

CLIMATE CHANGE AND SEA-LEVEL RISE IN FLORIDA:

**An Update of
THE EFFECTS OF CLIMATE CHANGE
ON FLORIDA'S OCEAN AND COASTAL RESOURCES**

December 2010

**Prepared by the
FLORIDA OCEANS AND COASTAL COUNCIL
Tallahassee, Florida**

The logo for the Florida Oceans and Coastal Council is a blue rectangular box with a white wave-like shape at the bottom. The text "FLORIDA OCEANS AND COASTAL COUNCIL" is written in white, uppercase letters within the white area.

**FLORIDA OCEANS AND COASTAL
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It is widely accepted that human activities can impact global climate patterns. While there are legitimate disagreements among scientists on the nature, magnitude, and impact of these changes, the potential risks to Florida's natural resources and our economy compel us to seek a thorough understanding of possible impacts and to provide current and future generations with the information necessary to adjust to them.

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PREFACE

In 2009 the Florida Oceans and Coastal Council (FOCC) published a report entitled, “The Effects of Climate Change on Florida’s Ocean and Coastal Resources.” A special report to the Florida Energy and Climate Commission and the people of Florida, the report provided an overview of climate change and why Floridians should care about climate change. Brief information was provided on Florida’s infrastructure, human health, and economy but the report focused on what was known, was probable, and was possible concerning climate-change effects on the state’s ocean and coastal resources. The 2009 report examined such effects resulting from increasing greenhouse gases, air temperature and water vapor, ocean temperature, and sea level. Emphasizing Florida-based research and research by Florida scientists, the report presented a dozen discussions on the effects of the four climate “drivers,” and recommended promising areas for future research.

The scope and depth of climate research have grown rapidly with important new work in and about Florida. To recognize and disseminate the latest findings and their implications for managing the state’s ocean and coastal resources, the FOCC undertook this update of one driver, sea-level rise, with the expectation that updates for increasing greenhouse gases, air temperature, and ocean temperature may be released in subsequent years. This sea-level rise update involved contributions by 5 Council members, 12 contributing authors, and 11 external reviewers whose technical contributions were based primarily on literature published by August, 2010. Two-thirds of the cited literature was published in this decade and one-third of it appeared in 2009 and 2010. As of December, many new research and resource management initiatives have begun around Florida, or soon will. Such increased activity testifies to the special relationship our state’s natural and cultural resources holds with respect to sea level, and the risks posed as sea level rises.

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EXECUTIVE SUMMARY

Sea level has risen slowly during the period of Florida's modern settlement. Over the course of centuries when sea level was stable by geologic standards, natural systems developed an intimate relationship with the land-sea boundary. Marshes and mangroves expanded to the very limit of their abilities; intertidal oyster reefs became closely calibrated to tides, and seagrass beds grew as deeply as light penetration allowed.

Humans have followed the same course and today, across the coastlines of the state, our infrastructure has extended as far out and as far down as we have been able to engineer. We literally live at the edge of the sea. Over the course of recent decades, the slowly rising sea level has affected structures such as roads, drains, seawalls, and buildings that were originally built with some margin of safety from the water's edge.

The rate of sea-level rise has increased from the 19th to the 20th century and for the past 20 years the rate of global sea-level rise has been about 80% faster than the best estimate of the IPCC Third Assessment Report released only a few years ago. The discrepancy is attributed to previously unreckonable contributions of water from melting ice reservoirs. Recent estimates of melt-water contributions support a sea level in 2100 that is significantly higher than projected by the last IPCC, and indicate that sea level will continue to rise long after 2100.

Even at today's rate, sea-level rise is causing discernable effects in natural coastal ecosystems around Florida, and presents everyday challenges to those responsible for maintaining drainage systems, recreational beaches, coastal highways, and emergency preparations. Stresses caused by today's rate of sea-level rise are more pronounced in southern Florida than in the Panhandle, but as the rate of sea-level accelerates nearly all of the state's coastal ecosystems and infrastructure will be challenged as never before.

Barrier islands and the ecosystems they support will be affected profoundly by accelerated rates of sea-level rise, as will beach and inlet systems. Ecosystems of Florida Bay, the Everglades, the Ten Thousand Islands, and the Big Bend coastline are already exhibiting signs of sea-level stress. Ecological forecasts for these low-lying areas are consequential. Effects of sea-level rise will manifest in Florida's large estuaries such as Tampa Bay, Charlotte Harbor, and the Indian River Lagoon, and then effects will become apparent in tidal rivers. Inland systems such as the St. Johns River will also be affected. Major shifts in the locations of plant and animal communities are expected.

Infrastructure of coastal communities is practically fixed in place although some was built to accommodate storm surge. Virtually none of Florida's infrastructure was built to accommodate significant sea-level rise. Much of the current infrastructure of coastal Florida will need to be replaced or improved as sea-level rises. Short-lived and localized storm surges will also reach higher and penetrate farther inland as sea level rises, but even without storms, sea level will continuously affect every part of Florida's shoreline wetted by tides. Even areas and resources removed from the coast, such as Florida's Biscayne aquifer, are already experiencing saltwater intrusion which is exacerbated by sea-level rise.

Sea-level rise is as clear a signal of climate change as increasing carbon dioxide concentrations and global temperature trends. No scientific evidence available today suggests that sea level will stabilize. Sea level is rising and is likely to rise faster as each decade passes, for a considerable period of time. Evidence marshaled in this report underscores the challenge facing Florida for generations to come. Several local communities have begun to respond. Our wisest course is to expand our response to all of Florida, now, while at the same time increasing our knowledge as recommended by this report.

INTRODUCTION

The Florida Oceans and Coastal Council prepared this report to provide a foundation for discussions of the effects of sea-level rise on Florida's ocean and coastal resources, and to inform Floridians about the current state of scientific knowledge regarding sea-level rise and how it is likely to affect Florida. It provides important information for legislators, policymakers, governmental agencies, and members of the public who are working to address, or who are interested in, issues related to sea-level rise in Florida.

Sea-level rise is not a science fiction scenario but a reality. The scientific consensus reached in 2007 by the United Nations' Intergovernmental Panel on Climate Change (IPCC) is that warming of the Earth's climate system is unequivocally taking place, and that such warming will affect sea levels. Two main processes causing sea level to rise are the expansion of ocean water caused by increasing ocean temperature, and the addition of "new" water from melting reservoirs of ice. Other processes are also at play.

