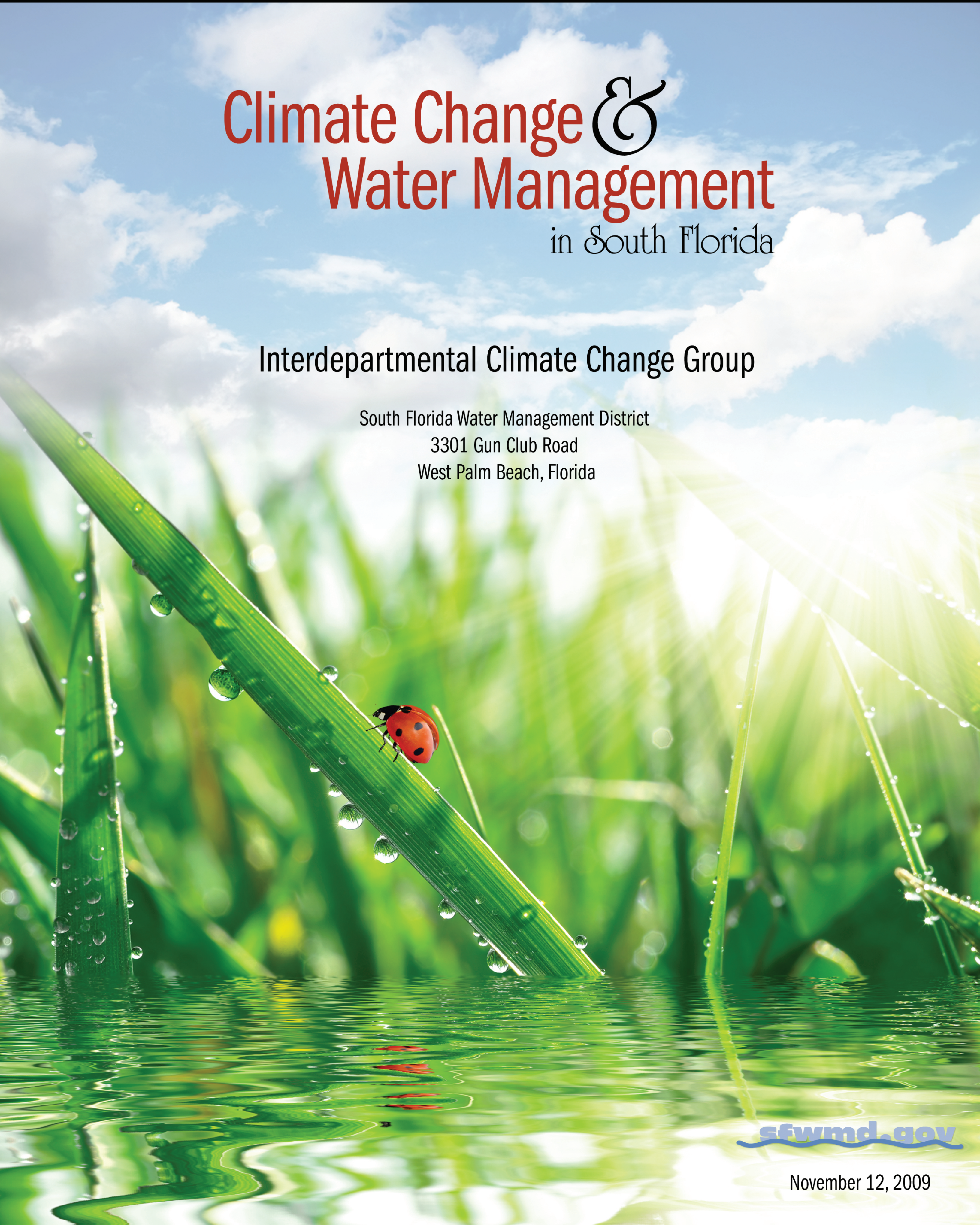
SOUTH FLORIDA WATER MANAGEMENT DISTRICT



Climate Change & Water Management in South Florida

Interdepartmental Climate Change Group

South Florida Water Management District
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Executive Summary

Global climate change and variability, particularly at regional levels, are not completely understood. Therefore, there are many significant uncertainties associated with forecasting future change and variability in places like South Florida. The purpose of this paper is to provide a high-level foundation for future discussions of the effects of global climate on water management planning and operations. By highlighting the current state of scientific knowledge, it provides policy- and decision-makers with important information when considering any potential actions.

More importantly, the intent is to focus the global concepts of climate change at the regional level by providing an overview of how it may affect South Florida's resources and the mission responsibilities of the South Florida Water Management District. The paper includes an initial vulnerability analysis of the potential threats of climate change and sea level rise to water supply, flood control, coastal ecosystems, and regional water management infrastructure. Due to the broad range of uncertainty, descriptions of the potential impacts of climate change on South Florida's water resources are based on the best-available science combined with the collective experience and best professional judgment of District staff.

The impacts of climate change are divided into four areas: 1) rising seas, 2) temperature and evapotranspiration, 3) rainfall, floods and drought, and 4) tropical storms and hurricanes.

Sea levels have been rising at a more rapid pace in the recent past in comparison to the last 2,000 years. Over the next fifty years, South Florida may experience seas that are in the range of 5 to 20 inches higher than current levels. As a result, there may be significant flooding of property and infrastructure, greater vulnerability to storm surges and erosion, and the destruction of coastal habitats. Sea level rise could accelerate saltwater intrusion of the coastal aquifers that are currently used to provide water for much of the region.

Temperatures and evapotranspiration in South Florida are predicted to rise, though projections vary greatly. With any rise in these factors, regional water demands will likely increase as well.

Changes to South Florida's rainfall have proven difficult to predict. Some studies suggest the region will be wetter, while others project 20 percent less rainfall. Either way, the environmental and operational impacts may be significant. In addition to changes in precipitation amounts, the intensity and timing of rainfall may also change, which could lead to more frequent droughts and floods.

Much like the rainfall predictions, scientists continue to debate how tropical storms and hurricanes will be different as a result of global climate change. The current research indicates overall storm frequency may decrease, while the number of strong hurricanes is expected to increase. Tropical storms and hurricanes cause significant damage to South Florida, but also provide huge amounts of rain for the area. The loss of storm-associated rainfall could have significant implications for the District's regional water supplies.

Although many aspects of climate change are still uncertain, the District is considering its possible impacts on South Florida. The combination of changes to sea levels, temperature, rainfall patterns, and tropical storms has the potential of significantly altering how the District operates to achieve its legislatively mandated mission.

I. Introduction: Confronting Change

According to the United Nations' Intergovernmental Panel on Climate Change, global climate change is real. The scientific consensus presented in their 2007 report is that warming of the Earth's climate system is unequivocally taking place[9]. The United States Supreme Court has ruled that the "harms associated with climate change are serious and well recognized."[*] And according to a 2009 special report prepared for the Florida Energy and Climate Commission by the Florida Oceans and Coastal Council[6], the question for Floridians is not whether they will be affected by global warming, but how much – that is, to what degree it will continue, how rapidly, what other climate changes will accompany the warming, and what the long-term effects of these changes will be.

