pocilloporids and often exceeded 30% of a local population (Table 4-1). Areas dominated by these species were heavily impacted by subsequent mortality when resurveyed in June and August (Hansen et al., in preparation-b).

Bleached corals in American Samoa. (Photo by Eric Mielbrecht.)

The above accounts confirm that coral reefs in American Samoa are vulnerable to abnormally elevated sea surface temperatures. The proportions of total coral that bleached may seem low, but the extent of bleaching observed in sensitive *Pocillopora*, *Acropora*, and *Montastrea* species was disproportionately high (10-70%) (Table 4-1) (Hansen et al., in preparation-b; Fisk and Birkeland, 2002; Green, 2002). Significant live coral cover was lost in areas dominated by these species. Also pointing toward a trend of increasing vulnerability to climate change is the observation that temperature-related coral bleaching at some level has occurred in American Samoa annually since 2002 (Hansen et al., in preparation-b; Fenner, 2005, 2004; Fisk and Birkeland, 2002; Green, 2002).

The long-term resilience to bleaching of these reef communities is still in question. There is little specific information on the recovery of bleached areas in American Samoa due to sporadic surveying. There is also limited comparison and analysis of changes in coral species richness and diversity. Full recovery from major bleaching events can take from 2-10+ years, depending on previous population diversity and cover (Glynn, 1993). The only basis for resilience assessment is comparison in the long-term region-wide coral monitoring project summarized by Birkeland et al. (2004). Based solely on general monitoring of coral cover conducted at limited sites in 1998 and 2001, this summary shows that strong recovery was taking place in American Samoa following a historic low in 1995 (Figure 4-1). This strong resilience capacity in the coral reef ecosystem suggests that while vulnerable, the coral community of the last two decades has been resilient enough to avoid drastic ecosystem phase changes following past acute perturbations.

4.2.2. Water Pollution and Climate Change

Elevated sea surface temperatures, combined with nutrient pollution, increased sedimentation, and chemical pollution, could stress reefs beyond their ability to recover (Hoegh-Guldberg, 1999; Hughes, 1994; Goreau, 1992). Poor water quality is potentially the most widespread of local stressors that–in combination with climate change stressors–may fully test the resilience of coral communities in American Samoa. Increased terrestrial runoff, due to greater precipitation and more intense rain events that are expected with climate change, coupled with a rapidly growing human population may increase the impacts of land-based water pollution.

The quality of the offshore waters around American Samoa is considered to be generally good (Craig et al., 2005). However, near-shore and stream water quality is quite variable, with some areas exhibiting poor water quality (e.g., Pago Pago Harbor) (Craig et al., 2005; ASEPA, 2004; Green et al., 1996). In American Samoa, water pollution is primarily from non-point sources in the form of excessive nutrient and bacteria loading from faulty or improperly constructed septic tanks and animal wastes from pen areas. Poor agricultural practices and other land disturbances also promote excessive erosion and sediment runoff during storm events, thereby further polluting the water (DiDonato and Paselio, in review; ASEPA, 2004). Generally, poor water quality in streams or at the shoreline (measured as nutrient or bacteria content) is proportional to human population density, especially near areas not serviced by the municipal sewage treatment systems (DiDonato and Paselio, 2006; DiDonato, 2005; DiDonato, 2004; Hansen et al., in preparation-b). Non-point sources of water pollution such as these are challenging to manage; however, the American Samoa Environmental Protection Agency (ASEPA) is monitoring and addressing these problems in a number of ways.

Water pollution in streams and along the shoreline is summarized annually in the water quality monitoring and assessment processes for the Territory as required by the Clean Water Act. These data are important for identifying water quality problems and provide some insight into potential pollution stresses on coral reefs. In 2004, ASEPA assessed 67.9 km of ocean shoreline out of a total of 239.8 km in American Samoa for aquatic ecosystem protection (ASEPA, 2004). ASEPA considered the water quality to be *fully supportive* of aquatic ecosystems for 23.7 km of the assessed shoreline. The remaining 44.3 km of assessed shoreline was deemed *supportive* but threatened by one or more water quality impairments. This suggests that coral reefs in 65% of the assessed shoreline may be experiencing stress due to one or more pollutants. Pollutants measured included polychlorinated biphenyls (PCBs), metals (mercury, arsenic, etc.), excess nutrients (nitrogen [N], phosphorous [P], etc.), organic enrichment/low dissolved oxygen, pathogenic bacteria, and turbidity (ASEPA, 2004).

The water quality of a larger area of shoreline was monitored for human health parameters. ASEPA assessed approximately 134 km of ocean shoreline for swimming risk and 60 km of ocean shoreline for fish consumption risk. Frequent pathogenic bacteria contamination along 117 km of shoreline (87% of total assessed) elevated health risk associated with swimming. Health risk associated with fish consumption was estimated to be high for 12.7 km of shoreline (21% of total assessed and primarily in Pago Pago Harbor) due to PCBs and metals found in local fish tissue (ASEPA, 2004). While not necessarily an indicator of direct threats to aquatic life, these contaminants are potential indicators of water quality problems that could affect coral reefs. For example, the major sources of shoreline bacteria contamination in American Samoa are reported by ASEPA to be poorly constructed or maintained septic systems and wastes from animal pen areas (piggeries), both of which are also significant sources of nutrient pollution stress to coral reefs (ASEPA, 2004).

This partial assessment of shoreline water quality begins to put into perspective the extent of water quality issues identified by the ASEPA. ASEPA is expanding the areas monitored but currently focuses much of its shoreline monitoring on areas where human use is common, development is extensive, and population density is high. Thus, impacted areas may be disproportionately represented. Regardless, heavily developed and populated areas have a demonstrated impact on the quality of the near-shore environment.

Pago Pago Harbor is an example of an area where poor water quality has been implicated in coral population decline. The Harbor is the economic and governmental center of the Territory and houses a busy industrial port, most of the island's heavy industry, and high population density. With harbor development and industrialization came extreme eutrophication and chronic chemical pollution from numerous industries and from periodic fuel spills, all of which have been linked to a significant decline in coral species diversity, abundance, cover, and colony size (Green et al., 1996; Dahl, 1981; Dahl and Lamberts, 1977). Additionally, many of the fringing reefs in the Harbor were destroyed by dredging and filling operations and near-shore construction as part of infrastructure improvements (Green et al., 1996; Dahl, 1981; Dahl and Lamberts, 1977).

Pago Pago Harbor, American Samoa. (Photo by Eric Mielbrecht.)

Water quality in Pago Pago Harbor and the surrounding watershed has improved in the recent past due to extensive regulatory and mitigation efforts, but it is still an area where aquatic ecosystems and human health have the potential to be negatively impacted. Shoreline water quality in the harbor is considered impaired for human swimming and fish consumption, and aquatic life is considered threatened (ASEPA, 2004).

Prior to its industrialization, Pago Pago Harbor supported numerous healthy coral communities and was the location of the first coral surveys on Tutuila Island (the Aua transect) (Mayor, 1924). The Aua transect is a single transect located in the outer harbor that was surveyed in 1917, 1973, 1980, 1998, and 1999. It is approximately 270 m long and traverses the reef from the shoreline near the village of Aua to the reef face. Surveys of this historic transect show a 75% decline in coral cover between 1973 and 1998, and an 82% decrease since 1917 (Figure 4.3). This accelerated declining trend since 1973 suggests a connection between industrialization in Pago Pago Harbor and decreasing coral cover when compared to island-wide coral cover trends, which have been increasing since 1995 (Figure 4-1) (Craig et al., 2005; Green, 1996; Dahl and Lamberts, 1977). Figure 4-3 is based on data summarized in two reports and not on a reanalysis of raw data. Survey methodologies varied between dates. Also, coral reefs are inherently heterogeneous, which leads to naturally high variability over time and between areas. Therefore, this figure is used to illustrate trends in mean coral density for a single transect and may not accurately reflect Pago Pago Harbor as a whole. Yet, casual observations of corals in this area by local scientists suggest that overall coral cover may have decreased even more at this site between 1980 and 2000 than Figure 4-3 shows.