The IPCC report projected a relatively low rate of sea-level rise during the present century, but acknowledged that contributions from glaciers and ice sheets were probably under-estimated. Studies conducted since 2007 indicate that such contributions are already becoming significant and will most likely increase, causing sea-level rise by 2100 to range between 0.5 meters (about 20 inches) to more than a meter (more than 3 feet). Much has yet to be learned before sea level can be projected with greater precision and certainty, but the differences are largely a matter of when not whether economically and ecologically critical levels will be reached.

Thus the question for Floridians is not whether they will be affected, but how much—that is, to what degree sea-level rise will continue, how rapidly, what other climate changes will accompany sea-level rise, and what the long-term effects of these changes will be. Some detrimental effects of sea-level rise are already well documented. Others will begin in the coming years and decades, and the time is coming when the state is simultaneously and continuously challenged by all of these effects.

Florida is especially vulnerable to the effects of sea-level rise. It has more than 1,200 miles of coastline; almost 4,500 square miles of estuaries and bays, and more than 6,700 square miles of other coastal waters. The entire state lies within the Atlantic Coastal Plain, with a maximum elevation less than 400 feet above sea level, and most of Florida's 18 million residents live less than 60 miles from the Atlantic Ocean or the Gulf of Mexico. Three-fourths of Florida's population resides in coastal counties that generate 79% of the state's total annual economy, and represent a built-environment and infrastructure with a replacement value in 2010 of \$2.0 trillion and by 2030 an estimated value of \$3.0 trillion.

In addition, Florida's coastal and marine resources comprise some of the nation's most diverse and productive ecosystems, supporting vast numbers of aquatic and terrestrial animals and plants—some of which exist nowhere else on Earth. These ecosystems include the coastal ocean, barrier islands, bays, estuaries, lagoons, sounds, tidal salt marshes and creeks, mangrove swamps, shellfish beds, seagrass beds, coral reefs, and oyster bars. They are an important source of food and other products; perform valuable and irreplaceable ecological functions at no cost;

and provide significant aesthetic and recreational opportunities. Florida's life-support system, economy, and quality of life depend on preserving and sustaining these natural resources over the long term.

This report updates and expands a section addressing sea level and sea-level rise in the 2009 report, "Effects of Climate Change on Florida's Ocean and Coastal Resources," prepared by the Florida Oceans and Coastal Council.

This report employs the same approach as the 2009 report. It carefully identifies what is known about sea-level rise and describes its effects on Florida's ocean and coastal resources. This report identifies effects for barrier islands, including beaches and inlets; estuaries, tidal rivers, and coastal forests; and coastal communities, including infrastructure, water supply and wastewater treatment, beach erosion and re-nourishment, coastal planning, and flooding risks.

Our knowledge of sea-level rise and its effects includes certainties and uncertainties. To distinguish the confidence associated with statements made in this report, each statement is categorized in terms of what is currently known, what is probable, and what is possible. "Probable" means that an effect is highly likely to occur in the future, while "possible" means that it may occur, but that predicted impacts must be carefully qualified to reflect the level of certainty.

SEA LEVEL AND SEA-LEVEL RISE

Florida's geology, chemistry, biology, and human population already have been, and will continue to be, profoundly affected by rising sea levels. For the past few thousand years, sea level around Florida has been rising very slowly (Maul and Martin, 1993), although a persistent upturn in the rate of sea-level rise has begun in recent decades. Geological studies show that in the more distant past, sea level around Florida and the world rose or fell much more rapidly than in more recent times. The response of ice reservoirs to global warming is the biggest unknown in the projections of sea level over the next century. The *rate* at which sea-level rises is equally as important to coastal resources as how much it rises.

WHAT WE KNOW:

Florida sea-level rise can for most practical societal purposes be considered to be essentially similar to global sea-level rise throughout the state's coastal areas (Engelhart et al., 2009).

The rate of global sea-level rise increased from the 19th to the 20th century (Kemp et al., 2009) and is still increasing due to both ocean warming and the contributions from both land-based ice melt from glaciers and the ice sheets of Greenland and Antarctica.

The most recent satellite observations confirm global average sea-level rise to be about 80% faster than the best estimate of the IPCC Third Assessment Report. See Figure 1 reproduced from Richardson et al. (2009).

WHAT IS PROBABLE:

Global sea level will continue to rise long after 2100 even if greenhouse gas concentrations are stabilized well before the end of the century.

Global average sea level will rise by 0.5 - 1.0 meter (about 20 – 40 inches) and possibly more by 2100 (NRC, 2010).

WHAT IS POSSIBLE:

Major inputs of water from the melting of high-latitude and high-altitude ice reservoirs could cause a global average sea-level rise of up to two meters this century, and several more meters over the subsequent centuries (Rahmstorf, 2010).

