POTENTIAL ECOLOGICAL CONSEQUENCES OF CLIMATE CHANGE IN SOUTH FLORIDA AND THE EVERGLADES

2008 Literature Synthesis

Potential Ecological Consequences of Climate Change in South Florida and the Everglades

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RESOURCE EVALUATION REPORT
SFNRC Technical Series 2009:1

South Florida Natural Resources Center
Everglades National Park
Homestead, Florida

National Park Service
U.S. Department of the Interior

Cover photograph shows the Ten Thousand Islands near Chokoloskee in Everglades National Park, looking toward the Gulf of Mexico.
Photo by William Perry, ENP

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EXECUTIVE SUMMARY

Global climate changes are likely to have profound effects on the Earth's ecosystems and on our perspectives on ecological conservation. Regional models project varying trends across the United States and even between southern and northern Florida. The purpose of this report is to summarize climate change literature pertinent to south Florida, particularly the Everglades, and to assess potential ecosystem vulnerabilities and the capacity for adaptation to climate change in this important ecosystem.

The Intergovernmental Panel on Climate Change (IPCC) is unequivocal in stating that the Earth's climate is warming on the basis of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising average global sea level during the last 100 years. Furthermore, anthropogenic drivers of climate change have greater influence than natural drivers (IPCC 2007a).

General Climate Trends for Florida

◆ Although climate observations have not shown a large warming for the southeastern United States to date, temperatures in south Florida have increased from 0.25 to 1.4 °C between the two most recent 30-year temperature normals, 1961-90 and 1971-2000 (Soule 2005). Global climate models predict an additional increase to the end of the century of from 2 to 5.5 °C (IPCC 2007a).

◆ IPCC models also address precipitation changes and predict a slight decrease in rainfall during December, January, and February—months that are within the dry season. However, a decrease in rainfall of 10 to 15 percent for the wet season also is predicted.

◆ A shift is expected toward a more positive phase of the North Atlantic Oscillation (NAO) and an El Niño-like pattern with higher temperatures in the Pacific. With even modest decreases in rainfall and increases in temperature, extended droughts with increased evaporation are expected with an accompanying reduction of recharge in the Everglades wetland ecosystems and surface aquifers. This may have dramatic consequences for fire patterns.

◆ Predictions for the amounts and timing of sea level rise are difficult to quantify. Seawater expands as it heats up, producing thermosteric sea level rise. Simulated changes in ocean temperature and salinity can be used over much of the ocean to forecast global average thermal expansion and sea level changes (Gregory et al. 2001, Lowe and Gregory 2006). Sea level rise along the coasts of Florida will at least approximate the global average (IPCC 2007a), which the IPCC projects to be between 0.2 and 0.6 meters (7 to 23 inches) by 2100, although observations of current sea level rise are higher than average adjacent to Florida coasts. These projections may be conservative primarily because of rapidly changing ice dynamics over land masses in Greenland and West Antarctic ice sheets. Modeling of glacier and ice cap contributions to sea level rise predicts a rise of from 0.8 to 2.0 meters (2.6 to 6.6 feet) by the end of the century, but the lower end of the range is most plausible (Pfeffer et al. 2008).

◆ Although changes in hurricane frequency and intensity are difficult to predict, models generally agree on increased wind strength and precipitation. The tropical North Atlantic Ocean is expected to experience more storms as well as more intense storms (IPCC 2007a).

Potential Ecological Effects

Studies of species responses to potential climate change in south Florida Everglades habitat are limited. However, some broad categories of potential effects exist (Table 1), including

◆ direct responses to temperature increases,

◆ response to drought, fire, and other environmental changes,

◆ loss of species synchronization, and

◆ habitat loss.

Species that are on the edge of their physiological range, that depend strongly on synchronizing life history events with environmental cues, or that have limited dispersal capability likely will be the most affected. Habitat fragmentation and urban development will complicate the ability of some animals to find new habitat.

One of the greatest challenges in south Florida is invasive species management. Invasive species may find new mechanisms for introduction, new invasive species may appear, existing invasive species may have altered impacts and distributions, and the effectiveness of control programs may change over time.

Vegetation Communities and Landscapes

◆ These communities are likely to change under scenarios of climate change and many may experience range expan-

sions and contractions. If increased periods of drought occur as predicted, some species, especially those dependent on wetlands or impacted by compounding factors such as fire, may be adversely affected.

