Kailua Beach and Dune Management Plan

December 2010

STATE OF HAWAI'I, DEPARTMENT OF LAND AND NATURAL RESOURCES
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Kailua Beach and Dune Management Plan

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On the cover: north-central Kailua Beach, 2006, showing natural native dune vegetation in foreground. Photo by Dolan Eversole.

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1. INTRODUCTION

1.1. Key Recommendations of the Plan

- ***Anticipate the effects of sea-level rise***
- ***Preserve and restore primary coastal dunes***
- ***Develop more proactive standards for new construction in the coastal zone***
- ***Increase public awareness and education***
- ***Provide reliable funding and support mechanisms***

1.2. Origin of the Plan

Hawaii's shorelines exhibit a wide variety of physical characteristics, depending on their geomorphic formation, off-shore conditions, and degree of human alteration or use. Not only are shoreline conditions quite variable according to location, they are also subject to change from long-term environmental factors such as sediment supply, island subsidence and sea-level rise.

The regulatory regime governing Hawaii's coastal environment is a complex blend of county, state and federal jurisdictions set forth in ordinances, statutes, and administrative rules and regulations. The basic framework of this regulatory system, established approximately four decades ago, has seen little substantive change, although criteria and procedures for defining the location of the shoreline and uses and activities that are permitted within certain distances inland from the shoreline have been refined and modified somewhat over the years.

Regulatory controls have had only limited success in preventing or mitigating damage to the coastal environment. It is clear Hawaii's regulatory function could be much more effective if it were tailored to reflect the unique and dynamic physical characteristics of each region or district. It is necessary to incorporate consideration of long-term effects such as climate change to our natural and built environment, and develop pro-active policies and practices that promote appropriate management of coastal resources based on the current state of knowledge. This is particularly the case for shorelines that are subject to continual change due to seasonal or long-term erosion or accretion and are now further impacted by the changing climate systems.

In many cases, these dynamic shorelines and beach environments are among Hawaii's most treasured and popular scenic and recreational attractions. Some of these beaches have not been altered to a degree that it destroys their value, but are still subject to actual and potential threats, both near-term and long-term, if proper and holistic management policies and practices are not put into place. For this reason, the Department of Land and Natural Resources, in cooperation with the University of Hawaii Sea Grant Program, has embarked on an effort to develop beach management plans for selected shoreline environments throughout the state,

starting with those beaches that meet the following criteria:

- High quality sandy beach with an ample width, including the presence of dunes, but with some evidence of both accretion and erosion patterns;
- Significant recreational and ecosystem value, based on public access to the beach and a high level of usage;
- A relatively low degree of shoreline erosion, alteration and erosion control, including seawalls, revetments, groins and breakwaters; and
- A private ownership pattern of properties fronting the beach that suggests the possibility of a cooperative, community-based management program for the beach and dune system through the use of incentives, volunteer efforts, and educational outreach.

1.3. Why Kailua Beach Was Selected as Prototype

Kailua Beach, located on the Windward coast of the Island of Oahu, meets all of the criteria listed above and therefore serves as a useful prototype for beach management plans at other locations. Not all of the specific proposals contained in the Kailua Beach Management Plan are readily transferable to every other beach in Hawaii, nor are they meant to be, but the basic approach and concept of location-specific beach management policies and practices and many of the specific measures can be replicated elsewhere.

There are a number of direct threats to Kailua beach. These include:

- Continued erosion in the Kailua Beach Park region due in-part to poor sand management practices related to clearing of Ka‘elepulu Stream mouth;
- Loss of recreational beach area and access and loss of sand impoundment due to aggressive vegetation growth on the dunes and beach on residential properties fronting the beach;
- Accreted land claims, subdivision, and new development makai of existing structures on private properties;
- Insufficient shoreline construction setbacks to ensure conservation and hazard mitigation over the long term, especially considering projected sea-level rise.

1.4. Objectives of the Plan

The Kailua Beach Management Plan has several objectives. These include:

- Enhance and protect the healthy sand-sharing system of Kailua Bay;
- Protect the cultural and natural resources of the coastal dunes;

- Monitor and document coastal processes and land use issues negatively impacting the beach and dune ecosystem to improve management plans;
- Review and assess the effectiveness of federal, state and county, Coastal Zone Management (CZM) laws and policies and community plans for beach and dune conservation;
- Reduce or otherwise mitigate coastal hazard exposure of abutting owners;
- Identify methods to clearly define the boundary between private property and public property;
- Educate the public (including abutting owners) on appropriate shoreline land use;
- Expand understanding of the potential impacts of climate change and sea-level rise in Kailua;
- Identify incentives options for abutting owners who proactively take appropriate steps for beach conservation and protection;
- Foster a community-based management arrangement with the Kailua community;
- Improve sand management practices at Kailua Beach Park;
- Develop recommendations for dune and beach management and restoration; and
- Develop recommendations for new or revised rules related to dune and beach management and long-term land use planning in Kailua.

1.5. Key Recommendations of the Plan

Following are highlights of the recommendations of the Kailua Beach Management Plan, including comments on the relevance of these recommendations to future beach management and climate change adaptation plans.

- ***Anticipate the effects of sea-level rise*** by providing more accurate information on the projected rate and extent of the rising sea level, developing contingency plans for the relocation of infrastructure in low-lying coastal areas of Kailua, and incorporating projected future shoreline locations into the planning and design of new developments within the coastal zone. This consideration needs to be integrated into all beach management plans.
- ***Preserve and restore primary coastal dunes*** by installing signs and walkovers to provide appropriate pedestrian access, identifying and marking the private and state-owned land boundaries, prohibiting inappropriate grading and fill in the shoreline setback area, encouraging dune restoration efforts with the use of incentives

for property owners and partnering with non-profit organizations, supporting the deposit of high-quality sand dredged from periodic stream channel maintenance onto the beach as a means to replenish the beach, and publishing a handbook on proper dune restoration and maintenance methods. These initiatives would be applicable to other beach dune systems, as well.

- ***Develop more proactive standards for new construction in the coastal zone*** by adopting into law the concept of a Coastal Construction Control Line (CCCL) and define it initially as the seaward edge of existing major structures for accreting beaches such as Kailua Beach, periodically review and revise the CCCL to account for new information about future projected shorelines, developing performance standards (e.g., construction style and estimated lifetime of structure) into the determination whether and in what manner a non-conforming structure may be repaired or replaced, conducting a detailed inventory of unauthorized structures and land alterations on accreted lands within the Conservation District (i.e., accreted lands claimed after 1985), and on State-owned lands, and taking appropriate enforcement actions against those unauthorized activities, and disseminating recommended development standards and practices to property developers. These recommendations, especially the CCCL concept, could be applied to other beaches with long-term accretion patterns.

- ***Increase public awareness and education*** by developing educational materials on beach systems and disseminating this information to key target audiences by partnering with outreach groups, local scientists and environmental groups to sponsor K-12 teacher training workshops and college-level internships focused on the maintenance of the beach and dune system. This recommendation could be replicated in other beach communities besides Kailua.

- ***Provide reliable funding and support mechanisms for management and adaptation planning*** by directing a portion of dedicated local funds (e.g., the City and County Clean Water and Natural Lands Fund) for beach maintenance, shoreline access improvements and beach and dune restoration projects, by augmenting these funds with grants from state, federal and private sources, and by providing start-up funding and enabling legislation for tax deductions or credits for a

conservation easement program that is managed by a non-profit land trust.

2. BACKGROUND

2.1. Description of the Setting

Kailua Beach is located on the windward coast of the island of Oʻahu, Hawaiʻi. Kailua Beach fronts Kailua Bay and is a wide, crescent-shaped, fine calcareous sand beach that stretches approximately 2.6 miles between two rocky points -- Kapoho Point to the north and Alāla Point to the south.

At the northern end near Kapoho Point, the region is backed by Kawainui marsh. Near Alāla Point, the beach is traversed by Kaʻelepulu Stream. Most of the beach, from Kapoho Point to north of the Kaʻelepulu Stream mouth, abuts residential single-family homes. The portion of beach near the mouth of Kaʻelepulu Stream and south to Alāla Point encompasses the City and County of Honolulu's Kailua Beach Park.

Kailua Beach is well known for its scenic beauty and recreational value and is widely marketed as a visitor attraction. Its shallow clear waters, gentle waves, soft white sands, and absence of coral or rock bottoms nearshore make this beach amenable to a wide variety of age groups, users, and activities.

Figure 1: Location map

Figure 2: Oblique Aerial View of Kailua Beach and Beach Park, 2010. Photo by Dolan Eversole.

North & Central Kailua Beach

The north and central portions of Kailua Beach, which abuts single-family homes, contains a small municipal public park, Kalama Beach Park. Kalama Beach Park has paved parking, restrooms, showers, and a paved connecting path to the beach. Along the length of Kailua Beach, there are various public and private beach access easements that provide pedestrian access to the beach from the nearest public rights-of-way. There are also approximately 20 roads connecting the various beach front subdivisions to the main roadway, Kalaheo Avenue. Roughly 120 privately-owned lots directly abut Kailua Beach.

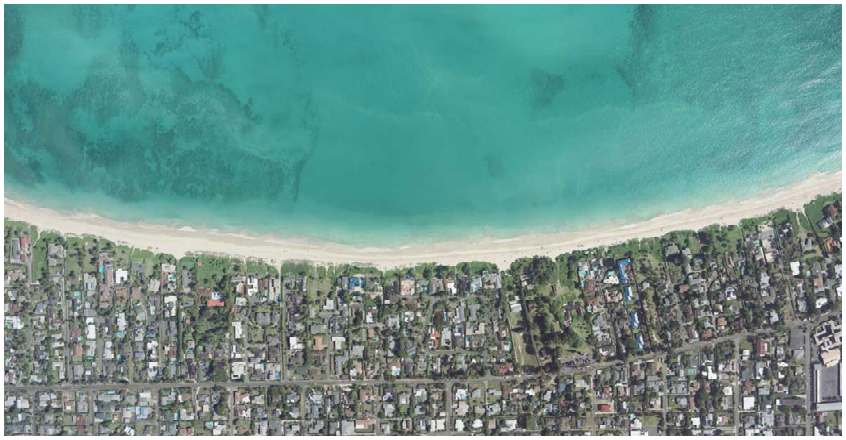

Figure 3: Aerial view of a portion of North & Central Kailua Beach, 2005.

Kailua Beach Park

The southern end of Kailua Beach abuts Kailua Beach Park. The 35 acre park is bordered by Kailua Road, Kawailoa Road, and Alāla Road. Its beach frontage is about a half-mile in length, including the mouth of Ka‘elepulu Stream.

The park is under the jurisdiction of the City and County of Honolulu, Department of Parks and Recreation, as identified in Hawai‘i Executive Order 115. Kailua Beach Park offers boating, fishing, snorkeling, surfing, windsurfing, canoeing, kayaking, swimming, picnicking, and sunbathing among other common recreational activities. A boat ramp is located at the south end of the park near Alāla Point. There are water sports rental businesses that operate within the park as well as a food concession operation for public use.

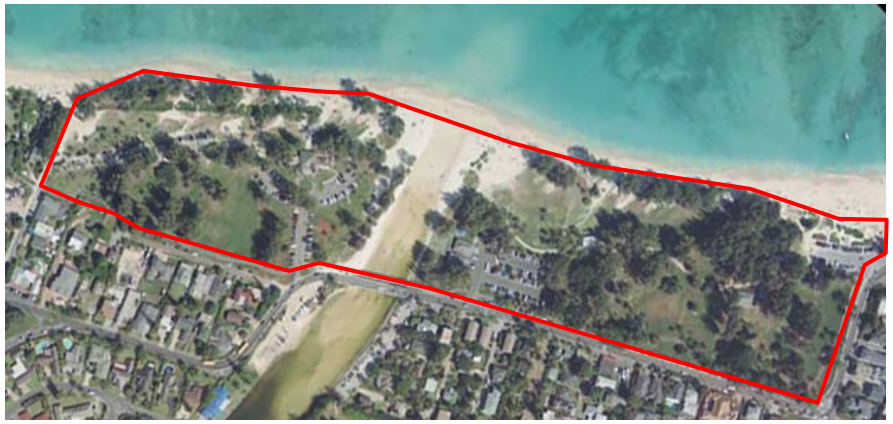

Figure 4: Aerial View of Kailua Beach Park (outlined), 2005.

2.2. Beach Processes

Historical Accretion/Erosion Patterns

Kailua Beach is an extremely dynamic coastal system; a result of the variable wind and wave forces that affect and influence the beach and dune. Beach loss and coastal erosion are not new phenomena at Kailua Beach, which has experienced periods of accretion and erosion, both seasonal and long-term, in the recent past and the present.

A 1981 beach erosion study of O'ahu using historic aerial photographs revealed patterns of erosion and accretion at Kailua Beach.[1] Measurements at various transects along the beach indicate that Kailua has three beach subsystems that accrete and erode at various rates and times in an apparent alternating pattern. The author of this study, Dennis Hwang, postulated that the subsystems are interrelated, and that what happens to one subsystem affects the others. He also observed that the historic record for Kailua Beach shows a cyclic erosion and accretion pattern, possibly based on cyclic patterns in the trade winds and/or ocean swells.

A subsequent coastal erosion study for the City and County of Honolulu showed that, between 1978 and 1988, Kailua Beach continued the long-term accretion trend along the center of the beach averaging a 27 foot increase.[2] At the southern portion, near Kailua Beach Park, the beach history showed an average beach width increase of 23 feet during the same 10-year period.

Figure 5: North & Central Kailua Beach, 2010.

A more recent shoreline change study of Kailua Beach reveals a similar picture of the erosion/accretion

[1] Dennis Hwang, *Beach Change on O'ahu as Reveal by Aerial Photographs* (Hawai'i, 1981), 67-71.

[2] Sea Engineering, Inc., *O'ahu Shoreline Study, Park 1 Data on Beach Changes* (Hawai'i, 1988), 34-35.

pattern.[3] The 2005-2007 University of Hawai'i shoreline change study effort, done under contract with the City and County of Honolulu, confirmed a long-term accretion trend in the North-Central section, an erosion trend in the southern section and reinforced the subsystem theory where the central section of the beach accreted between 1978 and 1988. The study mapped the Kailua Beach shoreline of 1928, which is much further inland than the current shoreline. This 1928 shoreline provides a reasonable basis for the delineation of a coastal erosion hazard zone. For much of the beach, particularly the residential portion, net accretion is occurring as indicated by shorelines since 1928. The area fronting the beach park, however, likely accreted until 1971, and has been eroding since.

Beach Loss and Human Impacts

The beaches in Hawai'i are subject to both socio-economic and natural influences. Seasonal surf, wind intensity and direction, episodic coastal storms, foot traffic on the dunes and shoreline development all influence the shoreline. Natural retreat of the shoreline while retaining width is referred to as coastal erosion. When the beach erodes too far landward and begins to threaten private property, landowners often erect seawalls or other forms of shoreline armoring to protect their investments. The armoring fixes the location of the shoreline, preventing further retreat and may inhibit accumulation of sand. If erosion pressures persist, armoring will eventually lead to the loss of the sand beach.

Kailua Beach is currently not armored; however, continued coastal erosion, combined with the potential long-term effects of sea-level rise, may result in property loss and a desire to armor the shoreline. The purpose of a beach management plan is to identify potential hazards and provide recommendations for planning alternatives that will prevent or lessen beach loss, including the impetus to armor the shoreline, and human exposure to hazards.

Figure 6: Example of Beach Loss and Shoreline Armoring Outside of Kailua, 2006.

[3] Fletcher, Charles et al., *Kailua, O'ahu, Hawaii: Shoreline Change Rates,* University of Hawai'i Coastal Geology Group, (2009) Web.

3. CURRENT AND FUTURE ISSUES

3.1. Jurisdiction and Ownership

History of Residential Development

Private residential development along Kailua Beach was first recorded when Hawai'i was still a U.S. territory. The earliest record of plots for the Kailua shoreline is from Map 002 of Land Court Application No. 323, dated 1923. This map indicates ten original lots fronting Kailua Bay. Map 001 of Land Court Application No. 677 dated 1926 shows 29 lots fronting Kailua Bay; an increase of 19 lots in three years. During that time, land was plotted out and homes were built well before shoreline processes were studied and coastal hazards were recognized as long-term land use problems. In addition, the lots were fairly large such that beach erosion would not be a significant threat and Kailua Beach was undergoing an accretion phase at that time, further minimizing the threat of beach erosion.

Since the first establishment of privately-owned lots in the 1920s, the number of lots has increased and existing lots have been subdivided, eventually creating the beach community we know today. Currently, privately-owned residential properties fronting Kailua Beach are zoned R-10 Residential District, which requires a minimum lot size of 10,000 square feet. At least 38 of the 122 residential lots that front the beach are larger than 20,000 square feet in area and are occupied by only one dwelling, which means that there is potential for additional development, either through the issuance of a building permit for a second dwelling or through the subdivision or cluster housing procedures. There is also the potential of more lots reaching the 20,000 square foot threshold as beachfront property owners claim accreted lands (see following section.)

Land Use and Shoreline Jurisdiction

In shoreline areas of Hawai'i, regulatory jurisdictional boundaries between the State of Hawai'i and the County Planning Departments are defined by both the State Land Use Law (Chapter 205, Hawai'i Revised Statues [HRS]), and the Coastal Zone Management Law (Chapter 205-A, HRS).

The adoption of the Hawai'i State Land Use Law in 1961 created four land use districts: Urban, Rural, Agricultural and Conservation. The counties have primary jurisdiction over the Urban and Rural districts and share jurisdiction with the State Land Use Commission over the Agricultural District.

The State Conservation District is under the jurisdiction of the Department of Land and Natural Resources (DLNR), which administers these lands under the provisions of Chapter 183, HRS. Since the purpose of the State Conservation District is to preserve and

protect lands that are important natural resources to the State, development on land in the Conservation District is very restricted. Any use of, or modification to, the land or ecosystem function is subject to approval by the DLNR.

The original land use district maps, adopted in October of 1964, placed lands seaward of the shoreline *at that time* within the State Conservation District. In areas where natural, stable accretion has migrated the shoreline seaward, as at Kailua Beach, the State Land Use Commission has generally, though not consistently, interpreted the Conservation District boundary line to follow the original Conservation District boundary as identified in 1964. Adding to the complexity of this situation is the 2003 amendment to the statute governing accreted land claims, as discussed in the following section.

Chapter 205-A, HRS establishes the jurisdictional boundary between the state and the counties (City and County of Honolulu in this case) as the shoreline, which is defined as "the upper reaches of the wash of the waves, other than storm and seismic waves (sic), at high tide during the season of the year in which the highest wash of the waves occurs, usually evidenced by the edge of vegetation growth, or the upper limit of debris left by the wash of the waves."[4] Land seaward, or makai, of this line is referred to as "submerged lands" and is regulated by the DLNR. The area landward, or mauka, of the shoreline is regulated by the City and County of Honolulu Department of Planning and Permitting (DPP), unless it is within the State Conservation District as designated by the State Land Use District Boundary maps.

DLNR is responsible for establishing procedures for, and certifying where, shorelines are located state-wide. They are also responsible for regulating uses and activities in the State Conservation District and on state land (Chapter 205A-42, HRS).

DPP, in turn, is responsible for administering zoning and subdivision regulations and the provision of the Coastal Zone Management Law (Chapter 205A-43, HRS) pertaining to Shoreline Setback Area (SSA) and the Special Management Area (SMA).[5]

Single-family dwellings and their accessory structures are exempt from SMA permit requirements, leaving SSA regulations in control of beachfront

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[4] Chapter 205A-1. Hawai'i Revised Statutes.

[5] Shoreline Setback Area and Special Management Area provisions are codified in Chapters 23 and 25, respectively, Revised Ordinances of Honolulu. In addition, DPP has promulgated administrative rules and regulations for the Shoreline Setback Area.

development for Kailua Beach. On most of the residential lots fronting Kailua Beach, the depth of the SSA, as measured from the certified shoreline, is 40 feet. About twelve lots have a SSA depth of 60 feet because they were subdivided or approved for cluster development after 1994, when deeper setbacks under those circumstances went into effect. Except for certain types of minor structures such as fences, and land alterations such as landscaping, no development is permitted within the SSA, except by variance, based on a test of hardship.

The jurisdictional interface at the shoreline can result in regulatory complications. For example, DPP typically does not authorize work within their jurisdiction without a shoreline survey certified by the DLNR. However, the DLNR will not certify a shoreline without proof that structures along the shoreline are legal in accordance to either the State Conservation District rules or the Revised Ordinances of Honolulu, the latter of which is often, but not always, recorded with DPP. If there happens to be no record of a structure with DPP in land under DPP jurisdiction, then DLNR will not certify the shoreline. This can become a problem where the structure was built more than three decades ago because building permit records do not include drawings for dwellings and minor structures that are accessory to a residential use prior to 1975. Even for later years, drawings are often incomplete or rudimentary.

Accreted Land Claims

For many years, private property owners have claimed adjoining accreted beachfront lands through Hawai'i common law under provisions for quieting land title.[6] Statutory amendments in recent decades have attempted to limit such claims. In 1985, the State Legislature adopted a measure that required the property owner to prove that the accretion was natural and fixed for twenty years in order to register or quiet title.[7]

In 2003, the Legislature again amended the statute to declare that all accreted land is owned by the State, unless the accretion restored previously eroded portions of private beachfront property.[8] This amendment also clarified that accreted lands are zoned State Conservation District, whether or not it is awarded to private ownership as intended in Act 221 of 1985. Enforcement of the amendment relative to ownership of accreted land has been stayed by court order until a legal challenge to this law is resolved.[9]

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[6] The governing statute is Chapter 669, Hawai'i Revised Statutes.

[7] Act 221, Session Laws of Hawai'i, 1985.

[8] Act 73, Session Laws of Hawai'i, 2003.

[9] *Maunalua Beach Ohana v. Hawaii*. Heard by the Intermediate Court of Appeals on November 10, 2009; decision pending.

Figure 7: Accretion Claims along Kailua Beach

Regardless of the disposition of the current legal challenge to the 2003 amendment, another statutory provision adopted in 1985 prohibits structures, grading, dredging or other use on accreted lands that "interferes or may interfere with the future natural course of the beach, including further accretion or erosion", will remain in effect.[10]

[10] Section 183-45, Hawai'i Revised Statutes.

The Effect of Accretion Claims on Kailua Beach

During the period prior to the creation of the State Conservation District, when Kailua Beach was accreting, many private property owners claimed accreted land and landscaped and/or built on the land (Figure 7). Given that accretion and erosion occur on an alternating cyclic pattern, it is reasonable to expect that the accreted beach area will erode back over time, potentially causing problems. This is compounded by episodic events and regional sediment deficiencies. Since the makai property line (that has moved seaward through claiming of accreted land) is fixed, the resulting public beach area will migrate to, and landward of, the makai property boundary on record through long-term erosion.

Another problem frequently associated with coastal erosion and the landward migration of beaches is the concurrent heightened potential for undermining and wave damage, by wave action and/or inundation, of dwellings and accessory structures that were built on accreted land. The likelihood of marine inundation and damage from coastal natural hazards is exacerbated by projected sea-level rise (see following section on sea-level rise).