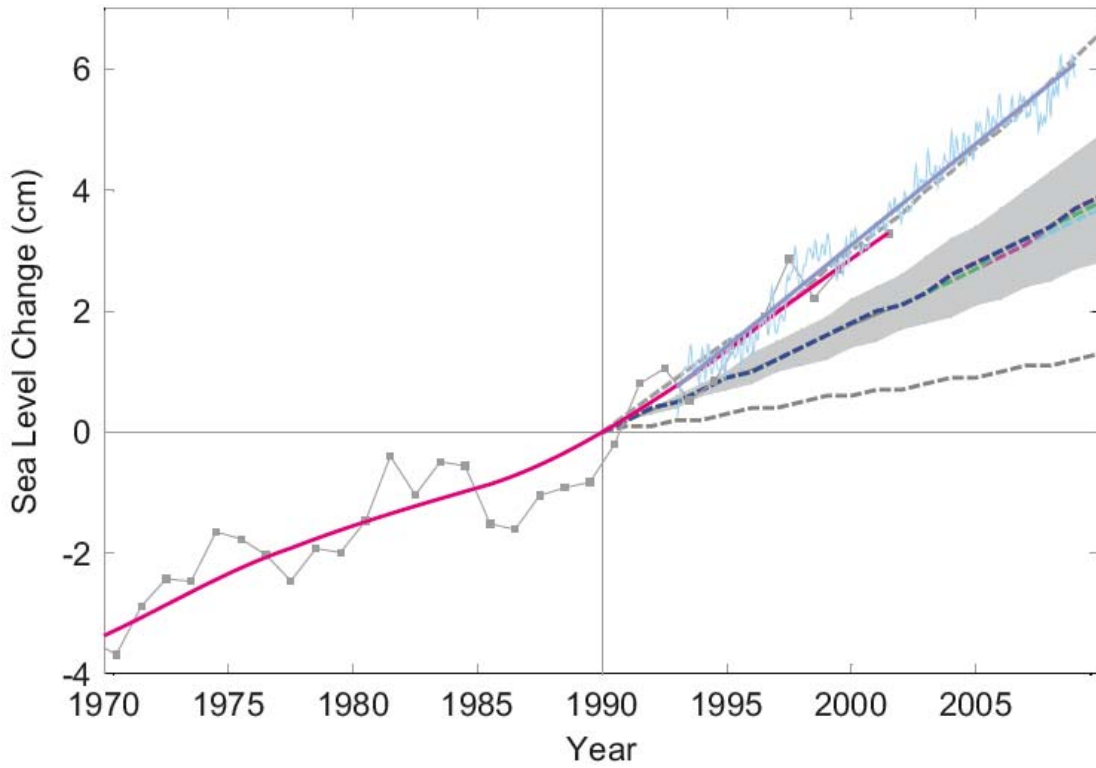


Figure 1
Change in sea level from 1970 to 2008, relative to the sea level at 1990. The solid lines are based on observations smoothed to remove the effects of interannual variability (light lines connect data points). Data in most recent years are obtained via satellite based sensors. The envelope of IPCC projections is shown for comparison; this includes the broken lines as individual projections and the shading as the uncertainty around the projections³.

EFFECTS OF SEA-LEVEL RISE IN FLORIDA

The potential risks of sea-level rise to Florida's natural resources and our economy compel us to seek a thorough understanding of its possible impacts and to provide current and future generations with the information necessary to adjust to higher sea level.

THE IMPACTS OF SEA-LEVEL RISE ON FLORIDA'S BARRIER ISLANDS, BEACHES, AND INLETS

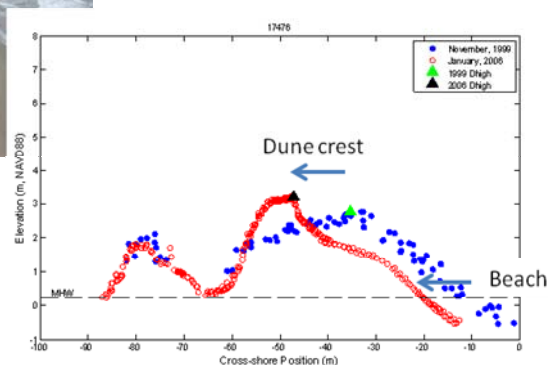
Beaches and inlets are regional systems of sediment deposition, erosion, and transport. These processes are profoundly affected by changes in sea level and rates of sea-level change, as well as storm events. Scientists and resource managers will be challenged to separate the effects of sea-level changes from the effects of storms and the alterations resulting from beach and inlet management actions.

WHAT WE KNOW:

Both shoreline advance due to sediment accumulation, and shoreline retreat due to erosion, and overwash are occurring now (Sallenger et al., 2006).

Presently, on Florida's Atlantic coast, the average (over the past 100 years) shoreline position has advanced by about 20 cm/year (about 8 inches per year). This shoreline advance occurred along about 60% of the coastline.

The remaining 40% of the coast retreated. Both the elevation of mean water levels and increased frequency of major hurricanes will cause increased barrier island erosion and overwash deposition, contributing to shoreline retreat. This is a natural process that allows barrier islands to migrate onshore and, potentially, maintain their elevations above sea level.



Example: The coastline at Cape Canaveral is experiencing steady, long-term erosion due to dune overwash. The blue profile shows LIDAR elevations sampled in November of 1999. The red

profile shows the elevations in 2006. The dune and beach have migrated approximately 25 m inland in this time period. The slight increase in dune elevation is a result of restoration efforts.

However, Florida has been successful in stabilizing some of its beaches through nourishment and an effective Coastal Construction Control Line program that maintains good location and construction standards along its coastline. These steps help to counteract the long-term impacts of coastal erosion.

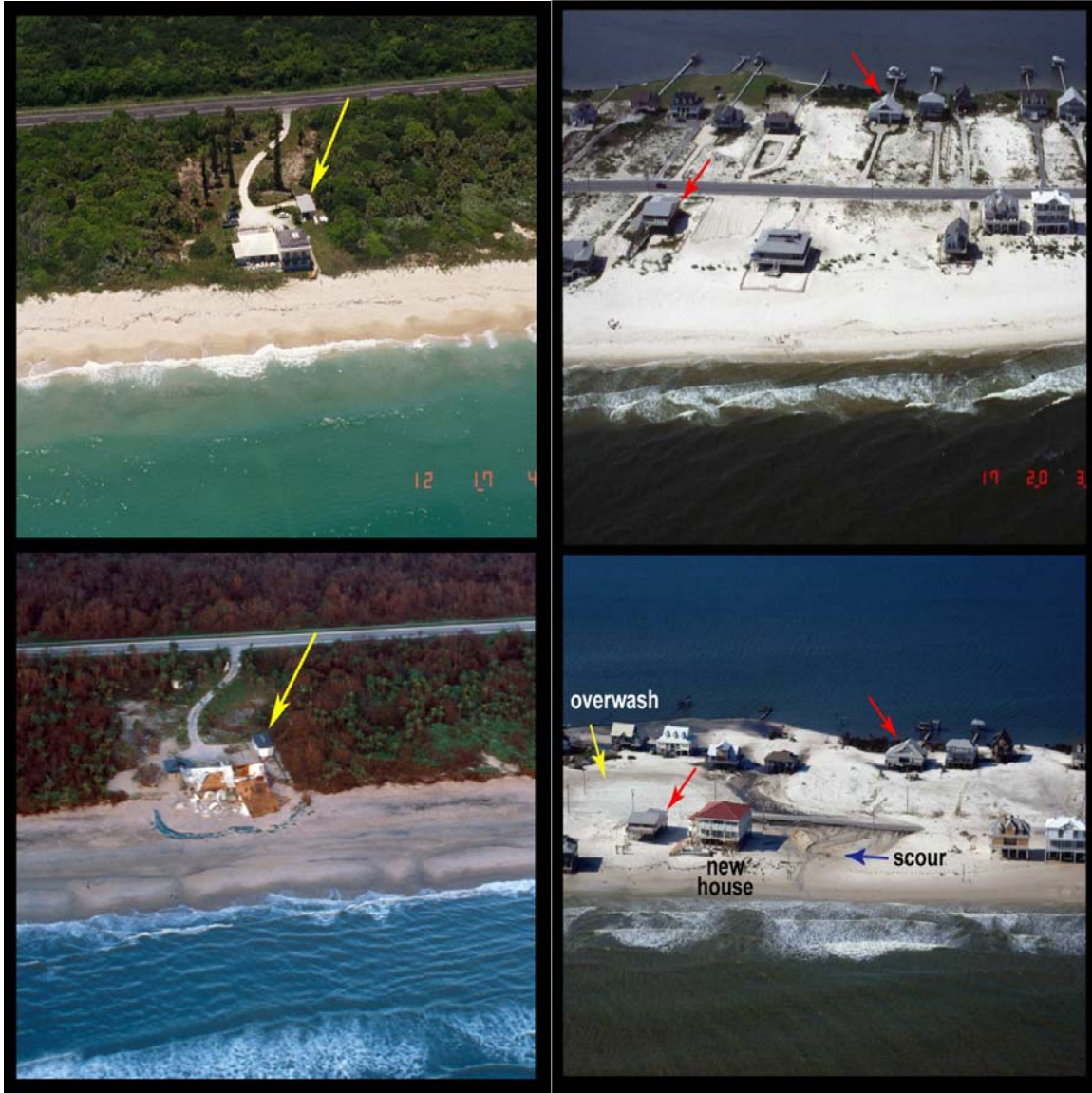
There is an increase in the formation of barrier island inlets and in island dissection events, in which islands are eroded by wind and waves (Sallenger et al., 2005; 2006).