Although current available models – including those used by the Intergovernmental Panel on Climate Change – are too coarse to provide useful projections for smaller, specific regions such as South Florida, the potential implications of the published range of modeled climate change impacts could be significant. While debate and research gaps continue to surround the nature, magnitude, speed, and ultimate impact of global climate changes, the potential risks to South Florida's natural and managed systems are high and oblige us to investigate possible water management ramifications.

While the study of natural and human-induced global climate change includes a multitude of far-reaching aspects, the four primary areas of focus for the District are sea level rise, temperature, rainfall patterns, and tropical storms/hurricanes. The impacts of these four elements alone could fundamentally alter traditional water management assumptions.

Recognizing the significant level of uncertainty, this paper addresses these four issues in terms of what is currently known, what is probable, and what is possible. "Probable" means an effect is highly likely to occur in the future, while "possible" means it may occur, but predicted impacts must be carefully qualified to reflect the level of certainty. The paper also examines the potential consequences on existing water management infrastructure and flood protection capabilities, along with water supply and restoration/natural systems impacts.

It is important to note that parts of the current regional network are over 50 years old and were designed and built according to known climate averages and extremes of the time. Over the last two decades, South Florida Water Management District scientists have researched how natural, global climatic patterns such as the El Niño/La Niña-Southern Oscillation and the Atlantic Multidecadal Oscillation are linked to South Florida's weather and climate. Based on this expanded experience and knowledge, the District has already adopted progressive measures to incorporate climate outlook into its planning and operations. Other District scientists continue to study the natural climate cycles affecting South Florida, including the rates of soil accretion near Florida Bay and its potential to offset the effects of sea level rise.

The development of any recommendations or adaptation strategies regarding global climate change requires a holistic investigation of the current state-of-the-science, along with an initial assessment of vulnerabilities with respect to the District's mission responsibilities. The intent of this paper is to provide that solid foundation.

[*] Massachusetts v. EPA, 2007

II. Climate Change and Water Management: Historical Climate Variability

Cyclical changes in climate are well known. Long-term data show rises and falls in temperature, precipitation, extreme events, and every other climate factor. However, many recent changes appear to be outside normal historical variability. The last few decades have experienced higher temperatures than much of the past two millennia[11]. Arctic sea ice levels have reached record or near-record lows over the last three summers and scientists are witnessing changes in seasonal migrations, pollen release, and bird nesting as plants and animals adjust to what is happening around them[12]. While climate changes are occurring over the entire planet, the impacts differ from one region to another.

In South Florida, annual rainfall is a perfect example of climatic variability. The amount of rain from one year to another can cause the area to swing between extreme dry and wet conditions (**Figure 1**). These annual changes in precipitation are a major challenge to water management. While surface and groundwater storage compensates for short-term variations, droughts have dried wetlands and lowered lake levels significantly. On the other extreme, wet conditions can result in local flooding and trigger freshwater flood control discharges to delicate estuarine environments. For water managers, understanding past and predicting future climate variability is vitally important.

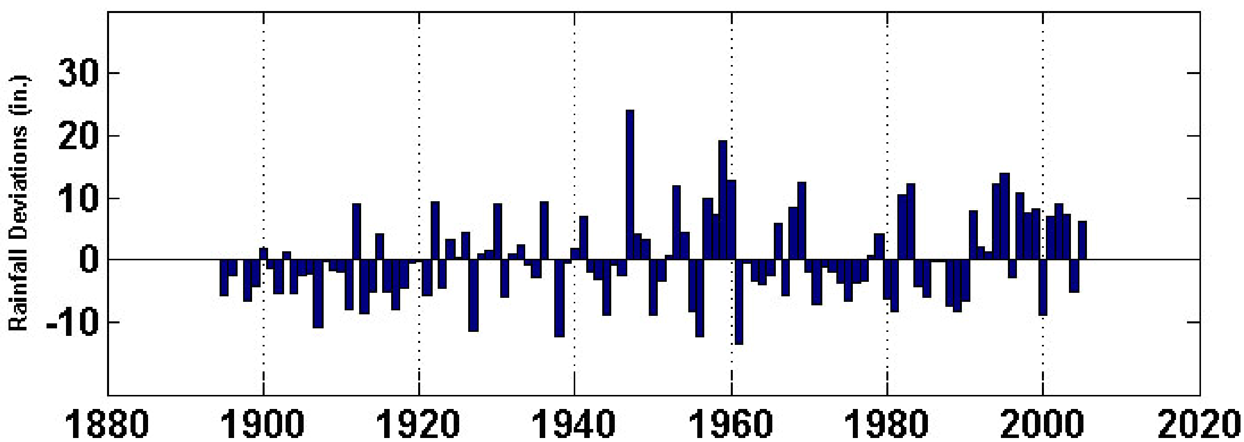

Figure 1. Deviations from average District-wide, long-term rainfall patterns demonstrate the extreme variability of dry and wet periods in the region over more than a century.

Scientists are now able to link climate variability in specific regions (such as South Florida) to global patterns. The District uses this knowledge to prepare and adjust operations prior to changes due to El Niño/La Niña, the Atlantic Multidecadal Oscillation, and other global patterns.

Predicting climate change and its consequences remains an inexact science. Many factors, including solar radiation, atmospheric composition, cloud cover, ocean currents, and land activities (for example, deforestation and urbanization), influence climate and make longer-term change difficult to predict. Further complexity comes from the circular relationships between elements of the system. For example, as temperatures rise, the atmosphere holds more water vapor. Since water vapor is one of the most effective greenhouse gases, more of it means the atmosphere will continue to get warmer and thus be able to hold more water vapor[3].

Similar relationships exist between the amount of ice coverage and the reflectivity of the Earth's surface and the amount of carbon dioxide in the atmosphere and plant productivity. Scientists have been studying these relationships for years, but still have limited knowledge of their effects on climate change.

Despite the broad range of unknowns and uncertainties, any significant change in the natural cycles could limit the flood control effectiveness of existing and planned water management infrastructure in the region, increase the likelihood of further encroachment of sea water into groundwater supplies, and virtually inundate the southernmost tip of the peninsula and other low-lying areas.

III. The Global Climate Change Quartet and Implications for Water Management

For the purposes of this paper, the discussion of impacts is limited to implications on the effective management of South Florida's water resources. These have been categorized into four critical areas:

- Rising seas
- Temperature and evapotranspiration
- Rainfall, floods and drought
- Tropical storms and hurricanes

Each of the following sections summarizes the state of the science and identifies the possible implications for water management in South Florida. Although separated into four distinct sections here for discussion purposes, the impacts of global climate change are very much interrelated.

Given the extremely wide timeframe of global climate change predictions, a planning period for projections of approximately 50 years – to 2060 – is generally used in this document based on District planning experience. Changes and impacts will certainly extend beyond this period, but with increasingly more unknowns and less certainty. Much of the research cited in this paper covers a wide range of projections, many continuing far past the paper's planning period.