3.2. Alteration of Beach Dunes

Dunes form naturally along sandy shores as waves deposit sand and winds or large storm waves transport the sand further inland. Dunes typically form as a mound or ridge and are usually naturally covered by native species of grasses and vines that are able to tolerate winds, salt spray, and occasional wave action. In Hawai'i, typical native dune plants are 'Aki 'aki (grass), Pōhuehue (beach morning glory), Pōhinahina (beach vitex), 'Ākulikuli kai, Beach Heliotrope (Tahinu) and Naupaka kahakai.

Coastal dunes serve as a natural protection against erosion during storm and high wave events. They are primary sand reserves that buffer the land as higher waves scour the upper beach area, transporting sand into the nearshore waters. This mobile sand is deposited in the offshore area, creating shallow sand bars, which in turn lessens wave energy before it reaches the beach. As storms subside, the smaller waves push the sand back to shore and the dune building process begins again. Sand dunes are not very effective for preventing prolonged seasonal erosion or long-term erosion.[11]

[11] Spencer Rogers and David Nash, *The Dune Book* (Wilmington, 2003).

Alteration of Dunes at Kailua Beach

Because the function and value of coastal dunes are often misunderstood, the dune system at Kailua Beach has been damaged in a variety of ways. In some instances, foot traffic and/or recreational vehicles have carved many paths through the dunes, killing the natural vegetation, exposing the sand to wind erosion, and destabilizing natural plant growth in adjacent areas of the dune.

Figure 8: Example of Foot-Traffic Damage to Kailua Beach Dunes, 2009.

In other instances, dunes have been leveled, grubbed, and/or re-landscaped. Some landowners have built structures, legally or not, on portions of dunes. Others have been deliberately watering dune vegetation and even installing new plants in the hope of extending the certified shoreline seaward to add land eligible for an accreted land claim or for circumventing shoreline setback regulations.

Figure 9: Example of Dune Leveling and Vegetation Alteration, 2009.

Cumulatively, these actions compromise the dune's ecosystem and protective functions and could result in greater property damage during severe storm or erosion events.

3.3. Sea-Level Rise

Global History, Trend, and Projections

Sea-level rise is a growing concern for coastal areas worldwide. Sea-level rises through thermal expansion, as the water warms, and through increased water volume, as landlocked ice melts and flows into the ocean. In general, as ocean volume increases, due to

additional heat and mass, and sea-level rises, the shoreline will often retreat unless other natural processes are involved that prevent it. There are several factors that contribute to local variations in sea-level rise, such as the rate of ocean heating, the rate of global ice volume reduction, global warming, weather patterns, ocean currents and local land subsidence.

Church and White (2006)[12] established a 19.5 cm global mean sea-level rise between 1870 and 2004. There is mounting scientific evidence that the rate of global sea level rise is accelerating. The Intergovernmental Panel on Climate Change (IPCC) projected one scenario of global sea-level rise of 0.9 to 1.3 m by the 2090 to 2099 decade.[13]

The U.S. Army Corps of Engineers (USACE) recently issued an engineering circular (EC 1165-2-211 of July 2009) to provide national guidance for incorporating sea-level change in future projects. USACE recognizes the research efforts of the IPCC and echoes its conclusion that global mean sea-level rose at an average rate of about 1.7 ± 0.5 mm/year during the 20th century. They anticipate a continued or accelerated global mean sea-level rise throughout the 21st century. The range of global mean sea-level rise in the year 2100 is projected to be between 0.5 to 1.5 meters, relative to the 1986 level.

The USACE circular provides a method to incorporate sea-level into planning and equations that may be used to calculate local sea-level rise. They state that:

> *Planning, engineering, and designing for sea level change must consider how sensitive and adaptable 1) natural and managed ecosystems and 2) human systems are to climate change and other related global change.*

They also state that:

> *Planning studies and engineering designs should consider alternatives that are developed and assessed for the entire range of possible future rates of sea-level change. These alternatives will include structural and nonstructural solutions, or a combination of both. Evaluate alternatives using "low," "intermediate," and "high" rates of future sea-level change for both "with" and "without" project conditions.*

[12] John A. Church and Neil J.White "20th century acceleration in global sea-level rise" *Geophysical Research, Letters,* 33(1) (2006).

[13] Aslak Grinsted et al. "Reconstructing sea level from paleo and projected temperatures 200 to 2100AD" *Climate Dynamics,* doi:10.1007/s00382-008-0507-2 (2009).

According to the USACE, the "low" rate is to be based on the historic recorded rate of sea-level change through tidal records and the "intermediate" and "high" rates are to be modified projections developed by the National Research Council.

Responses to Sea-Level Rise in Other States

Some coastal states and agencies around the U.S. are already beginning to recognize and address the impacts of sea-level rise to coastal communities. For example, the state of North Carolina, a leader in shoreline management, has conducted and sponsored numerous studies pertaining to sea-level rise and beach management.

North Carolina is similar to Hawai'i in that its beaches are a visitor attraction and a large economic resource. The North Carolina Coastal Resources Commission (CRC) is already drafting a report on the current and projected rates of sea-level rise in North Carolina. The report will project sea-level rise ranges in 25-year intervals through 2100. The intent is that with the projection, the state has the foundation for policy development and adaptation planning to take a proactive course in minimizing impacts.

The state of California has also recognized a need for planning for sea-level rise and has taken action in the form of an Executive Order to complete a sea-level rise assessment report by the end of 2010 and establish a research and monitoring agency[14]. The assessment report is to include a discussion of impacts to California's infrastructure, natural areas, and coastal and marine ecosystems.

Sea-Level Rise in Hawai'i

According to the National Aeronautics and Space Administration (NASA), which maintains satellites that have been mapping the sea surface for 17 years, mean global sea level is increasing at a rate of ~3mm per year[15]. However, sea level change is not uniform across the planet. Between 1950 and 1999, tidal gauges at Honolulu Harbor have shown a mean sea-level trend increase at a rate of about 1.5 mm per year[16]. Several studies anticipate an acceleration of global sea-level rise rates, concluding that a global rise of 1 meter is possible.[17]

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[14] Executive Order S-13-08 by the Governor of the State of California. November 14, 2008.

[15] National Aeronautics and Space Administration. "Key Indicators" *Global Climate Change*. (2010) Web..

[16] National Oceanic and Atmospheric Administration. "Sea Levels Online" *Tides & Currents* (July 21, 2010) Web.

[17] Vermeer, M. and S. Rahmstorf, "Global sea level linked to global temperature" *Proceedings of the National Academy of Sciences,*

Hawai'i does not yet have a statewide policy to address sea-level rise and its impacts to its lands, infrastructure, natural resources, and economy. However, each county, in coordination with state, federal and University partners are beginning to acknowledge the hazard with regard to their land development policies. With a rise in sea level, salt intrusion will intensify in coastal wetlands and groundwater systems, taro lo'i, estuaries, and elsewhere. Extreme tides already cause drainage problems in developed areas, and Hawaiian communities located at the intersection of intensifying storm runoff and rising ocean waters will endure increased flooding.[18]

Future Scenario for Sea-Level Rise at Kailua Beach

Kailua Beach has been spared much of the shoreline erosion effects of a rising sea because it continues to have a sufficient supply of sand to replenish the beach as well as enough room to accommodate natural fluctuations. In fact, Kailua is one of the few accreting beaches on Oahu, having grown wider by a half meter per year over the last 70 years despite sea-level rise during the same period.[19] Nevertheless, the effects of sea-level rise will eventually appear at Kailua Beach, as well as other beaches statewide, and may result in beach erosion, dune failure, and flooding; creating threats to residential development nearby. Long-term land use planning should take a precautionary approach and begin to incorporate climate adaptation measures into community plans.

Sea Engineering, Inc., (SEI) estimated future shoreline locations for Kailua Beach based on current scientific knowledge, including the sources cited above. The methodology is explained in Appendix A. Figures 9 through 14 are aerial photos of Kailua Beach showing the estimated location of the shorelines (i.e., vegetation lines). These projections are based on the current state of scientific knowledge, including the federal guidelines put forth by the U.S. Army Corps of Engineers, and represent the current state of scientific understanding. These shoreline projections provide a useful picture of what may occur if sea-level rise accelerates at Kailua Beach as predicted by the global scientific community. These maps suggest that the long-term trend of beach accretion will eventually reverse, and the shoreline will retreat landward beginning in the coming decades.

106.51:21527-21532 (2009). See also C. H. Fletcher "Sea Level by the End of the 21st Century: A Review" Shore and Beach, 77.4: 1-9. (2009).

[18] University of Hawaii Sea Grant College Program, Center for Island Climate Adaptation and Policy. *Hawai'i's Changing Climate*. Briefing Sheet (2010).

[19] Zoe Norcross et al., "Annual and interannual changes on a reef-fringed pocket beach: Kailua Bay, Hawaii", *Marine Geology* (2002).

Figure 10 below is the key map for the locations of the section maps (Figures 11-15) that follow. Note that the shoreline projection years are as follows: 30 cm in year 2052, 61 cm in year 2078, and 1 meter in year 2104.

Figure 10: Key for Sectional Maps of Existing (year 2005) and Projected Shorelines along Kailua Beach (where VL is the Vegetation Line and VL defines the shoreline under current rules).

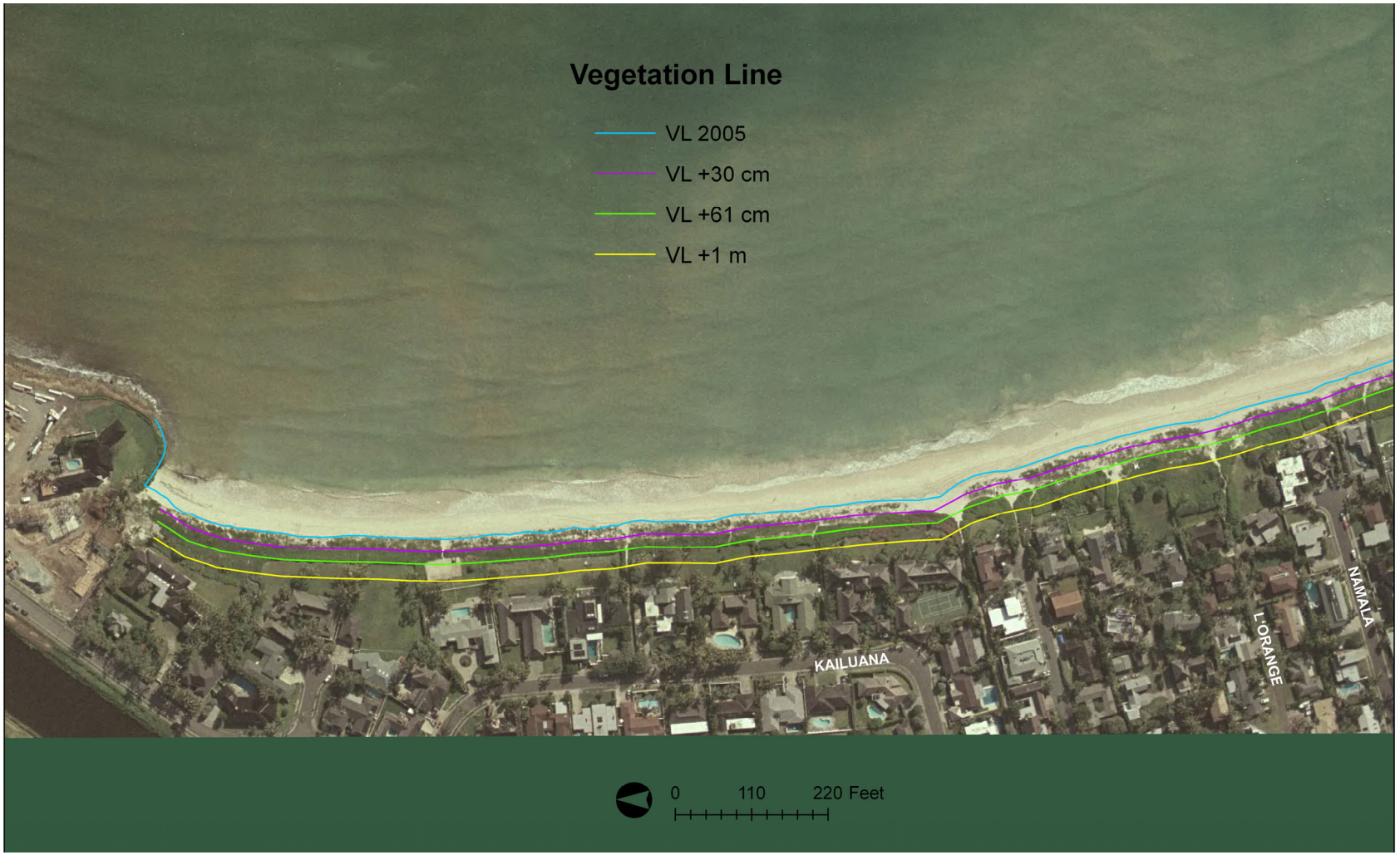

Figure 11: Projected Vegetation Lines under various sea-level rise scenarios, Kailua Beach, Section A. Base year is 2005, 30 centimeters is projected for the year 2052, 61 centimeters is projected for the year 2078, and 1 meter is projected for the year 2104.

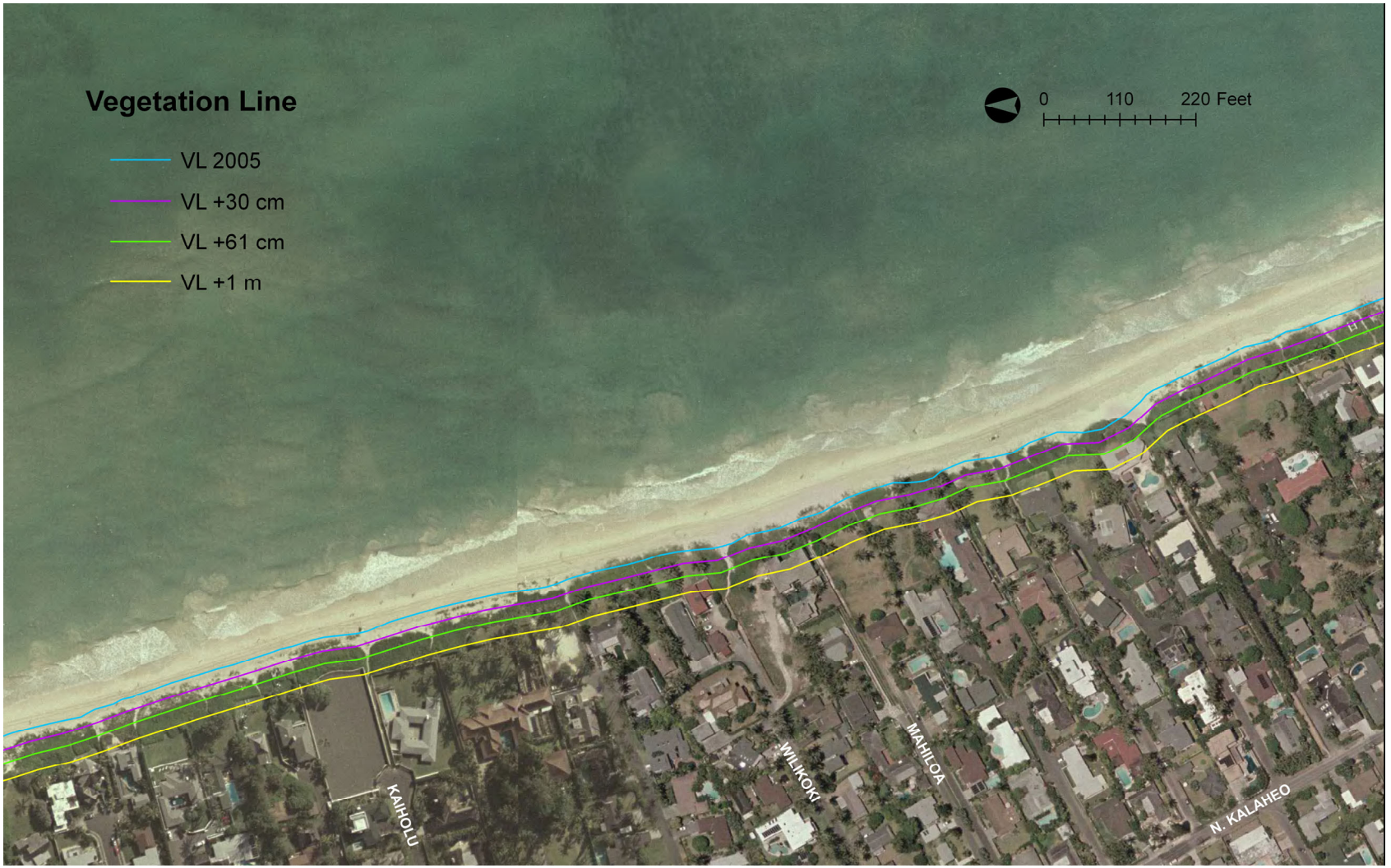

Figure 12: Projected Vegetation Lines under various sea-level rise scenarios, Kailua Beach, Section B. Base year is 2005, 30 centimeters is projected for the year 2052, 61 centimeters is projected for the year 2078, and 1 meter is projected for the year 2104.

Figure 13: Projected Vegetation Lines under various sea-level rise scenarios, Kailua Beach, Section C. Base year is 2005, 30 centimeters is projected for the year 2052, 61 centimeters is projected for the year 2078, and 1 meter is projected for the year 2104.

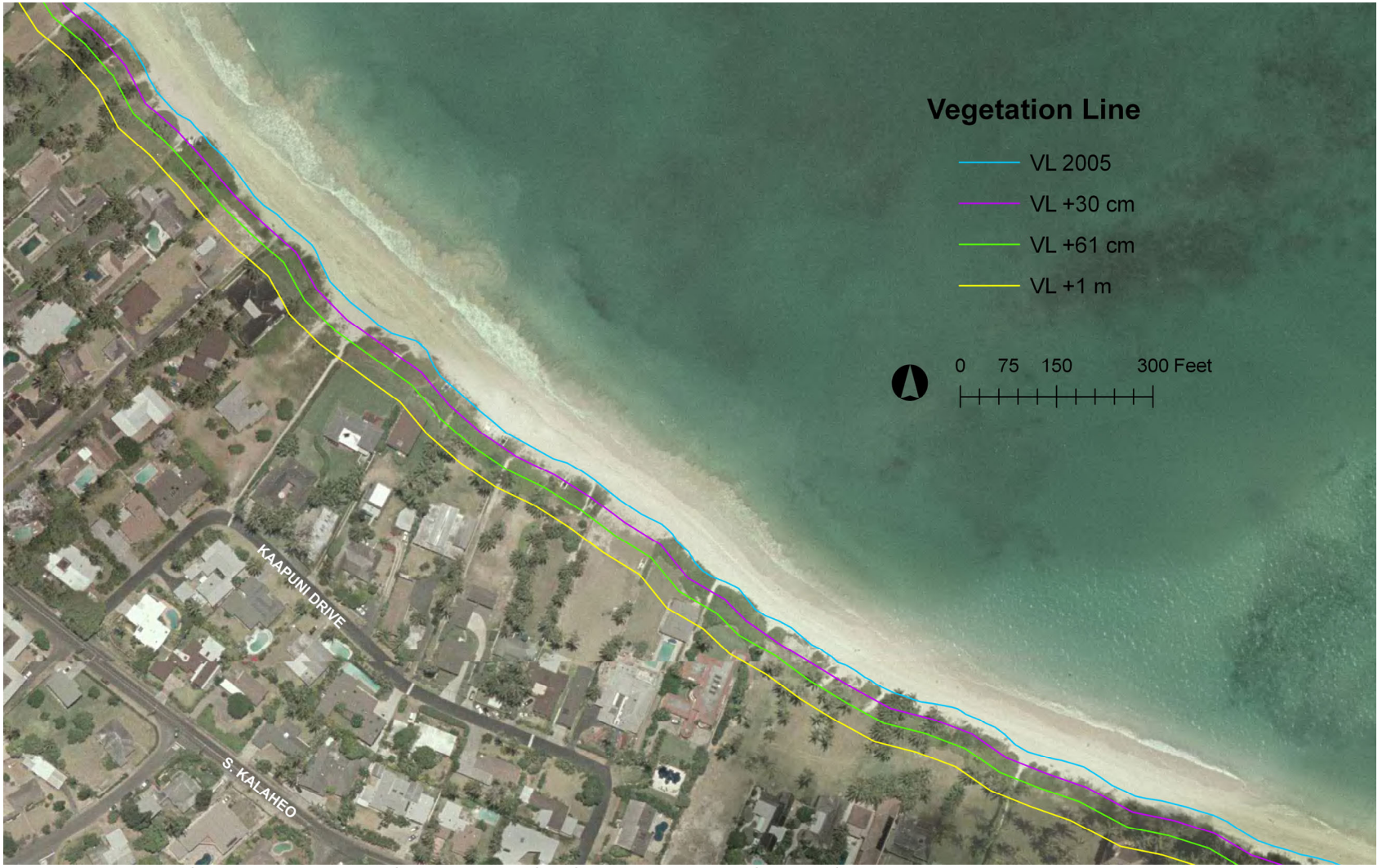

Figure 14: Projected Vegetation Lines under various sea-level rise scenarios, Kailua Beach, Section D. Base year is 2005, 30 centimeters is projected for the year 2052, 61 centimeters is projected for the year 2078, and 1 meter is projected for the year 2104.

Figure 15: Projected Vegetation Lines under various sea-level rise scenarios, Kailua Beach, Section E. Base year is 2005, 30 centimeters is projected for the year 2052, 61 centimeters is projected for the year 2078, and 1 meter is projected for the year 2104.

3.4. Interference with Natural Littoral Process

Ka'elepulu Stream and Kailua Beach Park

Because Kailua Beach experiences both alongshore and onshore/offshore sand transport, it is important to manage the dune, beach, and offshore environments as a single, sand-sharing entity. Erosion stemming from sand deficiencies in one part could affect sand availability along other parts of the beach.

Ka'elepulu Stream, adjacent to Kailua Beach Park, may play a significant role in the proper management and restoration of Kailua Beach. Sand is regularly dredged from the mouth of the stream in order to prevent upstream flooding and improve water circulation. The dredged sand however, is currently not placed back on the beach to replenish it as basic beach sand management principles would suggest. The Hawai'i Department of Health (DOH) regulates Hawai'i nearshore water quality and requires permits to place the cleared sand back on the beach. This may be a significant source of sand that is being removed from the accessible coastal sediment system. A dike further upstream within the Kawainui marsh prevents stream surges and flooding that would likely flush sand stored in the stream mouth back onto the beaches.[20] Ka'elepulu Stream mouth management represents a human perturbation or altering of the natural processes, which may be significantly affecting the health of the beach.

Figure 16: Ka'elepulu Stream Mouth, 2010.

Figure 17: Dredging the Sand Stored at Ka'elepulu Stream Mouth, 2010.

[20] Rob Shikina, "Saving Kailua Beach", *Honolulu Star Bulletin*, (January 1, 2009).

4. KAILUA BEACH MANAGEMENT OPTIONS

4.1. Management Approaches

Beach Characteristics Variability

Beach management and conservation should be a holistic but site-specific process. There are many different factors to take into account when developing a resource management plan, such as implementation time frame, costs, coastal hazards, regulatory agencies roles and policies, engineering and planning techniques, and all the compounding and complex interactions between environmental (eco)systems. More recently, climate change adaptation and coastal hazard mitigation principles are becoming more recognized as critical planning factors. In fact, in 2000, a statewide Coastal Erosion Management Plan (COEMAP) was developed by the DLNR in order to address some of the pressing coastal erosion issues[21].

