Assessing and Managing Coastal Ecosystem Response to Projected Relative Sea-Level Rise and Climate Change

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Abstract

Accelerated global sea-level rise is regarded as one of the more certain outcomes of global warming, and it is already likely taking place. Relative sea-level rise is a major factor contributing to recent losses and projected future reductions in the area of valued coastal habitats in many areas. This leads to an increased threat to human safety and shoreline development from coastal hazards. Small island developing states and low-lying coastal areas of continents are particularly vulnerable to small increases in sea-level. Land-use planners can manage shoreline response to relative sea-level rise to minimize loss of coastal habitat and concomitant risk of damage to coastal development and habitat critical for sensitive wildlife. This paper presents an overview of how coastal habitats will respond to relative sea-level rise and climate change, describes a method to assess site-specific shoreline response to projections for change in relative sea-level developed and being applied in American Samoa, and describes options for selecting and implement policies to manage shoreline changes deemed suitable for different sections of coastline, including abandonment, adaptation, habitat rehabilitation, and coastal hardening. Recommendations are also presented to establish a regional coastal habitat monitoring network to enhance understanding of shoreline response to changes in sea-level and climate. Establishing baselines of coastal habitats and monitoring these gradual changes through regional networks will enable the separation of site-based influences from global changes to provide a better understanding of the response of coastal habitats to global climate and sea-level change, and alternatives for mitigating adverse effects.

1. Introduction

Accelerated global sea-level rise is regarded as one of the more certain outcomes of global warming, and it is already likely taking place (Church et al., 2001; Intergovernmental Panel on Climate Change, 2001a; Holgate and Woodworth, 2004). Small island developing states and low-lying coastal areas of continents are particularly vulnerable to small increases in sea-level. Relative sea-level rise is a major factor contributing to recent losses and projected future reductions in the area of valued coastal habitats, including mangroves and other tidal wetlands, coral reefs, beaches, and sea grass beds. This leads to an increased threat to human safety and shoreline development from coastal hazards. Relative sea-level rise and global warming also pose a threat to coastal habitat supporting sensitive species such as seabird colonies and marine turtle nesting beaches. Global mean sea level is projected to rise by 0.09 to 0.88 m between 1990 and 2100 (Intergovernmental Panel on Climate Change, 2001b).

Accurate information on response of coastal habitats to predicted climate change and projected relative sea-level rise over coming decades will enable educated coastal land use planning decisions to minimize and mitigate losses of valued habitats, reduce the risk of damage to coastal development, and select and implement policies to manage shoreline changes deemed suitable for different sections of coastline, including abandonment, adaptation, habitat rehabilitation, and coastal hardening (Dixon and Sherman, 1990; Mullane and Suzuki, 1997; Ramsar Bureau, 1998; Hansen and Biringer, 2003; Ellison, 2004).

Most small island states have limited capacity to adapt to relative sea-level rise and climate change, including accommodating landward migration of coastal habitats. This is a result of their small land mass, high population densities and population growth rates, limited funds, poorly developed infrastructure, and susceptibility to damage from natural disasters (Nurse et al., 2001). Many of the low islands do not exceed 4 m above current mean sea level, and even on high islands, most development is located on narrow coastal plains. It may be physically and economically difficult for some small island state communities to retreat from landward migrating coastal habitats, or to establish zoning setbacks from coastal habitats for new development.

Projections are available over coming decades for rising sea-level and changes in climate and weather (Church et al., 2001; Intergovernmental Panel on Climate Change, 2001b). These changes are expected to alter the position, area, structure, species composition, and health of most coastal communities. Identifying effects on coastal habitats from relative sea-level rise and climate change will require a regional, long-term monitoring network (Nurse et al., 2001; Gilman and Ellison, 2004). Establishing baselines of coastal habitats and monitoring these gradual changes through regional networks will enable the separation of site-based influences from global changes to provide a better understanding of the response of coastal habitats to global climate and sea-level change, and alternatives for mitigating adverse effects.

2. Review of Global Climate and Sea-Level Change Causes and Projections

Main Points

- Since the late 19th century, the global average surface temperature has increased 0.6 degrees C. Most of the observed warming over the last 50 years is likely due to increases in atmospheric concentrations of greenhouse gas.
- Global averaged surface temperatures are projected to increase by 1.4 to 5.8 degrees C from 1990 to 2100.
- Global average sea level rose between 0.1 and 0.2 m during the 20th century at a rate of 1.0 to 2.0 mm/year.
- Global mean sea level is projected to rise by 0.09 to 0.88 m between 1990 and 2100 due primarily to thermal expansion of seawater and transfer of ice from glaciers and ice caps to water in the oceans, which are results of global warming.

Changes in global mean climate over human time scales, on the order of decades, is primarily a result of changes in the Earth’s output of radiation to space. The Earth absorbs radiation from the Sun primarily at the surface. This energy is distributed by the atmospheric and oceanic circulations and is radiated back to space as infrared radiation. Any change in the balance between incoming solar radiation and outgoing terrestrial radiation, as well as alterations to the distribution of energy within the atmosphere, land,

and ocean, can change the Earth's climate (Intergovernmental Panel on Climate Change, 2001b). Factors contributing to short-term climate change are summarized in Figure 1.

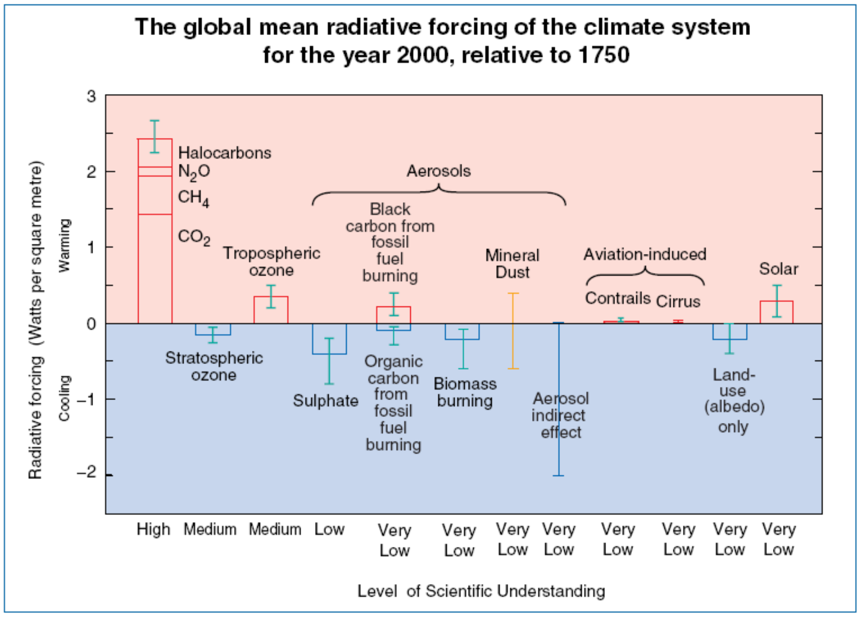


Figure 1. Factors that contribute to climate change, subjective level of scientific understanding of each factor, and estimated contributions of each factor towards warming and cooling the Earth's surface and lower atmosphere (where radiative forcing, or change in the net radiative energy available to the Earth climate systems, is presented in watts per square meter) for the year 2000 relative to a baseline from the year 1750 (the beginning of the Industrial Era). Rectangular bars represent best estimates of the contributions of each factor to radiative forcings, and vertical lines about the rectangular bars indicate the range of published estimates for each forcing factor. Vertical lines without a rectangular bar indicate a forcing factor for which no best estimate can be given due to the low degree of scientific understanding of this factor (Intergovernmental Panel on Climate Change, 2001a and 2001b).