A. Rising Seas

Sea Level Rise – Historic Rates and Projection Ranges

Global sea levels rose about 400 feet as the glaciers of the last ice age retreated approximately 21,000 years ago. Between 3,000 and 2,000 years ago, the rate of sea level rise slowed dramatically and continued at that pace until recently[9]. In the more recent past, the pace of rise of global mean sea levels has been increasing (**Figure 2**). From 1961 to 2003, sea levels rose about 3 inches, an average of 0.071 inches per year[9]. However, the average sea level rise was faster during the last 11 years of that period (1993 to 2003), increasing to a rate of about 0.12 inches per year. Well in line with those figures, the seas around Florida have been rising about 0.1 inches per year[6].

Two primary factors account for most sea level rise:

- Thermal expansion. As the oceans warm, their volume increases – a process called thermal expansion. Since the world's oceans absorb roughly 80 percent of the heating of the climate associated with global warming, thermal expansion is expected to have the greatest influence on sea level rise as the planet warms.
- Melting ice. Sea levels also rise as water is added to the oceans from melting glaciers, ice caps, and ice sheets. Differences in scientific opinion regarding the melting of Greenland and Antarctic ice sheets contribute greatly to the uncertainty in sea level rise projections.

Land-based water input (extraction of groundwater, building of reservoirs, changes in runoff, and seepage into aquifers), along with vertical land movement (subsidence in river delta regions, land movements, and tectonic displacements) also contribute to changes in sea levels.

What is known:

Sea level has been rising in the nineteenth and twentieth centuries; the rate of rise has also been increasing over the last few decades. The majority of sea level rise is due to thermal expansion, but projections vary greatly due to uncertainties regarding the future of land-based ice sheets in Greenland and Antarctica.

What is probable:

Sea level rise may range from 5 to 20 inches in South Florida by 2060.

What is possible:

Rising seas will likely have direct impacts on coastal beaches, infrastructure, and wetlands due to high tides and storm surges. Urbanized areas along the coasts may be more prone to flooding. Coastal water supplies could be impacted by accelerated saltwater intrusion. Natural systems may suffer significant impacts.

Information gaps:

Projections for sea level rise vary greatly. Without more regional-specific and firm projections, it is difficult to accurately predict the potential affect and develop adaptation strategies of sea level rise on District mission elements. A better understanding of the uncertainties in the sea level rise projections and a detailed analysis are needed to identify the impact of projected sea level rise on urban flooding, utility wellfields at risk of saltwater intrusion, and wetlands in the coastal areas.

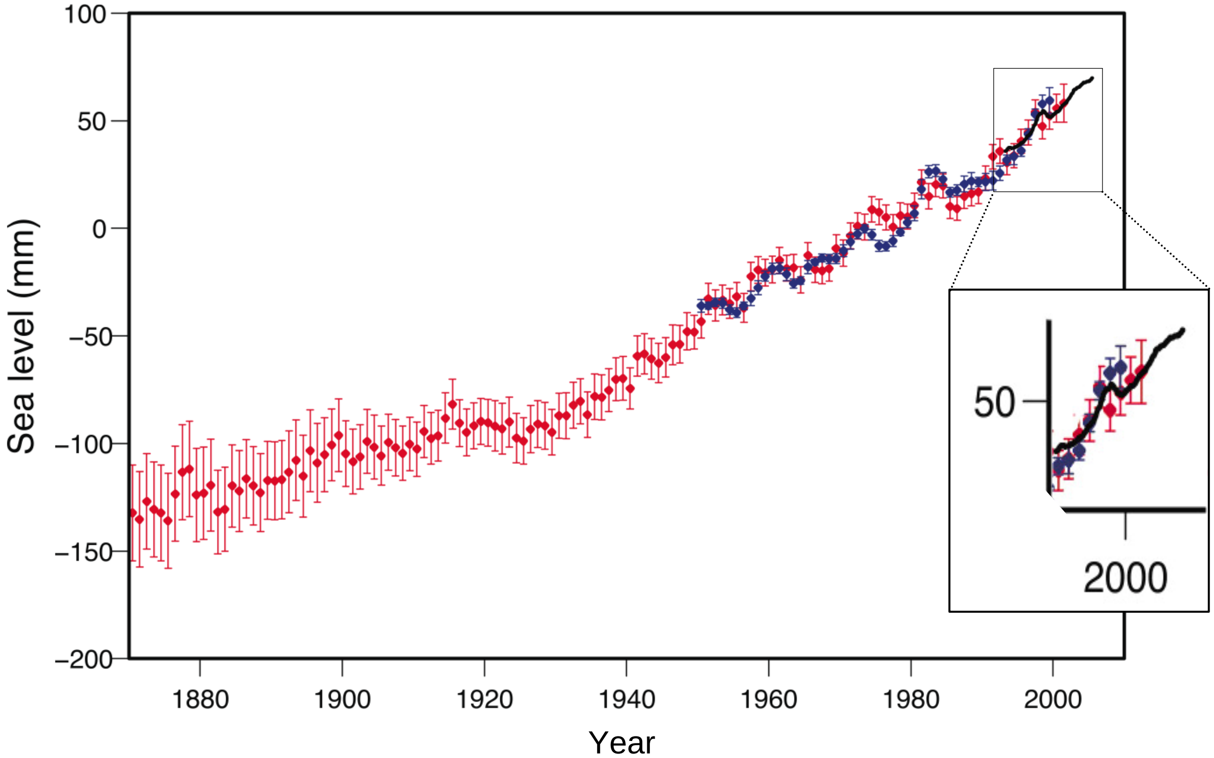

Figure 2. The present rate of both global and local sea level rise is approximately 12 inches per century. This chart reflects the rise of sea levels since the nineteenth century and the accelerated pace over the last few decades. Red points show reconstructed data since 1870, blue points show coastal tide gauge measurements since 1950, and the black curve is base on modern satellite altimetry. Fifty millimeters is approximately two inches (from Figure 5.13, Intergovernmental Panel on Climate Change[9]).

The projections from the Intergovernmental Panel on Climate Change indicate that sea levels will rise from 7 to 23 inches by the year 2100[9]. The Miami-Dade County Climate Change Task Force projects up to 60 inches of rise in that same period due to an expectation of much faster ice sheet melting[13]. Many others have attempted to produce sea level rise trends to predict the sea level rise through 2100. Clearly, there are wide-ranging uncertainties in the projections as shown in **Figure 3**. Based on the information from multiple sources summarized in this figure, **the District may experience sea level rise on the order of 5 to 20 inches within the next 50 years.** This range provides a lower and upper bounds for planning purposes until better and region-specific information is made available from scientific research being conducted by various organizations.