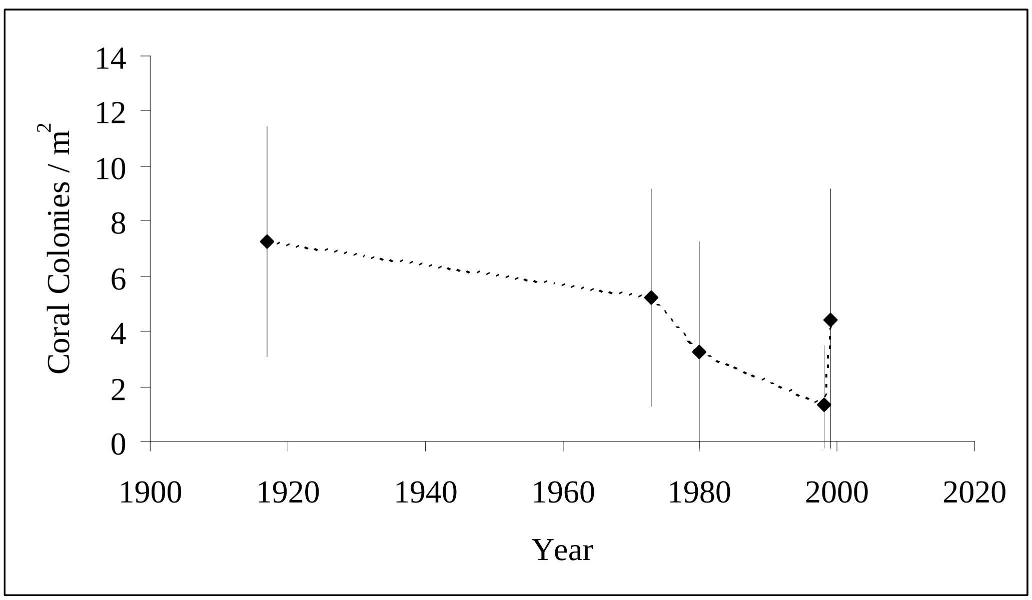


Figure 4-3. Trends in mean coral density on the Aua transect, Pago Pago Harbor, 1917-2001. Error bars are ±1 SD based on the division of the transect into nine end-to-end squares. Data are from Dahl, 1981; Birkeland and Green, 1999.

However, these same observations show that recently there has been a trend of recovery that parallels improving water quality in the harbor (Craig, 2005). Since 1995 and the advent of increasing pollution controls, coral cover island-wide has increased (Figure 4-1) (Craig et al., 2005; Green, 1996; Dahl and Lamberts, 1977).

Faga'alu is another area within Pago Pago Harbor where poor water quality has impacted coral communities (Houk et al., 2005). Recent work by Houk et al. (2005) addressed non-point source pollution stress on coral reefs at six locations around Tutuila Island, including Faga'alu. Based solely on benthic surveys, Houk et al. determined that Faga'alu was heavily impacted from land-based pollution and sediment loading, which resulted in comparatively low coral abundance and density (2005). A gravel quarry upstream from this site has been reported as a source of sediment input at this location (Hansen et al., in preparation-b).

The extent of this decline is consistent with the notion that the resilience capacity of the coral community at this location in Pago Pago Harbor may be compromised and that these populations have become vulnerable to dramatic ecosystem changes (Houk et al., 2005; Green et al., 1996; Dahl and Lamberts, 1977). The addition of climate change-related stresses in the form of potentially greater storm-related terrestrial runoff and elevated sea surface temperatures may compound water quality stressors in the Harbor. It is possible that bleaching has already impacted Harbor coral populations. In 2002, bleaching was reported in the Aua area (Green, 2002). However, this area was not surveyed for bleaching in 1994 or 2003.

Most perennial streams on Tutuila Island are small, with low average flows that influence only a small portion of the adjacent reef. However, stream flows increase greatly during heavy rain events, sending large plumes of sediment onto the reefs. Careless development on coastal lands, where the land has been extensively disturbed and natural buffer zones have been covered, enhances the transport of sediments and pollutants directly to the ocean during extreme rain events. Increasing precipitation and more frequent and intense extreme rain events in this region caused by climate change may worsen the chronic and acute stresses of storm water runoff on Tutuila Island.

Coral communities may also be impacted by poor water quality at other locations around Tutuila Island, especially where local human populations are burgeoning. The population of American Samoa is roughly 60,000 people. It is growing rapidly at an annual rate of more than 2%. This is much higher than the U.S. national average of 0.9% (U.S. Census Bureau, 2005). The majority of American Samoa's population lives on the narrow coastal plain on the south side of Tutuila Island. Figure 4-4a shows a current population density of seven to nine people per hectare in this area (2000 population data). Stream water quality is already considered impaired in many of these populated watersheds, and shoreline aquatic life may already be threatened (ASEPA, 2004). By 2025, population density is expected to almost double to 16-18 people per hectare in some watersheds. Figure 4-4b depicts the population in the year 2025, based on the current growth rate.

The concentration of humans and associated development on the limited coastal areas increases the potential for anthropogenic stresses to adjacent reefs (Wilkinson, 1996). Without appropriate community involvement, education, regulation, and infrastructure support (waste water treatment facilities, maintained drainages and wetlands, etc.), terrestrial sources of sediments, nutrients, and pollution are all expected to increase, adding to chronic water quality stress to adjacent coral reefs. Inevitably, this will further tax the ability of these coral communities to remain resilient in the presence of increasing regional and global stressors.

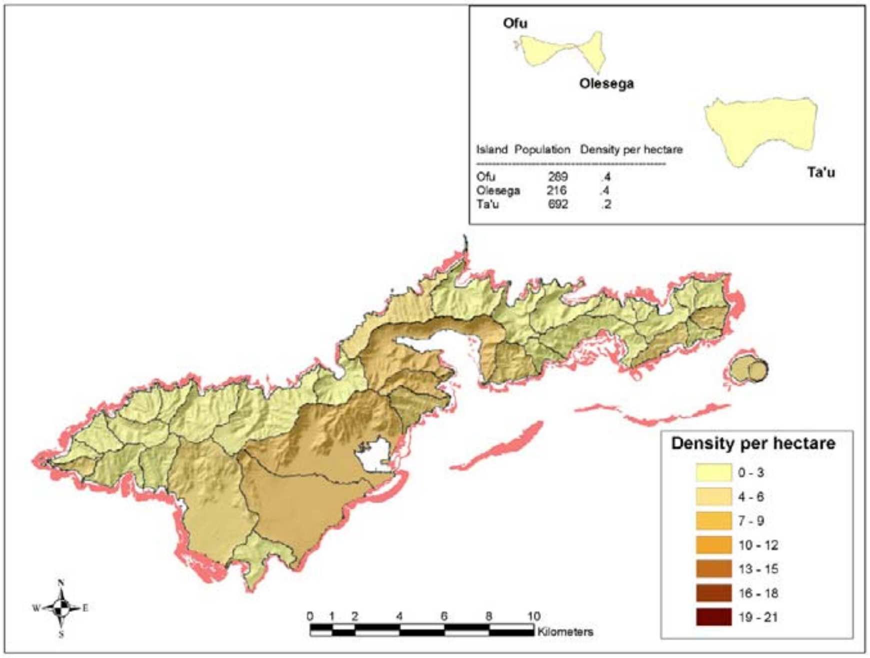
4.2.3. Extreme Weather Events and Climate Change