Human-induced climate change by the production of greenhouse gases and aerosols, such as the combustion of fossil fuels, biomass burning, and deforestation, affect the composition of the atmosphere and Earth's radiative budget. An increase in atmospheric concentrations of greenhouse gases warms the Earth's surface and lower atmosphere, and is thought to be the largest anthropogenic factor contributing to global warming (Figure 1): Greenhouse gases absorb infrared radiation emitted by the Earth's surface, the atmosphere, and clouds, and emit infrared radiation both upward and back towards the Earth's surface, retaining heat within the atmosphere, tending to raise the temperature of the Earth's surface and lower atmosphere (Baede et al., 2001). The higher the concentration of greenhouse gases in the atmosphere, the more terrestrial infrared radiation from the Earth's surface will be absorbed by the atmosphere and less heat radiates to space, making the Earth's surface and lower atmosphere warmer.

Since the late 19th century, the global average surface temperature has increased 0.6 (+/- 0.2 95% confidence interval) degrees C (Figure 3) (Intergovernmental Panel on

Climate Change, 2001b). Most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas atmospheric concentrations (Intergovernmental Panel on Climate Change, 2001b).

The Intergovernmental Panel on Climate Change has developed a range including 35 climate projections based on several climate models. The full range of these 35 scenarios result in a projection that global averaged surface temperatures will increase by 1.4 to 5.8 degrees C from 1990 to 2100 (Figure 2) (Intergovernmental Panel on Climate Change, 2001a).

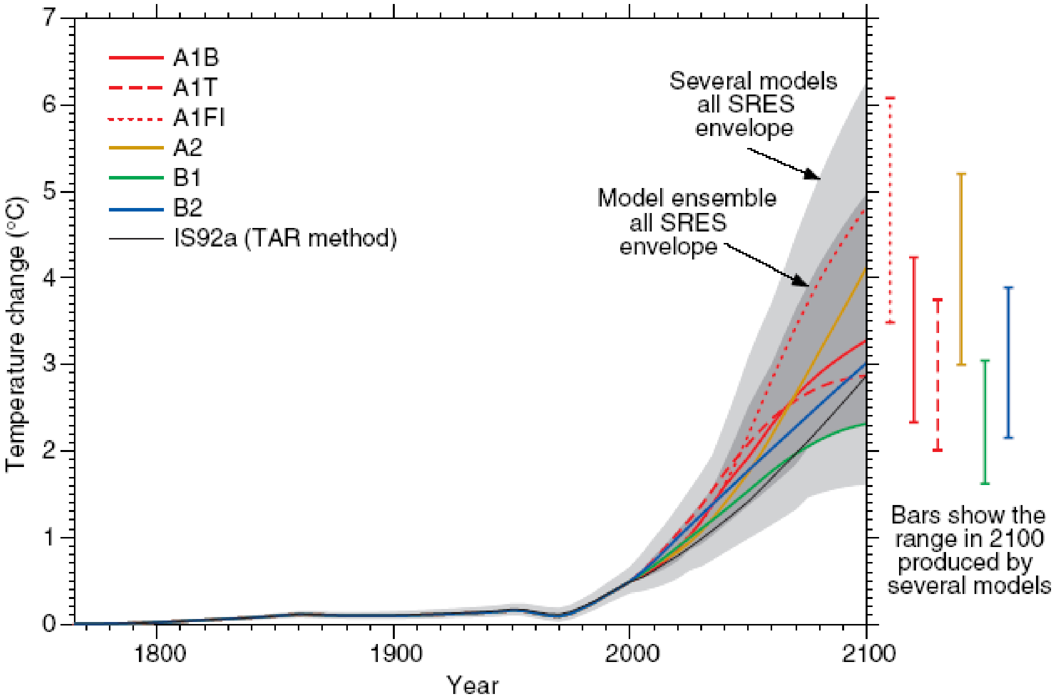


Figure 2. Intergovernmental Panel on Climate Change climate models project the response of global mean temperature of the Earth's surface and lower atmosphere to scenarios of greenhouse gas and other human-related emissions for the period 1750 to 2100. The seven lines in the key are results for various Atmosphere-Ocean General Circulation Models. The full range of 35 climate projections based on several climate models result in a projection that global averaged surface temperatures will increase by 1.4 to 5.8 degrees C from 1990 to 2100. (Intergovernmental Panel on Climate Change, 2001b).

Tide gauge data show that global average sea level rose between 0.1 and 0.2 m during the 20th century at a range of 1.0 to 2.0 mm/year (Church et al., 2001; Intergovernmental Panel on Climate Change, 2001a). Global sea-level rise during the 20th century has very likely been significantly influenced by global warming through thermal expansion of seawater and loss of land ice (Intergovernmental Panel on Climate Change, 2001b). The processes that influence global sea-level, estimated contributions for the period 1910 to 1990, and the level of uncertainty for predicted influence on sea-level change rates are illustrated in Figure 3.

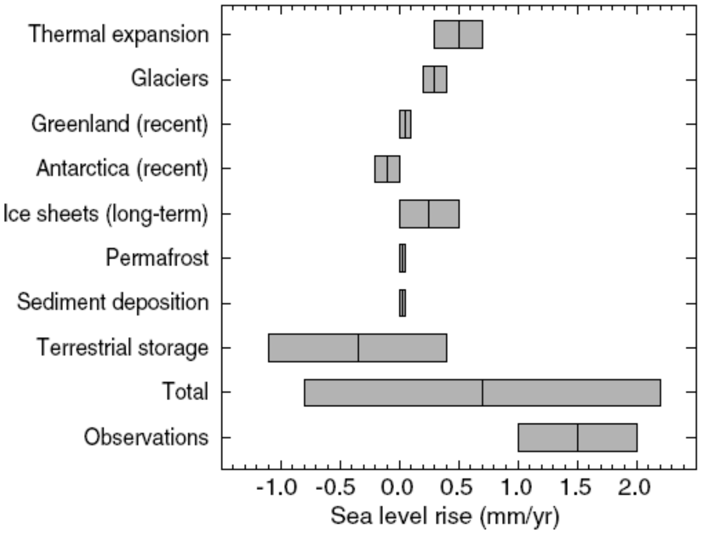


Figure 3. Eight processes believed to contribute to the change in the rate of sea-level rise from 1910 to 1990, the estimated contribution from each process, and the range of uncertainty for each processes' contribution to average rate of sea-level rise during this period (Church et al., 2001).

Figure 4 presents a range of Intergovernmental Panel on Climate Change (2001a) projections for global sea-level change from 1990 to 2100. Global mean sea level is projected to rise by 0.09 to 0.88 m between 1990 and 2100 based on the Intergovernmental Panel on Climate Change's full range of 35 climate projection scenarios (Intergovernmental Panel on Climate Change, 2001b). The projected short-term sea-level rise from 1990 to 2100 is due primarily to thermal expansion of seawater and transfer of ice from glaciers and ice caps to water in the oceans, which both change the volume of water in the world oceans (Intergovernmental Panel on Climate Change, 2001a).

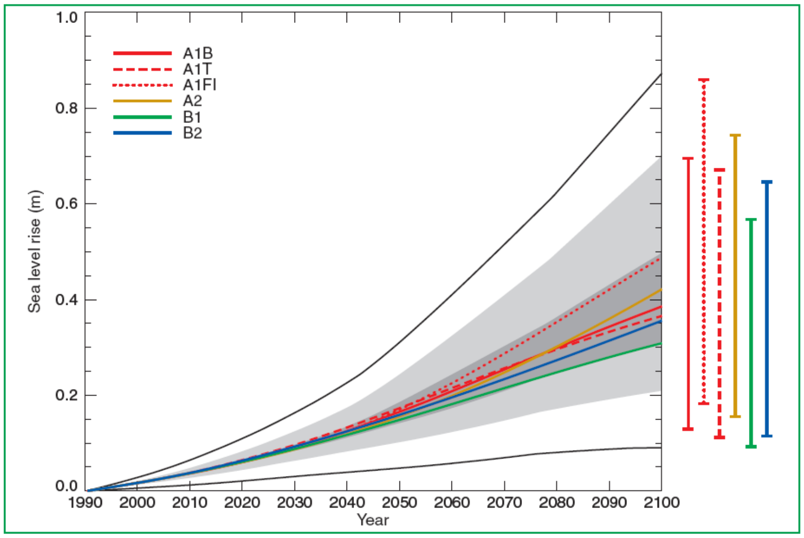


Figure 4. Intergovernmental Panel on Climate Change (2001a) climate models project the response of sea level to scenarios of greenhouse gas and other human-related emissions

for the period 1990 through 2100. The six lines in the key are the averages of results of a range of Atmosphere-Ocean General Circulation Models. Bars show the range in possible sea-level elevation by 2100 produced by several climate models.