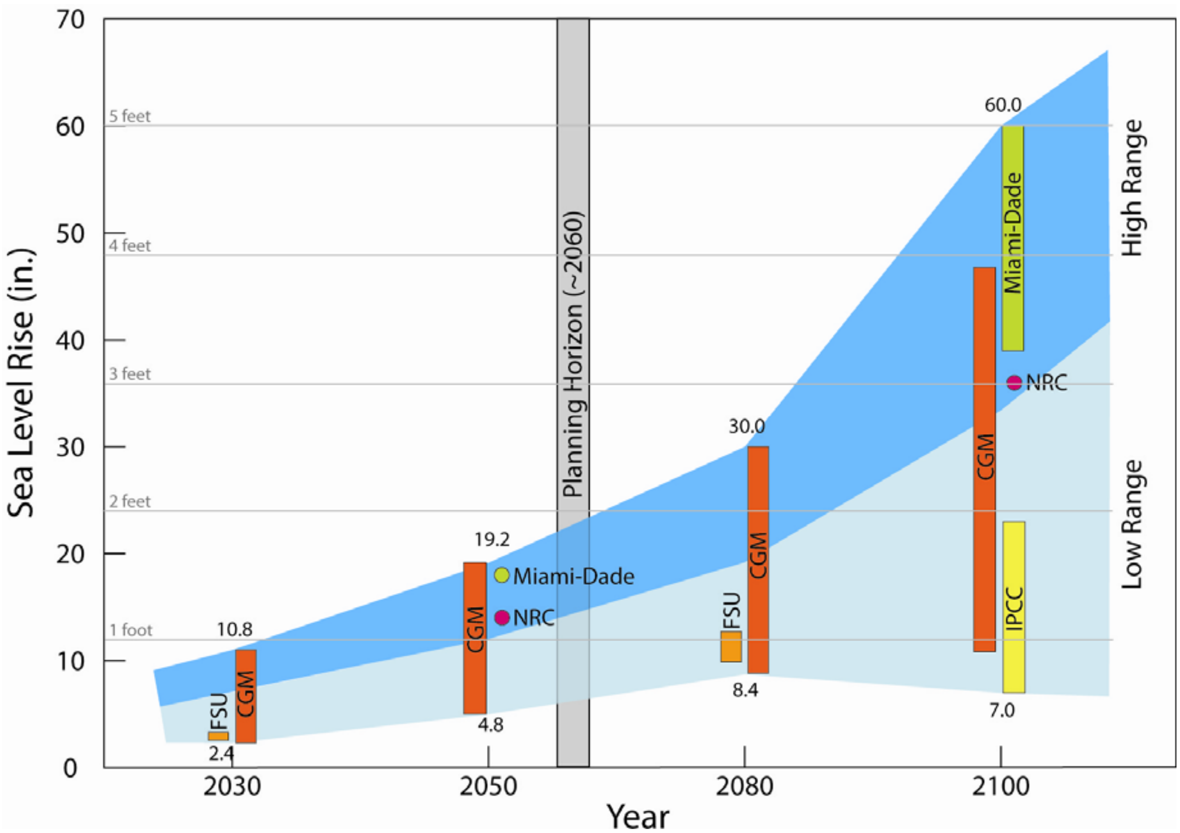

Figure 3. Range of sea level rise projections through 2100 with 1990 as the reference year. Projections were derived from CERP Guidance Memorandum (CGM)[5], National Research Council (NRC)[15], Miami-Dade County Task Force (Miami-Dade)[13], Florida State University (FSU)[7], and the Intergovernmental Panel on Climate Change (IPCC)[9]. The District is focusing on the 50-year planning horizon (2060) range of 5 inches to 20 inches above the 1990 level. These estimates will be revised to incorporate additional information provided for regional application by the U.S. Army Corps of Engineers' Engineering Circular 1165-2-211[19].

Potential Implications

South Florida's coast is extremely vulnerable to sea level rise. While projections of impacts of sea level rise specific for South Florida are not readily available in peer-reviewed scientific literature, District scientists and engineers are able to make the following general predictions of potential impacts based on extensive knowledge and experience with the region's managed and natural systems.

Flood Control / Operations and Maintenance

Projected sea level rise may cause significant saltwater flooding of coastal property and infrastructure, greater vulnerability to storm surges and erosion, and the destruction of vital coastal habitats[6]. Water management infrastructure and regional water control structures located near the coast may be highly vulnerable.

The projected rises in ocean levels may limit the District's ability to protect areas of South Florida from rain-driven flooding. The canal networks in Palm Beach, Broward, and Miami-Dade counties and in the lower West Coast are typically maintained at predetermined water levels to reduce saltwater intrusion into the wellfields that provide drinking water to the region and to provide flood protection. Water control structures maintain the water levels of the canals. When these structures discharge to the ocean, the water level difference between upstream (land side or headwater) and downstream (ocean side or tailwater) may be as little as 6 inches or less for some structures under design conditions. Projected sea level rise may reduce the flood discharge capacity of coastal structures, thus affecting flood protection in urban areas. The location of existing District coastal structures potentially impacted by sea level rise is shown in **Figure 4**.