American Samoa is subject to periodic tropical cyclones and extreme rain events, both of which could increase in severity with climate variability and change. Tutuila Island has been impacted by six tropical cyclones from 1981 to 2005: Esau in 1981, Tusi in 1987, Ofa in 1990, Val in 1991, Heta in 2004, and Olaf in 2005. The strongest and most damaging in recent history were Ofa and Val, both category 4 cyclones (Green, 2002). Cyclone Ofa brought winds up to 250 kilometers per hour, and cyclone Val produced winds up to 260 kilometers per hour and remained near Tutuila Island for five days. These two cyclones caused substantial damage to live coral and structural damage to reef framework deposits and overturned and destroyed large coral colonies island-wide (Birkeland et al., 2002; Green, 2002; Green et al., 1999). Heavy precipitation also accompanied these cyclones, causing extreme terrestrial runoff that transported significant amounts of sediment and nutrients to the near-shore environment (Craig et al., 2005). There has been at least one recent extreme rain event not associated with a cyclone, which caused widespread flash floods and mudslides. This was the May 18-19, 2003 Pago Pago/Fagatogo flood, during which approximately 25–40 cm of rain fell in approximately 24 hours (Brakenridge et al., 2003). Associated impacts on near-shore water quality and coral reefs were not assessed at the time.

The long-term coral monitoring project measured a precipitous decrease in coral cover around Tutuila Island between 1987 and 1995, which was attributed to the 1990 and 1991 cyclones (Figure 4-1) (Birkeland et al., 2002; Green, 2002). This is a good example of the potential effects of successive stresses. However, these events do not seem to have exhausted the resilience capacity of the coral ecosystem around Tutuila Island. Signs of recovery were already apparent in 1995 as indicated by the abundance of crustose coralline algae, which had begun to cement and stabilize the dead coral rubble. The crustose coralline algae also presented an ideal substrate for rapid recruitment of new coral colonies (Birkeland et al., 2002).

Cyclones are regular occurrences to which coral reefs in American Samoa have adapted over thousands of years. While cyclones are occasionally quite destructive, coral populations in American Samoa appear to show strong signs of recovery within three to five years (Figure 4-1). However, cyclone intensity has increased over the last 30 years and is expected to escalate according to climate change projections (Emanuel, 2005; IPCC, 2001b).

a)



b)

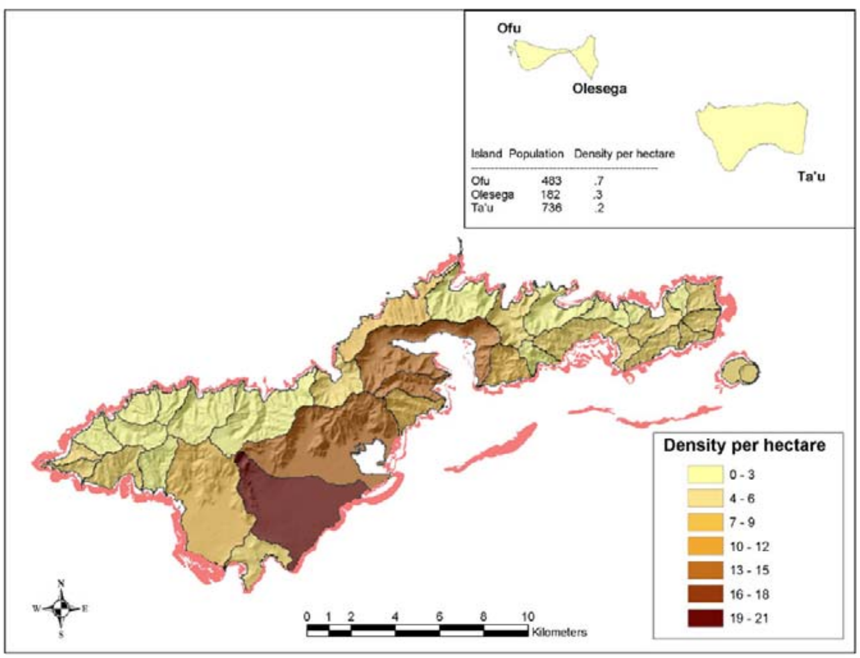


Figure 4-4. Human population density distribution for 2000 (a), and projected to 2025 (b). Shading refers to population density within major watersheds. Major fringing and offshore reef formations are indicated in pink. Courtesy of Dan Catanzaro, T N & Associates, Inc.

Such negative effects on coral cover could be further exacerbated if cyclones were to regularly overlap with, precede, or follow warm water events. The probability of successive or overlapping cyclone events and mass bleaching events may increase if there is a shift toward more consistent ENSO-like conditions as projected by climate models (IPCC, 2001b). In American Samoa, the 1994 bleaching event followed closely after the destructive 1990 and 1991 cyclones and dealt another blow to coral populations island-wide. Coral monitoring was too infrequent to distinguish cyclone and bleaching effects on island coral cover, but it is probable that the historic low coral cover reported in 1995 was due to the relatively close succession of these three events. This supports the notion that coral communities in American Samoa become very vulnerable when a rapid series of large-scale acute stresses like this occur. Additionally, there is evidence that some sites–such as the shallow reef flat areas of Fagatele Bay and Pago Pago Harbor–have actually not recovered as well as other areas (Birkeland et al., 2004).

Cyclone damage in American Samoa. (Photo by Eric Mielbrecht.)

4.2.4. Coral Diseases, Opportunistic Species, and Climate Change

Coral communities in American Samoa face a potentially escalating vulnerability to the stresses of coral disease when combined with climate change. Outbreaks of disease can occur naturally, but they may also be worsened by changes in the natural balance of ecosystems brought on by climate variability and change (Buddemeier et al., 2004; Harvell et al., 2002; McCarthy et al., 2001; Williams Jr. and Bunkley-Williams, 1990). Pathogen development rates, reduced cool-season restrictions on pathogen populations, and host susceptibility to infection may all be influenced by warming sea surface temperatures (Harvell et al., 2002).

Very little was known of the status of coral diseases in American Samoa until recently (Work and Rameyer, 2002). In 2004 and again in 2005, Aeby (2005) performed quantitative surveys for coral diseases at seven sites around Tutuila Island as a follow-up to a 2002 exploration. Preliminary results from these surveys show that disease prevalence is very low

(<1% of coral colonies surveyed), but statistical site-to-site comparisons have not been completed. Indications of at least 10 different diseases were found; however, histopathological verification is still in progress (Aeby, 2005). These studies show that coral disease is present in American Samoa although its effects are minimal compared to the large-scale epizootic events that have taken place in the Caribbean (see Section 3.4). Current vulnerability of the American Samoa coral reef ecosystem to diseases may be low, but resource managers are concerned that the reefs may become increasingly vulnerable if local diseases are aggravated by climate change. There is the potential for coral disease to spread with increasing sea surface temperatures (Harvell et al., 2002; McCarthy et al., 2001). Other local stresses, such as increasingly poor water quality, can also increase the severity of coral diseases (Bruno et al., 2003).