2.1. Observed Relative Sea-Level Rise Rates from the Pacific Islands Region

Main Points

- Pacific regional relative sea-level change trends are estimated to be about +0.77 mm per year over the past few decades.
- Tide gauge records show there have been relative sea-level rise trends of about 2.0 and 3.4 mm per year respectively on Tutuilla Island, American Samoa, Rarotonga, and the Cook Islands.
- Some islands and atolls are experiencing relative sea-level lowering as a result of positive vertical land movement exceeding regional sea-level rise, such as observed on Pohnpei, Federated States of Micronesia and Noumea, New Caledonia.
- Global sea-level is projected to accelerate over coming decades – relative sea-level trends will likely show increased rising through the year 2100.

Mitchell et al. (2000) report an average relative sea-level rise trend of +0.77 mm/year for 27 islands in the Pacific region containing a minimum of 25 years of hourly tide gauge data, however they neglect to estimate probable uncertainty, and tide gauge records probably need to be a minimum of four to five decades duration to provide accurate long-term sea-level trends (Hunter, 2002). Based on global projections, sea-level rise is expected to accelerate in coming decades (Figure 4) (Intergovernmental Panel on Climate Change, 2001a).

Figure 5 presents the mean monthly relative sea-level from October 1948 through May 2004 for Pago Pago, American Samoa.

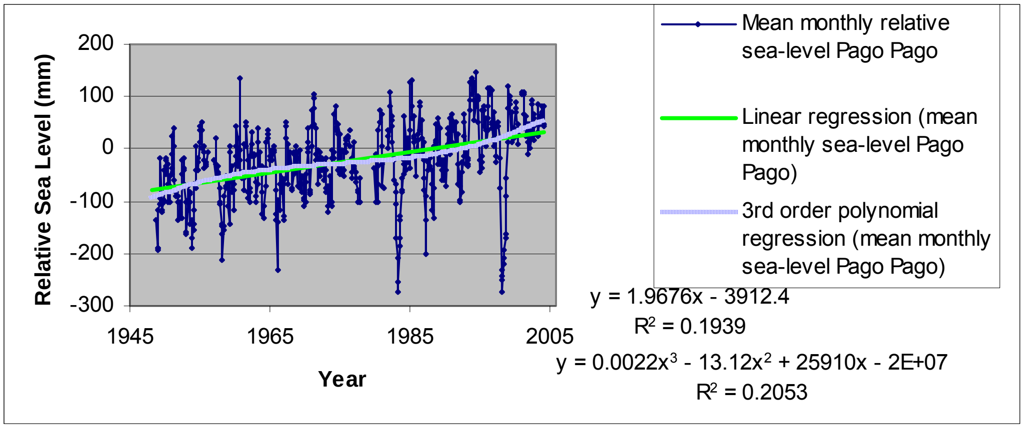


Figure 5. Mean monthly relative sea-level from a tide gauge located in Pago Pago harbor, American Samoa, from October 1948 – May 2004 (n = 619). Gaps appear in the data

plots where there were not enough data to produce a reliable monthly mean. Linear and third order polynomial regression models are fit to the data. (Data sources are the Permanent Service for Mean Sea Level and the University of Hawaii Sea Level Center Joint Archive for Sea-Level and GLOSS/CLIVAR databases)

The linear regression of the mean monthly sea-levels indicates an average relative sea-level rise trend of 1.97 mm/yr over the observed time period of 54.67 years. Additional analysis could be conducted to determine the best fit for modeling this relationship. The American Samoa relative sea-level trend is over 2.5 times higher than the average trend for the Pacific region reported by Mitchell et al. (2000). The third order polynomial regression model of the 54.67 years of tide gauge records from American Samoa indicates that there may have been accelerated relative sea-level rise since about mid-1997 (Figure 5).

Figure 6 shows that Rarotonga, Cook Islands, has experienced an average relative sea-level rise trend of 3.4 mm per year over the observed time period of 23.67 years based on a linear regression of mean monthly sea-levels. This is over 4.4 times higher than the regional average relative sea-level rise trend reported by Mitchell et al. (2000) for the Pacific region.

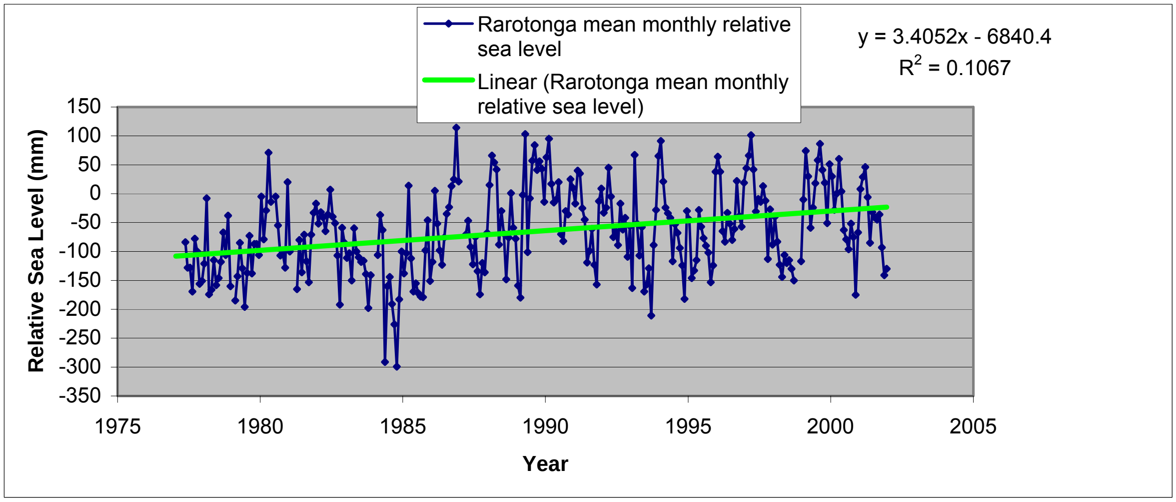


Figure 6. Mean monthly relative sea-level from a tide gauge located Rarotonga, Cook Islands, from May 1977 – December 2001 (n = 286). Gaps appear in the data plot where there were not enough data to produce a reliable monthly mean. A linear regression model is fit to the data. (Data source is the Permanent Service for Mean Sea Level database).

Mitchell et al. (2000) reports that Kiritimati (Christmas) Island, Republic of Kiribati has experienced no change in relative sea-level based on an analysis of 38.3 years of tide gauge data. Some islands and atolls in the tropical Pacific are experiencing relative sea-level lowering as a result of a positive trend in vertical land movement that exceeds regional changes in sea-level. For instance, Mitchell et al. (2000) report that Pohnpei, Federated States of Micronesia has a relative sea-level lowering trend of 0.7 mm per year based on an analysis of 25.9 years of tide gauge records, and Noumea, New Caledonia, has a relative sea-level lowering trend of 0.4 mm per year based on an analysis of 31.6 years of tide gauge records.

3. Response of Coastal Habitats to Relative Sea-Level Rise

Main Points

- Beaches and tidal wetlands tend to migrate landward as a response to relative sea-level rise.
- Most coral reef communities are expected to be able to keep pace with projected rates of sea-level rise. However, some reef flat and deepwater reef communities may experience substantial mortality as a result of sea-level rise, and reefs experiencing increased stress from human activities and global climate change will be less resilient to accelerated rates of relative sea-level rise.
- Relative sea-level rise is a major factor contributing to recent losses and projected future reductions in the area and health of valued coastal habitats, including mangroves and other tidal wetlands, coral reefs, beaches, and sea grass beds.
- Natural landward migration of tidal wetlands and beaches as a response to relative sea-level rise can be obstructed by seawalls and other development, reducing the area of the wetlands and beaches.
- Reduced area and health of coastal habitats will result in increased threats to human safety and shoreline development from coastal hazards.