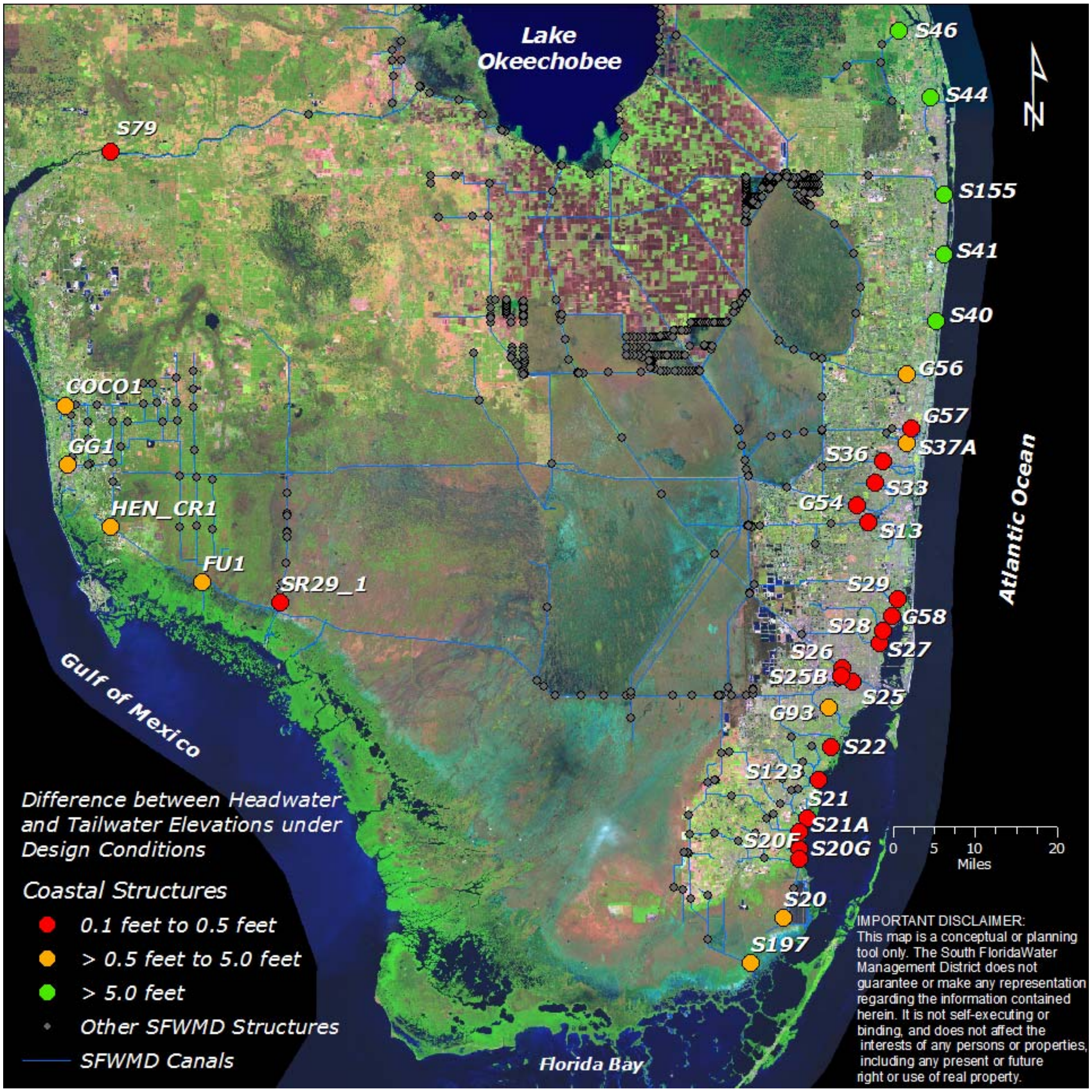

Figure 4. Vulnerability of District coastal structures to potentially rising sea levels. High vulnerability structures are red, medium vulnerability are orange, and low vulnerability are green. (Map produced by the SFWMD.)

Water Supply

Most coastal communities in South Florida depend on wellfields that tap underground freshwater aquifers for their water supply. Saltwater intrusion into these aquifers due to the current sea level and coastal development already threatens the region's water supply. Between the years 1995 and 2000 a compilation of county data[2,8,17] has resulted in an approximate location of the freshwater/saltwater interface on the Lower East Coast with measured chloride levels of 100 mg/L to 250 mg/L and above at the base of the aquifer (**Figure 5**). The highly populated area from Miami to Palm Beach is considered especially vulnerable by the Florida Oceans and Coastal Council[6]. A more detailed analysis is needed to identify the impact of projected sea level rise on selected utility wellfields at risk of saltwater intrusion. Miami-Dade and Broward counties have both initiated studies to help with this determination. Similar studies are needed to understand the vulnerability of the aquifers of the Lower West Coast.

Figure 5. Estimated freshwater/saltwater interface in the lower east coast for the years 1995 through 2000 based on measurements from 100 mg/L chloride to 250 mg/L chloride and above. (Map produced by the SFWMD.)

Environmental Systems

Much of South Florida, including many of the region's most environmentally sensitive areas, is at low elevations. The low elevation of these areas makes them prone to flooding at today's sea levels and sea level rise will cause them to become permanently inundated or prone to flood more frequently (**Figure 6**). The environmental impacts of the flooding depend on how much and how quickly water levels change.

A slow rise of 1 to 2 feet could result in both environmental benefits and harm. This rate of expansion would slowly affect salinity in areas that were once fresh, allowing habitats to transition into new states without massive fish kills or die-offs of vegetation. With sea levels rising gradually, the productive and diverse estuarine zone would probably grow. This landscape would change as some wetlands become open water and some terrestrial habitats convert to mangroves. A gradual change in sea level may allow for shifts in community structure and some species like manatees may thrive. While animals and plants may shift locations, for the most part, the environment will remain healthy. However, there also could be environmental costs because the rise of sea levels and associated conversion of habitats increases the turbidity of waters discharged into coastal zones, which in turn would cause reefs and underwater plant communities to degrade. For some endangered or listed species, such as the Cape Sable seaside sparrow, coastal mice species, and even the Florida panther, critical habitats may be lost. Turtles and sea birds would have to shift to new locations as rising seas drown traditional nesting areas.

In comparison, a very rapid sea level rise would likely have more severe implications for the South Florida environment. As waters rise, the estuarine zone would shrink and coastal wetlands and terrestrial habitats may be lost as they become open water marine habitats. Oxygen levels would drop and concentrations of hydrogen sulfide (a toxin) would likely increase as large amounts of newly submerged organic matter decompose. Large sediment plumes would likely discharge into coastal zones and this increased turbidity may cause most reefs and submerged aquatic vegetation communities to die. If these habitats disappear, then so would the keystone and endangered species they support, such as sea birds, turtles, Cape Sable seaside sparrow, coastal mice species, alligators, and Florida panthers. If freshwater flows are not restored, most plants and animals would not have time to adjust to the saltwater flooding and there may be catastrophic food web changes across thousands of acres in the Everglades, river mouths, coastal lagoons, and bays.