Diseased *Pocillopora* coral. (Photo by Eric Mielbrecht.)

Population outbreaks of predatory Crown-of-Thorns Starfish (COTS) in American Samoa have been infrequent but highly damaging to some coral communities. The only documented outbreak began in 1977 on Tutuila Island and remained active until 1980 (Zann, 1992). This outbreak was unexpected since COTS were rare on the island in previous decades, as learned though interviews with elderly fisherman (Zann, 1992; Birkeland et al., 1987). Coral mortality in Fagatele Bay on Tutuila Island was as high as 95%, while the other islands apparently were not affected by the outbreak (Green, 2002; Zann, 1992). Not until 1998 did Fagatele Bay show signs of recovery of coral cover (Birkeland et al., 2004). However, the cyclones of 1990 and 1991 and the mass bleaching event in 1994 may have hampered this recovery.

Across the Pacific, a simple cause for periodic dramatic increases in COTS numbers has eluded scientists; however, several hypotheses have been formulated (Brown, 1997b; Zann, 1992). Among them are suggestions that COTS outbreaks in the southern and western Pacific are correlated with ENSO events (Zann, 1992) and that outbreaks may be linked to reef disturbances related to increased sea temperatures (Hoegh-Guldberg, 1999) or input of excess nutrients from nearby land, particularly during periods of heavy precipitation (Brown, 1997b). Coral populations in American Samoa have already shown great vulnerability to past COTS outbreaks. These outbreaks may become more frequent or more extensive if there is indeed a link between climate change and COTS outbreaks.

4.2.5. Over-Fishing, Resource Extraction and Climate Change

Researchers and managers agree that the reefs in American Samoa are over-fished (Craig and Green, 2005; Craig et al., 2005). Recent surveys confirm that there are relatively few or only small sizes of fish commonly taken for food (Craig and Green, 2005). However, there is still an abundance of small herbivorous surgeonfish and parrotfish that can help control populations of macroalgae on the reefs (Craig et al., 2005). Without these herbivores, rapidly-growing macroalgae would likely out-compete corals and crustose coralline algae.

Subsistence fishing has declined substantially over the past two decades, primarily due to the move toward a cash-based economy and away from a subsistence lifestyle, but also due to declines in reef fish and invertebrates (Craig et al., 2005; Tuilagi and Green, 1995). Artisanal catch has fluctuated greatly since 1987 and suffered a steady decline after SCUBA-based spear fishing exceeded sustainable catch in 1998 (Craig et al., 2005). Incidental damage to the reef from such fishing practices is infrequent; however, damage from illegal dynamite and poison-based methods has been observed more frequently.

Climate change is impacting, and will continue to impact, marine and estuarine fish (Roessig et al., 2004). Changes in coral reef fish communities may occur, which can alter interdependent relationships with coral populations. Coral bleaching mortality and the resulting loss of reef complexity may be a key factor in reducing abundances and biodiversity of reef fishes. However, comparatively little is known of the physiological thermal tolerance limits of reef fish (Roessig et al., 2004). This undermines an understanding of how climate change may interact with local reef fish populations and again, how these changes will affect coral communities. Currently there is not enough information to determine the vulnerabilities to coral communities and to coral and reef fish interdependence when fishing pressures are compounded with climate change stressors.

4.2.6. Conclusions

This section focused on assessing the ecosystem vulnerabilities that increase when local stressors are compounded with potential climate change stressors. Comparisons were limited by the available data, and conservative inferences were made where feasible. Numerous other combinations of stressors are possible, but research is inadequate in American Samoa–and often globally–to assess the full range of potential vulnerabilities. The following sections will discuss in more detail how the limitations of this assessment could be addressed with monitoring and research resources, and how reef resilience could be supported through strategic management.

4.3. INFORMATION GAPS

Studies addressing climate change issues in American Samoa are limited. Studies that address the effects of local stressors on coral reefs are also few. Only recently have climate change questions been integrated into local hypothesis-driven research or monitoring efforts

(Hansen et al., in preparation-a; Hansen et al., in preparation-b; Mielbrecht and Hansen, in preparation; Birkeland, 2003), and findings from these studies are still pending. Fortunately, American Samoa does benefit from one long-term coral monitoring project and several studies that, although limited in scope, directly address local stresses.

The evaluation of local coral reef ecosystem vulnerabilities would benefit greatly from studies that specifically address interactions of climate change and local stressors, or even examine local stressors that overlap in place or time, or occur in rapid succession. No specific accounts of these kinds of interactions were available at the time this report was written. Inferences were made from information that exists for single stressors in separate timeframes or locations around American Samoa, and sometimes from other global locations, to assess hypothetical vulnerabilities. Clearly, there is much room for improvement of this initial assessment as more data become available.

Specifically, the resource managers of American Samoa would benefit from local information derived from hypothesis-driven studies in key areas. It is recommended that efforts include gathering comprehensive information in the areas of near-shore water quality, coral bleaching, and resilience-conferring biological and physical factors in coral communities. Incorporating these elements into a comprehensive, hypothesis-driven monitoring and research plan for the Territory is a suggested first step and could yield valuable information within a short period of time. However, it is impossible to address all of these issues at once. Suggested priorities for research and monitoring are discussed in Section 5. The interrelation of resilience capacity, vulnerability, and resource management planning is further developed in the next sub-section.

4.4. SUSTAINING RESILIENCE

The information presented in this report reveals existing patterns of vulnerability in the coral communities of American Samoa and touches upon the range of innate resilience capacity of its coral reefs to climate change and other stresses. Understanding, maintaining, and enhancing this resilience capacity through appropriate resource management efforts could help reduce vulnerability in the face of climate change (Hughes et al., 2005; West et al., 2005; Tompkins and Adger, 2004). The impacts of climate change are already a reality in American Samoa and are expected to increase. Local conditions are changing with rapid population growth so the potential is high for associated stresses on the environment to also increase. Resource managers would benefit by focusing on specific stresses and combinations of stresses. However, they ought to also consider a broader concept of resilience when developing longer term management strategies (Hughes et al., 2005; West et al., 2005; Tompkins and Adger, 2004).

Sustaining the resilience of the overall reef ecosystem is an on-going endeavor. It includes identifying resilient coral reef areas and the factors that confer resilience, strategically using marine protected areas, and embracing creative and adaptive management strategies. Coral reef resource managers are not always able to directly regulate nearby anthropogenic sources of stress, which makes it difficult to address these issues. However, managers often have the ability to direct marine protected area (MPA) designation and associated planning. Therefore, one of the most effective strategies may be for managers to become familiar with resilience theories and share these ideas with the local village communities and other stakeholders while incorporating resilience concepts into local MPA planning processes. Excellent tools are available for understanding and enhancing coral reef resilience to climate change through adaptive management strategies. These concepts, along with specific recommendations to resource managers in American Samoa, will be further developed in the next section.

5. ADAPTIVE MANAGEMENT STRATEGIES AND DECISION-MAKING OPPORTUNITIES

Using an adaptive management paradigm that incorporates resilience, this section aims to (1) provide the natural resource managers of American Samoa with some tractable priority management strategies for coping with the vulnerability of coral reefs to climate change, and (2) identify where these strategies may be readily integrated into existing and future decision-making opportunities. This exercise represents the final phase of the logic process introduced in Figure ES-1.

Given that information on climate change issues in American Samoa is presently limited, potential strategies must necessarily fall within an "adaptive management approach" (Gunderson, 2000). Here, management plans are thought of as hypotheses, and actions are experimental tests. This approach supports immediate action by managers of coral reef resources, based on what is already known about climate change and possible interacting stressors, while allowing flexibility for refinement as new information becomes available (West and Salm, 2003).

