


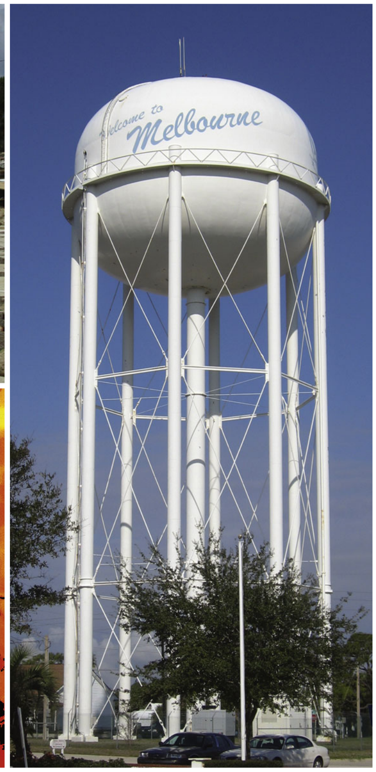


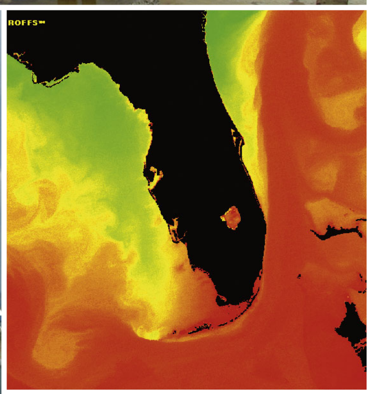


Climate Change and Sea-Level Rise in Florida

An Update of the Effects of Climate Change on Florida's Ocean & Coastal Resources

December 2010

Prepared by
The Florida Oceans and Coastal Council
Tallahassee, Florida

Florida Oceans and Coastal Council

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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Photos on front and back cover courtesy of Florida Department of Environmental Protection, Bureau of Beaches and Coastal Systems; Florida Fish and Wildlife Conservation Commission; Dave Gilliam; NASA; Roffer's Ocean Fishing Forecasting Service, Inc.; University of South Florida; Harold Wanless; Guy Weeks; and istockphoto.com.

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 update on sea-level rise involved contributions by 5 Council members, 12 contributing authors, and 11 external reviewers whose technical contributions were based principally 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 begin. Such increased activity testifies to the special relationship that our state's natural and cultural resources hold with respect to sea level and to 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. 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 live literally 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 century to the 20th, and for the past 20 years the rate of global sea-level rise has been about 80% faster than the best estimate of the United Nations' Intergovernmental Panel on Climate Change (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 the estimates 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 rise 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, continuing 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.

Photo courtesy of David Shafer, Shafer Consulting

SECTION

I.

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 are causing sea level to rise: 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 it acknowledged that contributions from glaciers and ice sheets were probably underestimated. 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 meter (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 will be 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. These counties represent a built-environment and infrastructure whose replacement value in 2010 is $2.0 trillion and which by 2030 is estimated to be $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 *The 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 renourishment, coastal planning, and flooding risks.

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.

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, whereas "possible" means that it may occur but that predicted impacts must be carefully qualified to reflect the level of certainty.

Photo courtesy of Harold Wanless, University of Miami

II. Sea-Level Rise and Its Effects on Florida's Ocean and Coastal Resources

DRIVER: Sea-Level Rise

Florida's geology, chemistry, biology, and human population have already 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 (Merrifield et al., 2009).

The rate of global sea-level rise increased from the 19th century to the 20th (Kemp et al., 2009) and is still doing so. This rate increase is 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).