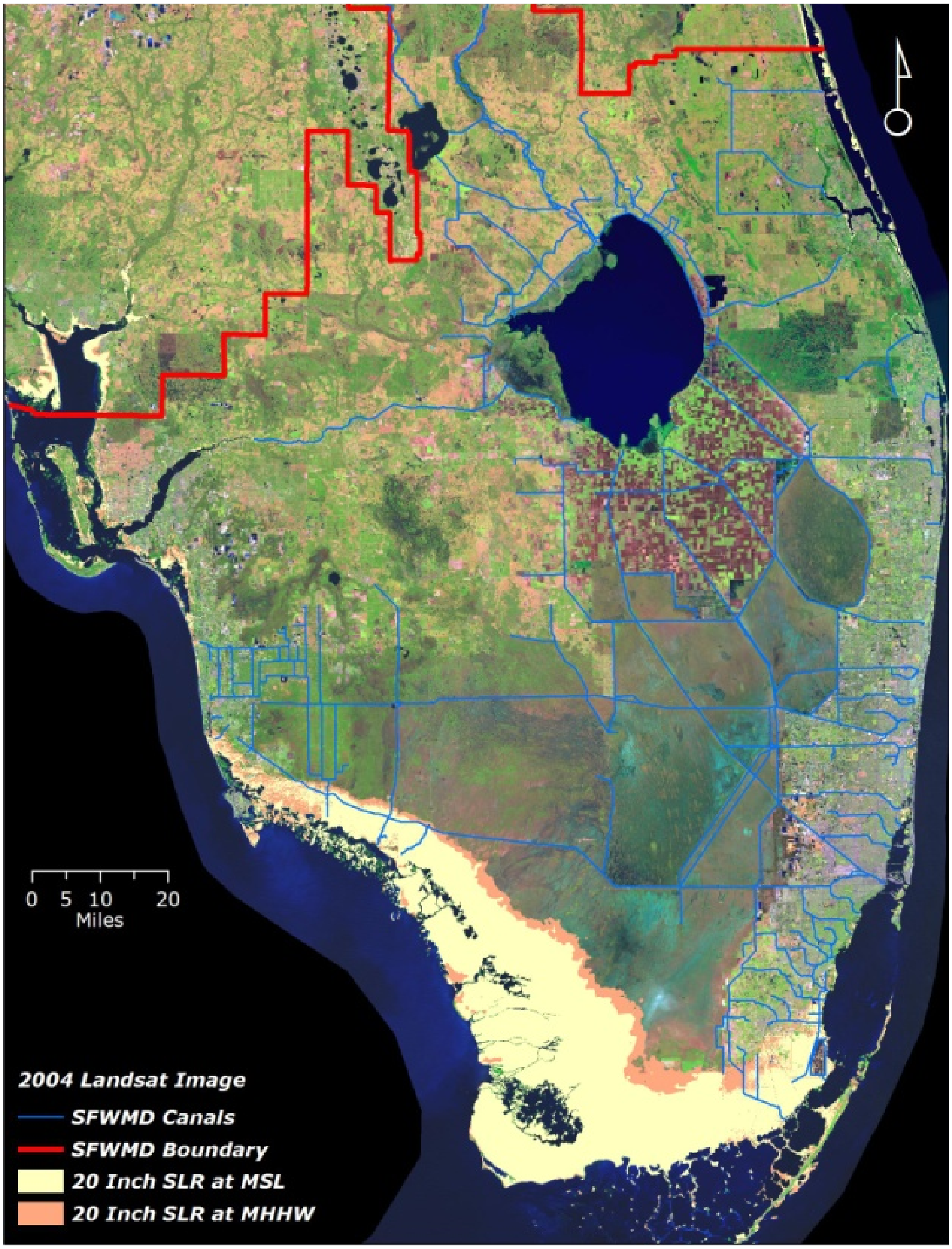

Figure 6. Possible permanent inundation and/or increased flooding of land within the District with a sea level rise (SLR) of 20 inches, the upper bound of projections for this paper, at mean sea level (MSL) and mean higher high water (MHHW). Tidal station data is averaged across the District and related to NAVD88. (Map produced by the SFWMD.)

B. Temperature and Evapotranspiration

Temperature Projections

Global temperatures are expected to increase by about 0.4°F per decade according to the Intergovernmental Panel on Climate Change[9]. Based on those estimates, temperatures will be about 2°F warmer by 2060 and almost 4°F warmer by 2100. Improvements in climate science allow limited projections of temperature changes for specific regions. A 2001 report by the Union of Concerned Scientists expects winter lows to increase 3°F to 10°F and summer highs to rise by 3°F to 7°F by the end of the century along the Gulf Coast. The July heat index, which represents the temperature actually felt, could rise by 10°F to 25°F[18,21]. Considerable uncertainties exist in the regional projections of temperature resulting from climate change.

Water demands are expected to increase significantly as temperatures rise (**Table 1**). Agricultural and domestic water use will likely rise as temperatures go up. The potential for wildfires, especially during the dry season, will also increase.

What is known:

The majority of climate models predict an increase in temperature during the next 50 years. In addition, evaporation from open water and soil and transpiration from plants will likely increase.

What is probable:

Climatologists predict air temperatures will increase, with projections of summer temperatures being up to 3°F to 7°F warmer by 2100[18,21]. Evaporation and transpiration are expected to increase. Impacts include increased/competing water demands; more rapid loss from surface water supplies and disruption in the ecosystem food chain.

What is possible:

Temperatures could significantly increase over time. Impacts include much higher water demand as less water is available due to evaporation from surface water supplies. Increased temperatures could also impact freshwater and marine ecosystems.

Information gaps:

Some gaps exist in the information available on temperature and evapotranspiration projections, especially changes in timing, amounts, and spatial distribution. This limits the ability to predict changes in the water cycle and its impacts to South Florida's natural vegetation, water supply, urban areas, and ecosystems.

Evapotranspiration Projections

Increases in air temperature, solar radiation, and water vapor deficit due to climate change are expected to increase evapotranspiration, which is the combined loss of water through evaporation from soil and surface water and plant transpiration. Models used by Calanca et al. predict a 20 percent increase in evapotranspiration if summer temperatures increase from 4°F to 7°F[4]. Increased evapotranspiration may, in turn, increase water demand for irrigation and natural wetlands areas.

In South Florida, evapotranspiration is expected to increase due to climate change, though there is great uncertainty in the projections. Maps produced by the Intergovernmental Panel on Climate Change suggest annual evapotranspiration rates in South Florida may increase by up to an estimated 15 percent for the period 2080 to 2099 compared to the historical measurements from 1980 to 1999[1].

Table 1. Potential impacts due to increased temperature.

	Temperature Variables – Potential Duration and Intensity	
	Warmer Compared to Normal	**Much Warmer Compared to Normal**
Flood Control	Not much impact	Not much impact
Water Supply	Increased water demand, including high irrigation water demand due to higher evapotranspiration	Increased water demand, including much higher irrigation water demand due to higher evapotranspiration
Natural Systems	Lower dissolved oxygen and loss of fish and wildlife; increased coral bleaching	Extreme reduction in dissolved oxygen and a significant loss of fish and wildlife; widespread coral mortality

Potential Implications

South Florida's ecosystems may go through a variety of changes if the region gets 3°F to 7°F warmer. In general, higher temperatures may make it harder for ecosystems to resist and recover from the various threats they face, such as hurricanes, droughts, fires, invasive species, and diseases. Warmer temperatures will likely cause increases in water needs, bacterial processes, nutrient cycling, and peat degradation. If these potential changes occur, there will be less food for fish and wildlife, more disease, less oxygen, and more carbon dioxide. The lower oxygen levels will increase the number and severity of fish kills.

Regional surface water storage systems (lakes, rivers, canals, reservoirs, water conservation areas) will most likely experience more rapid water loss when compared to current levels, ultimately impacting availability of water supplies. In addition, accelerated evaporation losses from Stormwater Treatment Areas could impact their phosphorus removal performance, increasing the need for supplemental water for these facilities.

While warmer temperatures will cause increased evapotranspiration and make droughts more severe, extreme high temperatures can have more abrupt affects on human health, agriculture, water availability and quality, and the health of existing ecological systems over a much shorter time span. Increases in the extreme high temperatures in the future may require changes in both societal and agricultural practices.

C. Rainfall, Floods and Droughts

Rainfall Projections

There is a significant gap in the available literature on the impact of climate change on rainfall and the uncertainty associated with it. Some climate models predict South Florida will get wetter, while others predict a drier region. An Intergovernmental Panel on Climate Change report predicts up to 20 percent less rainfall for South Florida for the period between 2080 and 2099 in comparison to historical measurements from 1980 to 1999[9].

> **What is known:**
>
> Rainfall amounts and intensities will likely change, but projections vary greatly. Some scientists predict rainfall increases while others forecast decreases compared to historical observed normal amounts.
>
> **What is probable:**
>
> Rainfall amounts in South Florida are projected to either increase or decrease by as much as 20 percent. This could result in longer stretches of wet and dry periods with droughts more likely to occur.
>
> **What is possible:**
>
> Changes in rainfall (intensity and frequency) can cause significant damage to managed and natural environments. Major impacts to the regional water supplies could occur.
>
> **Information gaps:**
>
> Significant gaps exist in the information needed to project rainfall accurately, especially changes in timing, amounts, and distribution. Due to the amount of uncertainty of rainfall projections, the need for changes in the flood control system is currently unknown.