In the context of a changing climate, successful adaptive management will require integration of resilience concepts into existing management activities. Resilience to climate stresses can be enhanced through two primary acts: (1) reducing or eliminating interacting non-climate stresses, and (2) protecting sufficient and appropriate habitat, including populations that already show strong resilience (Hansen et al., 2003). While management activities may already address some of these issues independent of climate change, building sufficient resilience for future climate change stress necessitates including an additional margin of safety.

A variety of stakeholders are involved at multiple levels in the management of coral reef resources in American Samoa. Any successful coral reef management activity in American Samoa will depend on strong village community involvement. It is vital that the traditional family and leadership structure be included. To date, the most successful conservation actions have only come about with the commitment of the local community (e.g., Matu'u village stream water quality improvements described in Buchan and Matatumua, 2004).

At the center of the stakeholder structure are several local and federal governmental agencies and local institutions that are directly responsible for the management decision processes, policy enforcement, and scientific research for American Samoa's coral reef systems. Together, these agencies and institutions comprise the Governor's Coral Reef Advisory Group (CRAG), a committee that works under a mandate from the Office of the Governor of American Samoa to manage coral reefs in American Samoa. The CRAG also serves as a local working group of the U.S. Coral Reef Task Force (CRAG, 2005). The CRAG membership includes local government agencies (American Samoa Environmental Protection Agency, Department of Marine and Wildlife Resources, Department of Commerce), federal agencies (the National Park of American Samoa, the Fagatele Bay National Marine Sanctuary), and other institutions (e.g., the American Samoa Community College) that are concerned with coastal and coral reef resources. The Department of Marine and Wildlife Resources manages a large proportion of marine resources in American Samoa, either directly or by working closely with local communities in such areas as community-based fisheries management. The National Park of American Samoa and Fagatele Bay National Marine Sanctuary independently manage the resources within their boundaries, but their activities are coordinated through the CRAG.

Village communities are key stakeholder groups for all management actions in American Samoa. (Photo courtesy of the National Park Service [NPS].)

Furthermore, American Samoa is not alone in addressing these complex resource management issues. Pacific island nations such as nearby Samoa, the Kingdom of Tonga, Fiji and the Republic of Palau are beginning to address climate change issues at different levels. The South Pacific Regional Environment Programme (SPREP) in Samoa has been a strong force in organizing regional studies and planning. It has made significant progress in investigating the potential socio-economic and ecological effects of climate change (Campbell and de Wet, 2000; Jones et al., 2000; 1998; Nunn and Waddell, 1992). Pursuing partnerships with SPREP and other organizations may help American Samoa stretch resources and promote the sharing of region-specific information. Additionally, global resources are available, such as the U.S. Coral Reef Watch Program and associated Coral Reef Early Warning System, which are designed to provide managers with real-time sea surface temperature information and coral bleaching risk analyses (see Appendix). However, the management strategies outlined below will be discussed within the American Samoa specific context and the CRAG's existing management concerns and activities.

Priority management actions that derive from the integration of the vulnerability analysis, resilience concepts, and stakeholder capacities/concerns, fall into three general categories according to the time frames over which they might be implemented: immediate, near-term and long-term. Management strategies that may be implemented immediately are those that (1) are supported by existing research or by monitoring data that show a clear existing need and (2) may be adapted readily into current management activities. Previous identification of “key issues” by resource managers and support in the form of mandates from existing government regulations or laws further emphasize the immediate relevance of these strategies. This is where the first aspect of resilience planning (elimination of non-climate stresses) is addressed. Non-climate stresses are those “traditional” stresses (see Section 3) that are already recognized as threats to reef health. Resource managers often have the ability to address these immediately at local scales and can begin to include the needed margin of safety to accommodate the potentially-increasing stress of climate change.

Near-term strategies are those that center on hypothesis-driven research and monitoring to fill information gaps, especially where the strategies easily overlap with current management activities. Baseline monitoring and hypothesis-driven monitoring have often been advocated by resource managers but have yet to be fully acted upon due to lack of information on optimum design and/or limited financial and human capacity. These are considered near-term activities because there is a crucial need to address basic information gaps by finalizing and implementing hypothesis-driven monitoring and research programs in the next several years. Such near-term activities allow assessment of the effectiveness of “immediate” actions taken today and provide data to support the adaptive management process. They also provide needed information for future long-term management steps.

Long-term management strategies involve large-scale management concepts and provide the framework for designating the adequate and appropriate habitat needed to sustain resilience. They provide a clear direction and goal for shorter-term actions and are continually adapted from interim findings. They also require a more holistic vision of the large-scale coral reef system, its many stresses, and how the stresses will change over time. These management strategies will be refined as new information becomes available and can provide guidance for developing the information gathering process. The following sections expand on some of these potential priority actions across the three time frames.

5.1. IMMEDIATE TIME FRAME: IMPLEMENT WATER QUALITY IMPROVEMENTS

The vulnerability assessment indicates that (1) water pollution is likely to be a chronic stressor to coral reefs in American Samoa, (2) human population pressure–which is projected to increase dramatically in coming decades– will likely contribute to further deterioration in water quality, and (3) such multiple stressors will likely render American Samoa's coral reefs more vulnerable to climate change by reducing reef resilience. The CRAG (2004) has already acknowledged the severity of these problems, and the ASEPA has begun to better assess and address water pollution issues. Thus, the first and most immediately beneficial management strategy would be to expand activities that improve water quality.

Land-based, non-point sources of water pollution are currently listed as key threats to coral reefs by the CRAG. They are the primary cause of water quality problems in streams and along the shoreline, according to ASEPA. Thus, it would be straightforward to expand existing management activities. Improvements in highly-impacted areas would immediately benefit coral communities and increase reef resilience to climate change (Hansen, 2003; Hughes et al., 2003; Hoegh-Guldberg, 1999). While improving water quality is a complex issue, it could be successfully addressed through the expansion of regulation enforcement, community education and involvement, and best management practices.

The CRAG, which has been working on comprehensive strategies for managing American Samoa's unique coral reef resources, has highlighted four key threats to coral reefs in its Three-Year Local Action Strategy for 2003-2007 (LAS) (CRAG, 2004). These include water pollution, population pressure, climate change, and overfishing. At least three of these four key threats (climate change, water pollution, and population pressure) are highly inter-related according to the scientific assessment presented in this report and could be addressed simultaneously through support of certain water quality projects that are already underway. For example, the LAS advocates monitoring of coral health parameters for impacts of water pollution in support of the American Samoa Coastal Non-point Pollution Control Program (ASCNPCP). Additionally, and more importantly, the LAS proposes that the CRAG develop, coordinate, and implement education and outreach programs that can help the growing human population understand non-point source pollution, the effects of pollution on coral and human health, and how everyone can help reduce it. These are all justified priority actions that should begin as soon as possible.

The ASCNPCP is an already-existing management framework through which near-shore water pollution can be improved. The comprehensive ASCNPCP includes strategies to monitor water quality for ecosystem and human needs, organize and coordinate efforts to reduce land-based pollution, and also evaluate the effectiveness of management actions. ASEPA established this program to address water quality problems that appeared in assessments mandated by Section 305b of the Clean Water Act and embraces cooperation with the CRAG and other local agencies involved in coastal management. Established programs include providing waste automobile oil collection facilities, the inspection of home sewage containment and treatment facilities, the inspection of animal holding facilities (piggeries), and the permitting and inspection of construction and earth moving operations for erosion control. The findings of this report clearly support the expansion of such existing programs and establishment of additional programs that would improve near-shore water quality and evaluate the effectiveness of projects that aim to reduce water quality stress to corals.