When barrier island dune elevations are reduced below a threshold that allows complete inundation during storms, the overland flow of water can cut a channel (breach) that connects ocean and estuary. The threshold may be reached by increasing surge elevations (more powerful storms), raising sea level, or progressively eroding and lowering the dune elevations—or all three at once.



Example: North Captiva Island, Florida breaching as a result of the landfall of Hurricane Charley in 2004.

There will be an increase in the impacts on coastal infrastructure. This is an ongoing problem associated with the location of populations near the shoreline and at low elevations.



Example: The top photograph in each sequence was obtained prior to land fall of (left) Hurricane Ivan and (right) Hurricane Frances, both in 2004. Ivan made landfall along the Gulf Coast on Florida's panhandle and Frances made landfall along the Atlantic Coast.

WHAT IS PROBABLE:

Continued sea-level rise will exacerbate erosion (Sallenger et al., in review). Rising sea-level may shift the beach profile, and therefore the shoreline, landward, i.e., the Brunn Rule (Bruun, 1965; Dean, 1991)

Analysis of data from along the entire US Atlantic coast indicates that there is a correlation between the long-term erosion rate and sea-level rise rates. Thus, it is expected that long-term erosion rates (not just from major hurricanes) will increase as sea-level rises.

Barrier islands will continue to erode, migrate landward, and be reduced in elevation (Sallenger et al., in review).

Large storms may lead to a “change-in-state” causing island breaching. The possibility of a correlation between an increased frequency of larger storms and increased sea level will exacerbate the erosion impacts. Furthermore, human development may prevent some of the natural process of island migration and may lead to increased vulnerability or catastrophic failure.

Coastal transportation infrastructure will be affected.

Recent hurricanes provide guidance regarding the damage to infrastructure. Notable in recent large hurricanes has been the destruction of bridges that connect coastal communities to each other and connect barrier island communities to the mainland.



Example: Damage to bridge and roadway (Gulf Shores, AL) Hurricane Ivan 2004.

This looks like one photograph. Place side by side.

Rising sea level may increase the size of bays behind barrier islands and therefore increase the tidal prism (the amount of water flowing through tidal inlets) and alter the beach-inlet interaction. Beach-inlet interactions and associated tidal inlet management efforts are responsible for more than 80% of Florida’s beach erosion problems (Dean, 1988).

WHAT IS POSSIBLE:

Increased overwash, breaching of coastal roads, and dissection of barrier islands will occur (Sallenger et al., 2006).

Because there are thresholds between coastal elevation, sea level, and storm-driven surges and waves, dramatic changes in coastal topography can result when these thresholds are crossed. Glimpses of this sort of response are available from recent storms that have made landfall in Florida.



Example: Low barrier island topography with a small breach due to landfall of Hurricane Ivan, 2004.

Low barrier islands will vanish, exposing marshes and estuaries to open-coast conditions (Sallenger et al., in review).

A location that illustrates the progressive disappearance of barrier islands is the Chandeleur Islands, off the coast of Louisiana. Here, there is a locally high rate of sea-level rise (due to a substantial amount of land subsidence). This can be used as a proxy for what might occur elsewhere if sea-level rise rates increase to very high rates (i.e., 10 mm /year; about $3/8^{\text{th}}$ inch), which are suggested in some studies.

The changes seen in Louisiana results from a loss of a sediment source as the Mississippi River tributary abandoned this region; however, the situation provides a rare glimpse into how coasts respond under a high rate of sea-level rise.



Example: Progressive land-loss of the Chandeleur Barrier islands. The islands are increasingly dissected as the beach is lost, breaching prevails, and marsh lands erodes.

THE IMPACTS OF SEA-LEVEL RISE ON FLORIDA'S ESTUARIES, TIDAL RIVERS, AND COASTAL FORESTS

Although Florida tide ranges are relatively small, tidal effects extend far inland because much of the state is low, relative to sea level, and flat. Because sea level has been rising only slowly for a long time, tidal wetlands such as mangrove forests and salt marshes have been able to accumulate sediment at the same rate as the rise in sea level and grow into expansive habitats for estuarine and marine life. However, these tidal wetlands are very sensitive to the rate of sea-level rise and will disappear if sea-level rise exceeds their capacity to accumulate sediment. With rising sea levels, sandbars and shoals, estuarine beaches, salt flats, and coastal forests will be altered. Predicted changes in rainfall will alter freshwater inflow from tidal rivers and in turn affect salinity regimes in estuaries. This is likely to alter the communities of aquatic plants and animals as well as patterns of terrestrial animals that also depend on these waters. Major redistributions of mainland and barrier island sediments may harm or benefit existing wetland, seagrass, or fish and wildlife communities, but these processes cannot be forecast with existing models.

WHAT WE KNOW:

Inland habitats are being impacted long before inundation by sea-level rise because of groundwater intrusion and abrupt changes from higher storm surge (Sternberg and Swart, 1987; Langevin et al., 2005).

The interplay of tides (and so sea level), freshwater flows, and channel geometry establishes the physical and chemical features of tidal rivers (McPherson and Hammett, 1990) and changes to coastal geological processes caused by sea-level rise have the potential to significantly affect the distribution, abundance, and productivity of tidal river ecosystems (Rodriguez et al., 2010).

Tidal wetlands may be keeping pace with current rates of sea-level changes by accreting vertically, migrating up-slope, or both (Williams et al., 1999; Raabe et al., 2004) providing there is a source of sediment or space landward of current wetlands. The rate of soil accretion is critical for tidal wetlands to keep pace with sea-level rise (Morris, 2010).