- In addition to overall temperature changes, sea level rise is anticipated to substantially impact vegetation communities. Sea level rise in the past has been slow enough to allow the protective mangrove and marl berms to continue upward accretion that, in company with a freshwater head, has been sufficient to inhibit saline intrusion. At the faster estimates of sea level rise, the berms are expected to be overstepped in numerous places by saline water with the accompanying loss of freshwater wetlands. At the fastest estimates of sea level rise, predictions point to catastrophic inundation of south Florida and loss of freshwater resources.

- Intense storms impact soil subsidence and accretion. Storms also may result in saltwater intrusion into freshwater wetlands and succession toward salinity-tolerant vegetation.

- Twenty-seven rare plant species (including four endemics) identified in coastal Everglades National Park are likely to be affected by sea level rise.

- Blue-green algae (cyanobacteria) blooms in near-coastal waters may increase with temperature increases.

- Restoration efforts that are aimed at increasing water flow to Shark River Slough and Florida Bay may be particularly important for maintaining the freshwater head necessary to offset saline transgressions as sea level rises.

Fishes

- Fishes will likely be affected by altered hydrologic regimes, increased surface water temperatures resulting in decreased concentrations of dissolved oxygen, and increased toxicity of pollutants.

- Rising CO_2 concentrations are causing a reduction in pH with unknown impacts to marine species. Community


Florida gar (*Lepisosteus platyrhincus*) in Everglades National Park. Photo by Elise Pearlstine, University of Florida.

composition is likely to change as ranges of many species shift.

- Commercial fisheries in interaction with climate stressors may exacerbate changes in fish populations, size structure, and distribution.

- Within the Everglades, extended droughts substantially reduce fish biomass and availability of refugia (DeAngelis et al. 2005).

Coral

- Coral bleaching is caused by significant declines in zooxanthellae microalgae. Mass bleaching events have been exclusively linked to unusually high sea-surface temperatures (Glynn and D'Croz 1990, Brown 1997, Hoegh-Guldberg 1999, Patterson et al. 2006). Temperature increases of the magnitude projected to cause extensive coral bleaching and death are predicted to occur in south Florida and the Caribbean. Additionally, if sea level rises faster than reef formation is possible, lower light levels also will likely contribute to coral death (Glynn 1993).
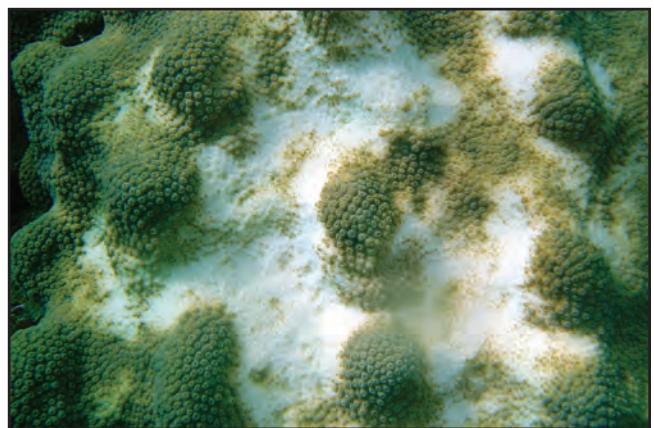
Bleached coral (*Montastraea faveolata*). Photo by ©William Fit, University of Georgia, used with permission.

- Predicted ocean acidification will reduce the availability of calcium carbonate that is used in reef building and could result in decreased growth and decreased skeletal density.

- Stewardship of fish and invertebrate herbivores can play an important conservation role in the resilience of reefs to larger-scale macroalgal disturbances.

Amphibians and Reptiles

- Amphibians have been the most sensitive species to changes in temperature and precipitation (Corn 2005); some species have shown shifts in breeding.

- The amphibian immune system is highly temperature dependent. Species with an immune system that has

evolved to successfully cope with pathogens adapted to specific temperature ranges may not be able to respond quickly to new pathogens in a changed climate (Fisher 2007).

♦ American alligators are at the southern edge of their tolerance range and may be affected by increased temperatures and changing hydropattern, habitat loss, and reduced prey availability.

♦ American crocodiles are at the northern edge of their range and may not experience as great a negative effect from climate warming as may be expected for American alligators.

♦ Loss of sea turtle nesting habitat is likely where beaches are inundated by rising seas and enhanced beach erosion.

♦ Reptiles are susceptible to increased ambient temperatures because the sex of some species, including the American alligator, American crocodile, and sea turtles, is determined by nest temperature during incubation.

Birds

♦ Birds already are responding to climate change with shifts in migratory phenology (Cotton 2003) and other phenological timing events (Parmesan 2007, Brown et al. 1999).