The *Hawaii Coastal Hazard Mitigation Guidebook (Guidebook)*[22] serves as a reference manual for planners and regulators to effectively anticipate, mitigate, and plan for coastal natural hazards such as sea-level rise, tsunami, erosion, and flooding. The Guidebook notes that a wide variety of conditions exists along Hawai'i's shorelines and asserts that an appropriate management strategy should be based on the specific characteristics of the region. It also emphasizes assessment and recognition of hazards early in the development process rather than waiting until after subdivision and construction occur to address hazards.

Full development of a beach classification system that can be routinely employed to assess the quality of beaches regarding both natural and socioeconomic characteristics would be useful in identifying high priority areas worth preserving, and areas with the potential for more intensive use.[23] In 2005, the DLNR Office of Conservation and Coastal Lands developed a prototype Shoreline Assessment Model designed to assess the quality of beaches. Kailua Beach, because of its high quality beach and water, and importance as a recreational, scenic and economic resource, stands high on the list for preservation. It is the relatively high environmental resource ranking of Kailua Beach, stable geomorphology, and the high degree of land use

[21] State of Hawai'i, Department of Land and Natural Resources, Coastal Erosion Management Plan (COEMAP). (2000).

[22] Dennis Hwang, *Hawaii Coastal Hazard Mitigation Guidebook* (Honolulu: University of Hawaii Sea Grant, 2005).

[23] Marina Christina Barbosa de Araujo and Monica Ferreira da Costa, "Environmental Quality Indicators for Recreational Beaches Classification", *Journal of Coastal Research*, 24(6), (2008), 439-1449.

planning options that make Kailua a top priority for long-term beach management planning.

Management Strategies

Comprehensive beach management plans should address the need to protect the beach and dune resources *balanced* with recreation and private (development) interests of the coastal zone (State of Hawai'i, DLNR, 2000). Private and public pressures should not take precedence over the sustainable management of the natural resource that is a public good and is a driving force of the state's economy.

The international scientific community anticipates that sea-level rise will be a significant factor in the loss of many low-elevation tidal areas and beaches in the coming decades. Increased rates of sea-level rise in recent decades must be taken into account when developing beach restoration and management plans.[24]

4.2. Management Options- Kailua Beach

- *Managed Retreat* – Allow the beach to function naturally regardless of the cause of erosion or the impacts that shoreline retreat may have upon inland properties. Strategically selected properties can be allowed to erode to preserve the natural beach system. These in turn may become future beach parks or open space corridors.
- *Adaptation* – Modify shoreline development patterns and policies to allow erosion to occur naturally without interfering with development improvements. Protect natural shoreline attributes from the impact of human alterations to coastal processes, but require modification of human occupancy and use of the coastal zone. This typically involves controls on coastal construction through shoreline setbacks and construction style, as well as regulations and incentives to preserve and restore the dune system.
- *Restoration* – Replace sand and natural vegetation within a littoral system. To be effective and relatively long-lasting, beach and dune restoration must be accomplished at a relatively large scale. Restoration areas should be determined by the limits of each littoral, or sediment, cell. In Hawai'i, beach restoration requires authorization from county, state, and federal agencies. This option is most effective if done in conjunction with managed retreat and /or adaptation.

[24] Rob Davis, "A Sea Change: Worries Over Rising Tide", *VoiceofSanDiego.org,* Web (2006).

- *Erosion Control* – Arrest or shape the pattern of erosion with engineered structures that take into account a specific reach of beach. Erosion control can take various forms, such as groins, artificial reefs, breakwaters, and dune fencing. These measures serve to slow down the rate or prevent erosion by trapping sand or decreasing wave impact, but do not address the initial cause of erosion.
- *Shoreline Armoring* – Protect specific properties with armoring, such as shore-parallel seawalls and revetments, or with temporary devices such as sandbags. These should be considered measures of absolute last resort, where coastal erosion is chronic and severe, significant property improvements are threatened, and the shoreline is already mostly hardened (Lanikai is a local example). A possible consequence of hardening is beach narrowing and loss, although the degree of loss can be somewhat mitigated by appropriate design of the armoring structure and in combination with beach restoration.

At Kailua Beach, there is currently no pressing need for erosion control or hardened structures to protect the beach. A combination of the first three strategies – managed retreat, adaptation, and restoration – would be appropriate. These strategies will help protect the shoreline in its natural state and lessen the likelihood of hazards to humans or property for the long-term. Empirical evidence suggests erosion control and hardening options can result in the loss of the beach and should not be considered in the context of beach management options but rather private property protection.

4.3. Kailua Beach Management Tools

A. Dune Preservation and Restoration

Sand dune preservation and restoration is another alternative that can be effective in mitigating coastal hazards including beach erosion. Dunes provide a natural buffer to beach erosion; however, there must be adequate space to achieve a proper dune and allow for seasonal variability.[25] Much of Kailua's coastal dunes abut private property, thus managing the entire dune system will require the cooperation of multiple coastal property owners. Sand dune management offers several advantages and challenges as a preservation and restoration tool:

[25] North Carolina Department of Environment and Natural Resources, *CAMA Handbook for Development in Coastal North Carolina,* (North Carlolina, 2007).

Coastal Dune Restoration Advantages:

- Provides a low-cost alternative to other erosion control measures while providing some degree of coastal hazard mitigation;
- Provides a natural appearance and ecosystem function with habitat for native flora and fauna;
- Preserves cultural and natural resources, such as burial sites, which commonly occur in dunes. Public access can be dedicated through permanent dune pathways and boardwalks that also help mitigate dune erosion due to foot traffic.

Coastal Dune Restoration Challenges:

- Requires clear, enforceable management policies or agreements between private landowners and the public or non-profit entity managing the dune;
- Needs to balance public access to the beach with the public interest in dune stabilization and the rights of private property owners;
- Establishing a healthy thriving plant system will take time and effort;
- Requires periodic maintenance and should include dune walkovers, sand fencing or similar dune erosion control measures;
- Can complicate the shoreline certification process and may be viewed as an encroachment onto state land, if not appropriately permitted and maintained.

Currently, SEI is working on dune restoration projects on the island of Maui. If successful, these projects will serve as a model for dune restoration elsewhere in Hawai'i, including Kailua Beach.

B. Sediment Management

The USACE recently completed the *Regional Sediment Management Plan for Southeast O'ahu.*[26] This project studied the nearshore dynamics and sediment transport characteristics of the region and identified several alternative erosion control measures. The plan also provides a sand source inventory and a sediment management plan for southeast O'ahu, including Kailua Beach.

[26] U.S. Army Corps of Engineers. "Southeast O'ahu RSM", *Hawaii Regional Sediment Management.* Web. 2010.

C. Controls on Coastal Construction

As mentioned earlier, controls on development and construction landward of the certified shoreline and in the Urban Zoned areas of Kailua come under the jurisdiction of the City. The City's Shoreline Setback Rules and Regulations, administered by DPP, establish a standard setback of 40 feet (60 feet for new subdivisions or cluster housing) for new construction, regardless of the characteristics of the beach and the degree to which the shoreline is subject to seasonal or long-term change. For an accreting beach like Kailua Beach, this means that substantial construction has migrated seaward following the shoreline seaward over time. This creates a long-term hazard and land use management problem when the accretion trend reverses to erosion, as it is expected to do with sea-level rise (see Section 2.3).

Under this scenario, homes built increasingly seaward will be the most vulnerable to coastal hazards such as storm surges, tsunamis, and beach erosion. Fortunately, this problem can be mitigated by recognizing these potential hazards and providing land use policies and options during the re-development and renovation of oceanfront properties. Still, a consistent regulatory challenge is the accommodation of legal, non-conforming or "grandfathered" dwellings that are not required to upgrade to the new shoreline rules and policies.

D. Coastal Hazard Mitigation Planning Examples:

The counties of Maui and Kaua'i have revised their Shoreline Setback Area Ordinances in recent years to take into account the rate of erosion along particular beachfronts relative to the expected life of a structure.

Maui's rules, adopted in 2003, require a minimum setback that is the *greater* of the distances derived from *a* and *b* below:

a. 25 feet plus the product of 50 times the annual erosion rate [25 ft. + (50 x annual erosion rate)]

b. 25 feet for lots with depths of 100 feet or less, 40 feet for lots with depths between 100 feet and 160 feet, or 25 percent of the lot depth for lots with a depth of 160 feet or more, up to a maximum 150 feet.

This method is felt to be an improvement of the previous rules, but not sufficiently protective if future erosion rates increases faster than the expected life of the structure.[27]

Kaua'i's rules, adopted in 2008 and updated in 2010, require a more conservative construction shoreline setback for new structures: 40 feet, plus 70 years multiplied by the average annual erosion rate. This standard is based on the average life span of wood-

[27] Hwang, *Hawaii Coastal Hazard Mitigation Guidebook*, 69.

framed coastal structures (70 years) as derived by FEMA from scientific analysis. Kaua'i's rules provide for an adjustment of 10 percent in the average annual erosion rate for sea-level rise in some cases.[28]

The counties of Maui and Kaua'i are comparable in terms of the extent and value of real estate development along their shorelines. Kaua'i's more progressive posture on shoreline regulations may be explained by its experience with widespread destruction of shoreline properties in two catastrophic storms over the past three decades.[29] Kaua'i was the first county in Hawai'i, for example, to adopt new building code standards intended to protect structures from hurricane damage. However, all Hawaiian Islands are exposed to similar risks from coastal natural hazards, including shoreline erosion that should be considered within the shoreline setback rules.

Outside of Hawai'i, other states in the U.S. that have dealt with catastrophic storms have tended to adopt policies and standards for shoreline areas that consider average annual erosion rates and the life span of structures. Below is a summary of the approaches used in three of those states.

Florida established a Coastal Construction Control Line (CCCL) to protect beaches and dunes from improperly sited and designed developments.[30] The CCCL represents the projected landward limit of significant damage to upland structures from water forces from a one-hundred year coastal storm. Structures located seaward of the CCCL are required to be designed and built to withstand the high winds and storm surges which accompany those events. Florida's experience has found reduced property damage to structures built according to CCCL standards. This, in turn, reduces risks and losses for shoreline property owners, thereby reducing their insurance premiums and increasing their ability to obtain insurance. In addition to construction standards, Florida's CCCL also serves as a seaward construction setback and establishes special conditions for allowing development in this zone.

North Carolina's Coastal Area Management Act (CAMA), adopted in 1972, established the Coastal Resources Commission, which in turn designated "Areas of Environmental Concern" (AEC) within the 20 coastal

[28] University of Hawai'i Sea Grant College Program, Center for Island Climate Adaptation and Policy, *Shoreline Impacts, Setback Policy and Sea Level Rise* (Honolulu: University of Hawaii, 2009), ii.

[29] Hurricanes Iwa (1982) and Iniki (1992).

[30] The provisions are codified as Section 161.053, Florida Statutes. See also, Florida Department of Environmental Protection, *Homeowner's Guide to the Coastal Construction Control Line Program*, February, 2006.

counties and set rules for managing development within these areas. The AEC includes areas of natural importance that may be easily destroyed by erosion or flooding or may have environmental, social, economic or aesthetic values to the state. All new construction or substantial improvements to existing structures (an increase of 50 percent or more in the value of existing square footage) must meet standards that are similar to those for Florida's area seaward of the CCCL. North Carolina sets the CCCL at 30 years times the average annual erosion rate, with a minimum setback of 60 feet.

Texas's coastal construction controls are based primarily on two statutes: the Texas Open Beaches Act (TOBA) of 1959, which guarantees public access to the beach with an easement over the dry beach up to the vegetation line; and the Dune Protection Act (DPA) of 1973, which establishes state permitting authority up to these "dune protection lines." An amendment to the DPA in 1991 expanded regulatory authority up to the greater of 1,000 ft from the vegetation line or to the first public road running parallel to the beach for beach access purposes, and up to 1,000 ft from mean high tide to protect critical dune areas. Any structure, bulkhead, revetment, or excavation is effectively prohibited on the beach. Since the boundary is the line of vegetation, the result is a "rolling easement" that follows an eroding or accreting shoreline. Fixed structures can be built prescribed distances landward of the easement (typically 200 ft, but this can vary by locality), but they are subject to forced removal if the vegetation line moves landward of the structure. The developer and property owner assume the risk. If the shoreline is stable or accreting, the structure is physically and legally "safe." If the shoreline erodes, it is difficult for the owner to avoid the impacts of what amounts to trespassing on the public easement.

Application of the CCCL to Kailua Beach

The CCCL, combined with factors that consider erosion rate, the effect of sea-level rise, and the expected life span of structures, is a useful concept that could be applied to Kailua Beach, as well as other unhardened Hawai'i beaches. The *Hawaii Coastal Hazard Mitigation Guidebook* includes a reference table that can serve as the guide for defining the CCCL based on these factors.[31]

Applying the recommended setback formula from the guidebook for an accreting beach with no erosion rate, such as Kailua Beach, the calculated setback is 49 feet from the shoreline for structures designed to survive 70 years on average (e.g., structures that are accessory to residential dwellings or other use) and 53 feet for more substantial structures (e.g., residential dwellings and

[31] Hwang, *Hawaii Coastal Hazard Mitigation Guidebook*, 69.

other higher-value buildings) that may be expected to have an average life span of 100 years. These setbacks, while more conservative than the existing 40 foot setback, still may not be adequate to accommodate future beach changes and coastal hazards.

An alternative approach is to define the CCCL at the seaward edge of all existing "major" structures, i.e., those structures that would require a Shoreline Setback Variance under current city shoreline rules. This would immediately halt the incremental seaward movement of the building line as shorelines are certified further seaward. It would also be a simpler and more equitable approach to administering the issuance of building permits, setback calculations, and shoreline certifications for new structures, since the location of the CCCL would be fixed and pre-recorded. As in Florida, the CCCL would be reviewed periodically (roughly every 5 years) to determine whether a revision based on the effects of sea-level rise and/or a change in the erosion or accretion pattern would warrant the relocation of the CCCL alignment.

Based on initial, conceptual discussions with state and city regulatory and planning agencies, the CCCL option has generated a favorable reaction for application to Kailua. The CCCL may be the most practical and viable land use tool readily available to achieve the goals of beach and dune conservation balanced with coastal hazard mitigation for private interests in Kailua.

Figure 18: Example of a CCCL at Kailua Beach, the orange line represents a conceptual CCCL and would determine the seaward extent of new coastal development in Kailua. The inset (2009) shows the most seaward structure along the beach.

5. GOALS, OBJECTIVES AND IMPLEMENTATION ACTIONS

The following section sets forth the goals, objectives, recommendations, and subsequent implementation strategies and actions for managing the beach and dunes of Kailua Beach. The goals and objectives address key issues presented in previous sections and serve to focus and direct future action in order to maintain and improve Kailua Beach. Many of the goals presented are complimentary and may be considered as stand-alone goals or more comprehensively as coastal policy focus areas.

Implementation strategies identify specific steps needed to achieve the goals and objectives and the key actions and implementation timeframes are represented as three years (short-term) or six years (long-term) to correspond to Capital Improvement Program budget formats. This is not meant to imply that actions should be delayed if there is reasonable opportunity or need to proceed earlier.

Goal 1. Timely Response to Sea-Level Rise

Objective - To recognize and plan for the potential impacts of climate change and sea-level rise on Kailua Beach and adjacent low-lying coastal lands.

Recommendations

1.1) Develop high-accuracy LIDAR-based sea-level rise (SLR) inundation maps for Kailua's low-lying coastal areas. These maps will serve as the basis for subsequent community risk and vulnerability assessments and coastal hazard resiliency profiles.

Implementation Strategy

Seek possible sources for matching funding. Specify goals, priority areas of study, and plan for updates. Identify potential research leads.

Timeframe

Within three years and periodically thereafter.

1.2) Conduct a community risk and vulnerability (R&V) assessment and coastal hazard resiliency profiles. Identify critical infrastructure at risk of sea-level rise inundation and coastal flooding. Develop disaster response plans for the community and develop community-based priority assessments for beach and dune management.

Implementation Strategy

Map likely scenarios of flooding and existing infrastructure within flood areas. Identify infrastructure prone to damage and program the relocation of infrastructure to outside of the flood areas to coincide with any scheduled upgrades or

replacements. Develop community resiliency profiles that account for socio-economic priorities for the implementation and support of future beach management actions. These efforts may also partner with existing state and federal efforts to improve Coastal Community Resilience (CCR).

Timeframe
Within six years.

1.3) Amend shoreline setback and coastal development policies. Incorporate projected future shoreline locations due to sea-level rise into long-range design plans and controls on coastal development.

Implementation Strategy

Issue a statewide objective for making scientific projections of sea-level rise and/or shoreline locations due to sea-level rise. The development and implementation of options presented in the Kailua Beach and Dune Management Plan may serve as a demonstration of the application of this approach.

Timeframe
Within three years.

Goal 2. Preservation and Restoration of Primary Coastal Dunes

Objective - To protect and preserve existing sand dunes and restore degraded sand dunes.

Recommendations

2.1) Use signs, fencing, and movable dune walkovers at public beach access points throughout Kailua beach to provide pedestrian access while preserving dune vegetation.

Implementation Strategy
Identify critical areas for protection and the most appropriate measures for those areas. Involve, educate, and inform adjacent land owners and community groups prior to construction. Fund and construct appropriate signage and public education measures. Evaluate effectiveness of outreach and protection strategies.

Timeframe
Within six years.

2.2) Amend state statutes and City and County of Honolulu ordinances to prohibit the grading of dunes in the shoreline setback area, require dune delineation for grading permits for coastal properties, recover beach-quality sand excavated during construction projects for dune restoration projects, and specify that any fill used in the

setback area must be beach-quality sand.

Implementation Strategy

Map and record the existing dune extent and condition to establish a baseline of dune location and extent. Draft a bill for amending HRS Chapter 205A and the Revised Ordinances of Honolulu Chapters 23 and 25 to require dune delineation and protection under Special Management Area and Shoreline Setback rules. Incorporate dune identification, restoration, and protection procedures in all grading permit reviews for shoreline properties. Note various proposed amendments to HRS 205A in the legislative sessions of 2008, 2009 and 2010 included a provision to prohibit grading of the primary coastal dune. (Maui County enacted a dune grading prohibition in 2003).

Timeframe

Within three years.

2.3) Encourage and support dune restoration efforts (dune fencing, re-vegetation, sand nourishment, etc.) with incentives such as grants or a conservation easement program managed by a non-profit land trust to manage the dune system and provide participating private landowners with tax relief or credits.

Implementation Strategy

Partner with a non-profit organization(s) to develop and manage a conservation easement program. Collaborate with federal programs and grants directed to dune and coastal ecosystem conservation and restoration.

Timeframe

Within six years.

2.4) Conduct additional studies and remediation or monitoring programs, as necessary, to obtain approval from the Hawai'i Department of Health's Clean Water Branch to allow the beneficial use of dredged sand from periodic dredging of the mouth of Ka'elepulu Stream to replenish the beach fronting Kailua Beach Park.

Implementation Strategy

Continue pursuing a Memorandum of Understanding with the City Department of Parks and Recreation (DPR) or negotiate other agreements between the DPR and DOH.

Timeframe

Within six years.

2.5) Publish a handbook detailing the methodology and practice for future dune restoration projects.

Timeframe

Within three years.

Goal 3. Proactive Development Standards for New Construction

Objective - To adopt construction and planning standards that improve the safety of coastal residents and property improvements from coastal hazards, while also protecting coastal resources from inappropriate development in Kailua; and to promote proactive development practices by providing relevant information for governmental agencies, buyers and their agents when purchasing shoreline property, and design professionals and landowners when planning any development along the shoreline.

Recommendations

3.1) Adopt the concept of a Coastal Construction Control Line (CCCL) in the state statutes (Chapter 205-A, HRS) and define it at Kailua Beach as the seaward edge of existing major structures -- i.e., those that would require a variance under present Shoreline Setback Area Rules and Regulations -- and update the CCCL alignment periodically as prescribed in Action 3.2, below.

Implementation Strategy

HB 593 was introduced in 2009 to establish a two year interim CCCL. It crossed over to the Senate where it was amended and passed as SB1318 SD1. It did not pass out of the House of Representatives.

Timeframe

Within three years.

3.2) Review and revise, as necessary, the CCCL alignment based on a study that identifies the coastal hazard zone that takes into account high hazard areas for hurricane, tsunami high surf and erosion. Incorporate performance standards (e.g., construction style and estimated lifetime of structure) into the determination whether and in what manner a non-conforming structure may be repaired or replaced.

Implementation Strategy

Provide funding for the study. The CCCL could be the greater of either the seaward face of existing development or the coastal hazard zone, once the hazard zone is mapped. DPP to follow-up on standards and rules.

Timeframe

Within six years.

3.3) Conduct a geospatial field survey of property boundaries and detailed inventory of unauthorized structures and land alterations on accreted lands within the Conservation District (i.e., accreted lands claimed after 1985), and on State-owned lands, and take appropriate enforcement actions against those unauthorized activities.

Implementation Strategy
Field and geospatial data investigations by DLNR enforcement, in cooperation with DOCARE. Field survey of property lines would benefit from permanent property boundary markers and signs to identify state vs. private lands.

Timeframe
Within six years.

Goal 4. Increased Public Awareness and Education

Objective - To raise public and private sector awareness and improve education on coastal and marine resource protection. A better educated and informed community will not only better steward the Kailua environment but also support their political leaders in making politically difficult decisions related to the coastal environment and development.

Recommendations

4.1) Develop educational materials (e.g., booklets, website, presentations) describing the critical role of dunes in maintaining healthy beach systems and ways to help protect and avoid damaging dunes (see Goal 2.5). Disseminate this information to key target audiences in Kailua (e.g., schools, community associations, neighborhood boards, real estate and construction industry organizations, ocean activity owners.), as well as public agencies involved in land use and activity along the shorelines.

Timeframe
Within three years.

4.2) Partner with local scientists and environmental groups to sponsor K-12 teacher training workshops and college-level internships focused on Kailua Bay and the maintenance of its beach and dune system.

Timeframe
Within six years.

Goal 5. Established Reliable Funding and Support Mechanisms

Objective - To increase and provide continuous funding and/or volunteer support for beach management, coastal land acquisition, and coastal research and monitoring.

Recommendations

5.1) Direct a portion of annual allocations from applicable county and state natural resource funds for beach maintenance, shoreline access, and beach and dune restoration projects in Kailua. Kailua-specific coastal land use fines and penalties could also be allocated to such a fund. Seek to match or augment these resources with funds from state and federal grant programs and

private organizations.

Timeframe
Within six years, and continuously thereafter.

5.2) Provide start-up funding and enabling legislature for real property, state income and inheritance tax deductions or credits for a conservation easement program, managed by a non-profit land trust, that negotiates and receives conservation easements on dune areas owned by private beachfront landowners and enters into management contracts and projects with state and county agencies.

Timeframe
Within three years.