Open estuarine waters, some brackish marshes, and mangroves in south Florida are expanding landward (DeSantis et al., 2007; Hine and Belknap, 1986; Glick and Clough, 2006). However, vital wetlands of the Big Bend and Everglades are substantial examples of estuarine and coastal forests and swamps that are retreating or perishing and being replaced by saltmarsh vegetation or open water (Williams et al., 1999; Raabe et al., 2004; Grawe DeSantis et al., 2007).

Even at constant rates of sea-level rise, some tidal wetlands will eventually “pinch out” where their upslope migration is prevented by roads, developments, and upland defenses such as seawalls and development on the upland interface (Estevez, 1988; Shleupner, 2008).

Studies at Cape Sable recorded rapid filling of bays to the point that mangrove forests could colonize and flourish - even though this is a period of quite rapid sea-level rise (Vlaswinkel and Wanless, 2009).

Estuarine circulation, salinity, and faunal use patterns are changing (Peterson et al., 2008).

Sea-level rise may not be the only, or even major, cause of changes observed in some systems: mud banks are increasing in Florida Bay as it becomes more saline (changing Everglades flow, changing seaward gaps, and rising sea level) (Vlaswinkel and Wanless, 2009).

Seagrass extent has increased in Florida Bay, trapping sediment and encouraging increased mudflat height (Vlaswinkel and Wanless, 2009).

WHAT IS PROBABLE:

Inundation of habitat on low-lying barrier islands of the Florida Keys and Ten Thousand Islands will reduce or eliminate habitat for many endemic and rare species of plants and animals (U.S. Fish and Wildlife Service, 1999).

More low-lying upland coastal forests will be lost during the next one to three centuries as tidal wetlands expand across low-lying coastal areas and the retreat of forests is blocked by urban development (Castaneda and Putz, 2007).

Plant communities in tidal rivers and bayheads will be replaced by low-lying, flood-prone ecosystems or open water (Rodriguez et al., 2010). Increased saline flooding will strip upland soils of their organic content (Williams et al., 1999; Raabe et al., 2007; Wanless et al., 1997).

Increased air temperatures and reductions in freeze events will result in mangroves moving northward, replacing salt marsh in some areas (Doyle et al., 2003; Root et al., 2003). Some climate models predict increases in extreme events (Gaines and Denny, 1993) so hard freezes like that experienced in 2010 can negatively affect the northern range of mangroves, as well.

Low-diversity saline-tolerant or brackish wetlands will replace high-diversity freshwater wetlands in the tidal freshwater reaches of coastal rivers (Van Arman et al., 2005).

Major spatial shifts in wetland communities, including invasions of exotic species, will occur (Dahdouh-Guebas et al., 2005).

Most tidal wetlands in areas with low freshwater and sediment supplies will “drown” where sea-level rise outpaces their ability to accrete vertically (Nyman et al., 1993).

The loss of tidal wetlands will result in dangerous losses of the coastal systems that buffer storm impacts (Badola and Hussain, 2005; Wanless et al., 1977).

Recreational and commercial fish species that depend on shallow water, or intertidal and subtidal plant communities, will be at risk (Glick and Clough, 2006; DeAngelis et al., 2005).

As coastlines and wetlands erode with rising sea level, large volumes of sediment will be delivered and recycled elsewhere. Some of this sediment will move offshore, but much may

feed shoreward, filling coastal bays, building mudflats, and being swept into coastal wetlands. In some areas there will be large amounts of organic- and nutrient-rich mud reducing the water clarity of our coastal waters (Vlaswinkel and Wanless, 2009).

Seagrasses and tidal freshwater plants will be redistributed from existing habitats, including expansion inland. Increased water depth will reduce the amount of light reaching underwater seagrasses, with direct reduction of plant productivity where plants are light limited (Short and Neckles, 1999).

Oyster reefs will become less productive and prolific, particularly in Southwest Florida where oysters are restricted to intertidal habitat. Higher rates of sea-level rise will result in upstream movement of optimal salinity regimes for oysters, and reef production will shift upstream into the narrow portion of the estuary/river. Given the reduced amount of space, area for reef development will be decreased. This may have the confounding effect of altering estuarine ecology by reducing the amount of oyster reef habitat in estuarine areas (Savarese and Volety, 2001).

WHAT IS POSSIBLE:

The coastal mangrove-forested islands throughout southern Florida, those responsible for the restriction of freshwater to enrich estuaries, may disappear because of their incompatibility with accelerated sea-level rise. This will reconfigure the coastal geomorphology and ecology (Saverese et al., 2004; Parkinson, 1989; Wohlpart, 2007).

More than half of the salt marsh, shoals, and mudflats critical to birds and fishes foraging in Florida estuaries could be lost during the 21st century (Glick and Clough, 2006).

The extended hydroperiods associated with higher sea levels will reduce the ability of coastal plant communities to grow and form peat. However, the largest uncertainty could involve the responses of the faunal components of tidal wetland communities, to sea-level rise and concurrent alterations in hydrology.

A rapid rise of 3-4 feet will diminish the protection that the seaward barrier islands provide to our coastal wetlands within lagoons and estuaries. Existing wetlands may be diminished due to increased physical storm wave, surge and current stress associated with increased water levels (Vlaswinkel and Wanless, 2009).

THE IMPACTS OF SEA-LEVEL RISE ON FLORIDA'S COASTAL COMMUNITIES

I. SEA-LEVEL RISE, STORM SURGE, AND COASTAL INFRASTRUCTURE

Rising sea level has the potential to cause catastrophic damage to coastal communities in Florida, especially as it exacerbates storm surge generated by hurricanes when they hit large urban regions such as those in southeast Florida. As sea level continues to rise, deeper waters near shore will translate to higher storm surge, faster flow, higher waves and hydrodynamic pressure and wave impact loads on buildings near the shoreline, which are likely to exceed their designed capacities by wide margins resulting in significant damage and loss of function.

WHAT WE KNOW:

Fifteen of Florida's 20 major population centers are located in coastal counties around a bay, an estuary, or at the mouth of a river that flows into the ocean. 76% of Florida's population resides in coastal counties that generate 79% of the state's total annual economy (Kildow, 2008), and represent a built-environment and infrastructure with a replacement value in 2010 of \$2.0 trillion and by 2030 an estimated value of \$3.0 trillion (Climate Works Foundation, 2009; U.S. Census Bureau; Enterprise Florida).

Coastal regions are especially vulnerable to hurricanes and storm surges and waves that they generate. These will be exacerbated by sea-level rise. In Florida, the impacts from exacerbated storm surge will occur long before there are effects from static sea-level rise (U.S. Global Change Research Program, 2009).