Long-term, landscape-level response of mangroves and other tidal wetlands to relative sea-level rise, over a period of decades and longer, is determined by (a) the difference between the relative sea-level rise rate and the change in elevation of the mangrove surface and (b) the mangrove's physiographic setting (slope of the land on which the mangrove sites and landward, obstacles to landward migration) (Ellison and Stoddart, 1991; Ellison, 1993, 2000, and 2001; Woodroffe, 1995; Alleng, 1998; Lucas et al., 2002). This description of mangrove response to relative sea-level rise assumes that there are no human activities that cause changes in the position of mangrove boundaries, or otherwise that the force from human activities as it affects mangroves is small relative to the force from the rise in relative sea-level. Furthermore, this description hypothesizes that the force of the relative sea-level rise rate, as balanced by the change in elevation of the wetland surface, is the predominant natural force causing change in the mangrove position over a period of decades.

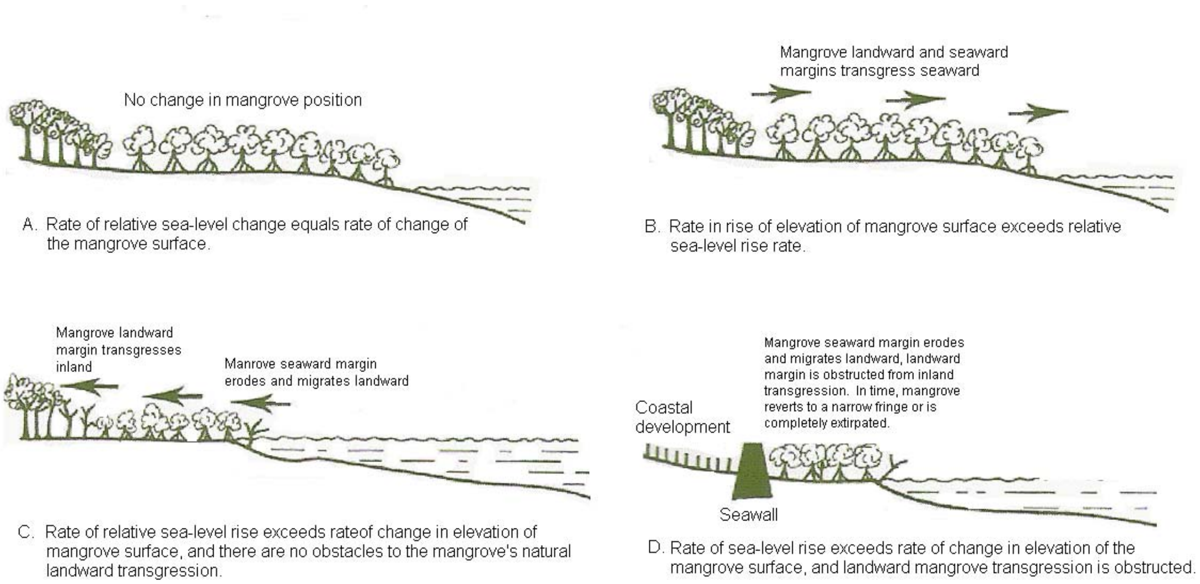
There are three general scenarios for tidal wetland response to relative sea-level rise, given a landscape-level scale and time period of decades or longer (Figure 7):

- <u>Relative sea-level rise rate = rate of increase in elevation of mangrove surface</u>: If the rate of change in elevation of the mangrove surface (sediment accretion rate minus any sediment compaction) keeps pace with relative sea-level rise, mangrove elevation, salinity, frequency of inundation levels and other factors that determine if a mangrove community can persist at a location will remain relatively constant and the mangrove margins will remain in the same location (Figure 7, A). Mangroves have been documented to cope with rates of relative sea-level rise when the sediment accretion rate allows mangrove community aggradation to keep pace, such as in the Ganges delta mangrove (Blasco, 1996), and in Jamaica (Alleng, 1998).

- <u>Relative sea-level rise rate < rate of change of mangrove surface elevation</u>: If the rate of increase in elevation of the mangrove surface exceeds the relative sea-level rise rate, this will force the mangrove seaward and landward boundaries to migrate seaward (Figure 7, B), as has been observed in Fiji (Nunn, 2000), and may explain observed mangrove progradation in Florida (Snedaker et al., 1994). Under these conditions, the mangrove may also expand laterally, displacing other coastal habitats.
- <u>Relative sea-level rise rate > rate of change of mangrove surface elevation</u>: If the rate of change of the elevation of the mangrove surface is exceeded by the relative sea-level rise rate, the mangrove's seaward and landward margins will retreat landward, the mangrove species zones will migrate inland as they maintain their preferred elevation as the seaward margin dies back, and tidal creeks will widen, with erosion and slumping at their margins (Semeniuk, 1980; Ellison, 1993, 2000, 2001; Woodroffe, 1995). An illustration of mangrove response under these conditions, where there are no obstructions to landward migration, is shown in Figure 7, C. Mangrove zonation is largely controlled by the elevation of the substrate surface relative to mean sea level, and mangrove's seaward margin is closely controlled by sea-level elevation (Ellison, 2004). The seaward mangrove margin migrates landward from mangrove tree dieback due to stresses caused by a rising sea-level such as erosion resulting in weakened root structures and falling of trees, increased salinity, and too high a frequency of inundation (Ellison, 1993 and 2000). Mangrove zones migrate landward via seedling recruitment and vegetative reproduction as new habitat becomes available landward through erosion, inundation, and concomitant change in salinity (Semeniuk, 1994). Mangroves colonize upper reaches of tidal creek banks and slopes as the surface is progressively lowered to the zone of mangrove habitation (Semeniuk, 1994). The salinity structure of the groundwater and soil water systems will also migrate landward (Semeniuk, 1994).

A rising sea-level will reduce the width of mangroves at sites where relative sea-level rise exceeds the mangrove sedimentation rate and the landward migration rate of the landward mangrove boundary is less than the migration rate of the seaward mangrove margin due to the slope of the adjacent shoreline or because the mangrove is otherwise obstructed from migrating landward by the presence of structures such as seawalls. Depending on the slope of adjacent uplands and the presence of obstacles to landward migration of the landward boundary of the mangrove, such as seawalls and other shoreline protection structures, some sites will revert to a narrow mangrove fringe or possible survival of individual trees, as is hypothesized to have occurred in the Pacific islands region prior to 6500 years before present when there was rapid sea-level rise and a lack of suitable sedimentary shorelines, or even experience extirpation of the mangrove community (Figure 7, D) (Ellison and Stoddart, 1991).

There will also be increased shoreline erosion rates when the relative sea-level rise rate exceeds the change in elevation of the mangrove surface. Ellison (1993) and Semeniuk (1980) demonstrated that mangrove sediment is subject to erosion by rising sea levels as generally described by predictive models of beach response to sea-level rise (Bruun, 1962; SCOR Working Group, 1991).



A. Rate of relative sea-level change equals rate of change of the mangrove surface.

B. Rate in rise of elevation of mangrove surface exceeds relative sea-level rise rate.

C. Rate of relative sea-level rise exceeds rateof change in elevation of mangrove surface, and there are no obstacles to the mangrove's natural landward transgression.

D. Rate of sea-level rise exceeds rate of change in elevation of the mangrove surface, and landward mangrove transgression is obstructed.

Figure 7. Mangrove response to relative sea-level rise under four different scenarios (adapted from Kennedy et al., 2002). A similar response applies to other tidal wetlands.

Figure 8. The seaward margin of mangroves will erode and trees will die back with relative sea-level rise (photo left by J. Ellison, right by author).