Summary Table: Goals, Recommendations, and Implementation Timeframe						
Goals and Recommendations	**Implementation Timeframe (Max Years)**					
	1	**2**	**3**	**4**	**5**	**6**
1. Timely Response to Sea-Level Rise						
1.1 Develop high-accuracy LIDAR-based sea-level rise (SLR) inundation maps for Kailua's low-lying coastal areas. These maps will serve as the basis for subsequent community risk and vulnerability assessments and coastal hazard resiliency profiles.	●	●	●			
1.2 Conduct a community risk and vulnerability (R&V) assessment and coastal hazard resiliency profiles. Identify critical infrastructure at risk of sea-level rise inundation. Develop disaster response plans for the community and develop community priority assessments for beach and dune management.	●	●	●	●	●	●
1.3 Amend shoreline setback and coastal development policies. Incorporate projected future shoreline locations due to sea-level rise into long-range design plans and controls on coastal development.	●	●	●			
2. Preservation and Restoration of Primary Coastal Dunes						
2.1 Use signs, fencing, and movable dune walkovers at public beach access points to provide pedestrian access while preserving dune vegetation.	●	●	●	●	●	●
2.2 Amend state statutes and City and County of Honolulu ordinances to prohibit the grading of dunes in the shoreline setback area, require dune delineation for grading permits for coastal properties, recover beach-quality sand excavated during construction projects for dune restoration projects, and specify that any fill used in the setback area must be beach-quality sand.	●	●	●			
2.3 Encourage and support dune restoration efforts (dune fencing, re-vegetation, sand nourishment, etc.) with incentives such as grants or a conservation easement program managed by a non-profit land trust to manage the dune system and provide participating private landowners with tax relief or credits.	●	●	●	●	●	●

Summary Table: Goals, Recommendations, and Implementation Timeframe						
Goals and Recommendations	**Implementation Timeframe (Max Years)**					
	1	**2**	**3**	**4**	**5**	**6**
2.4 Conduct additional studies and remediation or monitoring programs, as necessary, to obtain approval from the Hawai'i Department of Health's Clean Water Branch to allow the beneficial use of dredged sand from periodic dredging of the mouth of Ka'elepulu Stream to replenish the beach fronting Kailua Beach Park.	●	●	●	●	●	●
2.5 Publish a handbook detailing the methodology and practice for future dune restoration projects.	●	●	●			
3. Proactive Development Standards for New Construction						
3.1 Adopt the concept of a Coastal Construction Control Line (CCCL) in the state statutes (Chapter 205-A, HRS) and define it at Kailua Beach as the seaward edge of existing major structures - i.e., those that would require a variance under present Shoreline Setback Area Rules and Regulations - and update the CCCL alignment periodically as prescribed in Action 3.2.	●	●	●			
3.2 Review and revise, as necessary, the CCCL alignment based on a study that identifies the coastal hazard zone that takes into account high hazard areas for hurricane, tsunami high surf and erosion. Incorporate performance standards (e.g., construction style and estimated lifetime of structure) into the determination whether and in what manner a non-conforming structure may be repaired or replaced.	●	●	●	●	●	●
3.3 Conduct a detailed inventory of unauthorized structures and land alterations on accreted lands within the Conservation District (i.e., accreted lands claimed after 1985), and on State-owned lands, and take appropriate enforcement actions against those unauthorized activities.	●	●	●	●	●	●

Summary Table: Goals, Recommendations, and Implementation Timeframe						
Goals and Recommendations	**Implementation Timeframe (Max Years)**					
	1	**2**	**3**	**4**	**5**	**6**
4. Increased Public Awareness and Education						
4.1 Develop educational materials (e.g., booklets, website, presentations) describing the critical role of dunes in maintaining healthy beach systems and ways to help protect and avoid damaging dunes. Disseminate this information to key target audiences in Kailua (e.g., schools, community associations, neighborhood boards, real estate and construction industry organizations, ocean activity owners.), as well as public agencies involved in land use and activity along the shorelines.	●	●	●			
4.2 Partner with local scientists and environmental groups to sponsor K-12 teacher training workshops and college-level internships focused on Kailua Bay and the maintenance of its beach and dune system.	●	●	●	●	●	●
5. Established Reliable Funding and Support Mechanisms						
5.1 Direct a portion of annual allocations from the applicable county and state natural resource funds for beach maintenance, shoreline access, and beach and dune restoration projects in Kailua. Kailua-specific coastal land use fines and penalties could also be allocated to such a fund. Seek to match or augment these resources with funds from state and federal grant programs and private organizations.	●	●	●	●	●	●
5.2 Provide start-up funding and enabling legislature for real property, state income and inheritance tax deductions or credits for a conservation easement program, managed by a non-profit land trust that negotiates and receives conservation easements on dune areas owned by private beachfront landowners and enters into management contracts and projects with state and county agencies.	●	●	●			

BIBLIOGRAPHY

Church, John A. and Neil J. White. "20th century acceleration in global sea-level rise." Geophysical Research. Letters, 33(1), L01602 (2006).

de Araujo, Maria Christina Barbosa and Monica Ferreira da Costa. "Environmental Quality Indicators for Recreational Beaches Classification." *Journal of Coastal Research.* 24(6), (2008), 1439-1449.

Davis, Rob. , "A Sea Change: Worries Over Rising Tide." *VoiceofSanDiego.org.* Web. (December 14, 2006). http://www.voiceofsandiego.org/articles/2006/12/14/news/01sealevel.prt

Fletcher, C.H. "Sea level by the end of the 21st century: A review." *Shore and Beach.* v. 77, no. 4, Web. http://www.soest.hawaii.edu/coasts/publications/fletcher2009_sealevelreview.pdf (2009), 1-9.

Fletcher, Charles H. and Mark A. Merrifield, *Sea Level by the End of the 21st Century: A Review.* University of Hawai'i Department of Geology and Geophysics, Honolulu, HI (2009).

Fletcher, Charles, Bradley Romine, Matthew Barbee, Saing-Chyn Lim, and Matthew Dyer. *Kailua, Oahu, Hawaii: Shoreline Change Rates.* University of Hawai'i Coastal Geology Group, School of Ocean and Earth Sciences and Technology. Web. (2009).

Florida Department of Environmental Protection. *Homeowner's Guide to the Coastal Construction Control Line Program* (February 2006).

Grinsted, Aslak, John C. Moore, and Svetlana Jevrejeva. "Reconstructing sea level from paleo and projected temperatures 200 to 2100AD." *Climate Dynamics.* doi:10.1007/s00382-008-0507-2 (2009).

Hwang, Dennis. *Beach Change on Oahu as Revealed by Aerial Photographs.* State of Hawaii, Department of Planning and Economic Development, Honolulu, HI (1981).

Hwang, Dennis J. *Hawaii Coastal Hazard Mitigation Guidebook*. Prepared for the State of Hawai'i Department of Land and Natural Resources, Office of Conservation and Coastal Lands; the State of Hawaii Office of Planning, Coastal Zone Management Program; the University of Hawaii Sea Grant College Program, School of Ocean and Earth Science and Technology; and the U.S. National Oceanic and Atmospheric Administration, Pacific and Coastal Services Center, Honolulu, HI (2005).

National Aeronautics and Space Administration. "Key Indicators" *Global Climate Change*. Web. http://climate.nasa.gov/keyIndicators/index.cfm#SeaLevel (2010).

National Oceanic and Atmospheric Administration. "Sea Levels Online" *Tides & Currents*. Web. http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml (July 21, 2010).

Norcross, Zoe, Charles Fletcher and Mark Merrifield. "Annual and interannual changes on a reef-fringed pocket beach: Kailua Bay, Hawaii." *Marine Geology* (2002).

North Carolina Department of Environment and Natural Resources. *CAMA Handbook for Development in Coastal North Carolina* (October 2007).

Rogers, Spencer and David Nash. *The Dune Book*, North Carolina Sea Grant, Wilmington, NC (2003).

Sea Engineering, Inc. for the City and County of Honolulu, Department of Land Utilization. *O'ahu Shoreline Study, Part I Data on Beach Change* Honolulu,HI (1988).

Shikina, Rob. "Saving Kailua Beach." *Honolulu Star Bulletin*, Honolulu, HI (January 1, 2009).

State of Hawaii, Department of Land and Natural Resources. *Coastal Erosion Management Plan (COEMAP)*. Honolulu, HI (2000).

University of Hawai'i Sea Grant College Program, Center for Island Climate Adaptation and Policy. *Shoreline Impacts, Setback Policy and Sea Level Rise* (2009)

University of Hawai'i Sea Grant College Program, Center for Island Climate Adaptation and Policy. *Hawaii's Changing Climate*. Briefing Sheet (2010).

U.S. Army Corps of Engineers. *Low Cost Shore Protection*, Rogers, Golden & Halpern, Inc., Philadelphia, PA (1981).

U.S. Army Corps of Engineers. "Southeast O'ahu RSM", Hawaii Regional Sediment Management. Web. http://gis.poh.usace.army.mil/rsm/seo.htm (2010).

Vermeer, M. and S. Rahmstorf. "Global sea level linked to global temperature" *Proceedings of the National Academy of Sciences*, 106.51:21527-21532. (2009).

Appendices

Appendix A

Analysis of the Effect of Sea Level Rise on Future Shorelines at Kailua Beach

Sea Engineering, Inc.

Approach

Sandy shorelines are dynamic systems whose features continually respond to changing wave conditions. Beaches act to dissipate wave energy, reducing overall beach slope and shifting the breaking zone offshore during large wave conditions. Beaches can change shape and position in a matter of hours in response to storms, or over periods of months and years in response to seasonal or other long term wave variations.

Sea level rise will also result in shoreline changes, shifting the profile higher and likely landward. Projections of these changes are now an often discussed topic and planners and engineers are actively working to predict the future shoreline positions resulting from sea level rise. The USGS (2009) has published basic approaches to calculate these future shoreline positions. One of the approaches uses the Bruun Model, a two-dimensional model that relates profile change to rising water level. The concept of the model, shown in Figure 5-1 involves the offshore portion of the profile rising equally to sea level rise, out to the depth of closure, which is defined as the point where the profile no longer changes. The increase in sand volume along the offshore portion of the profile is equated to the volume of sand lost from the foreshore, resulting in shoreline retreat.

The Bruun Model is generally simple to apply to a typical profile, and shoreline retreat, R, is calculated as

$$R = \frac{L_*}{B + h_*} \times S$$

where

h_* = the depth of closure
B = berm height
L_* = length of beach profile to h_*
S = sea level rise

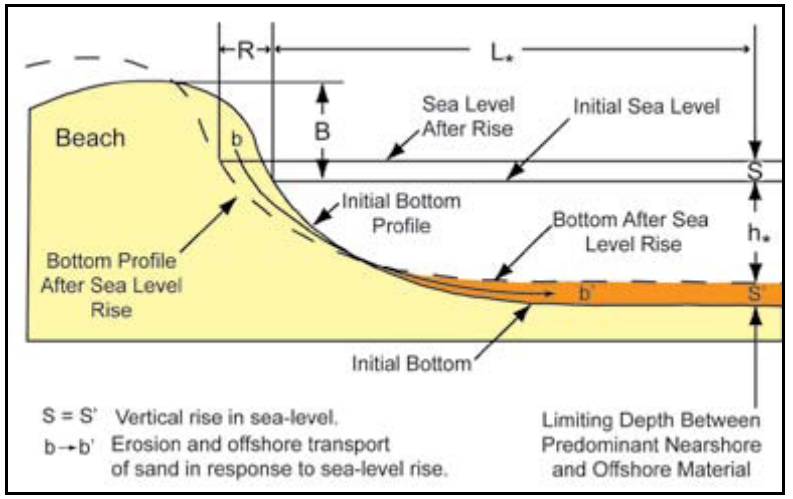

Figure 5-1. Illustration showing Bruun Model concept and inputs (USGS, 2009)

Figure 5-1 shows an increase in the elevation of the backshore portion of the profile; however, it is not clear how the equation accounts for this volume of sand.

An alternative model for conceptualizing shoreline change due to sea level rise is referred to as the RD-A model (Davidson-Arnott, 2005). There are several key differences between the RD-A Model and the Bruun Model. The RD-A Model shows the offshore portion of the profile shifting shoreward and upward along the offshore slope, with the profile features maintaining the same elevations relative to sea level. Additionally, unlike the Bruun Model, the RD-A model accounts for the accretion of the backside of the dune through sediment eroded from the beach foreshore and the dune face. The RD-A model concept is presented in Figure 5-2. In the figure, points C1 and C2 have the same locations along the old and new profiles and the difference in elevation is equal to the rise in sea level.

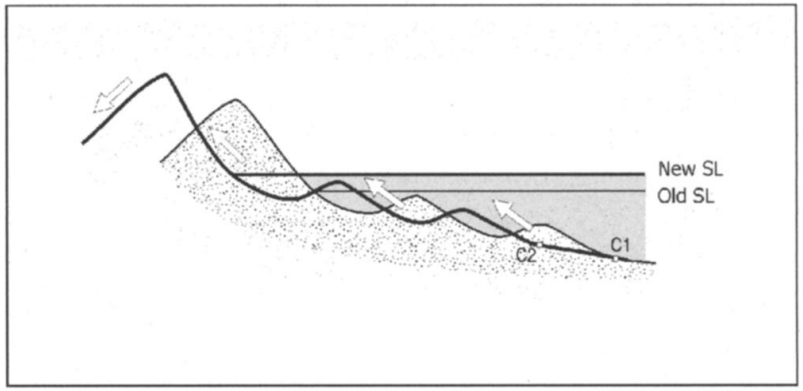

Figure 5-2. Illustration showing RD-A Model (Davidson-Arnott, 2005)

Kailua Beach Profiles

A profile along the central Kailua shoreline was measured at Kalama Beach Park by Sea Engineering in 2008 and the elevations measured were referenced to the local tide datum (mean lower low water). Annually from 2005 to 2007, the USGS measured beach profiles at a location 600 feet south of Kalama Beach Park. While the USGS profiles were not vertically referenced, the profiles can be seen to have the same general characteristics (foreshore slope, berm elevation relative to toe elevation) as the Kalama Beach Park profile. The USGS profiles were adjusted to a MLLW datum by overlaying them on the SEI profile and using the beach toe and foreshore as elevation reference features. A single "composite" profile was then produced from the four profiles. The profiles are shown in Figure 5-3 and can be seen to be quite similar seaward of the vegetation line. The composite profile combined the different features measured at the two locations—the SEI profile measured the dune in the backshore; however, the profile did not extend as far offshore as the USGS profiles.

Two sets of USGS profiles measured from 2005 through 2007 are also available in north Kailua Bay and Kailua Beach Park. The USGS profiles in Kailua Beach Park are vertically referenced and supplemented by an SEI profile measured in 2008, while the USGS profiles from north Kailua Bay were vertically adjusted so the beach toe elevation matched the beach toe elevation measured at Kalama Beach Park. These two sets of profiles are shown as Figure 5-4 and 5-5. Composite profiles were also produced for these two locations. Since Kailua Beach Park has been experiencing erosion for the past few years, the composite profile there was biased toward the more recent SEI profile.

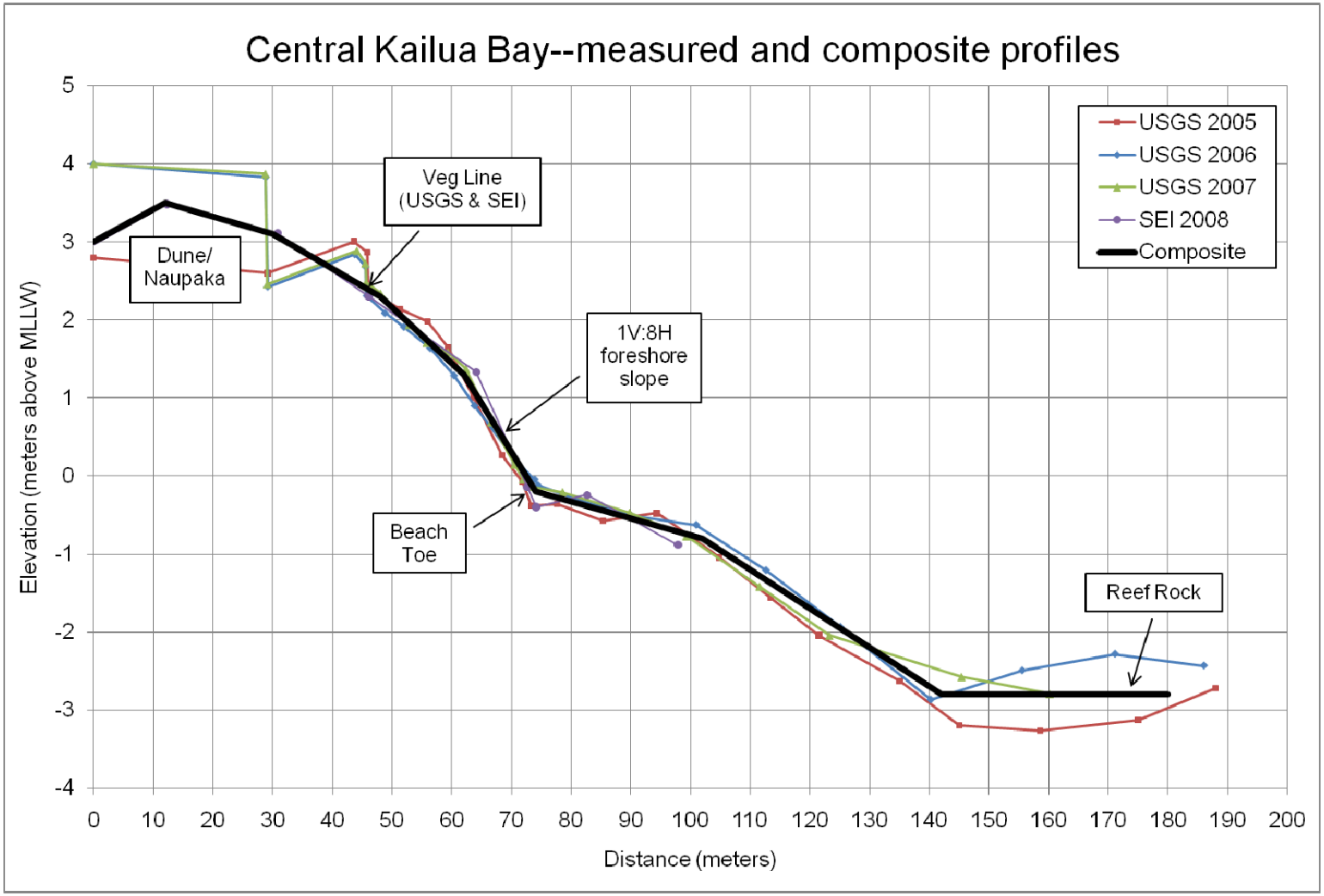

Figure 5-3. Beach profiles, Kalama Beach Park and vicinity

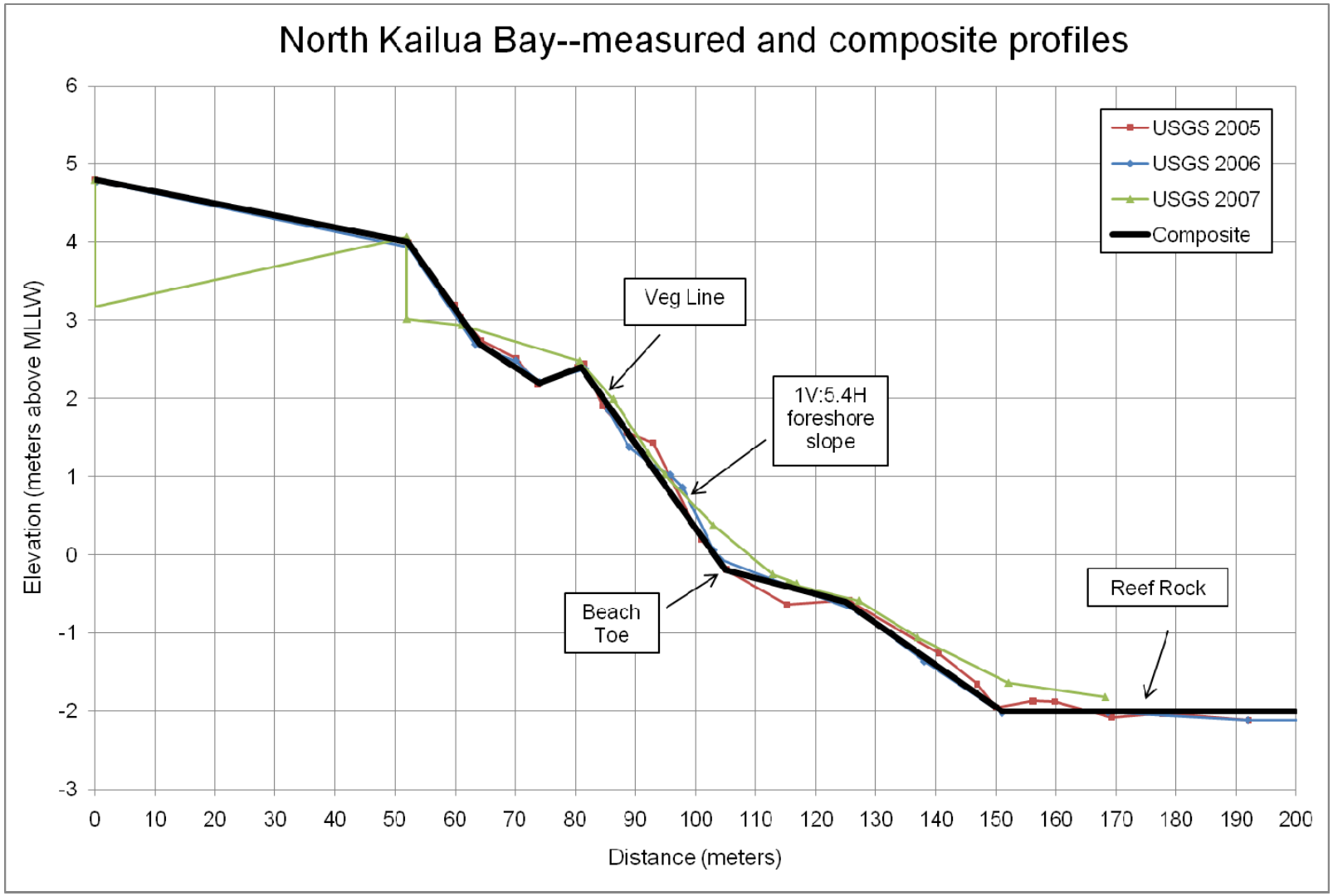

Figure 5-4. Beach profiles, north Kailua Bay

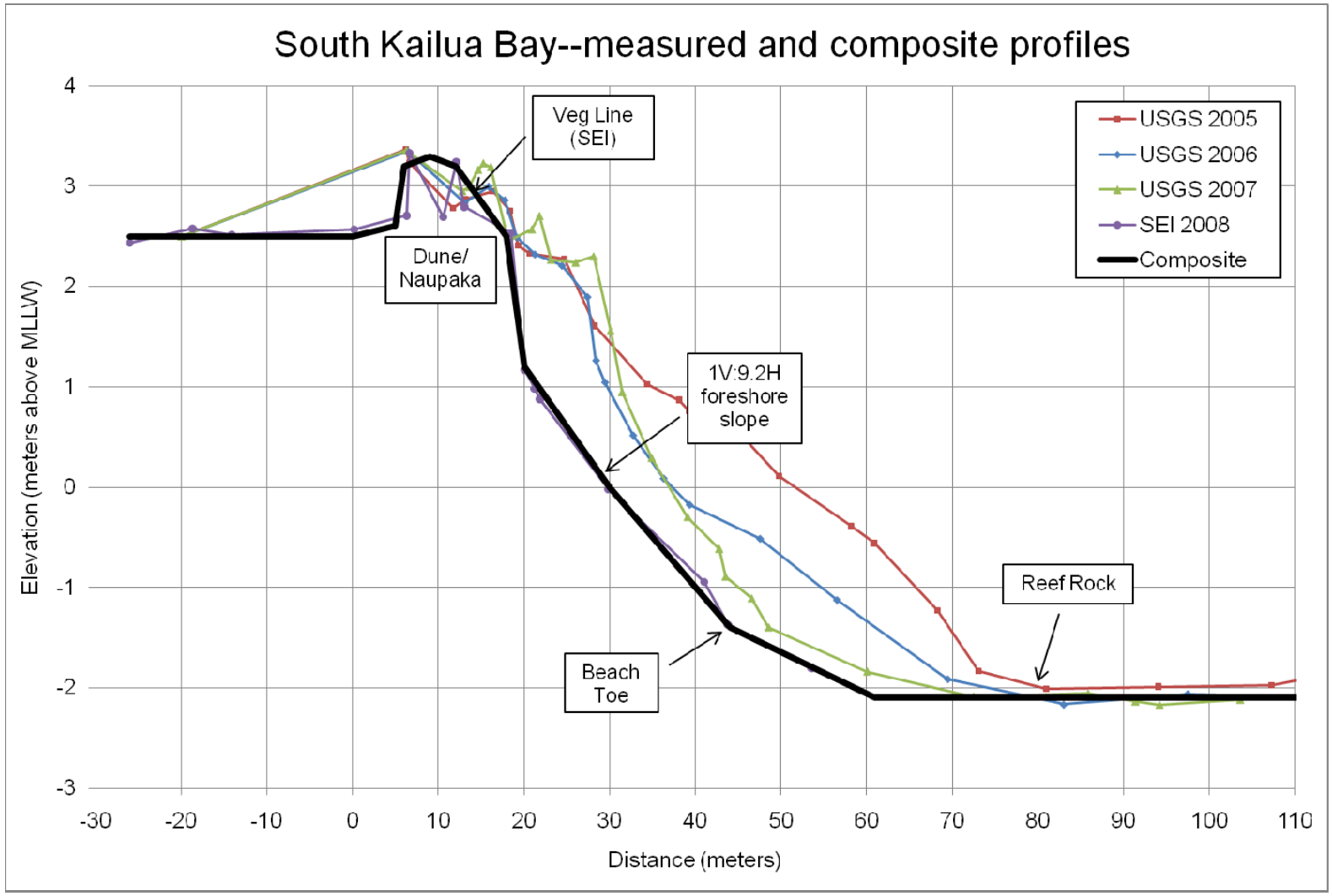

Figure 5-5. Beach profiles, south Kailua Bay

Application of Models

Both the Bruun and RD-A models described above were utilized to estimate shoreline recession resulting from sea level rise of 0.3 0.6 and 1.0 meters.