Most of the coastal infrastructure was designed and built using criteria based on historical data for local mean sea level and flooding referencing NGVD 1929, which took into account neither current nor future sea level (Florida Climate Action Team, 2008).

Infrastructure vulnerability to storm surge damage was observed in Florida during the 2004 and 2005 hurricane seasons (Florida Division of Emergency Management, 2007).

Much of the current infrastructure of coastal Florida will need to be replaced or improved during the time course of ongoing sea-level rise. An opportunity exists to relocate, harden, and adapt the infrastructure to conditions in ways that avoid or mitigate the potential impacts (U.S. Climate Change Program, 2008).

WHAT IS PROBABLE:

Sea-level rise until 2100 is likely to be at least twice as large as projected by IPCC 2007 and this increases the vulnerability of coastal infrastructure in Florida by several-fold (Allison et al., 2009; Rahmstorf, 2010).

Coastal communities now vulnerable to flooding are likely to flood more frequently while other communities not currently subjected to coastal flooding are likely to gradually be at increased

risk of flooding due to sea-level rise. Consequently the risk of damage from flooding to coastal infrastructure is likely to increase in parallel with sea-level rise (U.S. Global Change Research Program, 2009).

Infrastructure that is location-dependent because of its function, such as port facilities, marinas, piers and others that must be located at or near the waterline are very likely to gradually be at increased risk of damage from flooding, hydrodynamic pressure from storm surge, and wave impact because of sea-level rise; this will likely require hardening or elevation through retrofit, relocation or even abandonment of some such facilities (R.A. Alvarez, personal communication).

Sea-level rise will stress this infrastructure (buildings, roads, bridges, etc.) physically, as salinity changes may affect the structural integrity and/or functionality of physical materials that comprise the features of roads, ports, airports, and rail systems. This stress will increase infrastructure fatigue, reducing its effective functional life and requiring accelerated maintenance (NOAA, 2008; Southeast Climate Change Partnership, 2005; U.S. EPA, 2008).

Increased flooding will affect human-inhabited areas and result in more roadway washouts (NOAA, 2008; U.S. EPA, 2008).

Even roads further inland may be threatened, since road drainage systems become less effective as sea levels rise. Many roads are built lower than surrounding land to begin with, so reduced drainage capacity will increase their susceptibility to flooding during rainstorms (Titus, 2002).

WHAT IS POSSIBLE:

The annual number of tropical cyclones in the Atlantic basin may decrease (independently of the multi-decadal Atlantic oscillation) while the annual frequency of major hurricanes (Safir-Simpson Scale category 4 and 5) may gradually increase in response to global warming. Major hurricanes usually generate the highest levels of storm surge, which will be exacerbated by sea-level rise. The potential for damage to infrastructure from these events may increase by a factor of 30% compared to current levels (Bender et al., 2010; Hoyos et al., 2006).

Shoreline retreat and coastal erosion will continue to increase as sea-level rise accelerates, and combined with higher water tables, this will undermine sea walls and other protective structures. Higher sea level and water tables will also create higher hydrostatic pressure of ground floor slabs and foundations of buildings and infrastructure, resulting in increased risk of structural damage especially during hurricanes and coastal flooding events (U.S. Global Change Research Program, 2009; R.A. Alvarez, personal communication).

With a 1 meter (about 40 inch) rise in sea level by 2100, there will be impacts to 9% of Florida's land area, which includes more than 4,700 square miles and 1/10th of the state's population. Absent successful steps to build up or otherwise protect this land area, which will be expensive and in some areas is likely impossible, the land will be submerged at normal high tide (Stanton and Ackerman, 2007).

There will be major impacts to real estate now valued at over \$130 billion; half of Florida's existing beaches, and substantial critical infrastructure, including-- 2 nuclear power plants, 3 state prisons, 68 hospitals, 74 airports, 115 solid waste disposal sites, 140 water treatment facilities, 334 public schools, 341 hazardous-material cleanup sites including 5 Superfund sites, 1,025 churches, synagogues, and mosques, and 19,684 historic structures (Stanton and Ackerman, 2007).

II. SEA-LEVEL RISE, COASTAL WATER SUPPLY, AND WASTEWATER TREATMENT

Sea-level rise already threatens the aquifers which have been the primary source of much of Florida's drinking water in low-lying coastal areas. This problem will worsen as sea level continues to rise and as withdrawals of water increase for the anticipated growth in Florida's population.

WHAT WE KNOW:

Florida's Biscayne aquifer, the primary water supply to Southeast Florida and the Florida Keys, is recharged by rainfall and the freshwater Everglades. Surficial coastal aquifers are already experiencing saltwater intrusion. Rising sea level will increase the hydraulic backpressure on coastal aquifers, reduce groundwater flow toward the ocean, and cause the saltwater front to move inland, thus threatening to contaminate water supply wells in coastal areas with seawater. In the low-lying southernmost Everglades, sea-level rise will cause brackish waters to encroach further northward. If the saline water front moves far enough north, it could contaminate the headwaters of the Biscayne Aquifer and southern Miami-Dade County's water supply (IPCC, 2007; Karl et al., 2009; Heimlich et al., 2009).

The Comprehensive Everglades Restoration Plan's primary purpose is to increase freshwater flow to the southern Everglades. This will help offset the effect of sea-level rise and help preserve Everglades ecologies and south Florida's water supply (SWFWMD, 2009a).

The South Florida Water Management District already spends millions of dollars per year to prevent Miami's Biscayne aquifer from becoming brackish (Miller et al., 1989).

Rising sea level will cause groundwater near the coast to become more saline and groundwater levels to increase. This would increase the salt content of leakage into sewer collection systems and complicate wastewater treatment operations. Water and wastewater treatment facilities that are located at low elevations in coastal regions may be subject to more frequent flooding during spring tides and storm surges (Bloetscher et al., 2009).

WHAT IS PROBABLE:

As sea level continues to rise, these effects will increase the extent of saltwater intrusion especially during periods of drought and the dry winter/spring season (Heimlich et al., 2009).

Sea-level rise of 15 cm (about 6 inches) and more will require implementation of adaptation strategies such as water conservation, wastewater reuse, recovery and recharge, stormwater storage, alternative water supplies including desalination, and other advanced water management strategies in order to assure adequate water supplies (Heimlich et al., 2009).

Interior regional hydrologic systems of Florida should not be significantly affected (Trimble et al., 1998).

The Pensacola, St. Johns River watershed, and south Florida from Palm Beach to Miami, the Florida Keys, Naples and Fort Myers are especially vulnerable to saltwater intrusion into municipal fresh water supplies with rising sea levels (Freed et al., 2005; Dausman and Langevin, 2005; Murley et al., 2008).