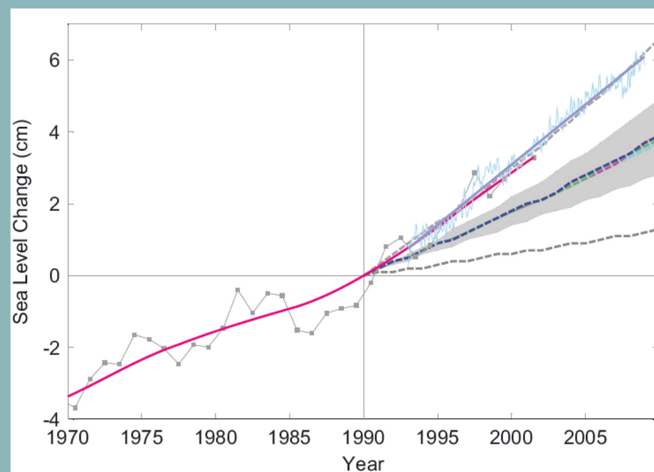


Figure 1: *Change in sea level from 1970 to 2008, relative to the sea level at 1990. The solid lines are based on observations smoothed to remove the effects of interannual variability (light lines connect data points). Data in most recent years are obtained via satellite-based sensors. The envelope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

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 (National Research Council, 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).

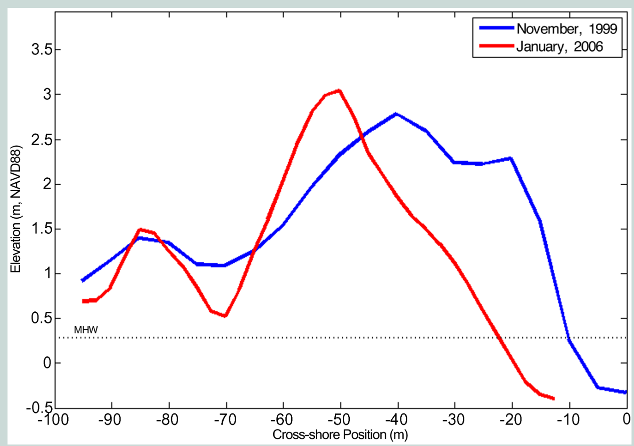
EFFECT: Changes in Barrier Islands, Beaches, and Inlets

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 by 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:

Florida's shoreline is both advancing because of sediment accumulation and retreating (Sallenger et al., 2006). On Florida's Atlantic coast over the past 100 years, shoreline position has advanced by about 20 centimeters (about 8 inches) per year. This shoreline advance occurred along approximately 60% of the coastline. The remaining 40% of the coast retreated. The increases in elevation of mean water levels combined with major hurricane landfalls have 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.

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 (Dehring, 2006; Klein and Osleeb, 2010).



Example: *The coastline at Cape Canaveral is experiencing steady, long-term erosion that is 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 12 meters inland in this period. The slight increase in dune elevation is a result of restoration efforts. (Photo and diagram: USGS)*

II. Sea-Level Rise and Its Effects on Florida's Ocean and Coastal Resources

New inlets can be cut through barrier islands by waves superimposed on storm surges (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 (Sallenger et al., 2005, 2006). The threshold may be reached by increasing the surge elevations (more powerful storms), raising the sea level, or progressively eroding and lowering the dune elevations—or all three at once.

Even with beach nourishment and other mitigation efforts, there will be an increase in the impacts on coastal infrastructure. This is an ongoing problem associated with populations being located near the shoreline and at low elevations.

Example: *North Captiva Island, Florida, breaching as a result of the landfall of Hurricane Charley in 2004. (Photo: USGS)*

Example: *The top photograph in each pair was obtained prior to landfall of (left) Hurricane Frances and (right) Hurricane Ivan, both in 2004. Frances made landfall along the Atlantic coast, and Ivan made landfall along the Gulf of Mexico coast on Florida's panhandle. (Photos: USGS)*

WHAT IS PROBABLE:

Continued sea-level rise will exacerbate erosion. Rising sea level may shift the beach profile, and therefore the shoreline, landward (Bruun, 1962; Dean, 1991). Analysis of data from along the entire U.S. Atlantic coast indicates that there is a correlation between the long-term erosion rates and sea-level rise rates. Thus, it is expected that long-term erosion rates will increase as sea level rises.