With sufficient village community motivation and involvement, mitigation efforts through the ASCNPCP can be very effective in improving water quality. For example, small-scale pig farms in the Matu'u village watershed contaminated the stream with a high level of bacteria and nutrients and were a source of leptospirosis exposure to the public. Through ASCNPCP projects, which included regular stream water monitoring, community education/outreach, and enforcement of environmental and public health regulations, the average bacteria load in the stream was reduced by over 90%. Leptospirosis risk was also reduced. Annual N and P loads to the near-shore environment were reduced by 58% and 43%, respectively (Buchan and Matatumua, 2004). This example illustrates the importance of community outreach and education in managing water pollution in American Samoa, which will be vital as the human population grows. The issues of climate change can be incorporated into these outreach programs. Human health concerns add further weight to mandates for water quality improvements.

Water quality testing by researchers in American Samoa. (Photo by Eric Mielbrecht.)

Additional resilience building can be incorporated into the ASCNPCP and other ASEPA decision-making processes beyond the immediate need for improving near-shore water quality. The ASEPA establishes and enforces water quality criteria for water parameters and contaminants and is establishing specific biocriteria for local aquatic ecosystems, including coral reefs (American Samoa Administrative Code, 2005). Anticipatory safety buffers for interacting climate change stressors should be considered by managers and decision-makers when water quality criteria are modified. Bio-criteria focus on the biological response of organisms to environmental stressors. Established bio-criteria parameters should distinguish between climate change and water quality stressors where possible and also be sensitive to potential interactions between climate change and water quality stressors.

In summary, this report further underscores the importance of this already-recognized issue by showing that poor water quality can increase the vulnerability of reefs when compounded with climate change stressors. This supports taking the following actions in the immediate time frame:

- Implement improvements in water quality through the expansion and enhancement of the ASCNPCP.
- Expand village community outreach and education as part of the ASCNPCP process and emphasize the human health benefits of improving water quality.

Climate change is not the only reason to act on these issues as water pollution can also be an important human health threat if surface waters and food become sources of pathogens or contaminants. Thus, a focus on water quality may yield concomitant advantages in the form of increased protection of human health, improvements in the condition of coral reef ecosystems, and greater reef resilience in the face of future climate variability and change.

5.2. NEAR-TERM TIME FRAME: DEVELOP AND IMPLEMENT HYPOTHESIS DRIVEN MONITORING AND RESEARCH

While a variety of interesting and useful studies have been conducted on American Samoa's coral reefs in the past, there is insufficient information to systematically and simultaneously compare trends in coral condition, bleaching incidence and severity, water quality, and other stressors at individual sites. An expansion of research and monitoring programs would help fill vital information gaps and continue to test hypotheses on climate change and interacting stressors in American Samoa. These near-term monitoring and research actions would provide critical information for both on-going "immediate" actions and long-term strategies. Furthermore, as an important part of the adaptive management paradigm, specific monitoring would be required to determine whether on-going management actions are successful (e.g., water pollution is being measurably reduced) and effective (e.g., coral condition and/or reef resilience improve as a result).

Researchers monitor coral reef condition in American Samoa. (Photo by Eric Mielbrecht.)

The capacity of small island agencies to undertake complex research and monitoring is often limited. The demands of the additional monitoring and research that is needed to address these climate change related questions are large but worthwhile as climate change is quickly moving to the top of the list of conservation threats (Hannah et al., 2005). In order to help accommodate limited local capacity, research and monitoring recommendations have been divided into two categories: (1) questions that can be more easily integrated into existing or proposed local management activities (Table 5-1a) and (2) questions that may be more appropriate for the added capacity of visiting researchers or external agencies, with local or external funding (Table 5-1b).

This list of suggested basic research questions is presented to help direct hypothesis-driven research and monitoring in order to address the crucial information gaps revealed in the vulnerability assessment. These questions focus on identifying the relationships among climate change stressors, other potentially-interacting local stressors, and determinants of coral reef resilience. This list is in no way exhaustive, nor are these questions developed fully; this is because each question requires background research (i.e., re-analysis of existing data) and full development of experimental hypotheses that build on existing information paralleled by appropriate experimental design. This level of specificity is beyond the scope of this report; however, there are tools available to help in designing research projects for gathering climate change-specific information. For example, A Global Protocol for Assessment and Monitoring of Coral Bleaching (Oliver et al., 2004) provides several different methods for conducting a coral bleaching survey, depending on what questions need to be answered. See the Appendix for additional support materials.

Optimally, this information would be organized into an easily-interpreted format in order to provide vital baseline and event-specific information. This could help resource managers prepare for, respond to, and assess ecosystem changes that result from large-scale bleaching events (Marshall and Schuttenberg, 2006). Organizing data in a Geographic Information System (GIS)-based electronic database would be ideal. With this basic information, managers could assess the potential impacts to coral communities, vulnerabilities to combined stressors, and efficacy of actions to address pollution, location by location. The information could also play an important role in marine protected area (MPA) planning processes. In the longer term, these efforts could be supplemented with additional water quality, coral disease, over-fishing, and MPA planning information along with investigations of other important climate factors such as local weather variability, ocean carbonate chemistry, sea level rise, and possible changes in UV-radiation levels.

Several management activities have already been proposed, into which many of the suggested near-term, hypothesis-driven monitoring and research needs can be integrated. These suggested integrations are outlined in the third column of Table 5-1a and b and are paired with key projects proposed by the CRAG or by the ASEPA (Buchan and Matatumua, 2004; CRAG, 2004). In addition to monitoring and research, developing public awareness about climate change and coral bleaching to clarify the need to reduce local anthropogenic stressors is vital. Both the CRAG and the ASEPA support education and outreach activities. This report emphasizes the importance of these activities as priority actions, along with the priority research and monitoring questions that have been outlined.

An example of an opportunity to integrate suggested research questions into already-proposed management actions exists in the activities supported in the draft American Samoa Coral Reef Monitoring Program plan (Whaylen and Fenner, 2005). This CRAG-instigated monitoring plan establishes the annual collection of basic–but important–coral reef monitoring parameters at several sites around Tutuila Island. Quantification of coral bleaching is included in the basic monitoring. With a small investment in capacity, data collection could also address

Table 5-1a. Research questions and activities that could be integrated into local management activities

	RESEARCH TOPIC AREAS		
	Climate change stressors	**Non-climate interacting stressors**	**Sustaining resilience**
Research questions or activities	• Under what conditions does bleaching occur in American Samoa? • What is the extent of bleaching during large-scale events? • What is the extent of recovery and mortality following a large-scale bleaching event? • Have extreme rain events become more intense? • Has precipitation increased on average?	• Are coral communities impacted by areas of poor water quality? • Is pollution associated with rain events or other periodic events? If so, will pollution worsen with increasing severity of rain events? • How can near-shore monitoring be expanded to better detect poor water quality? • Does existing management of sources of water pollution adequately protect coral communities, considering the added stressors of climate change?	• Are there reef areas that regularly show less bleaching during large-scale bleaching events? • Are there reef areas with characteristics that have been hypothesized to enhance resilience to bleaching (see table 5.2 for a list of factors)? What are the correlations between bleaching/recovery and these characteristics?
Existing management activities into which research could be integrated	• Planned projects in the CRAG 2004-2007 LAS focal area: Climate change • American Samoa Coral Reef Monitoring Program • Planned projects in the CRAG 2004-2007 LAS focal area: Land-based sources of pollution • Coastal Non-point Pollution Control Program	• Planned projects in the CRAG 2004-2007 LAS focal area: Land-based sources of pollution • Coastal Non-point Pollution Control Program • American Samoa Coral Reef Monitoring Program • American Samoa's Marine Protected Areas Strategy	• American Samoa's Marine Protected Areas Strategy • American Samoa Coral Reef Monitoring Program • Planned projects in the CRAG 2004-2007 LAS focal area: Climate change