Municipal sewer systems will have to be tightened to significantly reduce groundwater seepage in order to protect wastewater treatment operations (Bloetscher et al., 2009).

WHAT IS POSSIBLE:

Eventually, as sea level continues to rise, coastal surficial aquifers throughout the state will be increasingly threatened (Murley et al., 2008).

Water and wastewater treatment facilities that are located at low elevations in coastal regions will require enhanced flood protection (Bloetscher et al., 2009).

III. SEA-LEVEL RISE AND BEACH EROSION & RE-NOURISHMENT

WHAT WE KNOW:

During the 20th century, all 30 coastal states, including Florida, have experienced moderate to severe erosion of some of their shorelines and beaches. Much of the erosion can be attributed to man-made inlets and to storms, and it is difficult to ascertain the influence of coincident sea-level rise (Williams et al., 2009).

There is a high degree of variability in shoreline erosion rates, with some areas along Florida's coast displaying rapid erosion while others experience a net gain in sand over time (Absalonsen and Dean, 2010).

Beach nourishment and re-nourishment (adding sand that is dredged from offshore areas) has been necessary to maintain beaches in locations that were experiencing a net loss of sand in the early part of the 20th century (Absalonsen and Dean, 2010) and with this technique of adding sand it has been possible to keep pace with losses in areas of moderate erosion and high economic value.

In some coastal Florida counties there is a large deficit of near-shore readily-available sand. Local governments will increasingly be forced to look for "beach quality" sand in other regions

of the state (therefore requiring a regional approach to sand sharing), and to more expensive or non-traditional sources (such as sand from deeper waters, imported sand from the Bahamas or sand from inland sand mines) to maintain beaches in upcoming years. Local expectations as to “beach quality” may have to be modified in this event. In Broward and Miami-Dade Counties, there is estimated to be a net deficit of 34 million cubic yards of sand over the next 50 years (Bender et al., 2010).

More than 90% of the loggerhead sea turtle nesting and almost all the green and leatherback nesting in the United States take place on Florida’s 825 miles of sandy beaches. In addition, Florida’s mid-Atlantic beaches host one of the most important loggerhead turtle rookeries in the world.

WHAT IS PROBABLE:

With rising sea level and associated larger waves and greater magnitude of storm surges, there will be increased beach erosion and this will require more frequent re-nourishment of beaches. The quantity of sand required to keep pace with erosion will increase.

There will be increased reliance on sand sources from outside the US or from inland sand mines in Broward, Miami-Dade and other counties that can afford the considerably higher cost compared to traditional near-shore sand sources (Bender et al., 2010).

There will be increasing pressure and need to harden shorelines with sea walls and implement other engineering strategies to protect upland structures and infrastructure.

WHAT IS POSSIBLE:

Shoreline protection projects, which typically are advocated as a solution to erosion, may not be effective against substantial rises in sea level because of escalating costs, dwindling sand reserves, cumulative impacts on natural resources and the porous nature of Florida’s geology (Parkinson and Donahue, 2010).

If beaches are lost to erosion, there will be significant impacts to animals including sea turtles, which depend on the state’s beaches as major nesting habitat (National Research Council, 1990).

Loss of beaches could result in substantive impacts to Florida’s tourist-based economy (Bell, 2005).

Loss of nesting beaches could threaten the recovery and survival of marine turtle populations.

With almost half of the state’s beaches already experiencing critical erosion that could threaten adjacent development, an increasing amount of structures and of infrastructure could be at risk from the surf.

IV. SEA-LEVEL RISE AND COASTAL PLANNING

Given the substantive impacts that sea-level rise may have on Florida's coastal communities, there is a need for comprehensive regional planning to develop effective adaptation strategies. Plans are being developed in certain coastal areas, however, a large percentage of the state's coastal communities have yet to contemplate such planning efforts. Because the effects of sea-level rise are likely to be seen first in relation to storm surges, planning for hurricanes and storm surges is at the front line of sea-level rise planning in Florida.

WHAT WE KNOW:

The Environmental Protection Agency (EPA) initiated a study of sea-level rise impacts on the nation's economy in 1998. In 2000, under a grant from EPA to the Southwest Florida Regional Planning Council (SWFRPC), six of the regional planning councils [the East Central, Treasure Coast, South Florida, SWFRPC, and Tampa Bay Regional Planning Councils] developed maps that distinguish shores that are likely to be protected from the sea from those areas that are likely to be submerged, assuming current coastal policies, development trends, and shore protection practices. Maps and studies of sea-level rise for coastal Florida were completed in a series of reports from 2003 to 2004. The updated studies' results with further analyses are published in Titus et al. 2009.

The EPA Climate Ready Estuaries Program started in February 2008 to work with the National Estuary Programs and other coastal managers to: 1) assess climate change vulnerabilities, 2) develop and implement adaptation strategies, 3) engage and educate stakeholders, and 4) share the lessons learned with other coastal managers.

The US Army Corps of Engineers Engineering Circular 1165-2-211, "Interim Guidance on Sea Level Change" was published in July 2009. On October 22, 2009 the Comprehensive Everglades Restoration Plan developed a Sea Level Change Guidance Update.

The Southeast Florida Regional Climate Leadership Summit was held October 23, 2009 in Broward County. This partnership of Broward, Palm Beach, Miami-Dade, and Monroe counties formed a regional Climate Change/Green Task Force. The purpose of this summit was to develop a regional collaboration to support a coordinated climate change strategy. The Florida counties signed the Southeast Florida Regional Climate Change Compact to coordinate positions on state and national legislation on climate change and to coordinate activities on mitigation and adaptation. They also committed to preparing an action plan that will include adaptation strategies ([Broward County, 2009](#)—not provided in References).

WHAT IS PROBABLE:

More local government jurisdictions will complete greenhouse gas (GHG) inventories and develop GHG Climate Change Mitigation Plans.

Statutory requirements direct the next round of state Evaluation and Appraisal Reports (EAR) to be adopted between November 1, 2010 and April 1, 2018. This round of EAR will include

climate change, sea-level rise, climate change vulnerability and adaptations plans into the Local Government Comprehensive Plans.

Based on 131 state and local land use plans, Titus et al. (2009) estimate that almost 60% of the land below an elevation of 1 m along the US Atlantic Coast is expected to be developed and thus unavailable for the inland migration of wetlands. Less than 10% of the land below 1 m has been set aside for conservation.

Environmental regulators routinely grant permits for shore protection structures (which block wetland migration) based on a federal finding that these structures have no cumulative environmental impact. This shore protection will have a cumulative impact. If sea-level rise is taken into account, wetland policies that previously seemed to comply with federal law probably violate the Clean Water Act.