Bruun Model

Application of the Bruun Model to Kailua's shoreline requires integration of the unique features of the profile. In this situation, the depth of closure is assumed to occur at the location where the sandy profile becomes rocky. Following the Bruun Model guidance, the depth of the sandy offshore area would increase with sea level and the inputs to the model for the central Kailua profile are

$L_* = 70$ m
$h_* = 2.8$ m
$B = 1.3$ m
$S = 0.30$ m, 0.61 m, and 1 m

The resulting shoreline recession R for central Kailua is presented in **Table 5-1**.

Table 5-1. Projected shoreline recession according to the Bruun Model (central Kailua Bay)

Sea Level Rise (*S*)	Shoreline recession (*R*)
0.30 m (1.0 ft)	5.2 m (17.1 ft)
0.61 m (2.0 ft)	10.4 m (34.1 ft)
1.0 m (3.3 ft)	17.1 m (56.0 ft)

The shoreline recession for north and south Kailua Bay, calculated similarly, are presented in **Table 5-2** and **Table 5-3**.

Table 5-2. Projected shoreline recession according to the Bruun Model (north Kailua Bay)

Sea Level Rise (*S*)	Shoreline recession (*R*)
0.30 m (1.0 ft)	4.2 m (13.8 ft)
0.61 m (2.0 ft)	8.4 m (27.6 ft)
1.0 m (3.3 ft)	13.8 m (45.4 ft)

Table 5-3. Projected shoreline recession according to the Bruun Model (south Kailua)

Sea Level Rise (*S*)	Shoreline recession (*R*)
0.30 m (1.0 ft)	2.9 m (9.4 ft)
0.61 m (2.0 ft)	5.7 m (18.8 ft)
1.0 m (3.3 ft)	9.4 m (30.8 ft)

RD-A Model

Application of the RD-A Model involves shifting the profile upward equal to sea level rise and inshore along the offshore slope. The offshore portion of the composite profile is not necessarily a single line, and the slope is therefore estimated as the slope between the beach toe and the intersection of the sandy portion of the profile with the reef rock. Projection of future profile location involves shifting the profile based on this slope.

The offshore profile slopes were calculated to be 1V:25.6H, 1V:26.2H, and 1V:24.3H for the north, central, and south profiles, respectively. The resulting shoreline recession of the profiles are presented in **Table 5-4** through **Table 5-6**.

Table 5-4. Projected shoreline recession according to RD-A Model (north Kailua Bay)

Sea Level Rise	Shoreline recession
0.30 m (1.0 ft)	7.8 m (25.6 ft)
0.61 m (2.0 ft)	15.6 m (51.2 ft)
1.0 m (3.3 ft)	25.6 m (84.0 ft)

Table 5-5. Projected shoreline recession according to RD-A Model (central Kailua Bay)

Sea Level Rise	Shoreline recession
0.30 m (1.0 ft)	8.0 m (26.2 ft)
0.61 m (2.0 ft)	16.0 m (52.4 ft)
1.0 m (3.3 ft)	26.2 m (86.0 ft)

Table 5-6. Projected shoreline recession according to RD-A Model (south Kailua Bay)

Sea Level Rise	Shoreline recession
0.30 m (1.0 ft)	7.4 m (24.3 ft)
0.61 m (2.0 ft)	14.8 m (48.6 ft)
1.0 m (3.3 ft)	24.3 m (85.3 ft)

Conceptual profile change due to sea level rise for the RD-A Model is shown in Figures 5-6 through Figure 5-8. .

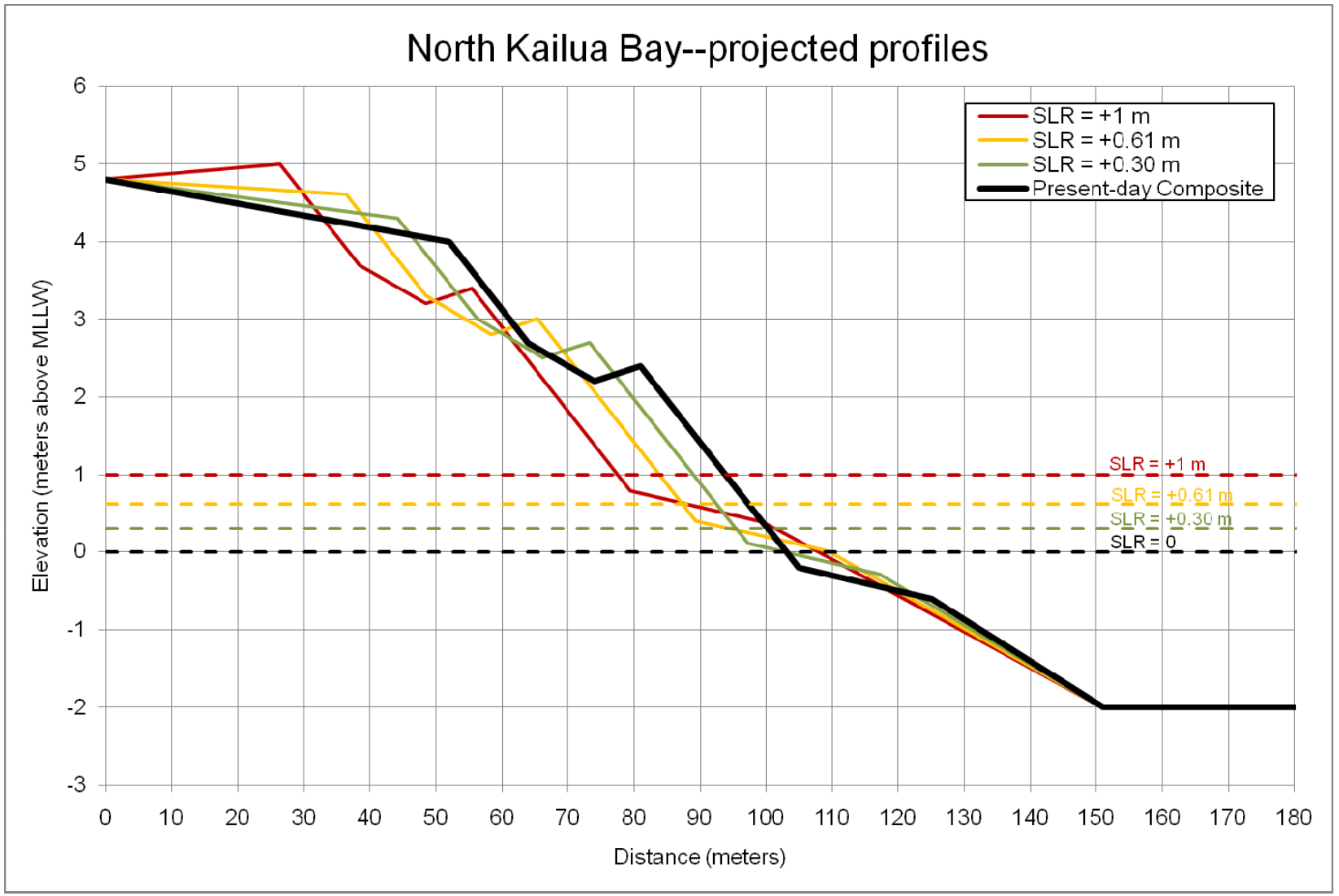

Figure 5-6. Projected beach profiles, north Kailua Bay

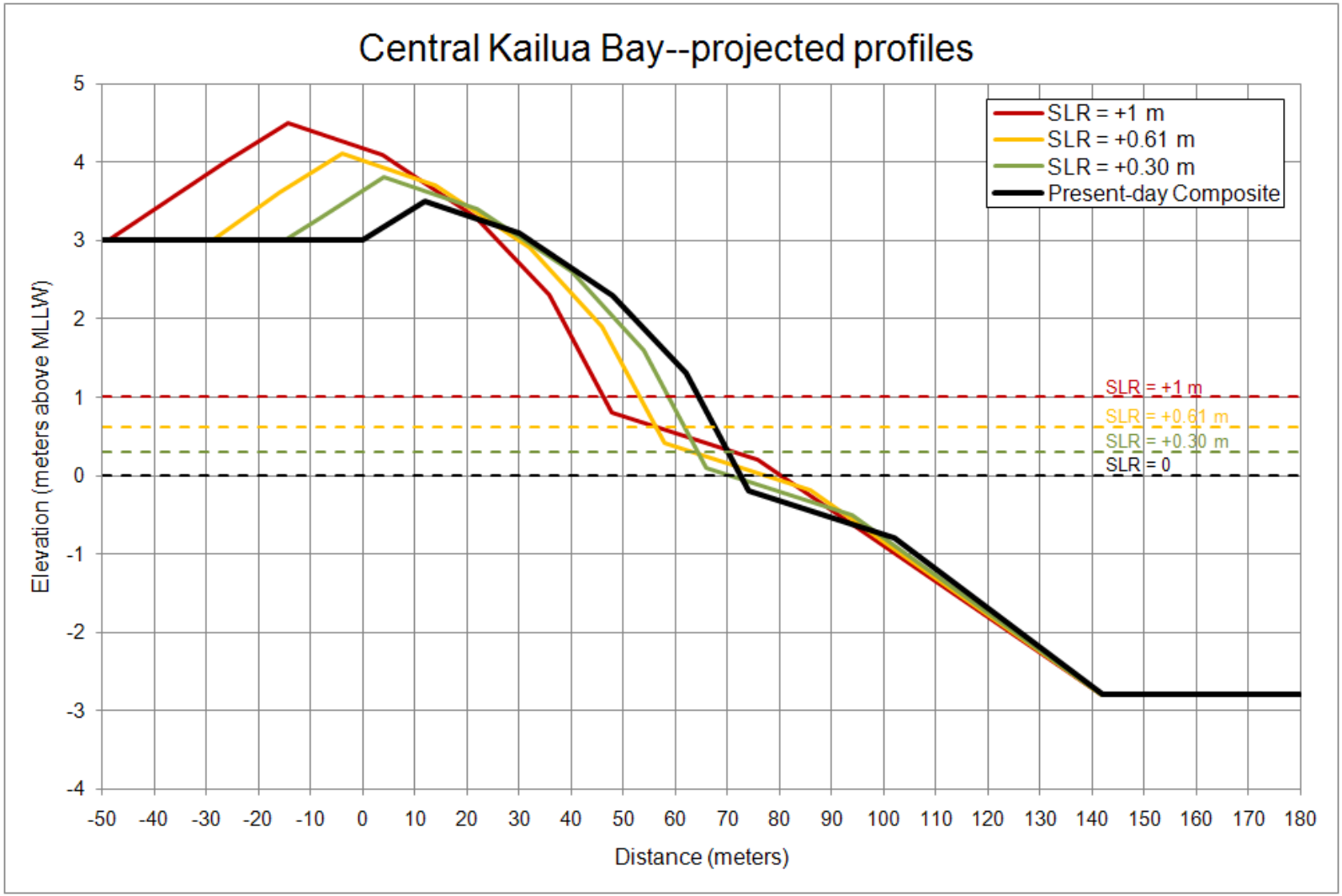

Figure 5-7. Projected beach profiles, central Kailua Bay

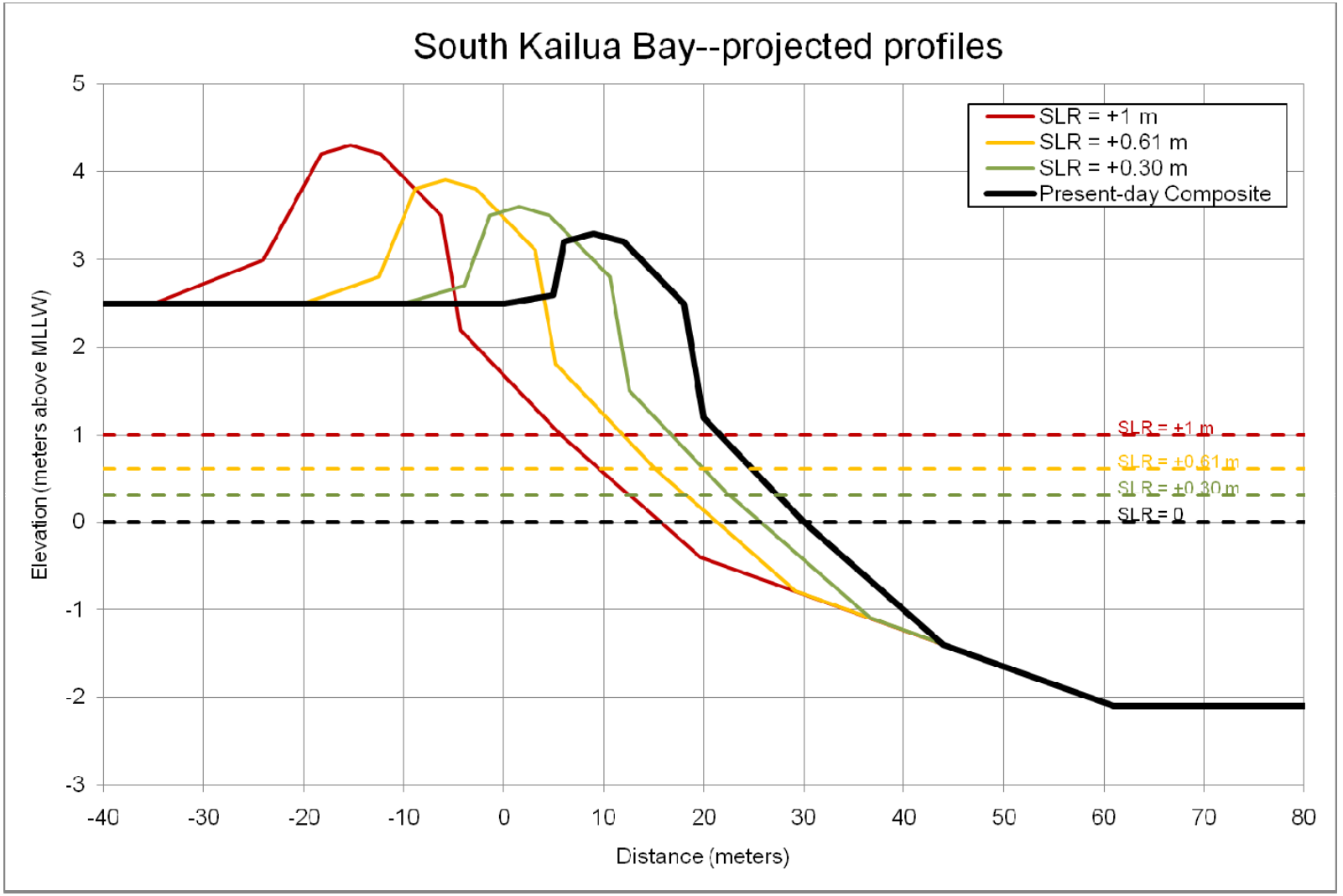

Figure 5-8. Projected beach profiles, south Kailua Bay

Selection of Appropriate Model and Construction of Projected Shoreline Positions

The Bruun Model is commonly referenced when discussing shoreline change due to rising sea level. The model is best applied to sandy shorelines, and its applicability to Hawaii's shores can be disputed. In the model, the offshore portion of the profile rises with sea level, and that gain in material is equated to material loss from the foreshore. In many locations in Kailua and Hawaii, fossilized reef rock is encountered along the profile, likely preventing continuous transition of the profile as presented in the Bruun Model. Additionally, the model accounts only for sediment eroding from the foreshore and being deposited offshore, with no consideration of dune dynamics or aeolian processes.

The RD-A Model, however, is based on maintaining the local beach profile characteristics. With rising sea level, the profile features shift landward along the offshore slope, and those profile features remain at the same elevations relative to sea level. As opposed to the Bruun Model, this allows the RD-A Model to account for dune dynamics and aeolian processes—nearshore erosion and landward migration of the dune system are inherent in the model. Since reef rock, dunes, and aeolian processes are all typical along the Kailua shoreline, the RD-A Model is believed to produce the most valid estimate of the future shoreline position resulting from sea level rise for Kailua Bay.

The University of Hawaii Coastal Geology Group has produced historical shorelines based on aerial photographs as recent as 2005. These shorelines were produced by digitizing the low water mark (LWM) and the vegetation line (VL) at approximately 200 transects throughout Kailua Bay. The present study produced estimated locations of these shoreline delineations resulting from sea level rise by using the calculated shoreline recessions shown in **Table 5-4** through **Table 5-6**. The average shoreline recession in Kailua Bay, calculated using the RD-A Model, is 7.7 m, 15.5 m, and 25.4 m in response to sea level rise of 0.30 m, 0.61 m, and 1 m, respectively. It should be noted that the lines are plotted with the assumption that there are no limitations in the backshore that would prevent shoreline recession. Such limitations would need to be analyzed case-by-case to determine the potential affects.

Application of Projected Shoreline Recession to Target Years

The original intent of this task was to determine sea level rise for three scenarios, such as 25, 50, and 100 years from present, and then produce projected shoreline locations for those level/date pairs. Due to the difficulty of assessing local sea level rise rates and likely future acceleration of those rates, our analyses proceeded by first estimating shoreline position for three discreet future sea levels and then estimating the date corresponding to those sea levels.

An often-discussed estimate for future global sea level is 1 meter higher than present in the year 2100. This level was affirmed recently as a useful benchmark for the Hawaiian Islands by University of Hawaii scientists (Fletcher and Merrifield, 2009). That sea level and date were selected as the upper bound in our analyses. Two intermediate levels of 1 foot (0.30 m) and 2 feet (0.61 m) above present were then

added to the model to project the location of future shorelines at Kailua Beach. The lower level (1 foot) might have more meaning to a homeowner, while the two higher levels would serve as targets for planners and government officials. Estimating when these levels might occur is difficult, because new information and new projections are frequently announced or published. The U.S. Army Corps of Engineers manual on sea-level change (EC 1165, published in 2009) presents scenarios for eustatic sea level rise based on updates to the NRC 1987 equation. If we consider 1 meter as the target sea level rise at 2100, then the rate of sea level rise could be approximated by the green curve ("Modified NRC-II") shown in Figure 5-9, and the three targets would be met in years 2052, 2078, and 2104 if this method holds true. (Note that a shift of the Y axis of 0.08 m, equivalent to the sea level rise between 1986 and 2010, is necessary to produce relationships beginning in 2010.)

The historical record, however, shows that sea level rise measured at Honolulu Harbor has been approximately linear since 1900, increasing at a rate of about 1.5 mm/yr (Figure 5-10), while the present eustatic mean rate of sea level rise has been measured to be greater than 3.0 mm/year and has been shown to be accelerating (Figure 5-11).