Based on an assessment of stratigraphic records of Pacific island mangroves during sea-level changes of the Holocene Period, Ellison and Stoddart (1991) generalize that low island mangroves (embayment, lagoon, and reef flat mangroves), which generally rely on the accumulation of vegetative detritus for peat production for substrate build-up and lack a large source of inorganic sediment, can keep up with a 1.2 mm/year relative sea-level rise rate. Mangroves of high islands (deltaic and estuarine mangroves) and continental coastlines, which have relatively large supplies of terrigenous inorganic and organic sediment from rivers and longshore drift can keep pace with a 4.5 mm/year relative sea-level rise rate (Ellison and Stoddart, 1991). Based on Intergovernmental Panel on Climate Change (2001b) projections of global sea-level rise, there will be an annual rise of between 0.8 mm and 8.0 mm (median of 4.3 mm) from 1990 to 2100, indicating that, based on predicted general rates of mangrove accretion, island mangroves could experience serious problems due to rising sea-level, and low island mangroves may already be under stress.

The response of beaches to relative sea-level rise will be similar to that of tidal wetlands. While relative sea-level rise rates are perceived as been small over years and decades, they can result in substantial shoreline retreat rates from erosion that are, for some shorelines, 50-100 times larger than the sea-level rise rate (Komar, 1989). As explained for tidal wetlands migrating landward, the presence of obstacles to the natural landward migration of beaches will result in reduced area or complete loss of this coastal habitat, similar to the scenario depicted in Figure 7D.

Bruun (1962, 1988) provides a simplistic model of change to beach profile with sea-level rise, and assumes a closed material balance system so that the migrating beach has no net loss of sand volume, and that there is a uniform sandy shoreface with no outcrops or other obstacles that could cause non-uniform retreat rates to sea-level rise spatially and temporally (Bruun, 1988; Komar, 1989; Pilkey and Cooper, 2004). The Bruun (1962, 1988) model assumes that with increased sea-level, the equilibrium beach profile and shallow offshore migrates upward and landward, the upper beach is eroded due to the landward translation of the profile, the material eroded from the upper beach is deposited immediately offshore, and the rise in nearshore bottom equals the rise in sea-level, resulting in the following simple equation, where R is the shoreline retreat rate, S is the amount of sea-level rise, B is the vertical berm height or other elevation estimate of the eroded area, and L is the cross-shore distance to the water depth h (the depth to which nearshore sediments exist versus finer-grained continental shelf sediments, the depth at the base of the profile beyond which significant sediment exchange is not considered to occur, referred to as the “closure depth”), and Ǿ is the profile slope angle (Bruun, 1962 and 1988; Komar, 1989; List et al., 1997; Pilkey and Cooper, 2004). Assuming that the average slope of many coastlines is 0.01-0.02, then $R = 50S$ to $100S$, showing that a small rise in mean sea-level can generally result in a large shoreline retreat (Figure 9) (Komar, 1989; SCOR Working Group, 1991).

$$R = L*S/(B+h) = S/\tan Ǿ$$

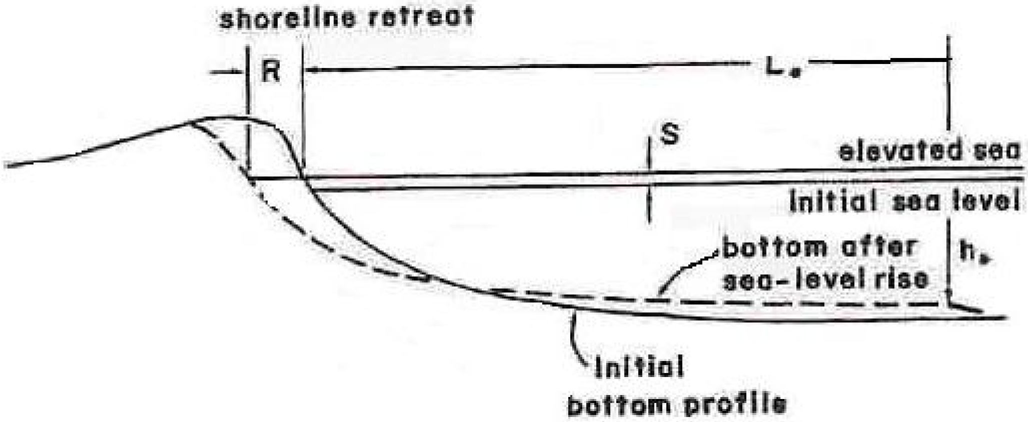


Figure 9. The net change in beach profile position due to a rise in sea-level, S, according to the Bruun model, resulting in a zone of offshore deposition and erosion of the upper beach, resulting in landward recession at rate R (Komar, 1989).

The Bruun equation can result in large error when applied to coastal systems other than beaches, when used for site-specific estimates of beach erosion even when model assumptions are met, and when used over short time periods (SCOR Working Group, 1991; List et al., 1997; Pilkey and Cooper, 2004). However, the general concept described by the Bruun model, where with increased sea-level, the equilibrium beach profile and shallow offshore migrates upward and landward, is well accepted (SCOR Working Group, 1991). Shoreline retreat of the seaward margin of mangroves resulting from a long-term rise in relative sea-level will likely result from a process of short-term episodic spurts of erosion and accretion with a long-term mean trend of landward transgression, rather than a continuous gradual landward migration (SCOR Working Group, 1991).

Most coral reef communities are expected to be able to keep pace with projected global sea-level rise (Brown, 1997; Wilkinson, 1999; McCarthy et al., 2001). Reef accretion rates range from 1-10 mm per year, with a rate of 10 mm per year accepted as the maximum vertical accretion rate that a reef can sustain (Brown, 1997). Reef systems may be able to build upward at faster rates, as high as 20 mm per year, when growing in water depths of less than 20 m where there is abundant sunlight for photosynthesis (Brown, 1997). The median projected global sea-level rise rate of the Intergovernmental Panel on Climate Change (2001a) is 4.3 mm per year, and the maximum projected scenario is 8.0 mm per year from 1990 through 2100.

However, some reef communities may experience mortality as a result of relative sea-level rise. Reef flat communities that undergo accelerated coral growth to keep pace with rising relative sea-level would become susceptible to subaerial exposure and substantial mortality if sea-level rise occurs in episodic pulses with periods of sea-level remaining steady (Brown, 1997). Also, deeper reefs may not be able to keep pace with projected sea-level rise scenarios. Furthermore, increased stresses placed on reef communities, including increased sedimentation, nutrient loading, rising temperatures, and indirect stresses resulting from the degradation of adjacent coastal communities, is expected to reduce coral reefs' resilience to accelerated rates of relative sea-level rise (Hubbard, 1997; Ellison, 2004).

Figure 10 illustrates four general responses of coral reefs to varying rates of relative sea-level rise. If sea-level rises at a rate that is slower than the reef's ability to produce carbonate, the reef will prograde seaward as well as aggrade vertically. If the relative sea-level rise rate is roughly equal to the reef's rate of carbonate production, then the reef will grow vertically and not grow seaward or landward. If sea-level outpaces the accreting reef, the reef will either backstep to higher ground or drown (Hubbard, 1997). Reefs may also survive at deeper depths as they grow upward at a lower rate than the rise of sea-level, and catch up if and when the sea-level rise rate slows (Brown, 1997).

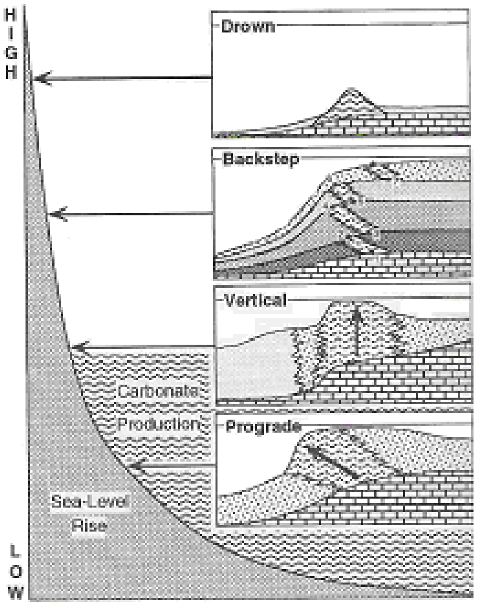


Figure 10. Four scenarios of coral reef response to various rates of relative sea-level rise (Hubbard, 1997).