WHAT IS POSSIBLE:

All Florida local government jurisdictions will have climate change adaptation plans completed and be in the process of implementing revised land use planning, infrastructure resiliency, adaptation and mitigation standards.

The Statewide Florida Climate Change Initiatives in the Statewide Climate Action Plan and a State Adaptation Plan will be funded and implemented.

Failure to develop and implement appropriate plans for proactive adaptation could cost the state billions in lost revenue. Overall, adaptation to climate change will not be a smooth or cost-free endeavor. Significant opportunity exists for economic development through land management for climate mitigation and participation in carbon markets (Mulkey, 2007).

V. SEA-LEVEL RISE AND INCREASED FLOODING RISKS

Sea-level rise will increase the risk of tidal flooding in coastal areas (Murley et al., 2008). Hurricane storm surge and wave heights during hurricanes will be higher with sea-level rise (R. Alvarez, personal communication). In low lying interior areas, stormwater drainage systems will be compromised as sea-level rises increasing the risk of flooding during heavy rain events (Heimlich et al., 2009).

WHAT WE KNOW:

As sea-level rises, low-lying coastal areas will be increasingly prone to coastal flooding, especially during spring and fall high tides and during sea swells due to seaward storms, strong onshore winds, and other causes (Murley et al., 2008).

Storm surge and wave heights during hurricanes will increase as coastal water depths increase due to sea-level rise, amplifying the damage potential of hurricanes (R. Alvarez, personal communication).

Because Florida's stormwater drainage systems primarily rely on gravity, sea-level rise will reduce their effectiveness (SFWMD, 2009).

Since climate change is expected to cause more intense rainstorms and hurricanes, sea-level rise will exacerbate the risk of inland flooding during intense rainfall events, especially in low-lying interior flood plains such as exist in southeast Florida (Heimlich et al., 2009).

WHAT IS PROBABLE:

Sea-level rise of as little as 3 to 6 inches may begin to compromise the effectiveness of the area's coastal flood control structures, reducing their capacity by as much as 20 to 40% by 2030. By about 2040, 6 to 9 inches of sea-level rise may reduce their capacity by 65 to 70%. Most of these early impacts will be felt in low-lying coastal areas, such as southern Miami-Dade and the St. Johns River watershed (Heimlich et al., 2009; Obeysekera, 2009).

With sea-level rise, storm surge could penetrate further inland and flood areas near primary canals and rivers with seawater. This could cause more serious flood damage during hurricanes and possibly temporarily contaminate aquifers with seawater (Heimlich et al., 2009).

WHAT IS POSSIBLE:

What is currently considered a 100 year flood event will likely become a 50- or 20-year event as sea level continues to rise.

Pumping of storm water from primary drainage canals to tide may be required to offset the effects of sea-level rise (Obeysekera, 2009).

Innovative approaches to augment flood control systems will be needed as sea-level rise compromises existing systems (Heimlich et al., 2009).

Considering sea-level rise and the likelihood of more intense hurricanes and rainstorms, engineering solutions such as dunes, dikes, seawalls, sea gates, locks, pumping stations, etc. should be evaluated (Heimlich et al., 2009).

SEA-LEVEL RISE PRIORITIES FOR FLORIDA'S OCEAN AND COASTAL RESEARCH

Effects of sea-level rise identified in this document are expected to result in major changes to Florida's marine resources, as well as to its developed coastal areas. To sustain the quality of life of residents, the diversity and productivity of marine ecosystems, and the economy of the state in the face of these changes, residents, elected officials, resource managers, and university scientists must work together to find timely, responsible, and effective solutions. These often may involve difficult decisions that consider tradeoffs among the various sectors that depend on coastal resources, and as such, they will be politically as well as technologically challenging. Thus it is imperative that decisions be based on sound science.

The Florida Oceans and Coastal Council will continue to address the critical information needs related to sea-level rise for coastal and marine systems during its future deliberations. The following recommendations from the Council's 2009 climate report directly support Florida's information needs concerning sea-level rise:

Identify and prioritize specific coastline areas around the state for bathymetric mapping, with the goal of mapping the state's entire coastline, to allow better monitoring and prediction of changes in the configuration of the state's coastline resulting from sea-level rise and storms.

Evaluate the long-term stability of coastal wetlands (marshes, mangroves, seagrasses) in relation to sea-level rise and episodic disturbances such as hurricanes.

Determine the locations and sizes, dominant physico-chemical features, living resources, and unique ecological functions of all oligohaline (brackish) and tidal-fresh waters in Florida.

Determine the social, economic, and environmental consequences of increasing rates of beach erosion, coastal armoring, and beach renourishment.

Determine the effect of continued beach renourishment projects on turtle, seabird, and adjacent coral and fish populations, and on other organisms that depend on beach ecosystems for food, shelter, and reproduction.

Determine the role of the shoreline in reducing wave and flood damage, including ways to implement shoreline protection measures that do not damage the coastal and offshore natural environment. Develop a scientific basis for determining erosion and coastal setback zones.

Establish continuous, long-term monitoring in estuaries and coastal waters to support the development of modeling tools; assess the impact of sea-level rise, and assist in resource management (for instance, commercial and sport fisheries).

2010 Recommendations for Florida Research

Additional needed research identified during the preparation of this report includes:

In Oceanography, fine scale (decadal) projections of sea-level rise, and coastal hydrological modeling of tides at future sea levels, are needed.

In Geology and Hydrology, studies are needed to increase resolution for coastal topography and bathymetry; understand impacts of sea level variability and rise on south Florida coastal groundwater systems; assess mechanisms and forecast freshwater peat collapse caused by salt-water intrusion, and model the relation between soil carbon and greenhouse gas production in fresh and salt-water wetlands.

In Ecology, research needs include an increased understanding of coastal plant environmental tolerances; rapid mapping methodologies for monitoring large-extent landscape vegetation community change; population viability assessments to understand potential species responses to environmental change and species interactions, and dispersal modeling to understand potential limitations to species movements in response to sea-level rise.

In Decision Support, management options for integrating directed research, resource management, research-focused monitoring, risk assessment, and database management specifically related to sea-level rise are recommended.

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THE LONG-TERM SOLUTION

Some effects of climate change, such as acceleration of sea-level rise, have already begun. Others will begin in the coming decades, and the time will come when Florida is simultaneously and continuously challenged by many of these effects. The long-term extent and severity of oceanic or coastal effects caused by climate change including sea-level rise ultimately depend on how rapidly humanity can eliminate human sources of carbon dioxide and other greenhouse gases entering the atmosphere at harmful levels, now and in the future.