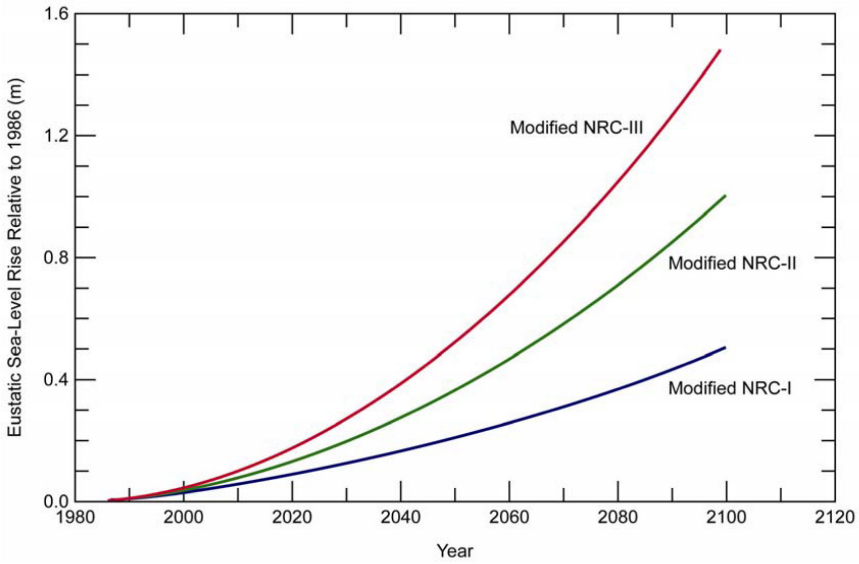

Figure 5-9. Scenarios for eustatic sea level rise (U.S. Army Corps of Engineers, 2009)

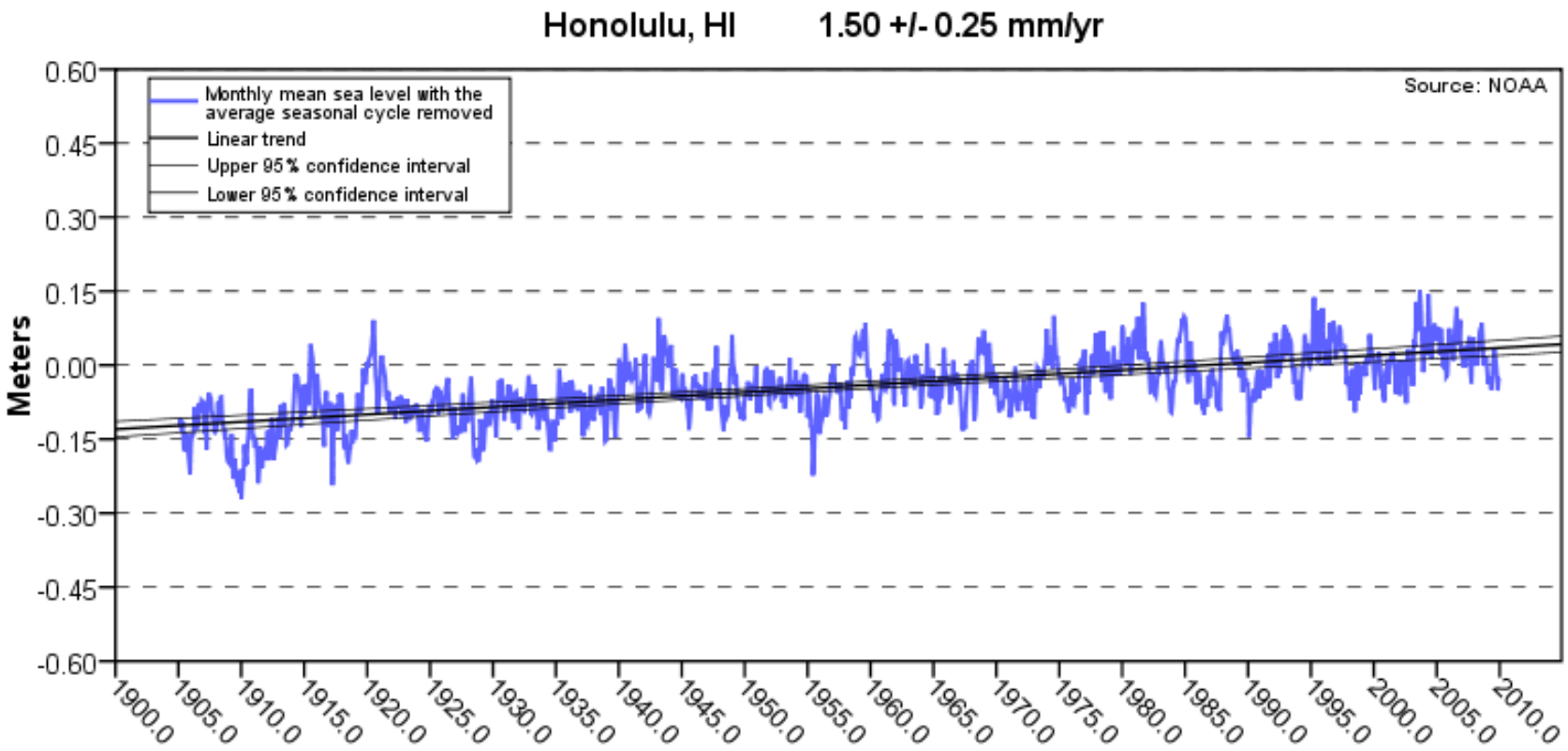

Figure 5-10. Monthly mean sea level for Honolulu Harbor (NOAA, 2010)

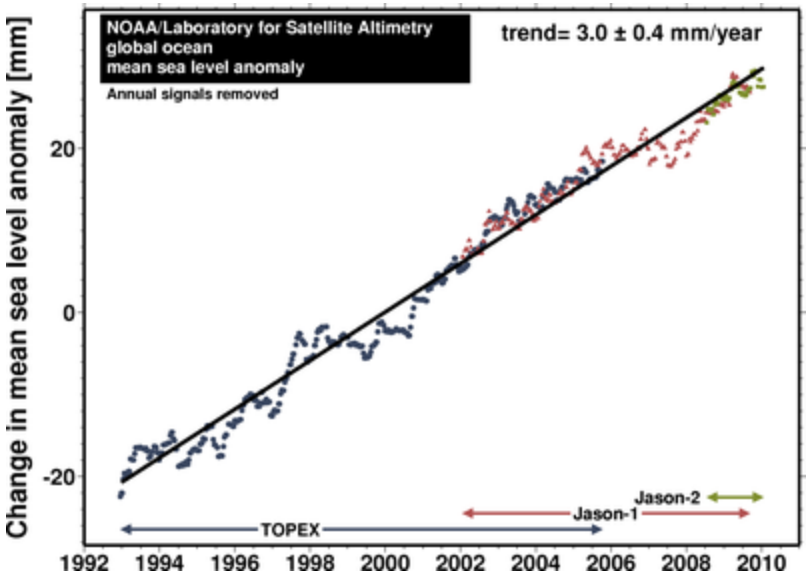

Figure 5-11. Sea level rise since 1993 (NOAA, 2010)

Sea level measurements across the Pacific Ocean show that sea level is rising in the western Pacific at rates approaching 10 mm/yr and falling in the eastern Pacific at rates of up to 3 mm/year (Figure 5-12). While it is unknown if these patterns will remain, there is a belief that sea level rise in Hawaii will follow the global trend and will begin to accelerate in the near future. Fletcher et al. (2010) have recently presented an analysis of historical tide gauge data for Honolulu Harbor, projecting that future sea level rise in Hawaii would be non-linear. They found the annual range of tide measurements to be on the order of one meter, when taking into account fluctuations due to such events as tides, storms, and large-scale eddies. A curve fit though their projected data shows that the target sea level elevations of 0.3, 0.6, and 1.0 meters would occur in the years 2052, 2075, and 2100, which are consistent with the results from the Modified NRC-II curve. The results from these two sets of data are not independent, however, as the 1-m in 2100 endpoint is fixed in both cases. Nonetheless, the results are based on projections from two reliable sources.

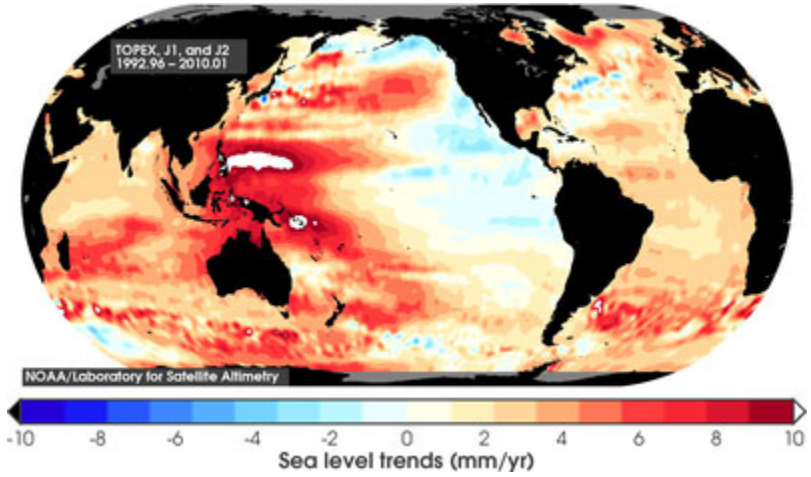

Figure 5-12. Global sea level trends

Discussion

Models for predicting shoreline response to sea level rise are generally simplistic, taking into account feature elevations and locations for typical profiles. These models have recently been applied to the East Coast of the United States (U.S. EPA, 2009) where the profile is sandy and the continental shelf is wide. The models assume that sea level will rise over a substantially long period of time such that

higher-frequency events, such as waves, tides, winds, and storms, will continue to shape the coastal morphology, with a slowly rising sea level in the background. This allows slowly-developing features such as dunes to properly form. Simply applying a higher water level in numerical or physical models does not adequately produce such features.

There are several aspects of the shoreline and wave environment that present challenges in applying shoreline change models to tropical islands. The existence of coral reefs affects both the wave environment and the profile dynamics under changing wave conditions. The offshore reef dissipates wave energy and alters wave patterns, making calculation of depth of closure and wave runup by standard methods unreliable and limiting the amount of sand movement. These are not easily accounted for in the models. Additionally, the existence of fossilized reef rock along the profile may change the way the profile adapts to changing wave conditions. The reef rock may serve to produce a "perched beach," keeping sand from migrating offshore, or it might prevent sand from accumulating on the reef rock.

Anthropogenic factors are also involved in the sea level rise scenarios. Throughout Kailua Bay, the backshore is highly developed with single-family houses, manicured lawns, and such additions as walls, swimming pools, and gazebos. Migration of the dunes inland might cause property owners to take steps to limit the effect on their property, such as planting vegetation or removing sand. Additionally, the existence of structures near the shoreline could alter wind patterns necessary for dune formation. These factors therefore add uncertainty to the future dune locations.

Sea level rise predictions are wide ranging and will be continually changing as new information becomes available. The "Modified NRC" curves presented in by the U.S. Army Corps of Engineers (2009) already appear to need updating, as ancillary results from this project show future sea level estimates to be better represented by a third-order polynomial than by the present second-order polynomial. A third-order polynomial would account for a non-linear rate of sea level change, the driving forces for which are reportedly already occurring (Velicogna, 2009). Recognized authorities studying sea level rise have recently published model results that show sea level rise ranging from 0.75 to 1.9 m for the time period of 1990 to 2100 (Vermeer and Rahmstorf, 2009). Our target of sea level rise of 1 meter by the year 2100 remains a suitable target for planning purposes.

References

Davidson-Arnott, R.G.D. 2005. "Conceptual Model of the Effects of Sea Level Rise on Sandy Coasts." *Journal of Coastal Research*, Vol. 21, No. 6, p. 1166-1172.

Fletcher, C.H., and M.A. Merrifield. 2009. "Sea Level by the End of the 21st Century: a Review." University of Hawaii memorandum. May 29, 2009.

Fletcher, C.H., E. Newsome, and M. Barbee. 2010. "A Schedule of Local Relative Sea Level Inundation." Abstract submitted to *2010 Hawaii Conservation Conference, Pacific Ecosystem Management & Restoration: Applying Traditional and Western Knowledge Systems*.

U.S. Environmental Protection Agency. 2009. *Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region*. January 15, 2009.

U.S. Army Corps of Engineers. 2009. *Incorporating Sea-Level Change Considerations in Civil Works Programs*. EC 1165-2-211. Washington, DC.

Velicogna, I. 2009. "Increasing Rates of Ice Mass Loss from the Greenland and Antarctic Ice Sheets Revealed by GRACE." *Geophysical Research Letters*, Vol 36, L19503

Vermeer, M., and S. Rahmstorf. 2009. "Global Sea Level Linked to Global Temperature." Proc. Of the Academy of Sciences of the United States of America, available online (http://www.pnas.org/content/106/51/21527.full.pdf+html).

Appendix B

Sea level by the end of the 21st century: A review

By

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ABSTRACT

The rate of global mean sea-level rise (~3 mm/yr; SLR) has accelerated compared to the mean of the 20th century (~1 to 2 mm/yr), but the rate of rise is locally variable and may be subject to quasi-periodic decadal fluctuations. Factors contributing to SLR include decreased global ice volume and warming of the ocean. On Greenland, the deficiency between annual ice gained and lost tripled between 1996 and 2007. On Antarctica the deficiency increased by 75%. Mountain glaciers are retreating and the cumulative mean thickness change has accelerated from about -1.8 m to -4 m in 1965 to 1970 to about -12 m to -14 m in the first decade of the 21st century. From 1961 to 2003, ocean temperatures to a depth of 700 m increased and portions of the deeper ocean are warming. The Intergovernmental Panel on Climate Change (2007) projected that sea level would reach 0.18 m to 0.59 m above present by the end of the 21st century but lacked an estimate of ice flow dynamics (calving). Calving was added by Pfeffer *et al.* (2008) indicating 0.8 m to 2 m of SLR by 2100 (favoring the low end of this range). Rahmstorf (2007) estimated SLR will reach 0.5 m to 1.4 m by the end of the century. Pielke (2008) points out that observed SLR has exceeded the best-case projections thus far. These approximations and others indicate that global mean SLR may reach 1 m by the end of this century. However, sea level is highly variable and planners should consider this variability as impacts will be scaled to local SLR.

ADDITIONAL KEYWORDS:
Sea-level rise, 21st century, global warming, global change, tide gauges, coastal management, sea level, coastal hazards.

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Global mean air temperature is increasing in relation to global warming (Hansen *et al.* 2006; GISS 2009). As a result, Earth's ice volume is decreasing (Zwally *et al.* 2008; Steig *et al.* 2009) and the heat content of the ocean is increasing (Levitus *et al.* 2009). Global mean sea level is therefore rising, and the rate of rise has accelerated (Church and White 2006; Jevrejeva *et al.* 2008, Merrifield *et al.* 2009). Sea-level rise (SLR) presents challenges to coastal communities and ecosystems, and planners are engaged in assessing management options (California Executive Order S-13-08 2008). Accordingly, it is desirable to have an estimate of SLR this century to properly design mitigation and adaptation strategies. An approximation of SLR by the end of the century will allow: 1) Estimates of coastal erosion and changes in vulnerability to coastal hazards; 2) Assessments of threats to coastal ecosystems; and 3) Development of climate risk management policies. This paper reviews recent studies of global warming, sea-level observations, global ice volume, ocean heating, and estimates of SLR by the end of the 21st century.

Based on current scientific understanding, we conclude that a global mean rise of approximately 1 m around the end of the century is indicated by present research and constitutes an appropriate planning target at this time. However, sea-level rise will have important local variability that planners should consider as knowledge of that variability improves. Global mean sea-level may rise significantly more than 1 m, but is unlikely to rise significantly less (Hansen 2007). Important questions remain regarding the melt rate of ice in West Antarctica and southern Greenland. Also unknown are the actual levels of natural climate variability and greenhouse gas accumulation that will be reached this century. However, even if atmospheric composition were stabilized today, global warming and SLR would continue (Meehl *et al.* 2005). Avoiding these changes requires, eventually, a reduction in emissions to substantially below present levels (Wigley 2005).

GLOBAL WARMING

Heat-trapping gases such as carbon dioxide, methane, and others have increased in atmospheric abundance due to human industrial activities (Solomon *et al.* 2009) driving a global trend of atmospheric warming (GISS 2009; Figure 1). Measurements indicate that the amounts of carbon dioxide and other greenhouse gases in the atmosphere have increased over the past century (CDIAC 2009; Canadell *et al.* 2007; MLO 2009) and exceed levels of the past 650,000 years as measured by ice cores from Antarctica (Siegenthaler *et al.* 2005; Spahni *et al.* 2005). Measurements also indicate that global atmospheric temperature has risen 0.74 ± 0.18 °C during the 100 years ending in 2005 (NCDC 2007), while precipitation (expected to increase in a warmer atmosphere) rose $1.4 \pm 0.5\%$ per decade (Wentz *et al*. 2007).

The calendar year 2007 tied 1998 as the second warmest year on the instrumental record (beginning 1880) while 2005 was the warmest (GISS 2008). This is remarkable considering that 2007 was a cool La Niña year and a time of low solar activity (the lowest in 20 years) and 1998 was a strong El Niño year characterized by high solar activity. Calendar year 2008, the coolest year since 2000, was nonetheless the ninth warmest year in the period of instrumental observations. Notably, the 10 warmest years all occur within the 12-year period 1997-2008. The annual growth rate of climate forcing by long-lived greenhouse gases slowed from a peak close to 0.05 W/m^2 per year around 1980-85 to about 0.035 W/m^2 in recent years due to slowdown of CH_4 and CFC growth rates. Resumed methane growth, if it continued in 2008 as in 2007, adds

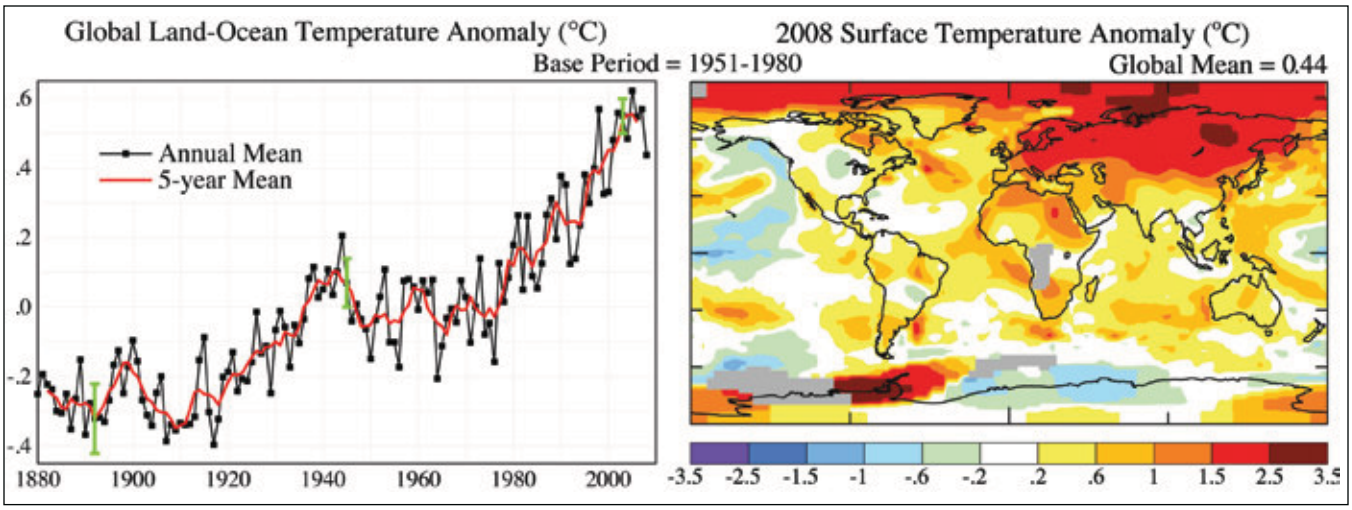


Figure 1. Left: Annual-means of global-mean temperature anomaly. Right: Global map of surface temperature anomalies, in degrees Celsius, for 2008 (*GISS 2009*).

about 0.005 W/m^2. From climate models and empirical analyses, this forcing trend translates into a mean warming rate of ~0.15°C per decade (GISS 2008).

SEA-LEVEL OBSERVATIONS

Radar altimeters can measure the sea surface from space to within a few centimeters (Leuliette *et al.* 2004; Beckley *et al.* 2007). The TOPEX/Poseidon mission (launched in 1992) and its successors Jason-1 (2001) and Jason-2 (2008) have mapped the sea surface approximately every 10 days for 16 years. These missions have led to major advances in physical oceanography and climate studies (JPL 2009).

Altimeter measurements indicate that global mean sea level has risen 4.5 cm from 1993 to 2008 at a rate of approximately 3 mm/yr (3.2+/-0.4 mm/yr; http://sealevel.colorado.edu/). However, this rise is not uniform across the oceans. Figure 2 shows a map of altimeter measurements depicting the rate of sea-level change since 1993. Rates are contoured by color: light blue indicates regions where sea level has been relatively stable; green, yellow and red show areas of sea-level rise; blue and purple indicate areas of sea-level fall. This complex surface pattern largely reflects wind-driven changes in the thickness of the upper layer of the ocean, and to a lesser extent changes in upper ocean heat content driven by surface fluxes.

Most noticeable on the map, sea-level rise in the western Pacific approaches 10 mm/yr. This pool of rising water has the signature shape of La Niña conditions in the tropical Pacific. The sea-level buildup in the western Pacific coincides with the absence of strong El Niño events, with the last occurring during 1997-98. The PDO (Pacific Decadal Oscillation) is a basin-wide climate pattern consisting of two phases, each commonly lasting 10-30 years (Mantua *et al.* 1997; Biondi *et al.* 2001; Zhang *et al.* 1997). In a positive phase of the PDO, surface waters in the western Pacific above 20° N latitude tend

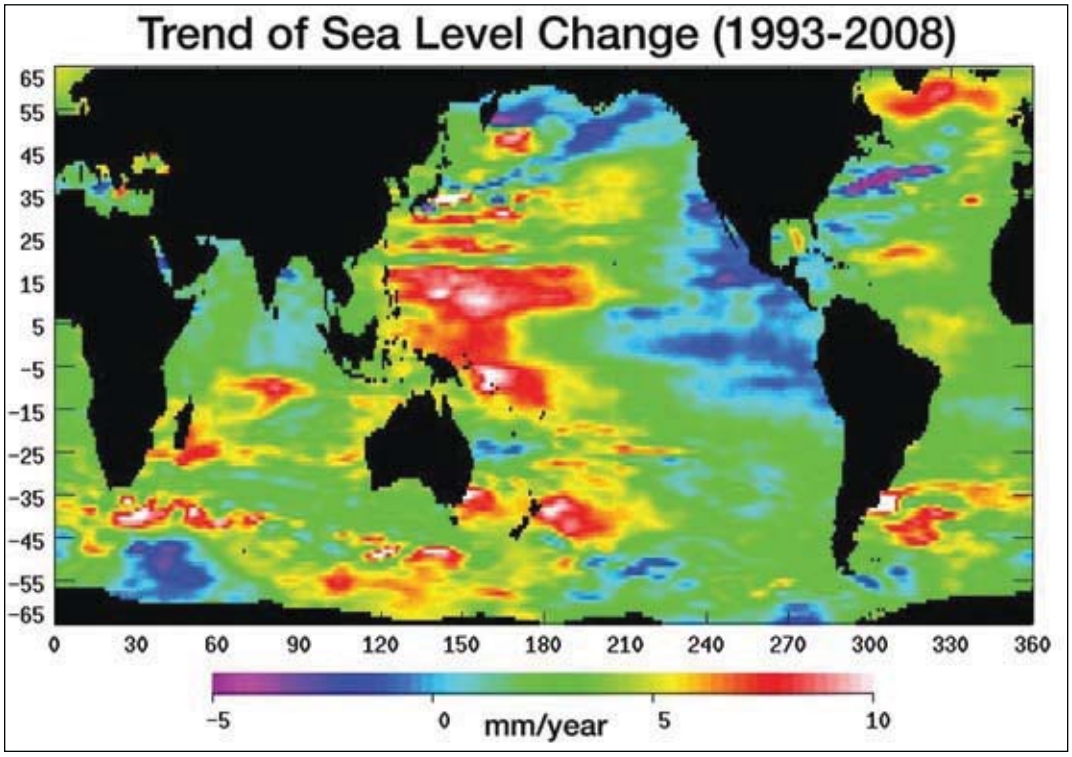


Figure 2. Warming water and melting land ice have raised global mean sea level 4.5 cm from 1993 to 2008 at a rate of about 3 mm/yr. But the rise is not uniform. This image, created with sea surface height data from the Topex/ Poseidon and Jason-1 satellites, shows where sea level has changed during this time and how quickly these changes have occurred (JPL 2009). The complex surface reflects the influence of warm and cool bodies of water, currents, and winds.