Table 5-1b. Research activities appropriate for external agencies or researchers

	RESEARCH TOPIC AREAS	
	Climate change stressors	**Non-climate interacting stressors**
Research questions or activities	• Are there areas where local stressors exacerbate bleaching? • Is there variability in bleaching? By species or area? • Have cyclones increased in intensity, locally? Is there evidence that this trend is continuing? • Have extreme rain events become more intense? • Is local ocean carbonate chemistry changing? If so, is this change altering coral calcification rates and skeleton integrity? • What are the past and future trends in sea-level rise? • What is the current UV stress to corals based on water attenuation of solar radiation? Does this fluctuate in the short or long term?	• For the establishment of appropriate biocriteria: how are climate change stressors likely to interact with local water quality stressors? • Is the prevalence of coral diseases increasing? Is it increasing with average sea surface temperature? • Is there a correlation between coral disease and bleaching events?
Management projects benefited	• Planned projects in the CRAG 2004-2007 LAS focal area: Climate change • Planned projects in the CRAG 2004-2007 LAS focal area: Land-based sources of pollution • American Samoa Coral Reef Monitoring Program • American Samoa's Marine Protected Areas Strategy • Coastal Non-point Pollution Control Program	• Coastal Non-point Pollution Control Program • Planned projects in the CRAG 2004-2007 LAS focal area: Land-based sources of pollution • American Samoa Coral Reef Monitoring Program • Planned projects in the CRAG 2004-2007 LAS focal area: Climate change

more specific climate change questions. A key addition to this project would be an event-triggered monitoring response to track bleaching extent, mortality, and recovery, as well as local variability.

Near-term monitoring activities are needed to fill important data gaps and to inform both immediate and long-term management decisions. This supports taking the following actions in the near-term:

- Integrate suggested climate change research questions into existing or proposed local management actions and
- Develop the capacity to accomplish increasingly comprehensive monitoring and research through partnerships with visiting researchers with local and outside funding.

Hypothesis-driven monitoring and research is crucial to successful adaptive management in response to climate change. A far-reaching benefit of near-term monitoring and research is additional insight into the usefulness of building long-term resilience. This can then be applied to the MPA planning processes.

5.3. LONG-TERM TIME FRAME: DESIGN AND IMPLEMENT RESILIENT MPA NETWORKS

While the first requirement for maximizing resilience to climate change (reducing and eliminating non-climate stresses) is addressed by immediate actions as described in Section 5.1, the second requirement (protecting adequate and appropriate habitat) is part of long-term planning. Effective management actions over the long term will likely include strategies for monitoring the resilience capacity of coral reef communities and, more importantly, protecting adequate and appropriate reefs in MPAs. The goal of sustaining the resilience of large-scale reef ecosystems is a complex undertaking. However, the adaptive management approach can support gradual progress by integrating resilience theories into management strategies at a basic level and expanding over the long-term as capacity evolves and more information becomes available. This scientific approach, coupled with enthusiastic village community involvement, could lead to effective and more resilient MPAs.

Any MPA can provide some resilience by creating a refuge from local stressors, a managed seascape, and a possible component of a network. However, more can be done to incorporate resilience theory into the criteria used for the selection of new MPAs and in the design of MPA networks.

The concept of protecting appropriate reefs involves MPA designation of sites where overall reef resilience is greatest and, in particular, where factors exist that are thought to specifically confer resilience to climate change stressors. While some of these factors overlap with what is already considered in selecting an MPA, other factors are only considered when climate change is added to the planning matrix. The general characteristics to consider include ecosystem condition (e.g., coral condition, water quality, fish abundance), local environment (e.g., reef topography, current speed, light levels), biological diversity (i.e., genetic diversity within species and species diversity within ecosystem functions), and connectivity (i.e., stable "seed" sources for repopulation) (Marshall and Schuttenberg, 2006; West et al., 2005). More specific factors can be indirectly recognized by studying a reef's response to past incidents of elevated sea surface temperatures or by examining an area for the presence of characteristics that confer resilience (West et al., 2005). Factors that may confer resilience to climate change stress include physical features such as sources of cool water provided by upwelling or strong currents, natural shading by nearby cliffs and screening by light-absorbing matter in the water column; as well as biological features such as innately-resistant and tolerant coral communities (Marshall and Schuttenberg, 2006; West and Salm, 2003). General characteristics, such as biological diversity and connectivity, are also emerging as key factors in the management of coral reefs in the face of climate change (Ayre and Hughes, 2004).

Table 5-2 proposes some specific characteristics that could be investigated as part of the MPA planning process. An easily-interpreted presentation of these location-specific characteristics, once they are determined, could include their incorporation into a GIS-based "resilience map" for American Samoa.

A variety of tools are available to help managers understand and sustain resilience (see Appendix for a full listing). These offer guidance on testing for resilience, managing resilience, and augmenting resilience (Marshall and Schuttenberg, 2006; West et al., 2005; West, 2001). Early information tools were geared towards coral reef MPA managers and identified the potential characteristics that would confer resilience (Salm and Coles, 2001; Westmacott et al., 2000). Subsequently, there have been additional products created to advise reef managers who work both within and beyond MPAs in response to coral bleaching (Marshall and Schuttenberg, 2006; West et al., 2005; The Nature Conservancy and Partners, 2003). Other tools cover the landscape/seascape beyond the reef and beyond bleaching (Hansen et al., 2003).

Selection and protection of the necessary habitat, even with a climate filter, cannot be a static or self-contained process if resilience is to be sustained. Continuous management must be employed in the MPA. This may require flexible zoning schemes or integrated coastal management actions for specific episodic management. Access to reefs (e.g., by village fishers) may need to be limited or other local stressors (e.g., sediment runoff from coastal development projects) reduced during a bleaching event. In American Samoa this would involve the scientific skills of local resource managers and a continual cooperation from nearby village communities over the long term. Building and sustaining resilience to climate change in a MPA will necessitate a holistic coastal zone management approach–from the top of the watershed to the open ocean–and involvement from all stakeholders, especially local village communities.