4. Response of Coastal Habitats to Climate Change Effects

Main Points

- All tropical ocean regions where small island states are located are expected to experience increased thermal stress during the summer, more frequent droughts in the dry season, more frequent floods in the wet season, and increased intensity and frequency of coastal hazards.
- Outcomes from global climate change other than sea-level rise, such as increased air and sea-surface temperatures, changes in precipitation, and changes in storms, are less certain than global change in sea-level and the response of mangrove wetlands and other coastal systems to these changes are not well understood.
- Global warming is considered a significant threat to coral reef health.
- Coastal ecosystems are functionally linked – degradation of one community will result in reduced health of adjacent communities.

Outcomes of global climate change besides global sea-level rise, such as increases in air and sea-surface temperatures, changes in precipitation, changes in frequency and intensity of storms, changes in prevailing ocean wave heights and direction, and changes in tidal regimes may affect coastal systems such as mangroves, coral reefs, salt marshes, seagrass beds, and estuaries. However, projected changes in these parameters are less certain than global change in sea-level, and the response of coastal systems to changes in these parameters are not well understood (McLean et al., 2001).

Many climate models of the Intergovernmental Panel on Climate Change project surface temperatures to become more El-Nino-like in the tropical Pacific, with an eastward shift in warming and precipitation (Intergovernmental Panel on Climate Change, 2001a; Nurse et al., 2001). If temperature differences between the tropics and polar regions are reduced, the atmospheric circulation patterns that cause trade winds and upwelling in the eastern equatorial Pacific could be weakened (McLean et al., 2001). All tropical ocean regions where small island states are located are expected to experience increased thermal stress during the summer, more frequent droughts in the dry season, more frequent floods in the wet season (Nurse et al., 2001), as well as increased intensity and frequency of coastal hazards (Intergovernmental Panel on Climate Change, 2001b).

Increases in temperature and direct effects of increased atmospheric CO_2 concentration are expected to increase mangrove productivity, change phenological patters (e.g., timing of flowering and fruiting), and expand mangrove ranges to higher latitudes (Ellison, 2000). Mangrove metabolic responses to increased atmospheric CO_2 concentration are slightly increased productivity and more efficient water use (United Nations Environment Programme, 1994). Mangroves reach a latitudinal limit at the 16 degree C isotherm for air temperature of the coldest month, and the margins of incidence of ground frost, where water temperatures do not exceed 24 degrees C (Ellison, 2000).

The upper temperature limit for mangrove survival is far higher than current climate change projections (Ellison, 2004).

Increased inundation from relative sea-level rise, causing prolonged flooding, may reduce mangrove photosynthesis rates, productivity, and survival (Ellison, 2000). Prolonged flooding is expected to result in lower ability of mangrove leaves to conduct water, an increase in stomatal closing, and degeneration of chloroplasts in *Bruguiera gymnorrhiza*, leading to reduced rates of photosynthesis (Naidoo, 1983). If inundation is sustained, and lenticels of aerial roots are inundated, oxygen concentrations in the plant will fall, and the tree will die (Ellison, 2004). This is why the seaward edge of mangroves will migrate landward when the relative sea-level rise rate exceeds the sedimentation rate.

The Intergovernmental Panel on Climate Change found evidence of increased precipitation in the equatorial Pacific and decreased precipitation to the north in the last few decades, and predicts that El Nino conditions will become more persistent over coming decades, resulting in a general increase in precipitation in the tropical Pacific (Intergovernmental Panel on Climate Change, 2001a). It is uncertain how precipitation patterns will change in for individual Pacific island States over coming decades. Some mangroves may experience increases in salinity from sea-level rise, increased evaporation, and groundwater depletion from human extraction (Ellison, 2000). Also, areas with decreased precipitation will have a smaller water input to groundwater and less freshwater surface water input to mangroves, increasing salinity. Increased salinity decreases mangrove net primary productivity, growth, and seedling survival, and may possibly change competition between mangrove species (Ellison, 2000 and 2004). Decreased rainfall and increased evaporation will reduce the extent of mangrove areas, with a conversion of landward zones to hypersaline flats, and there will be a decrease in diversity of mangrove zones and growth (Ellison, 2000). Mangrove areas experiencing increased rainfall will experience an increase in area, with mangrove colonization of previously unvegetated areas of the landward fringe, and there will an increase in diversity of mangrove zones and growth rates (Ellison, 2000). Areas with higher rainfall have higher mangrove diversity and productivity due to higher supply of fluvial sediment and nutrients, as well as reduced exposure to sulphate and reduced salinity (Ellison, 2000 and 2004).

Global warming is considered a significant threat to coral reef health (Nurse et al., 2001). Increased CO_2 concentrations may change the balance between carbonate and bicarbonate ions in seawater, reducing calcification rates of corals, and possibly resulting in biological and physical erosion of skeletons as a result of reduced calcificiation (Brown, 1997; Kleypas et al., 1999; LeClerq et al., 2002). The effect of increased CO_2 concentrations weakening coral skeletons and reducing coral calcification rates is expected to be greater at higher latitudes (Kleypas et al., 1999). Depending on the scale of temperature changes, the temperature tolerance of some species of reef-building corals may be exceeded in the next few decades and the incidence of bleaching may rise (Brown, 1997; Nurse et al., 2001). Corals are currently living close to their lethal upper temperature. While reef-flat and shallow-water coral reef communities show large ability to adapt to increased seawater temperatures, such as by producing stress proteins that protect both plant and animal cells in adverse conditions, this capability may be lower for species living subtidally in less variable surroundings (Brown, 1997). If the stratospheric ozone layer is degraded by human emissions of chlorofluorocarbons, there will be elevated levels of ultraviolet-B radiation levels, which could add an additional stress to coral reefs, although the effect of increased ultraviolet-B on corals is not well understood (Brown, 1997).

Degradation of one coastal habitat can result in reduced health of adjacent coastal habitats. Neighboring coastal ecosystems are functionally linked, although the functional links are not fully understood (Mumby et al., 2004). For instance, terrigenous sediments and nutrients carried by freshwater runoff are first filtered by coastal forests, then by mangrove wetlands, and finally by seagrass beds, before reaching coral reefs through streams and rivers. The existence and health of coral reefs are dependent on the buffering capacity of these shoreward ecosystems, which support the oligotrophic conditions needed by coral reefs to limit overgrowth by algae (Ellison, 2004). Coral reefs, in turn, buffer the soft sediment landward ecosystems from wave energy (Ellison, 2004). Mangroves of low islands and atolls, which receive a proportion of sediment supply from productive coral reefs, may suffer lower sedimentation rates and increased susceptibility to relative sea-level rise if coral reefs become less productive from climate change and sea-level rise. Another example of the functional links between coastal ecosystems is that mangroves supply nutrients to adjacent coral reef and seagrass communities, sustaining these habitats' primary production and general health. Also, decomposing phytoplankton detritus and decaying litter from mangroves and seagrass beds produce colored, chromophoric component of dissolved organic matter, which absorbs solar ultraviolet radiation, which can be transported over adjacent coral reefs and reduce coral reef exposure to harmful solar radiation (Anderson et al., 2001; Obriant, 2003). The existence of these functional links between coastal systems means that degradation of one habitat type will adversely affect the health of neighboring habitats.

5. Methodology to Assess Shoreline Response to Projected Relative Sea-Level Rise – Case Study from American Samoa

Main Points

- A method to assess the change in margins of coastal habitats as a response to projected relative sea-level rise, using a case study from American Samoa, includes identifying scenarios for future local sea-level, identifying the frequency and elevation of future extreme high water events, surveying current coastal habitat boundaries, calculating the sedimentation rate in wetlands and accretion rate for coral reefs, assessing the physiographical location, estimating the seaward margin erosion rate, and mapping scenarios of future location of the coastal habitat boundaries.

The following analyses enable an assessment of coastal habitat response to projected relative sea-level rise over coming decades. These analyses are being conducted as part of an assessment of shoreline response to relative sea-level rise in American Samoa (Gilman, 2004 and In Prep.).