The intensity of rainfall events is also changing. The District's data indicate that there has been an increase in heavy downpours in many parts of the region, while the percentage of the region experiencing moderate to severe drought increased over the past three decades. In the future, more frequent intense rainfall events are projected to occur, with longer dry periods in between[6]. While periodic heavy downpours may increase overall precipitation totals, much of the water may be runoff that is eventually lost to tide.

Changes in rainfall patterns associated with global climate change will likely influence the occurrence and severity of floods and droughts throughout much of the world.

Climate models predict longer stretches of dry days between more intense rain events in the subtropics. The combination of these conditions increases the likelihood of more severe floods in the region. For droughts, multiple models predict they will be more likely to occur. One study suggests that within 100 years, some 30 percent of the world's land area may be under extreme drought[20].

Potential Implications – Rainfall

Whenever there is a change in rainfall, there is an expected change in storm-generated runoff. Since runoff is normally non-linear, the impacts from changing rainfall patterns can be dramatic. While much uncertainty remains in projecting future rainfall in the region, the following scenarios are possible:

1. <u>Wetter than normal</u>: Under this scenario, the rainfall volume is higher than normal during the wet or dry season. The runoff from these scenarios could generate flood conditions. The duration, depth, and extent of flooding would vary from one event to another. Wetter than normal conditions also could involve more rain events, more successive rain events without a break, increased duration of rain events, and more intense (higher rainfall rate) rain events.

When combined with higher temperatures, the ecosystem impacts of wetter than normal conditions would be mixed. More freshwater runoff could further degrade the Caloosahatchee and St. Lucie systems, while creating improved estuarine habitats across the southern end of the Florida peninsula (**Table 2**).

2. Drier than normal: In this scenario, the rainfall volume is lower than what normally occurs during the wet or dry season. These conditions could result in drought; the intensity and duration of which would depend upon the amount of rainfall, the intensity and duration of rain events, and the number of dry days between rain events.

   Drier conditions with higher temperatures will likely harm many of the region's natural areas. Less rain will cause vast areas that are now shallow or marginally aquatic to dry out, causing fish, amphibian, reptile, bird, and mammal populations to significantly decline. Coastal freshwater habitats will see an intrusion of salt water, even if sea level does not rise. Large areas of freshwater wetland communities may dry up or change to short-lived inland lakes. Wildfire occurrence and extent would depend on the number of days between rain events and the soil moisture during the dry season. Increased fires and oxidation of soils could reduce ridge and slough habitats, tree island elevations, fish habitat, wading bird nesting sites, and peat accumulation. As a result, this scenario could significantly alter the community structure and biodiversity of the freshwater Everglades.

As with many aspects of the regional effects of climate change, there is a gap in the information regarding the impacts on the seasonality of rainfall. If the expected beginning or ending of the wet and dry seasons were to change, water supply and flood control assumptions related to water management would require revisions.

The possibility of wetter dry seasons also may have significant impacts on coastal ecosystems. During the winter, evapotranspiration is much lower than that during the summer. Extra rain could create a significant surplus of water that, without adequate storage, must discharge through the coastal estuaries to tidewater during a time of the year when excess water is especially undesirable for the natural estuarine ecosystems.

Table 2. Potential impacts due to changing rainfall conditions.

	Rainfall Variables – Potential Volume, Duration, Intensity, and Frequency	
	Higher than Normal High	**Lower than Normal Low**
Flood Control	Adequate storage concerns; required discharges to estuaries; possible crop damages; reduced flood protection	Not much impact
Water Supply	More irrigation water available (if captured and stored); higher surface water and groundwater levels	Higher demands/less available stored waters; lower groundwater levels with increased threat of saltwater intrusion into coastal wells; possible crop damage
Natural Systems	Terrestrial systems will degrade; some aquatic systems will improve; other aquatic systems will degrade due to loading of pollutants	Fire-adapted systems will improve; aquatic systems will degrade due to a loss of habitat for fish and wildlife

Potential Implications – Floods and Droughts

In developed parts of Florida, heavy rainfall poses a threat to homes, businesses, and water control structures. If flooding were to reach new extremes, the water management system already in place may not be adequate to provide the necessary levels of flood protection. Flooding could also further degrade water quality due to increased runoff, the loss of positive pressure in sewer systems, damage to septic systems, and pollutants washed into water bodies. Extreme flooding would significantly affect a water management system initially designed to protect 2 million people but that now serves a population of more than 7.5 million.

At the other end of the spectrum, the potential of increased frequency and duration of droughts poses a number of problems for water management. Water demands will likely increase if there is not enough rainfall to satisfy water supply and irrigation needs. Without adequate water to maintain vegetation during droughts, the performance of Stormwater Treatment Areas may be impacted when rains return.

The environmental impact of changes to floods and droughts depends on the relationship between the climate extremes.

- If flooding and drought frequency increase together, the Everglades may return to a more natural slough-ridge-island landscape because the floods would redistribute soils and sediments onto ridges and the droughts would allow recruitment of trees on islands.
- More droughts, without an increase in flooding conditions, pose a threat to the entire South Florida system. They would likely cause large shifts in community structure due to saltwater intrusion into freshwater habitats, drying of inland wetlands, disappearance of ridge and slough microtopography, and an increase in frequency of fires (both terrestrial and wetland). Without the ability to maintain minimum flows and water levels in South Florida, agriculture and public water supply wellfields may not be able to function as designed. In addition, wellfields may be contaminated by saltwater intrusion and higher salt levels in coastal waters may limit the usefulness of currently installed desalinization plants.
- More flooding may be good for the Everglades ecosystem because it would stimulate ridge-slough development and restore historic salinity regimes in Biscayne Bay and Florida Bay. However, increasing flooding alone may also create more frequent water level reversals during critical wading bird foraging periods, thus causing further declines in nesting success for wood storks, roseate spoonbills, white ibis, and others.

D. Tropical Storms and Hurricanes

What is known:

Hurricane frequency and strength have increased dramatically since 1995. Much of the change is attributed to natural cycles.

What is probable:

Hurricane and tropical storm frequency will continue to change in comparison to the historical record.

What is possible:

Warmer temperatures create the potential for stronger hurricanes. Hurricane frequency may remain the same or decrease as part of climate change. A lower number of tropical storms and hurricanes each year could reduce the region's water supply. Likewise, an increase in tropical activity could increase flooding. In either case, hydroperiod changes will be stressful to managed and natural systems.

Information gaps:

While the number and strength of tropical storms change naturally, the exact degree to which climate change may alter the natural cycles is uncertain.

Tropical Storm Activity

According to the National Center for Atmospheric Research, Florida tops all other states with the costliest damage due to extreme weather events through 2007. When ranked by event type, Florida was first in damage from hurricanes, fourth in flooding, and ninth in tornadoes[14]. Tropical storms and hurricanes also contribute significant amounts of water to the state, which make them an important part of water management planning and assumptions.