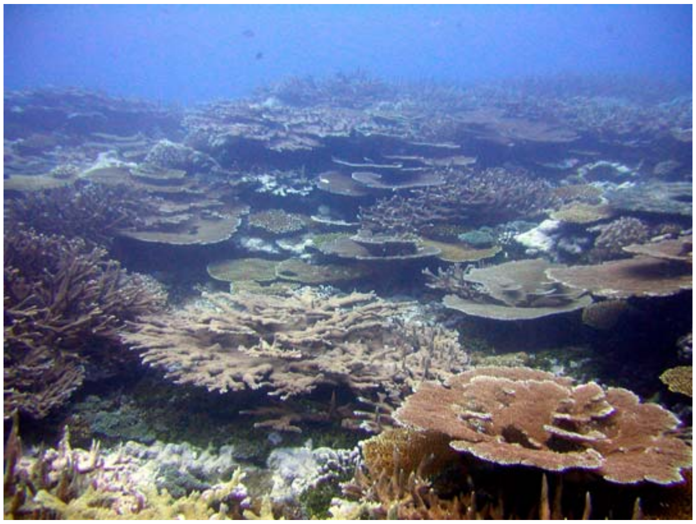
Table 5-2. Factors that may confer resilience to coral bleaching

Resilience factors
General factors - effective management regime
Physical factors that reduce temperature stress - exchange - upwelling - areas adjacent to deep water - wind-driven mixing
Physical factors that enhance water movement and flush toxins - fast currents - complex topography
Physical factors that decrease light stress - shade - incidental angle of sunlight - slope - turbidity - absorption /colored dissolved organic matter (CDOM) - cloud cover
Factors that correlate with bleaching tolerance - temperature variability - emergence at low tide
Indirect indicators of bleaching tolerance - broad size and species distributions - high genetic diversity - areas of greatest remaining coral cover - history of corals surviving bleaching events
Factors that enhance repopulation - availability and abundance of local larvae - connectivity to local and distant larvae sources - recruitment success - low abundance of disease, bioeroders, corallivores - suitable substrate

Source: Adapted from West and Salm (2003).

The support of communities toward establishing and maintaining MPAs is growing in American Samoa. Additionally, the long-term management approaches described in this section are highly compatible with the stated commitments of the American Samoa government and the CRAG with regard to MPAs. In 2000, the late Governor Sunia pledged that the American Samoa Government would establish no-take MPAs in at least 20% of the surrounding reefs by 2010. In response, the CRAG has drafted American Samoa's Marine Protected Area Strategy (Oram, 2005). While this plan centers on maintaining ecosystem services and meeting village community needs, it also lists "resilience-building" as one of its core goals. However, this plan could benefit from the incorporation of specific information on resilience to climate change stressors in particular, especially given the potential for the increasing vulnerability of American Samoa's coral reefs to future climate change. Comprehensive MPA planning will require the development of specific monitoring for the many desirable physical and biological characteristics that interest stakeholders. This provides an excellent opportunity to test hypotheses regarding factors that are believed to confer resilience to climate change. (See Table 5-2.)

In summary, MPAs can be powerful conservation tools for protecting coral resources. A key factor for establishing resilience is protecting adequate and appropriate habitat. MPAs can go beyond traditional concerns to also incorporate resilience to climate change. This supports incorporating the following elements into long-term planning:



A healthy reef in American Samoa. (Photo by Eric Mielbrecht.)

- Integrate climate change resilience actions in the American Samoa MPA planning process, including incorporation of factors hypothesized to confer resilience to climate change into American Samoa's Marine Protected Area Strategy and associated monitoring.
- Continue to develop community involvement and a holistic coastal-zone management approach.

6. CONCLUSIONS

The major goal of this report is to provide some priority adaptation options to be integrated into existing and future management processes in order to enhance the resilience of American Samoa's coral reefs to climate change. As is the case for most marine ecosystems globally, there are limited existing data for and publications on coral reefs that lend themselves directly to application in management actions. For example, while there are data on water quality, there is very little research on the causal relationship of reef condition to measured localized poor water quality in American Samoa. Another limitation in information has been that while good historical monitoring of coral cover exists, there is a lack of data on community composition, function, genetic diversity, and connectivity to local and distant larval sources. Finally, there are a number of on-going research projects in American Samoa that should soon provide additional useful information and fill some of these gaps. Throughout the report, when necessary, conclusions are qualified due to these kinds of data limitations.

In some cases, data may actually exist but have not yet been analyzed in terms of the management questions posed in this report. This lack of data or analysis becomes even more pronounced for the complex questions stemming from the interactions of climate change and local stressors. This report highlights recommended, basic research questions that would help address this lack of information. While suggestions and approaches are presented, detailed planning for implementation and adoption must be developed at the local level, taking into account the specifics of local issues and concerns. However, this report makes a first effort at integrating recommended management actions and research questions into existing management activities to facilitate progress.

While the report does indicate a need for continued research in American Samoa on climate change issues, this does not mean that it is impractical to develop an assessment of climate change and interacting stressors for coral reef management. Also, this report emphasizes that priority actions on these management approaches can be taken now. It is important to note that efforts to improve or maintain coral resilience in response to climate change require action sooner rather than later. Implementation, based on current knowledge using the adaptive management paradigm, can be undertaken, evaluated, and later modified based on new information.

Within an adaptive management approach and with the best available information, this analysis of climate change and interacting stressors in American Samoa supports the recommendation of the following priority management actions:

1. immediate time frame – implement water quality improvements
2. near-term time frame – develop and implement hypothesis-driven monitoring and research

3. long-term time frame – design and implement resilient MPA networks, with strong village community outreach and involvement.

This report provides a systematic approach by which these adaptive management strategies can be further developed. Ideally, future actions would encompass the priority management actions developed herein but be progressively customized for American Samoa based on existing regulatory and political conditions, community involvement, and information from additional research and analysis.

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APPENDIX

Resources specific to coral reefs

- A Reef Manager's Guide to Coral Bleaching (Marshall and Schuttenberg, 2006)
- Coral Bleaching and Marine Protected Areas (Salm and Coles, 2001)
- R2 Reef Resilience: Building Resilience into Coral Reef Conservation, Additional Tools for MPA Managers (The Nature Conservancy and Partners, 2003)
- Resistance and Resilience to Coral Bleaching: Implications for Coral Reef Conservation and Management (West and Salm, 2003)
- Great Barrier Reef Coral Bleaching Response Plan Summer 2006-2007 (Great Barrier Reef Marine Park Authority, 2006)
- Coral Bleaching: Causes, Consequences and Response (Schuttenberg, 2001)
- Management of Bleached and Severely Damaged Coral Reefs (Westmacott et al., 2000)
- How Climate Change Could Affect MPAs: What Practitioners Need to Know (MPA News, 2001)
- The Implications of Climate Change for Australia's Great Barrier Reef (WWF, 2004)

Resources spanning multiple ecosystems

- Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems (Hansen et al., 2003)

Field methodologies specific to coral monitoring

- A Global Protocol for Assessment and Monitoring of Coral Bleaching, 1st Edition (Oliver et al., 2004)
- Development of benthic sampling methods for the Coral Reef Assessment and Monitoring Program (CRAMP) (Brown et al., in press)
- C-NAV Coral Navigator, CD ROM with GCRMN and ReefCheck methods (Available at the AIMS Bookshop Science Communications, Townsville, Queensland 4810, Australia)
- Additionally, various Web sites detail different monitoring and assessment methods for coral reefs:
    - Hawaii Coral Reef Network – http://www.coralreefnetwork.com/research/methods.htm
    - Australian Institute of Marine Science Monitoring – http://www.aims.gov.au/pages/research/reef-monitoring/methods.html
    - Australian Government website on monitoring for coral bleaching – http://www.nrm.gov.au/monitoring/indicators/estuarine/coral-bleaching.html
    - Coral Reef Assessment and Monitoring Program (CRAMP) website – http://cramp.wcc.hawaii.edu/
    - Atlantic and Gulf Rapid Reef Assessment (AGRRA) – http://www.agrra.org/

– Reef Check manual – http://www.reefcheck.org/
– Global Coral Reef Monitoring Network (GCRMN) – http://www.coral.noaa.gov/gcrmn/
– Real-time sea surface temperature monitoring resources
– US Coral Reef Watch Program and the Coral Reef Early Warning System (CREWS) – http://coralreefwatch.noaa.gov/

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