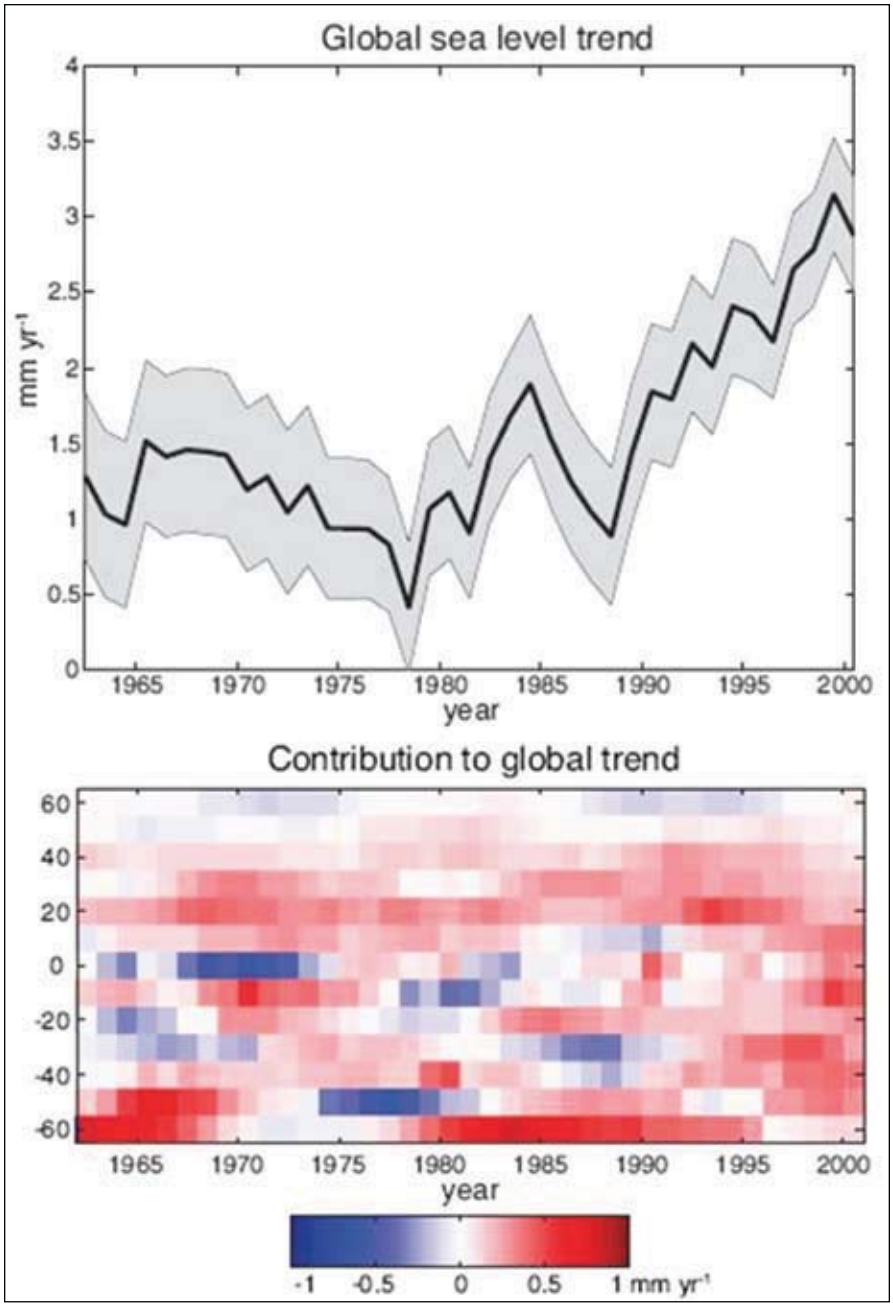


Figure 3. Top: Tide gauge derived global sea level trends estimated over 15-year segments and plotted versus the mid-year of the segment. One standard error is indicated by the shaded region. Bottom: The average sea level trend in each 10° latitude band as a function of the mid-year of the 15-year window used to compute the trend. The trends are multiplied by the fraction of total ocean surface area (-60° to 60°) in each latitude band (Merrifield *et al.* 2009)

to be cool, while equatorial waters in the central and eastern Pacific tend to be warm. In a negative phase, the opposite pattern develops. Hence, rapid sea-level rise in the western Pacific matches the current negative phase of the PDO. The degree to which this pattern contributes to the global mean rate of sea-level rise observed in satellite altimetry is not known.

Another important source of sea-level observations comes from the global network of tide gauges. Church and White (2006) used this network in combination with satellite altimeter data to establish that global mean sea-level rose 19.5 cm between 1870 and 2004 at an average rate of about 1.44 mm/yr (1.7 mm/yr during the 20th century). The SLR trend increases over this period, with a notable slope change around 1930, resulting in a significant acceleration of 0.013 ± 0.006 mm yr^{-2}. This is an important confirmation of climate change simulations predicting that SLR will accelerate in response to global warming. If this acceleration remains constant then the amount of rise from 1990 to 2100 will range from 28 cm to 34 cm. This is consistent with model results (IPCC 2007) in which global average sea level was projected to rise 18-59 cm by 2100. Cazenave et al. (2009) update and confirm the IPCC assessment of current global sea-level rise (~3.1 mm/yr) with observations from 2003-2008. They confirm their estimate (2.5 mm/yr) by evaluating contributions from thermal expansion and ice loss from Greenland. Importantly, Church and White (2006) note that the recent increase in SLR at the end of the 20th century is not statistically distinguishable from decadal variations in sea level that have occurred throughout the record.

However, further work with long tide gauge records (Jevrejeva *et al.* 2008) revealed that sea level acceleration may have started earlier, more than 200 years ago. They reconstructed global mean sea level since 1700 from tide gauge records and concluded that sea-level acceleration up to the present has been about 0.01 mm yr^{-2}; and began at the end of the 18th century. Sea level rose by 6 cm during the 19th century and 19 cm in the 20th century. They also discovered quasi-periodic fluctuations with a period of about 60 years superimposed on the long-term history. On the basis of this analysis, they conclude that if the conditions that established the acceleration continue, then sea level will rise 34 cm over the 21st century.

In their 4th assessment of global climate change, the IPCC (2007) reported that SLR since 1961 has averaged 1.8 (1.3 to 2.3) mm/yr and since 1993 it has averaged 3.1 (2.4 to 3.8) mm/yr, with contributions from thermal expansion, melting glaciers and ice caps, and the polar ice sheets. However, they caution that it is unclear if the faster rate since 1993 reflects decadal variation or an increase in the longer-term trend. Merrifield *et al.* (2009) examine an area weighted average of tide gauge trends and conclude that the recent sea-level acceleration reflects an anomalous trend increase that is distinct from a decadal variation (Figure 3). Increased rates in the tropical and southern oceans primarily account for the acceleration. The timing of the global acceleration corresponds to similar

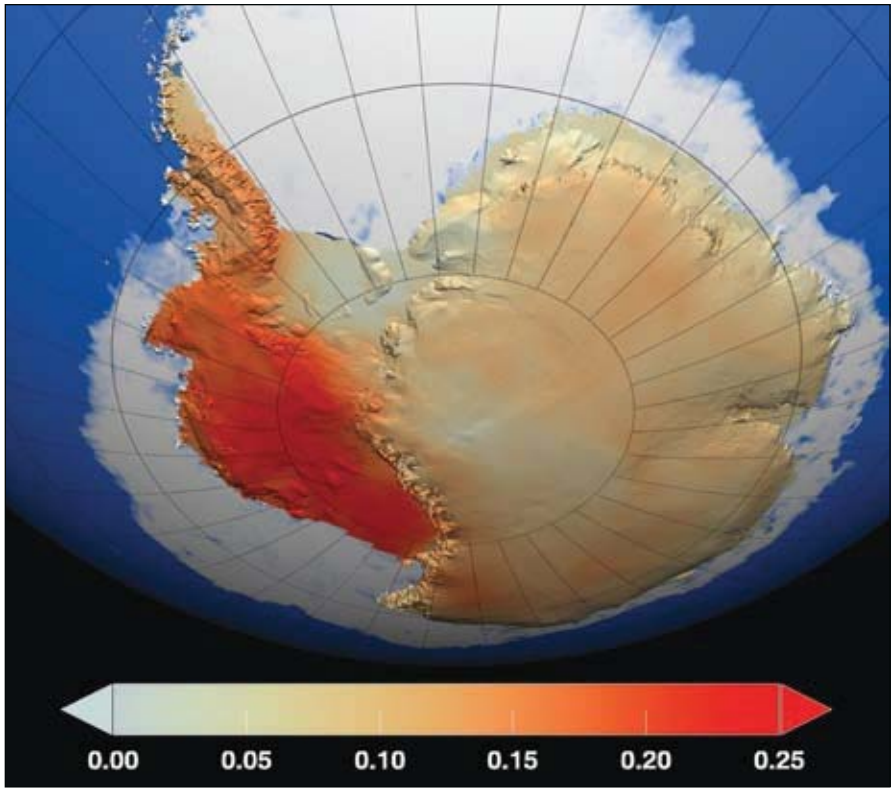
sea level trend changes associated with upper ocean heat and ice melt. Whether the recent change is associated with the 60 year variations noted by Jevrejeva *et al.* (2008) remains unclear.

Geologic observations can be used to improve understanding of the natural rate and magnitude of sea-level change within measured time periods. Researchers (Siddall *et al.* 2009) have reconstructed sea-level fluctuations over the past 22,000 years, spanning the last glacial maximum to the present interglacial warm phase. Hence, changing climate, in the form of shifts in ice volume and global temperature, is responsible for driving sea-level changes over this period. The reconstructed relationship between climate and sea level predicts 4-24 cm of sea level rise over the 20th century, in agreement with IPCC (2007). When used to forecast sea-level heights over the 21th century on the basis of modeled temperature projections (1.1° to 6.4° C; IPCC 2007), the reconstruction predicts 7 cm to 82 cm of sea-level rise by the end of the 21th century. This is slightly larger than the IPCC estimate of 18-76 cm, but Siddall and coworkers conclude it is sufficiently similar to increase confidence in the projections. Rahmstorf and Vermeer (2009) have criticized this conclusion as being too low and point out errors in the modeling of Siddall *et al.*

GLOBAL ICE VOLUME

Heat in the atmosphere leads to melting of glaciers and sea ice (Maslanik *et al.* 2007), a decrease in the extent of snow cover, and shifts from snowfall to rainfall. Melting of glacier ice and snow contribute to SLR, whereas melting sea ice does not directly contribute to sea-level rise because it already displaces its own mass in the oceans. However, as sea ice retreats, more dark open water is exposed to absorb heat from the atmosphere and from the sun, contributing to heating of the Arctic and Antarctic and further encouraging SLR. According to scientists from the National Snow and Ice Data Center in Boulder (NSIDC 2009a), retreating ice cover in the Arctic Ocean, long held to be an early warning of warming climate, shattered the all-time low record in the summer of 2007, and nearly matched it again in 2008.

Using satellite imagery, researchers now estimate that the summer Arctic ice pack covers 4.2 million km^2, equal to



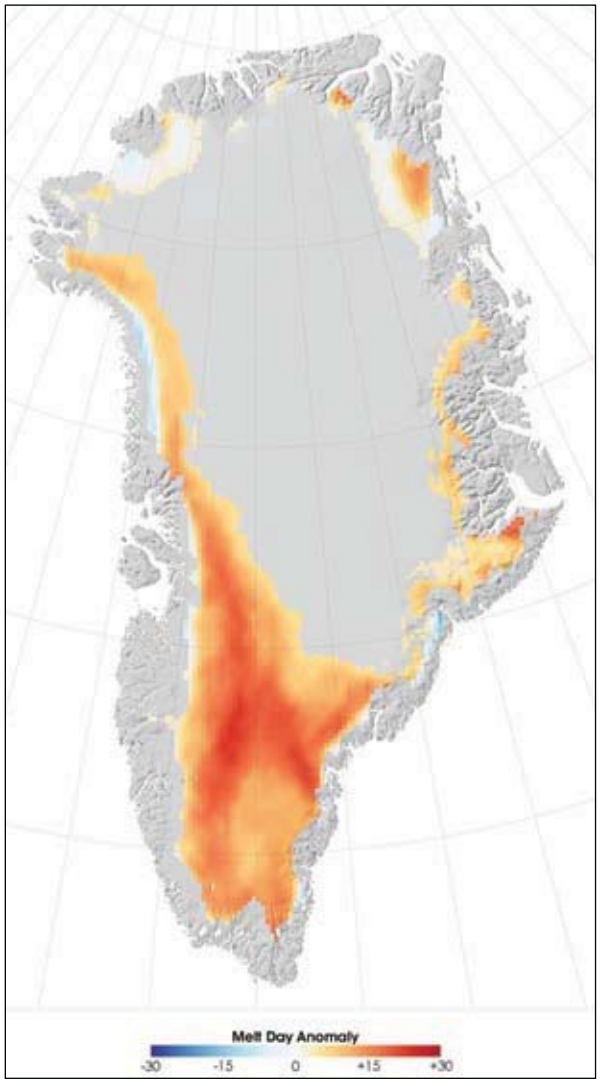


Figure 4. Left: Greenland 2007 melt anomaly, measured as the difference between the number of days on which melting occurred in 2007 compared to the average annual melting days from 1988-2006 (Earth Observatory 2009a). Above: Reconstruction of Antarctic surface temperature trends (° C per decade) for 1957-2006 (Steig *et al.* 2009). Overall, the continent is warming by about 0.1° C per decade.

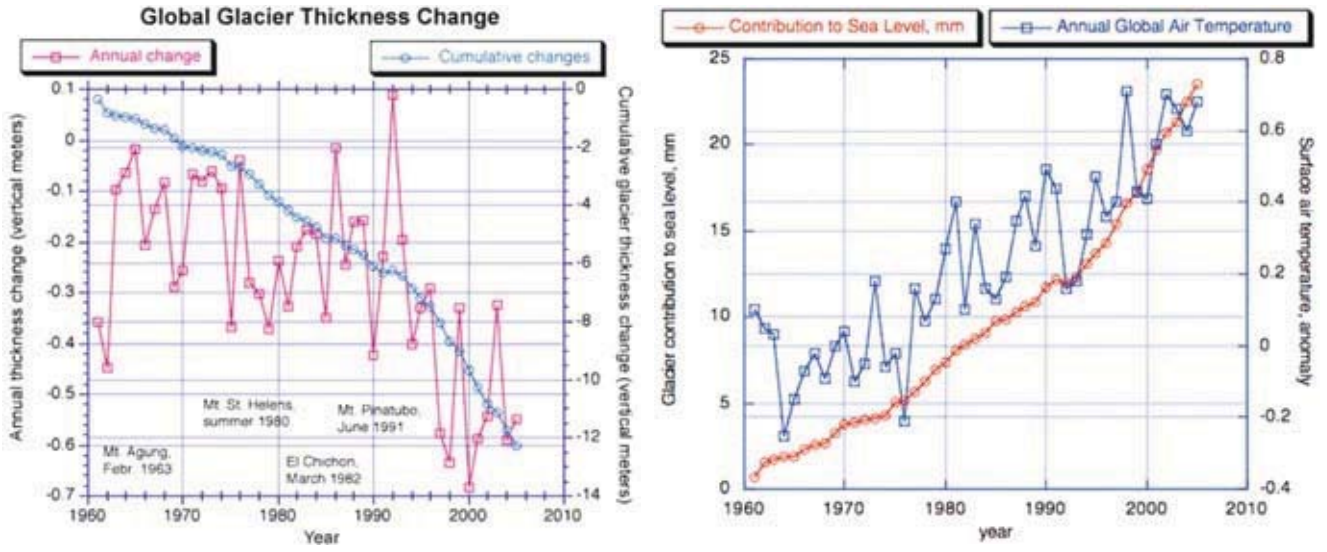


Figure 5. Left: Average annual and cumulative alpine (mountain) glacier thickness change, measured in vertical meters, since 1961. From 1961 to 2005, the thickness of "small" glaciers decreased approximately 12 m (NSIDC 2009b). Right: Cumulative contribution to sea level from small glaciers and ice caps (red) plotted with the annual global surface air temperature anomaly (blue). Image courtesy Mark Dyurgerov, Institute of Arctic and Alpine Research, University of Colorado, Boulder.

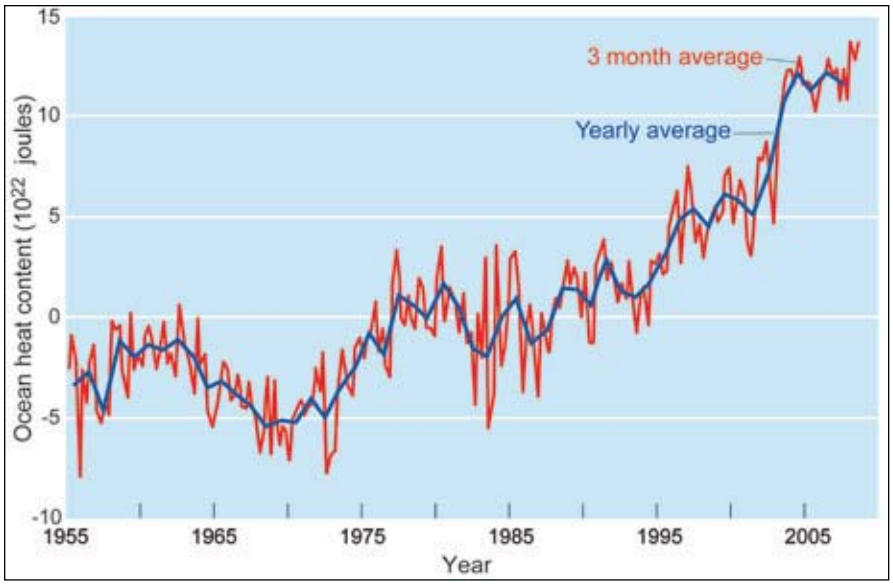


Figure 6. The global ocean heat content, 1955-2008 (Levitus *et al.* 2009).

just less than half the size of the United States. This figure is about 20 percent less than the previous all-time low record of 5 million km^2 set in September 2005 (GSFC 2009). Scientists report that the summer ice pack "absolutely stunned us" (ScienceDaily 2007) and was the most dramatic loss observed in the history of watching the Arctic ice pack. Most researchers had anticipated the complete disappearance of the Arctic ice pack during summer months after the year 2070, but now they speculate that losing summer ice cover by 2030 — or even earlier — is not unreasonable (Wang and Overland 2009). Thus the stage is set for what scientists refer to as an "albedo flip." Albedo is a measure of the reflectivity of Earth's surface. That is, the former heat-reflecting ice surface will become a heat-absorbing body of water.

Until recently, the contribution of the Greenland continental glacier to sea-level rise has been unknown. Now, however, increased melting of the Greenland ice sheet (Figure 4) has been observed and it is known that the glacier is getting smaller. The balance between annual ice gained and lost is in deficit and the deficiency tripled between 1996 and 2007 (Rignot *et al.* 2008a). In Greenland, the year 2007 marked a rise to record levels of the summertime melting trend over the highest altitudes of the Greenland ice sheet. Melting in areas above 2000 m rose 150% above the long-term average, with melting occurring on 25 to 30 more days in 2007 than the average in the previous nineteen years (Earth Observatory 2009a). Scientists have found that glaciers in southern Greenland are flowing 30% to 210% faster than they were 10 years ago, and the overall amount of ice discharged into the sea has increased from 21 km^3 in 1996 to 54 cubic km^3 in 2005, an increase of 250%.

Greenland's contribution to average sea-level rise increased from 2.3 mm per decade in 1996 to 5 mm per decade in 2005. This accounts for between 20% and 38% of the observed yearly global sea-level rise (Rignot and Kanagaratnam 2006). Two-thirds of Greenland's sea level contribution is due to glacier dynamics (chunks of ice breaking off and melting), and one-third is from direct melting. As glacier acceleration continues to spread northward from its current focus in southern Greenland, the global sea-level rise contribution from the world's largest island will continue to increase.

Antarctica consists of three main geographic regions: the Antarctic Peninsula, West Antarctica, and East Antarctica. In West Antarctica, which has warmed 0.17°C per decade at the same time that global warming was 0.13° C per decade, ice loss has increased by 59% in the early

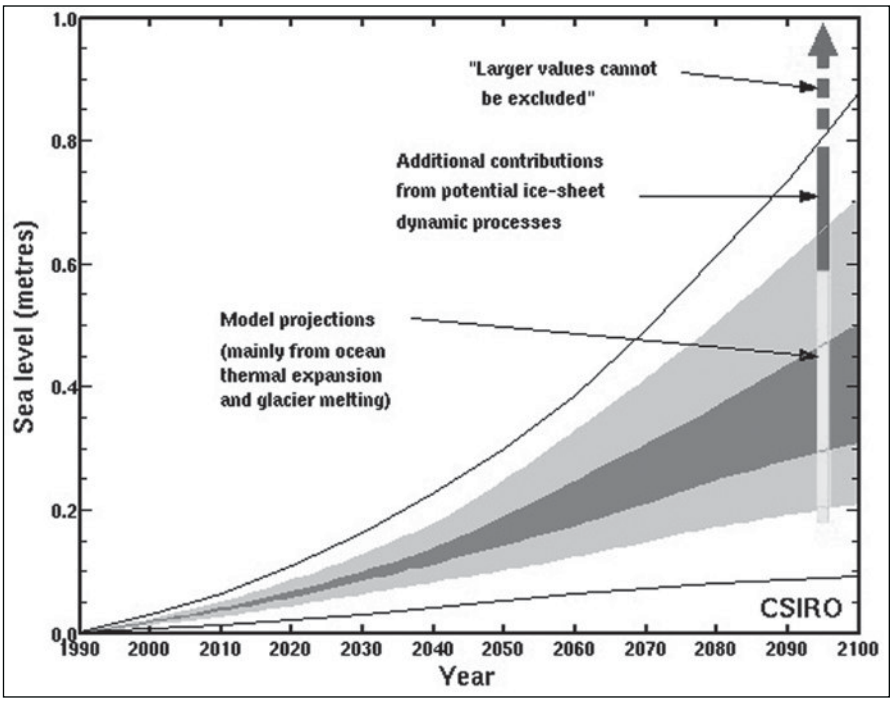


Figure 7. IPCC (2007) predicts that by 2100 sea level will rise between 18 and 59 cm, but does not include a component for ice calving (ice-sheet dynamic processes). The missing component was added by Pfeffer *et al.* (2008) who conclude that by 2100 sea level will rise between 0.8 m and 2 m, preferring the lower end of the range. (Image from Commonwealth Scientific and Industrial Research Organization, last viewed 5/22/09: http://www.cmar.csiro.au/sealevel/sl_proj_21st.html)

21st century to about 132 billion metric tons per year (Rignot *et al.* 2008b). The yearly loss along the Antarctic Peninsula has increased by 140% to 60 billion metric tons. The East Antarctic ice sheet, by far the largest region of the continent, has an ice budget that is overall stable to slightly melting. It is experiencing melting along the coastal margin in warming seas and snow accumulation in the hinterlands. Overall the entire continent of Antarctica is experiencing net melting (Steig *et al.* 2009). All three regions of Antarctica are warming (Figure 4) and overall ice loss in Antarctica increased by 75% in the past 10 years.

Alpine and other types of mountain glaciers are also retreating (Earth Observatory 2009b; Figure 5). In fact, for the millions of people that depend on seasonal ice melting as a source of freshwater, the retreat and eventual loss of this ice delivers a fundamental blow to the sustainability of communities. Mountain glaciers are retreating around the globe and the cumulative mean thickness change has accelerated from about -1.8 m to -4 m in 1965 to 1970 to about -12 m to -14 m of thinning in the first decade of the 21st century (Meier *et al.* 2007). To reach equilibrium with average climate over the period 1997-2006, mountain glaciers and outlet glaciers in Greenland and Antarctica will lose another 27% of their volume (Bahr *et al.* 2009).