Barrier islands will continue to change, and sand-starved barriers will migrate landward (Sallenger et al., 2009). Large storms may lead to a "change in state," causing island breaching. Hurricane landfalls 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. Notably, recent large hurricanes have destroyed bridges that connect coastal communities to each other and connect barrier island communities to the mainland.

Rising sea level will 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).

Example: *Damage to bridge and roadway, Gulf Shores, Alabama. Hurricane Ivan, 2004. (Photos: USGS)*

II. Sea-Level Rise and Its Effects on Florida's Ocean and Coastal Resources

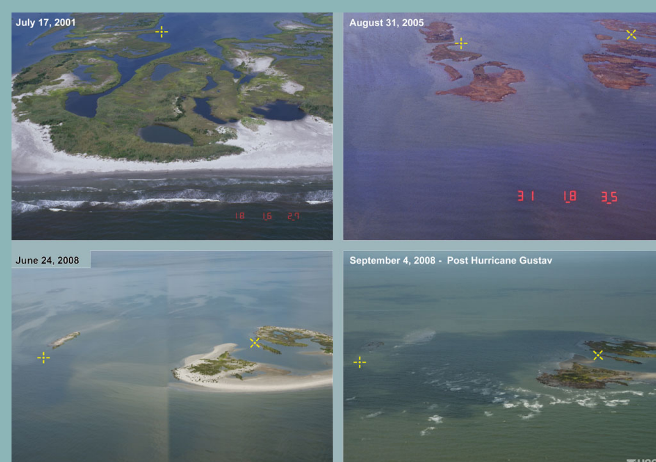
WHAT IS POSSIBLE:

Increased overwash, breaching of coastal roads, and dissection of barrier islands may occur. There are threshold levels of interaction between coastal elevation, sea level, and storm-driven surges and waves. When these thresholds are crossed, dramatic changes in coastal topography can result. Glimpses of this sort of response are available from recent storms that have made landfall in Florida.

Low barrier islands may vanish, exposing marshes and estuaries to open-coast conditions. A location that illustrates the progressive disappearance of barrier islands is the Chandeleur Islands, off the coast of Louisiana. Here, a locally high rate of sea-level rise exists because a substantial amount of land is subsiding. This example can be used as a proxy for what might occur elsewhere if rates of sea-level rise increase to very high rates (i.e., 10 millimeters [about 3/8 inch] per year), which are suggested in some studies.

The changes seen in Louisiana result from losing the sediment source of the Mississippi River tributary that abandoned this region; however, the situation provides a rare glimpse into how coasts can respond to a high rate of sea-level rise.

Example: *Low barrier island topography with a small breach that is due to landfall of Hurricane Ivan, 2004. (Photo: USGS)*



Example: *Progressive land-loss of the Chandeleur Barrier islands. The islands are increasingly dissected as the beach is lost, breaching prevails, and marsh lands erode. (Photos: USGS)*

EFFECT: Changes in 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 will 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 affected long before inundation by sea-level rise because of ground-water 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). 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 change by accreting vertically, migrating upslope, or both (Williams et al., 2009; Raabe et al., 2004) if 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 (Hine and Belknap, 1986; Glick and Clough, 2006; DeSantis et al., 2007). However, vital wetlands of the Big Bend and the Everglades are substantial examples of estuarine and coastal forests and swamps that are retreating or perishing and being replaced by salt-marsh vegetation or open water (Williams et al., 1999; Raabe et al., 2004; 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, which is becoming more saline as Everglades flow and seaward gaps change and the sea level rises (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 (Wanless et al., 1997; Williams et al., 1998; Raabe et al., 2007).

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). However, some climate models predict increases in extreme events (Gaines and Denny, 1993), so hard freezes such as that in 2010 can negatively affect the northern range of mangroves.

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 (Wanless et al., 1997; Badola and Hussain, 2005).