- **Identify future local sea-level**: Identify a range of relative sea-level rise projections over the next few decades. This requires the availability and analysis of observed relative sea-level trend from tide gauge records. The tide gauge observations are compared to the globally calculated rates of past sea-level change (Church et al., 2001) to determine a local correction for relative sea-level rise. This correction is then applied to the global sea-level rise projections through the year 2100 (Church et al., 2001) to determine a range of local relative sea-level projections.
- **Identify frequency and elevation of future extreme high water events**: Analyze tide gauge records to predict the periodicity and elevation of future extreme high water events.
- **Survey and map current coastal habitat boundaries**: This requires relatively current imagery from aerial photographs, satellite images, or maps from on-the-ground boundary surveys using traditional survey equipment or GPS.
- **Predict future change in elevation of the substrate of tidal wetlands and growth rate of coral reefs**: For mangroves and other tidal wetlands, measure recent past or current sedimentation rates such as by installing and monitoring sedimentation stakes, employing horizon markers, or conducting radiochemical studies of sediment from shallow cores. For coral reefs, determine the growth rate for prevalent species of fringing, patch, and barrier reefs.
- **Assess physiographic setting**: For mangroves, other tidal wetlands, and beaches, determine the slope of the upland adjacent to the landward margin of the coastal habitat, and identify the location of obstacles to natural landward migration, such as roads, seawalls, and buildings.
- **Estimate seaward margin erosion rate for tidal wetlands and beaches**: Reconstruct the recent historical positions of the seaward margins of tidal wetlands and beaches using available historical time series of aerial photos, satellite imagery, and maps. Project the observed erosion rate into the future. An assessment of the significance of correlation between observed shoreline mean erosion or accretion and observed relative sea-level change over the same time period (e.g., Saintilan and Wilton, 2001; Wilton, 2002) is needed to infer whether relative sea-level change is the dominant force causing change in shoreline position.
- **Map future boundary scenarios:** Map scenarios of future location of the coastal habitat margins.

6. Managing Site-Specific Shoreline Response to Projected Relative Sea-Level Rise

Main Points

- Depending on the level of development of a section of coastline, land-use planners can implement various policies to proactively manage coastal habitat response to projected relative sea-level rise. These policies range from abandoning the coastline to allow coastal habitats to migrate landward, to fortifying the coastline to protect existing development from inundation and storms.
- Rehabilitation of sensitive coastal habitats such as mangroves and seagrass beds will help reduce projected losses of these habitats as a result of relative sea-level and climate change.

Results of a cost-benefit analysis for some sections of shoreline will justify implementing policies of abandonment and adaptation to manage long-term retreat with relative sea-level rise (Mullane and Suzuki, 1997; Dixon and Sherman, 1990; Ramsar Bureau, 1998). Coastal development can remain in use until the eroding coastline becomes a safety hazard or begins to prevent landward migration of coastal habitats, at which time the development can be abandoned or moved inland. For these sections of shoreline, management authorities and local communities are encouraged to maximize relocating or removing existing human obstacles to landward mangrove migration, and preventing future development from being located in areas that would obstruct coastal habitat landward migration. Zoning rules for building setbacks and land use for new development can be used to implement this approach to reserve zones behind current coastal habitat, such as beaches and mangrove swamps, for future beach and mangrove habitats. Managers can determine adequate setbacks by assessing site-specific coastal erosion rates. Construction codes can be instituted to account for relative sea-level rise rate projections to allow for the natural inland migration of coastal habitats based on a desired lifetime for the coastal development (Mullane and Suzuki, 1997). Any new construction of minor coastal development structures, such as sidewalks and boardwalks, should be required to be expendable and non-permanent with a lifetime based on the assessed sites' erosion rate and selected setback, or else the structure should be portable. These measures will prevent the need to armor the shoreline to protect coastal development, as long as the community is willing to abandon their development once the retreating shoreline eventually threatens their development or their development prevents the natural inland migration of coastal habitats, whichever occurs first. Adoption of legal tools, such as rolling easements, can help make such eventual coastal abandonment more acceptable to coastal communities. Rules should prohibit or otherwise discourage landowners of parcels along these coasts from constructing coastal engineering structures to prevent coastal erosion and the natural inland migration of coastal habitats. Furthermore, existing development and new development should be located so as to avoid areas subject to increasing threat from coastal hazards as a response from relative sea-level rise. This managed coastal retreat will allow coastal systems to migrate and retain their natural functional processes, including protecting the coastline from wind and wave energy.

Employing shoreline erosion control measures, such as groins, surge breakers, dune fencing, and detached breakwaters, can help reduce the rate of coastal erosion (Mullane and Suzuki, 1997). Such measures should only be employed when it is determined that there is low risk of altering the natural landward migration of coastal systems or causing other adverse environmental impacts.

Management authorities are also encouraged to support rehabilitating mangroves and other coastal habitats as a means to mitigate predicted coastal habitat losses resulting from relative sea-level rise. For instance, restoring areas where mangrove habitat previously existed and creating new mangrove habitat will help to offset anticipated reductions in mangrove area as a response to relative sea-level rise. Enhancing degraded mangroves by removing stresses that caused their decline will increase their resilience to climate change effects (Hansen and Biringer, 2003; Ellison, 2004). Rehabilitation sites must meet the environmental conditions (wave energy, substrate conditions, salinity regime, soil and water pH, sediment composition and stability, nutrient concentrations, elevation, slope, period of inundation, depth of inundation, etc.) required for mangroves. Some site preparation requirements for mangrove rehabilitation include:

- <u>Elevation</u>: If necessary, grade the site to the elevation that provides optimal hydrologic and salinity regime for the desired plant species (Kusler and Kentula, 1990; Lewis, 1994);
- <u>Slope</u>: Gradual slope helps reduce erosion, filters runoff entering the wetland, and allows for surface drainage at low tide (Smith III, 1987; Kusler and Kentula, 1990; Lewis, 1994);
- <u>Tidal exchange and wildlife access</u>: It may be necessary for large mangrove rehabilitation sites to include drainage channels to simulate natural tidal creeks, providing requisite tidal exchange, salinity regime, and wildlife access (Kusler and Kentula, 1990; Lewis, 1994);
- <u>Fertilizer</u>: Time-release of fertilizer (N is a nutrient limiting growth of halophytes in intertidal areas) (Naidoo, 1990; Lewis, 1994) may increase survival rates of plantings.

Identifying target functions and values that are desired to be performed by the rehabilitated mangroves will help guide site selection. For instance, if one purpose of the rehabilitation wetlands is to improve water quality of areas with pollution or high sedimentation problems, site selection will focus on selecting locations that will maximize removal of pollutants and sediment. Other criteria to consider when identifying suitable and desirable sites to rehabilitate mangrove wetlands may include selecting sites that have water quality (pollutant and nutrient) problems, sufficient sedimentation rates to keep pace with relative sea-level rise and support establishment of the mangrove swamp, can be protected or are not threatened to be impacted by development, and are suitable to establish native mangrove species and mangrove associates. Rehabilitation may be more successful if mangrove wetlands are restored at sites where mangrove wetlands historically existed versus created in new locations (Gilman 1998, Kusler and Kentula

1990, U.S. Environmental Protection Agency 1993, U.S. Department of Defense et al., 1995: Weems and Canter 1995). However, it may be feasible to establish mangrove vegetation at new sites (Kusler and Kentula, 1990; Choudhuri, 1994). A monitoring program can be established to assess rehabilitation techniques that are effective and are in need of improvement.

Use of hard engineering technology, including groins, seawalls, revetments, and bulkheads, a traditional response to coastal erosion and flooding in small island states and worldwide, are likely to result in increased coastal vulnerability (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997; Mimura and Nunn, 1998; Nurse et al., 2001). These coastal engineering structures usually can effectively halt erosion of the upland as relative sea-level rises, but often lead to the loss of the coastal system located in front of and immediately downstream in the direction of longshore sediment transport from the structure, converting the seaward coastal system into deepwater habitat (Tait and Griggs, 1990; Fletcher et al., 1997; Mullane and Suzuki, 1997). It may be less expensive in the long term to avoid hard solutions to relative sea-level rise even for well-developed coastlines and instead allow coastal ecosystems to migrate inland. These ecosystems provide natural coastal protection that is likely more expensive to replace with artificial structures (Mimura and Nunn, 1998; Ramsar Bureau, 1998).