In their fourth assessment of global climate change, the IPCC (2007) estimated that the sum of all contributions to sea-level rise for the period 1961–2004 equaled 1.1 ± 0.5 mm/yr. The observed sea-level rise over the same period was 1.8 ± 0.5 mm/yr, thus leaving 0.7 ± 0.7 unexplained. To close this gap, researchers (Hock *et al.* 2009) computed the global surface mass balance of all mountain glaciers and ice caps and found that part of the missing sea level component can be attributed to mass loss from this source, especially around the Antarctic Peninsula. They estimate that mountain glaciers and ice caps account for 0.79 ± 0.34 mm/yr of sea-level rise compared to 0.50 ± 0.18 mm/yr estimated in the IPCC (2007). Antarctic mountain glaciers contribute 28% of this.

OCEAN HEATING

In terms of heat content, it is the world ocean that dominates atmospheric climate. The oceans store more than 90% of the heat in Earth's climate system and act as a temporary buffer against the effects of climate change. For instance, an average temperature increase of the entire world ocean by 0.01°C may seem small, but in fact it represents a very large increase in heat content. If all the heat associated with this anomaly were instantaneously transferred to the entire global atmosphere it would increase the average temperature of the atmosphere by approximately 10° C (Levitus *et al.* 2005). Thus, a small change in the mean temperature of the ocean represents a very large change in the total heat content of the climate system. Of course, when the ocean gains heat (Figure 6), the water expands and this represents a component of global sea-level rise.

Understanding how ocean warming and the resulting thermal expansion contribute to SLR is critically important to understanding climate change, and forecasting future temperature rises. Researchers (Domingues *et al.* 2008) found that from 1961 to 2003, ocean temperatures to a depth of 700 m contributed to an average rise in sea levels of about 0.52 mm/yr compared to a rise of 0.32 mm/yr reported by the IPCC (2007). Although recent warming is greatest in the upper ocean, observations (Johnson *et al.* 2006; Johnson *et al.* 2007) also indicate the deeper portions of the oceans are warming, estimated to cause sea-level rise of about 0.2 mm/yr. Over the period 1961-2003, alpine glaciers and ice caps contributed an estimated 0.5 mm/yr to global sea-level rise, increasing to 0.8 mm/yr for the period 1993–2003 (Dyurgerov and Meier 2005). The IPCC estimated the contributions of ice loss on Greenland (about 0.21 mm/yr) and Antarctica (about 0.21 mm/yr) to global sea level. By summing these various components of sea-level rise, Domingues *et al.* (2008) found that from 1961 to 2003 the sea-level rise "budget" totaled about 1.5+/-0.4 mm/yr. This agreed with their estimate of mean sea-level rise over the same period using observational tide gauge data (1.6+/-0.2 mm/yr).

SEA-LEVEL AT THE END OF THE CENTURY

The IPCC (2007) has predicted future sea-level changes to the year 2100. They are not the first body to attempt this important exercise, nor are their latest results their first attempt. Their estimate forecasts a range of global SLR from 18

cm to 59 cm by the end of this century. These projections are based on thermal expansion due to ocean heating and ice melting, but do not include a component based on ice sheet dynamics (calving). Hence, it is understood that they underestimate the potential for flooding due to rising seas by the end of the century.

Two studies published in 2007, both by German climate researcher Stefan Rahmstorf and colleagues, use an empirical approach relating future climate change and SLR based on recent history. In one study (Rahmstorf *et al.* 2007), Rahmstorf and colleagues compared projections of atmospheric warming and sea-level over the period 1990 to 2006, made in 2001 by the IPCC (2001), to observations over the same period. The results indicate that the climate system, in particular sea level, may be responding to global warming more quickly than models specify. While the observed carbon dioxide concentrations follow the model projections almost exactly, the temperature changes are in the upper part of the range predicted by the IPCC and the sea level changes are beyond the upper range of the predictions. Rahmstorf found that the rate of rise for the past 20 years is 25% faster than the rate of rise in any 20-year period in the preceding 115 years. In their conclusion, the authors state: "Overall, these observational data underscore the concerns about global climate change. Previous projections, as summarized by IPCC, have not exaggerated but may in some respects even have underestimated the change, in particular for sea level."

In his other paper in 2007 (Rahmstorf 2007), Rahmstorf estimates 21st century sea-level change on the historical relationship between 20th century temperature changes and sea-level changes. He presents the empirical relationship that connects global sea-level rise to global mean surface temperature over the period 1880-2000 and proposes that, for time scales relevant to global warming, the rate of sea-level rise is roughly proportional to the magnitude of warming above the temperatures of the pre-Industrial Age. The study establishes a proportionality of 3.4 mm/yr of sea-level rise per °C of global temperature warming. When applied to IPCC (2001) warming scenarios at the end of the century (1.4° to 5.8° C), this relationship results in a projected sea-level rise in 2100 of 0.5 to 1.4 m above the 1990 level with a mean of 0.95 m.

This estimate is confirmed by Pfeffer *et al.* (2008) who examine the physics of ice calving. Estimates of ice calving were absent in the 2007 IPCC report. Pfeffer adds estimates of SLR due to thermal expansion and ice melting to calving approximations and concludes that SLR by the end of the century will range 0.8 m to 2.0 m above present with an emphasis on the lower area of this range (Figure 7).

On the basis of the work by Rahmstorf and Pfeffer *et al*., the observed accumulation of heat in the ocean, and the acceleration of melting, there is a building consensus among scientists that SLR will approach and perhaps pass 1 m by the end of the 21st century (ScienceDaily 2009a, 2009b). For instance, members of the 2009 International Scientific Congress on Climate Change held at University of Copenhagen 10-12 March (ISCCC 2009) released a press statement titled "Rising sea levels set to have major impacts around the world." Conference delegates stated "Research presented today at the International Scientific Congress on Climate Change in Copenhagen shows that the upper range of sea level rise by 2100 could be in the range of about one meter, or possibly more." A key member of the congress was Dr. John Church, who pointed out that sea level is currently rising at a rate that is above any of the model projections of 18 cm to 59 cm provided by the IPCC (2007).

The U.S. Army Corps of Engineers (2009) published guidance for incorporating the direct and indirect physical effects of projected future sea-level change in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects. They cite the potential of sea-level change to cause a number of impacts in coastal and estuarine zones, including changes in shoreline erosion, inundation or exposure of low-lying coastal areas, changes in storm and flood damages, shifts in extent and distribution of wetlands and other coastal habitats, changes to groundwater levels, and alterations to salinity intrusion into estuaries and groundwater systems. Their guidance suggests that designers incorporate into their plans the potential of global mean sea-level rise to affect the local mean sea-level trend. They suggest that using local relative sea-level records shorter than 40 years is not advisable, and that the annual maximum and minimum behavior of sea level are useful in calculating local variability. In projecting future sea level, it is important to consider the confidence of present local trends, the local relative rate of change, the global rate of change, the absence of dramatic geologic or oceanographic events. The Army Corps guidance updates the National Research Council (1987) with findings from the IPCC (2007) and assumes a global mean sea-level change rate of 1.7 mm/year. This ignores altimetry data (~3 mm/year), as well as updates to IPCC (2007) by Rahmstorf (2007), Pfeffer *et al.* (2008), Domingues *et al.* (2008), and Merrifield *et al.* (2009).

POTENTIAL TO EXCEED 1 M

If greenhouse gas concentrations were stabilized today, sea level would nonetheless continue to rise for hundreds of years (Solomon *et al.* 2009). After 500 years, sea-level rise from thermal expansion alone may have reached only half of its eventual level, which models suggest may lie within ranges of 0.5 m to 2 m. Glacier retreat will continue and the loss of a substantial fraction of Earth's total glacier mass is likely. Areas that are currently marginally glaciated are likely to become ice-free. But it is unlikely that greenhouse gases will be stabilized soon, so we can probably count on additional atmospheric heating — and sea-level rise (Wigley 2005; Meehl *et al.* 2005; Solomon *et al.* 2009).

Pielke (2008) points out that observed SLR has exceeded the best-case projections thus far. Research (Overpeck *et al.* 2006) also suggests that Earth's warming temperatures may be on track to melt the Greenland and Antarctic ice sheets sooner than previously thought and ultimately lead to a global sea-level rise of at least 6 m. Mitrovica *et al.* (2009) focused on longer-term sea-level projections (next century and beyond) and raised the important point that physics-based investigations of the changes in the distribution of mass on the globe and their effects on crustal adjustment and Earth's rotation indicate that sea-level rise may be accentuated in some regions. They argue that because of this, current estimates which do not incorporate these factors will underestimate future sea-level rise.

Researchers found that if the current warming trends continue, by 2100 Earth

will likely be at least 4° C warmer than present, with the Arctic at least as warm as it was nearly 130,000 years ago when the Greenland ice sheet was a mere fragment of its present size. Study leader Jonathan T. Overpeck of the University of Arizona in Tucson said: "The last time the Arctic was significantly warmer than present day, the Greenland Ice Sheet melted back the equivalent of about 2 to 3 m of sea level." The research also suggests the Antarctic ice sheet melted substantially, contributing another 2-3 m of sea-level rise. The ice sheets are melting already. The new research suggests melting could accelerate, thereby raising sea level as fast, or faster, than 1 m per century.

SCIENTIFIC RETICENCE

Global warming and its consequences present new challenges to modern society. Among these is a degree of uncertainty among scientists about how to communicate the dramatic environmental changes that may be in store. For example, in 2007 James Hansen of the NASA Goddard Institute for Space Studies published a paper about scientific reticence in Environmental Research Letters, an online science journal open to the public (Hansen 2007). He proposed that normally quite articulate scientists become reluctant to communicate the full threat of potentially large and damaging future sea-level rise out of a misplaced sense of scientific conservatism.

Reticence, Hansen argues, prevents researchers from expressing their full understanding of the implications of global warming on human communities. He expresses the opinion that professional reserve and cautious judgment may be hindering the ability of society to recognize and respond to the signs of catastrophic future sea-level rise. This may lead to unnecessary future expense, damage, and even threats to public safety. In the words of the author: "We may rue reticence, if it serves to lock in future disasters." He describes how a scientist who has made an important discovery may have concerns about the danger of "crying wolf" and that this danger is more immediate in his mind than concern about the danger of "fiddling while Rome burns." He cites studies of human behavior that show a preference for immediate over delayed rewards, which may contribute to irrational reticence even among rational scientists.

CONCLUSIONS

Global SLR has accelerated in response to warming of the atmosphere and the ocean, and melting of the cryosphere. Projections indicate that a 1 m rise by the end of this century is plausible. Pielke (2008) points out that observed SLR has exceeded the best case projections thus far. Satellite altimetry suggests that sea-level rise will have significant local variability that is worthy of continued research to improve understanding. Planners should consider this variability as impacts will be scaled to local SLR.

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REFERENCES

Bahr, D.B., M. Dyurgerov, and M.F. Meier 2009. "Sea-level rise from glaciers and ice caps: A lower bound." *Geophys. Res. Letters*, 36, L03501, DOI:10.1029/2008GL036309.

Beckley, B.D., F.G. Lemoine, S.B. Luthcke, R.D. Ray, and N.P. Zelensky 2007. "A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits." *Geophys. Res. Letters*, 34(14), L1-4608.

Biondi, F., A. Gershunov, and D.R. Cayan 2001. "North Pacific Decadal Climate Variability since 1661." *J. of Climate*, v. 14 (1), p. 5-10.

California Executive Order S-13-08, 2008. Ordering the California Resources Agency to complete the first California Sea Level Rise Assessment Report. 14 November; last viewed 25 May 2009: http://gov.ca.gov/executive-order/11036/.

Canadell, J.G., Le Quere, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., and Marland, G., 2007. "Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks," *Proc. of the National Academy of Sciences*, v. 104, n. 47, p. 18866-18870; last viewed 22 May 2009: http://www.pnas.org/content/104/47/18866.full.pdf+html.

Carbon Dioxide Information Analysis Center (CDIAC), U.S. Department of Energy; last viewed 22 May 2009: http://cdiac.ornl.gov/.

Cazenave, A., Dominh, K., Guinehut, S., Berthier, E., Llovel, W., Ramillien, G., Ablain, M., and Larnicol, G., 2009. "Sea level budget over 2003-2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo." *Global and Planetary Change, 65*, 83-88.

Church, J. A., and N.J. White 2006. "20th century acceleration in global sea-level rise," *Geophys. Res. Letters*, 33(1), L01602

Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn 2008. "Improved estimates of upper-ocean warming and multi-decadal sea-level rise." *Nature,* 453, 1090-1093: DOI: 10.1038/nature07080.

Dyurgerov, M. B., and M.F. Meier 2005. "Glaciers and the Changing Earth System: A 2004 Snapshot" (Occasional Paper 58, Institute of Arctic and Alpine Research, Univ. of Colorado); last viewed 22 May 2009: http://instaar.colorado.edu/other/occ_papers.html.

Earth Observatory, press release, 2009a. "Melting Anomalies in Greenland in 2007"; last viewed 22 May 2009: http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=1784.

Earth Observatory, press release, 2009b. "Global Glacier Melt Continues"; last viewed 25 May 2009: http://earthobservatory.nasa.gov/Newsroom/view.php?id=36854.

Goddard Institute for Space Studies (GISS), 2008. "Global Temperature Trends: 2007 Annual Summation"; last viewed 22 May 2009: http://data.giss.nasa.gov/gistemp/2007/.

Goddard Institute for Space Studies (GISS), 2009. "Global Temperature Trends: 2008 Annual Summation"; last viewed 22 May 2009: http://data.giss.nasa.gov/gistemp/2008/.

Goddard Space Flight Center (GSFC), 2009. "Sea ice yearly minimum 1979-2007"; last viewed 22 May 2009: http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003464/index.html.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade 2006. "Global temperature change." *Proc. of the National Academy of Sciences*, v. 103, p. 14288-14293, doi:doi:10.1073/pnas.0606291103.

Hansen, J.E., 2007. "Scientific reticence and sea-level rise." *Environ. Res. Letters*, 2 (April-June) 024002, doi:10.1088/1748-9326/2/2/024002; last viewed 22 May 2009: http://www.iop.org/EJ/article/1748-9326/2/2/024002/erl7_2_024002.html.

Hock, R., M. de Woul, V. Radic, M. Dyurgerov 2009. "Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution." *Geophys. Res. Letters*, v. 36, L07501, doi:10.1029/2008GL037020.

Intergovernmental Panel on Climate Change (IPCC), 2007. *Climate Change 2007, The Physical Science Basis*. Cambridge University Press, Cambridge, 2007.

Intergovernmental Panel on Climate Change (IPCC), 2001. *Climate Change 2001, The Scientific Basis.* Cambridge University Press, Cambridge, 2001.

International Scientific Congress on Climate Change, 2009. Conference home page, Press release, last viewed 22 May 2009: http://climatecongress.ku.dk/newsroom/rising_sealevels/.

Jet Propulsion Laboratory (JPL), 2009. "Ocean surface topography from space — Rising waters: new map pinpoints areas of sea-level increase"; last viewed 22 May 2009: http://climate.jpl.nasa.gov/news/index.cfm?FuseAction=ShowNews&NewsID=16.

Jevrejeva, S., J.C. Moore, A. Grinsted, and P.L. Woodworth 2008. "Recent global sea level acceleration started over 200 years ago?" *Geophys. Res. Letters*, v. 35, L08715, doi:10.1029/2008GL033611.

Johnson, G.C., and S.C. Doney 2006. "Recent western South Atlantic bottom water warming." *Geophys. Res. Letters*, v. 33, L14614, doi:10.1029/2006GL026769.

Johnson, G.C., S. Mecking, B.M. Sloyan, and S.E. Wijffels, 2007. "Recent bottom water warming in the Pacific Ocean." *J. of Climate*, v. 13, p. 2987-3002.

Leuliette, E.W., R.S. Nerem, and G.T. Mitchum 2004. "Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change." *Marine Geodesy*, v. 27, p. 79-94.

Levitus, S., J.I. Antonov, T.P. Boyer, R.A. Locarnini, H.E. Garcia, and A.V. Mishonov 2009. "Global Ocean Heat Content 1955-2008 in light of recently revealed instrumentation problems." *Geophys. Res. Letters*, v. 36, L07608, doi:10.1029/2008GL037155.

Levitus, S., T. Boyer, J. Antonov, H. Garcia, and R. Locarnini 2005. Ocean Warming 1955-2003. Poster presented at the *U.S. Climate Change Science Program Workshop*, 14-16 November 2005, Arlington VA, Climate Science in Support of Decision-Making; last viewed 22 May 2009: http://www.climatescience.gov/workshop2005/default.htm.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis 1997. "A Pacific interdecadal climate oscillation with impacts on salmon production." *Bulletin of the Amer. Meteorological Soc.*, v. 78, pp. 1069-1079.

Maslanik, J.A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery 2007. "A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss." *Geophys. Res. Letters*, v. 34, L24501, doi:10.1029/2007GL032043.

Mauna Loa Observatory (MLO), U.S. Department of Commerce; last viewed 22 May 2009: http://www.mlo.noaa.gov/.

Meehl, G.A., W.M. Washington, W.D. Collins, J.M. Arblaster, A. Hu, L.E. Buja, W.G. Strand, and H. Teng 2005. "How much more global warming and sea level rise?" *Science*, v. 307, p. 1766-1769.

Meier, M.F., M.B. Dyurgerov, U.K. Rick, S. O'Neel, W.T. Pfeffer, R.S. Anderson, S.P. Anderson, and A.F. Glazovsky 2007. "Glaciers dominate eustatic sea-level rise in the 21st century." *Science*, v. 317, p. 1064-1067.

Merrifield, M.A., S.T. Merrifield, and G.T. Mitchum (2009) "An anomalous recent acceleration of global sea level rise," *J. of Climate.*

Mitrovica, J.X., N. Gomez, and P.U. Clark 2009. "The sea-level fingerprint of West Antarctic collapse." *Science*, v. 323, p. 753.

National Climatic Data Center (NCDC), 2007. U.S. Department of Commerce: http://www.ncdc.noaa.gov/oa/climate/globalwarming.html.

National Research Council 1987. "Responding to Changes in Sea Level: Engineering Implications." National Academy Press: Washington, D.C. http://www.nap.edu/catalog.php?record_id=1006.

National Snow and Ice Data Center (NSIDC), 2009a. "Arctic Sea Ice News and Analysis"; last viewed 22 May 2009: http://nsidc.org/arcticseaicenews/.

National Snow and Ice Data Center (NSIDC), 2009b. "State of the Cryosphere"; last viewed 22 May 2009: http://nsidc.org/sotc/glacier_balance.html.

Overpeck, J., B.L. Otto-Bliesner, G.H. Miller, D.R. Muhs, R.B. Alley, and J.T. Kiehl 2006. "Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise." *Science*, v. 311 (5768), p. 1698-1701.

Pfeffer, W.T., J.T. Harper, and S. O'Neel 2008. "Kinematic constraints on glacier contributions to 21st Century sea-level rise." *Science*, 321, p. 1340-1343.

Pielke, R.A., 2008. "Climate predictions and observations." *Nature Geoscience*, v. 1, p. 206.

Rahmstorf, S., 2007. "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science*, v. 315 (5810), p. 368-370.

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker, and R.C.J. Somerville 2007. "Recent Climate Observations Compared to Projections." *Science*, v. 316 (5825), p. 709.

Rahmstorf, S., and M. Vermeer 2009. "Ups and downs of sea level projections." RealClimate: http://www.realclimate.org/index.php/archives/2009/08/ups-and-downs-of-sea-level-projections/

Rignot, E., J.E. Box, E. Burgess, and E. Hanna 2008a. "Mass balance of the Greenland ice sheet from 1958 to 2007." *Geophys. Res. Letters*, v. 35, L20502.

Rignot, E., J. Bamber, M. van den Broeke, C. Davis, Y. Li, W. van de Berg, and E. van Meijgaard 2008b. "Recent mass loss of the Antarctic Ice Sheet from dynamic thinning." *Nature Geoscience*, doi: 10.1038/ngeo102.

Rignot, E., and P. Kanagaratnam 2006. "Changes in the velocity structure of the Greenland Ice Sheet." *Science*, v. 311, p. 986-989.

ScienceDaily, 2009a. "Sea level rise of one meter within 100 years"; last viewed 22 May 2009: http://www.sciencedaily.com/releases/2009/01/090108101629.htm.

ScienceDaily, 2009b. "Rising sea levels set to have major impacts around the world"; last viewed 22 May 2009: http://www.sciencedaily.com/releases/2009/03/090310104742.htm.

ScienceDaily, 2007. "Arctic Sea Ice Minimum Shatters All-time Record Low, Report Scientists"; http://www.sciencedaily.com/releases/2007/09/070920160226.htm.

Siddall, M., T.F. Stocker, and P.U. Clark 2009. "Constraints on future sea-level rise from past sea-level change," *Nature Geoscience,* v. 2, p. 571-575, DOI:10.1038/ngeo587.

Siegenthaler, U., T.F. Stocker, E. Monnin, D. Lüthi, J. Schwander, B. Stauffer, D. Raynaud, J.M. Barnola, H. Fischer, V. Masson-Delmotte, and J. Jouzel 2005. "Stable Carbon Cycle–Climate Relationship during the Late Pleistocene." *Science,* 25 November 2005, v. 310(5752), p. 1313-1317 DOI: 10.1126/science.1120130

Solomon, S., G.K. Plattner, R. Knutti, and P. Friedlingstein 2009. "Irreversible climate change due to carbon dioxide emissions." *Proc. of the National Academy of Sciences*, v. 106, no. 6, p. 1704-1709.

Spahni, R., J. Chappellaz, T.F. Stocker, L. Loulergue, G. Hausammann, K. Kawamura, J. Flückiger, J. Schwander, D. Raynaud, V. Masson-Delmotte, and J. Jouzel 2005. "Atmospheric Methane and Nitrous Oxide of the Late Pleistocene from Antarctic Ice Cores." *Science,* v. 310(5752), p. 1317-1321, DOI: 10.1126/science.1120132.

Steig, E.J., D.P. Schneider, D.R. Scott, M.E. Mann, C.C. Josefino, and D.T. Shindell 2009. "Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year." *Nature,* 457, p. 459-462.

U.S. Army Corps of Engineers, 2009. Expires 1 July 2001, "Water resource policies and authorities incorporating sea-level change considerations in civil works programs." Circular No. 1165-2-211, 3p plus appendices.

Wang, M., and J.E. Overland 2009. "A sea ice free summer Arctic within 30 years?" *Geophys. Res. Letters*, v. 36 (L07502), DOI: 10.1029/2009GL037820.

Wentz, F.J., L. Ricciardulli, K. Hilburn, and C. Mears 2007. "How Much More Rain Will Global Warming Bring?" *Science,* v.317 (5835), p. 233-235, DOI: 10.1126/science.1140746

Wigley, T.M.L., 2005. "The Climate Change Commitment." *Science,* 307, p. 1766-1769.

Zhang, Y., J.M. Wallace, and D.S. Battisti 1997. "ENSO-like Interdecadal Variability: 1900-93." *J. of Climate*, v. 10, p. 1004-1020.

Zwally, H.J., A.C. Breener, M.A. Beckley, H.G. Cornejo, M.B. Giovinetto, J. Li, S.B. Luthcke, J.L. Saba, and D. Yi 2008. "Greenland and Antarctic Ice Sheet Mass Balance from ICESat (2003-2007)." *Amer. Geophysical Union, EOS Transactions*, 89(53), Fall meeting supplement, abstract: C43A-08.