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

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 clarity of our coastal waters (Vlaswinkel and Wanless, 2009).

Seagrasses and tidal freshwater plants will be redistributed from existing habitats, including expanding inland. Increased water depth will reduce the amount of light reaching underwater seagrasses, directly reducing productivity of the affected plants (Short and Neckles, 1999).

Oyster reefs will become less productive and prolific, particularly in southwestern 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 portions of estuaries and rivers. 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, which are responsible for restricting nutrient-rich freshwater flow into estuaries, may disappear because of their incompatibility with accelerated sea-level rise. This change will reconfigure the coastal geomorphology and ecology (Parkinson, 1989; Savarese et al., 2004; 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 how the fauna in tidal wetland communities respond 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 by increased physical storm wave, surge, and current stress associated with increased water levels (Vlaswinkel and Wanless, 2009).

Photo courtesy of Llyn French—Fort Hamer

EFFECT: Higher Storm Surge and Impacts on 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. 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 and suffer 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 or 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). These counties represent a built-environment and infrastructure whose replacement value in 2010 is $2.0 trillion and which by 2030 is estimated to be $3.0 trillion (Climate Works Foundation, 2009).*

Coastal regions are especially vulnerable to the storm surges and waves that hurricanes generate. These will be exacerbated by sea-level rise. In Florida, the impacts of increased 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 National Geodetic Vertical Datum of 1929, which took into account neither current nor future sea level (Florida Climate Action Team, 2008).

* U.S. Census Bureau, Bureau of Economic Analysis data and Enterprise Florida data were used to estimate the "value" at risk represented by the built environment in the region. The method used data on the built environment/number of housing units as a function of total population and used projections of population in 2030, 2050, etc. to arrive at the estimated replacement value of the built environment (in current dollars) at a given year in the future.

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 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 factor 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, whereas other communities not currently subjected to coastal flooding are likely to be at gradually increasing risk of flooding as sea level rises. Consequently, the risk of flood damage to coastal infrastructure is likely to increase in parallel with sea-level rise (U.S. Global Change Research Program, 2009).

Infrastructure such as port facilities, marinas, piers, and others that must be located at or near the water-line are very likely to be at gradually increasing 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 because salinity changes may affect the structural integrity and/or functionality of physical materials that compose the features of roads, ports, airports, and rail systems. This stress will increase infrastructure fatigue, reducing its effective functional life and requiring accelerated maintenance (Southeast Climate Change Partnership, 2005; U.S. Environmental Protection Agency, 2008).

Increased flooding will affect human-inhabited areas and result in more roadway washouts (U.S. Environmental Protection Agency, 2008).

Even roads farther inland may be threatened because road drainage systems become less effective as sea levels rise. Many roads are built lower than the surrounding land, so reduced drainage capacity will further 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 Atlantic Multidecadal Oscillation), whereas the annual frequency of major hurricanes (Saffir-Simpson Scale categories 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 (Hoyos et al., 2006; Bender et al., 2010).

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 (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 on 9% of Florida's land area, which includes more than 4,700 square miles and 1/10 of the state's population. Without successful steps to build up or otherwise protect this land area, which will be expensive and in some areas is likely to be impossible, the land will be submerged at normal high tide (Stanton and Ackerman, 2007).

There will be major impacts on real estate now valued at over $130 billion, on half of Florida's existing beaches, and on 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 (of which 5 are Superfund), 1,025 houses of worship, and 19,684 historic structures (Stanton and Ackerman, 2007).

EFFECT: Threats to Coastal Water Supply and Wastewater Treatment

Sea-level rise already threatens the aquifers that have been the principal 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 principal water supply to southeastern 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 farther northward.

The Pensacola Bay and St. Johns River watersheds and southern Florida from Palm Beach to Miami, the Florida Keys, Naples, and Fort Myers are especially vulnerable to saltwater intrusion into municipal freshwater supplies as sea levels rise (Dausman and Langevin, 2005; Freed et al., 2005; Murley et al., 2008).