The frequency of tropical storms and hurricanes changes as part of natural cycles that occur over decades. The region is currently in a multiyear period of higher than average tropical storm activity that is largely due to a combination of a shift of the Atlantic Multidecadal Oscillation and, to a lesser extent, global climate change[6,16].

As the atmosphere warms, sea surface temperatures and wind shear will also increase. These two factors can have opposing effects on tropical storms. The role of sea temperatures is complicated. As the temperatures rise, overall storm frequency may decrease, but intensity of stronger storms may increase. Wind shear increase is expected to reduce the number of storms in the Atlantic Ocean[6].

Potential Implications

If a decrease in the number of storms does occur, there may be significant changes to the distribution of rainfall, which will affect the water supply and natural ecology of South Florida. Less rainfall may mean the region is under drought conditions more often.

If tropical storms and hurricanes become more intense, the potential damage to levees, canals, and other water control structures may also increase – resulting in an increased likelihood of flooding on a local and regional scale. Water supply and water quality may also be adversely affected by this extreme.

Ecologically, if tropical storms and hurricanes increase, the damage to the Everglades and coastal mangroves may also increase. Large regions of coastal pines could be destroyed. More wind may increase the extent that seeds and spores of plants, including invasive species, are spread across South Florida. When combined with rising sea levels, more tropical storms may cause vast areas of mangroves to die-off, creating a cascading impact on soil and nutrient processes. This, in turn, may lead to coastal erosion and large redistributions of sediments resulting in high turbidity. While hurricane-related damage to developed areas may increase, the ecosystems of South Florida will likely remain resilient, unless they are overwhelmed by other aspects of climate change.

IV. Conclusion

The District has used the historic record as the primary tool for predicting future water trends and making water management decisions. However, in view of the potential of future climate change, history alone is not a sufficient predictor of the future climate characteristics.

Some effects of global climate change, such as sea level rise, have already been documented. Other aspects could occur within the coming decades or not until well into the future. While specific data for the South Florida environment is limited, the data available and summarized in this paper suggests the following potential scenarios:

- Relative to 1990 level, a rise of 5 inches to 20 inches in sea levels by 2060. This range provides lower and upper bounds for planning purposes until better and more specific regional information on future sea level rise is available.
- An increase in air temperatures of up to 7°F and evapotranspiration up to 15 percent by 2100.
- A change in rainfall of up to ±20 percent.
- A change in the strength and frequency of tropical storms and hurricanes. Exact extent of the changes due to global warming is not clear at this time.

Despite all the research and continued scientific debate, the only certainty is the uncertainty of the wide-ranging projections. That makes it difficult to produce reasonable assumptions for planning purposes. **Over the next two years, more work is needed to understand the current trends and uncertainties in climate projections, and to develop tools for understanding the exact vulnerabilities of the water management system and regional water resources. During this period and beyond, appropriate adaptation strategies will be developed and implemented.**

The South Florida Water Management District will be continuously challenged to appropriately confront the impacts of global climate change and fulfill its mission to “manage and protect water resources of the region by balancing and improving water quality, flood control, natural systems and water supply.”

References

1. Bates, B., Z.W. Kundzewicz, S. Wu and J. Palutokof. 2008. Climate Change and Water. IPCC Technical Paper VI. UNEP.
2. Broward County. 2000. Enhanced Salt Water Intrusion Monitoring Program. http://www.co.broward.fl.us/emd/moi00612.pdf
3. Burroughs, W.J. 2007. Climate Change: A Multidisciplinary Approach, Second Edition. Cambridge University Press, New York, NY.
4. Calanca, P. A. Roesch, K. Jasper and M. Wild. 2006. Global warming and the summertime evapotranspiration regime of the Alpine region. Climate Change 79:65-78.
5. CERP Guidance Memorandum. 2004. Sea level rise considerations for formulation and evaluation of CERP projects. CGM 016.00. 9 pp.
6. Florida Oceans and Coastal Council. 2009. The effects of climate change on Florida's ocean and coastal resources. Tallahassee, FL. 34 pp.
7. Harrington J. and T.L. Walton. 2007. Climate change in coastal areas in Florida: Sea level rise estimation and economic analysis to year 2080. Center for Economic Forecasting and Analysis. Florida State University, Tallahassee, FL. 87p.
8. Hittle, C.D. 1999. Delineation of Saltwater Intrusion in the Surficial Aquifer System in Eastern Palm Beach, Martin, and St. Lucie Counties, Florida, 1997-98. http://fl.water.usgs.gov/PDF_files/wri99_4214_hittle.pdf.
9. International Panel on Climate Change. 2007. Climate Change 2007 – The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge University Press.
10. Langevin, C.D. and A.M. Dausman. 2005. Numerical simulation of saltwater intrusion in response to sea-level rise. Proceedings of the Water & Environmental Resources Congress: Impacts of Global Climate Change, Anchorage, Alaska. http://plaza.ufl.edu/clang001/papers/langevin_ASCE2005.pdf (December 18, 2008).
11. Mann, M.E., Z. Zhang, M.K. Hughes, R.S. Bradley, S.K. Miller, S. Rutherford and F. Ni. 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. Proceedings of the National Academy of Science 105:13252-13257.
12. Mascarelli, A.L. 2009. What we've learned in 2008. Nature Reports, Climate Change. 3:4-6.
13. Miami-Dade County Climate Change Task Force, Science and Technology Committee. 2008. Statement on Sea Level in the Coming Century. January 17. 9 pp.
14. National Center for Atmospheric Research. 2009. Extreme Weather Sourcebook. http://www.sip.ucar.edu/sourcebook.
15. National Research Council. 2008. Progress toward Restoring the Everglades, the Second Biennial Review. National Academies Press, Washington, DC.
16. Nyberg, J., B.A. Malmgren, A. Winter, M.R. Jury, K. Halimeda Kilbourne and T.M. Quin. 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. Nature 447:698-702.
17. Sonenshein, R.S. 1995. Delineation of Saltwater Intrusion in the Biscayne Aquifer, Eastern Dade County, Florida, 1995. http://fl.water.usgs.gov/Miami/online_reports/wri964285/.
18. Twilley, R.R., E.J. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D.J. Reed, J.B. Rose, E.H. Siemann, R.G. Wetzel and R.J. Zimmerman. 2001. Confronting Climate Change in the Gulf Coast Region. A report of the Union of Concerned Scientists and the Ecological Society of America. http://www.ucsusa.org/assets/documents/global_warming/gulfcoast.pdf.
19. U.S. Army Corps of Engineers. 2009. Water Resources Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs. EC 1165-2-211. Washington, DC.
20. U.S. Climate Change Science Program. 2008. Weather and Climate Extremes in a Changing Climate. Unified Synthesis Product – 3.3. http://www.climatescience.gov/Library/sap/sap3-3/final-report/sap3-3-final-all.pdf.
21. Union of Concerned Scientists. 2008. National Headquarters, 2 Brattle Square, Cambridge, MA 02238-9105 http://www.ucsusa.org/gulf/gcstateflo_cli.html.