Results of a cost-benefit analysis may justify taking measures, including the use of hard engineering technology and shoreline erosion control measures, to prevent erosion of some sections of highly developed coastline adjacent to coastal habitats such as tidal wetlands and beaches. As a result of this course of action, the coastal habitat's natural landward migration will be prevented and the wetland or beach fronting the development will eventually be lost, along with its valued function of buffering the developed coastline from wave and wind energy.

As a part of the recommended policy of managed adaptation to shoreline response to relative sea-level rise, the selection of sites for protected areas should account for functional linkages between coastal ecosystems (Gilman, 1997 and 2002; Anderson et al., 2001; Obriant, 2003; Ellison, 2004; Mumby et al., 2004). For instance, protected areas designed to preserve biodiversity and relatively pristine habitats should incorporate adjacent coastal forests, mangroves, seagrass beds, and coral reefs to ensure all functional links are maintained in a least disturbed state. Protected areas designed in this manner will have high resilience to global climate change, sea-level rise, and other stresses.

In addition to direct responses to sea-level change, such as avoiding obstacles to landward beach and mangrove retreat, and mitigating anticipated coastal habitat area losses through restoration and creation, managers can also take actions to increase community support for minimizing mangrove losses. For instance, implementing a community-based wetland or coral reef monitoring program will build local capacity to monitor changes in the area and quality (functional performance) of coastal resources (Gilman, 1998, 1999a, 1999b), while raising awareness of coastal ecosystem values and augmenting a conservation ethic.

Loss of the area and health of tidal wetlands and beaches will increase the threat to human safety and shoreline development from coastal hazards such as erosion, flooding, and storm waves and surges. Mangrove loss will also reduce coastal water quality, reduce biodiversity, eliminate fish nursery habitat, adversely affect adjacent coral reef and seagrass communities, and eliminate a major resource for human communities that traditionally rely on mangroves for numerous products and services. Because mangroves are functionally linked to other neighboring coastal ecosystems, including seagrass beds, coral reefs, and upland habitat, while the functional links are not fully understood, coastal management planning needs to account for the connectivity of coastal habitats by protecting adjacent connected habitats, instead of simply protecting each habitat in isolation (Mumby et al., 2004).

Short term economic and social benefits from development that results in direct or indirect loss of coastal habitat area and quality often outweigh less tangible long-term benefits that accrue from employing restrictions to conserve and sustainably use coastal habitats, especially on islands with high population growth and limited land suitable for development. Given this context, information resulting from the assessment of coastal habitat response to relative sea-level rise can be used to raise awareness of the valued services and products provided by coastal habitats to coastal communities to enhance the community’s conservation ethic to reverse trends in coastal habitat degradation and losses, and augment support for a policy of managed shoreline abandonment and adaptation. Most cost-benefit analyses only examine costs and benefits as measured by market prices, ignoring coastal system values not described by established monetary indicators (Dixon and Sherman, 1990; Ramsar Bureau, 1998). Cost-benefit analyses employed to determine if a section of coastline abutting a coastal habitat should be fortified or undergo managed abandonment and adaptation should account for the benefits of allowing coastal habitats to undergo natural landward migration under a rise in relative sea-level. These benefits include the continued provision of valued services and products, including consumptive benefits, education and research, aesthetic and cultural benefits, and future values such as a coastal habitat area’s future potential for tourism (Dixon and Sherman, 1990; Ramsar Bureau, 1998).

Costs associated with implementing the recommended policy of abandonment and adaptation, to allow coastal habitats to migrate inland unobstructed, include direct and opportunity costs. Direct costs include the cost of development that would eventually have to be abandoned or moved inland to allow the coastal systems to naturally migrate inland. And opportunity costs result from restrictions on present and future uses of upland adjacent to coastal habitats such as beaches and mangroves that are being allowed to migrate inland (Dixon and Sherman, 1990; Ramsar Bureau, 1998).

7. International and Pacific Island Regional Initiatives

Main Points

- The United Nations Framework Convention on Climate Change, Kyoto Protocol, and Intergovernmental Panel on Climate Change are main international initiatives to address global climate change and sea-level rise.
- There is a Pacific Islands regional initiative underway to assess technical and institutional capacity of Pacific Small Island Developing States to assess and manage coastal habitat response to projected relative sea-level rise.
- Identifying effects on coastal habitats from relative sea-level rise and climate change will require a regional, long-term monitoring network.

The First World Climate Conference in 1979 recognized that climate change posed a significant threat (Acosta et al., 1999). Concern about the impacts of climate change and sea-level rise on Small Island States was first brought to global attention in 1987 when President Gayoom of the Republic of Maldives addressed the United Nations about possible impacts to the Maldives (Ellison, 2004). This catalyzed the Small States Conference on Sea-Level Rise, held in the Maldives in 1989. Numerous vulnerability assessments followed, raising concern by governments of Small Island States about their vulnerability to global climate change and rising sea-level. The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992 one month before the 1992 Rio Earth Summit, and the Convention entered into force in 1994 (Acosta et al., 1999). The UNFCCC's mission is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (Climate Change Secretariat, 2004). At the Third Conference of the Parties of the UNFCCC in 1997, the parties adopted by consensus the Kyoto Protocol, which would create a legally binding commitment for developed, industrialized countries to reduce their collective emissions of six key greenhouse gases by at least 5% compared to 1990 levels by the period 2008-2012 (Acosta et al., 1999). The Kyoto Protocol was opened for signatures in 1998, and requires ratification by at least 55 Parties to the UNFCCC, with developed countries representing at least 55% of the total 1990 carbon dioxide emissions from this group (Acosta et al., 1999). The Kyoto Protocol has yet to enter into force because too few developed countries have ratified it.

The Intergovernmental Panel on Climate Change was established in 1988 by the United Nations Environment Programme and the World Meteorological Organization, and given a mandate to assess the state of knowledge on the climate system and climate change, impacts of climate change, and strategies for response to climate change (Acosta et al., 1999). Since the first release in 1999 of the Intergovernmental Panel on Climate Change's assessment report on the scientific basis for climate change and projected impacts, it is no longer a hypothesis but accepted as fact that humans have induced climate change and increased the rate of global sea-level rise, primarily through ocean thermal expansion, over human time scales from the emissions of greenhouse gases and aerosols (Houghton et al., 2001; McCarthy et al., 2001).

7.1. Assessment of Pacific Islands Region Institutional and Technical Capacity to Predict and Manage Shoreline Response to Relative Sea-Level Rise

A project has been initiated in 2004 to assess the institutional and technical capacity of Pacific Small Island Developing States to assess and manage shoreline response to relative sea-level rise over coming decades (Gilman, In Prep.).

7.2. Regional Shoreline Monitoring Network

Projections are available over coming decades for rising sea-level and changes in climate and weather (Church et al., 2001; Intergovernmental Panel on Climate Change, 2001b). These changes are expected to alter the position, area, structure, species composition, and health of most coastal communities. Identifying effects on coastal habitats from relative sea-level rise and climate change will require a regional, long-term monitoring network (Ellison, 2000; Nurse et al., 2001; Gilman and Ellison, 2004). Establishing baselines of coastal habitats and monitoring these gradual changes through regional networks will enable the separation of site-based influences from global changes to provide a better understanding of the response of coastal habitats to global climate and sea-level change, and alternatives for mitigating adverse effects. The monitoring system, while designed to distinguish climate change effects on coastal habitats, would also therefore show local effects, providing coastal managers with information to abate these sources of degradation. Identifying climate change and sea-level rise effects on mangroves requires monitoring mangrove parameters in a network of locations using standardized techniques. This could enable early detection of coastal habitat response to climate change and sea-level rise.

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