The Comprehensive Everglades Restoration Plan's main 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 southern Florida's water supply (South Florida Water Management District, 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.

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 centimeters (about 6 inches) and more will require implementing 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).

If the saline waterfront moves far enough north, it could contaminate the headwaters of the Biscayne Aquifer and southern Miami-Dade County's water supply (Intergovernmental Panel on Climate Change, 2007; Heimlich et al., 2009; Karl et al., 2009).

This contamination 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).

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

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).

EFFECT: Increases in Beach Erosion and Renourishment

Florida's beautiful beaches are a major tourist destination and thus have a high economic value to our state. They also provide critical habitat for marine animals: for example, nesting sites for sea turtles. Our beaches experience varying degrees of erosion, which is due not only to natural processes such as tropical storms but also to man-made situations, including inlets that enhance downshore sand loss. In areas where there is a net loss of sand, beaches are maintained by renourishment. Rising sea level may have a number of effects on the short- and long-term sustainability of our beaches and on how frequently the sand needs to be replenished.

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. Some areas along Florida's coast display rapid erosion, whereas others experience a net gain in sand over time (Absalonsen and Dean, 2010).

Beach nourishment and renourishment (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). By 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 nearshore, 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 from more expensive or nontraditional sources (such as sand from deeper waters, from inland sand mines, or imported from the Bahamas) 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. 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, erosion will increase, and beaches will require more frequent renourishment. The quantity of sand required to keep pace with erosion will increase.

There will be increased reliance on sand sources from outside the U.S. or from inland sand mines in Broward, Miami-Dade, and other counties that can afford the considerably higher cost compared to traditional nearshore 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 are typically 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 on animals including sea turtles, which depend on the state's beaches as major nesting habitat (National Research Council, 1990). Loss of nesting beaches could threaten the recovery and survival of marine turtle populations.

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

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

Photo courtesy of Guy Weeks—Alligator Point

EFFECT: Impacts on 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, but 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) in 1998 initiated a study of sea-level rise impacts on the nation's economy. In 2000, under a grant from EPA to the Southwest Florida Regional Planning Council (SWFRPC), five of the regional planning councils (East Central, Treasure Coast, South Florida, SWFRPC, and Tampa Bay) 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 coastal Florida sea-level rise 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 assess climate-change vulnerabilities, to develop and implement adaptation strategies, to engage and educate stakeholders, and to share the lessons learned with other coastal managers. The U.S. 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 the 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.

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 meter along the U.S. Atlantic coast is expected to be developed and thus will be unavailable for the inland migration of wetlands. Less than 10% of the land below 1 meter 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, and 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).

Photo courtesy of Florida Fish and Wildlife Conservation Commission

EFFECT: 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 rains (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 with sea-level rise, amplifying the damage potential of hurricanes (R. Alvarez, personal communication).

Because Florida's stormwater drainage systems rely mainly on gravity, sea-level rise will reduce their effectiveness (South Florida Water Management District, 2009).

Because climate change is expected to cause more intense rainstorms and hurricanes, sea-level rise will exacerbate the risk of inland flooding during intense rainfall, especially in low-lying interior flood plains such as exist in southeastern 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 farther inland and flood with seawater those areas near primary canals and rivers. 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.

Primary drainage canals may not be able to function without the aid of pumps 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. will need to be evaluated (Heimlich et al., 2009).

SECTION

Sea-Level Rise Priorities for Florida's Ocean and Coastal Research III.

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 may often involve difficult decisions that consider trade-offs 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 first Annual Science Research Plan, for 2006–2007, 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 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, to assess the impact of sea-level rise, and to assist in resource management (for instance, commercial and sport fisheries).

2010 RECOMMENDATIONS FOR FLORIDA RESEARCH

During the preparation of this report, the following additional needs were identified:

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

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

- *In Ecology,* research to increase 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.

Photo courtesy of University of South Florida

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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.

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