♦ Florida wading birds are likely to be affected by loss of coastal marshes through sea level rise and changes in prey availability.

♦ Migratory birds that fly through or winter in south Florida may leave their wintering grounds early to migrate north, increasing competitive interaction with local birds that often breed in late winter or early spring.

♦ Some Florida birds may experience a northern shift in their ranges.

Purple Gallinule (*Porphyrio martinica*) nest with eggs. Photo by Elise Pearlstine, University of Florida.

♦ Rather than following seasonal patterns of spring, summer, fall, and winter, many Florida birds are accustomed to timing their breeding events with hydrologic patterns and depend on the availability of suitable water. More intense drought, storm events, and sea level rise are likely to interact negatively with avian habitat requirements. Interruptions to natural seasonal drydown and flooding patterns can cause nest abandonment, prey die-offs, and nesting failures.

Mammals

♦ Mammals will respond to changes in habitat and prey availability.

♦ Inundation of habitat in the low-lying barrier islands of the Florida Keys and Ten Thousand Islands would leave many species, including a variety of endemic, rare species, particularly vulnerable.

Key deer (*Odocoileus virginianus clavium*). Photo by ©Katy Dimos Raits, used with permission.

Insects

♦ Insects likely will experience many of the same effects as vertebrates, including changed migratory patterns, loss of plant species that are food or shelter sources, and northern range expansion.

♦ Insects living in tropical climates are likely to be less tolerant of climate warming because they are already living in environments near the upper limits of their optimal temperature range (Deutsch et al. 2008).

♦ Butterflies are very sensitive to temperature and humidity and commonly are dependent on specific plant hosts and nectar sources. Climate and habitat changes could cause major physiological disruptions for these insect species.

Natural Resource Management Implications

- The Everglades ecosystem is at risk from the combined expected trends in greenhouse gases, temperature, precipitation, storm events, and sea level rise.

- Species frequently are not responding to a single environmental trend but to a complex relation of multiple environmental factors including geographic and hydrologic patterns, interactions with other species, and restriction to migration.

- The result of present and future climate changes and irreversible human alterations of the landscape is that restoration must be defined in terms of reducing ecosystem vulnerability and promoting adaptation and resilience. Climate change imposes variably continuous change on the system over the long term, making management goals a moving target and systems responses only partial indicators of success.

- Goals for Everglades restoration that are defined in terms of reducing ecosystem vulnerability and promoting adaptation and resilience should include maintenance of multiple areas of habitat and large-scale connectivity to facilitate species migration and protection of coastal communities. Meeting these goals will require attention to group decision and support tactics that include scientific, social, and political learning.

- Baseline biotic and environmental monitoring and continued development of region-wide spatial databases will be critical for forecasting spatial processes and responses to climate change. Continued, long-term commitment is required for monitoring networks to assist early warning and forecasts of potential ecosystem changes.

- Ecological research should address critical needs such as furthering understanding of differential floral and faunal responses to habitat changes by dispersal to new areas or disruptions in phenological synchronization among species and the potential for evolutionary adaptations.

Table 1. Summary of potential effects of global climate change on south Florida biodiversity. Groups affected in each event may experience one or more of the possible effects.

Projected Event	Possible Effect	Taxa/Group Affected
Increased temperature	Changing phenology of vegetation and plant communities Loss of species synchronization Increased surface-water temperatures with decreased concentration of dissolved oxygen and increased toxicity of pollutants Range shifts of fish and other vertebrates CO_2 concentrations reduce pH value Changing hydropattern	Plant communities including graminoids Cyanobacteria Fish Coral Invertebrate herbivores Aquatic communities Amphibians Insect eaters Migrants – birds and butterflies Pollinators Seed-eaters Invasive species Species on the edge of their range (either northern or southern)
Weather uncertainty/more extreme storm events	Altered fire patterns and dynamics Increased wind strength and precipitation during storms More storms and higher intensity storms Droughts Soil – subsidence or accretion Disconnect between breeding patterns of birds and hydrologic events	Vegetation communities Marshes and wetlands Mangroves Aquatic fauna Amphibians Florida Bay species Wading birds Species that time nesting/breeding with hydrologic cycles Most wildlife species Colonial waterbirds
Precipitation changes	Decreased rainfall during dry season Decreased rainfall during wet season Loss of dry season refugia	Amphibians Fish, especially small species Plants and plant communities
Sea level rise	Saltwater intrusion Increased sea level in current coastal areas – loss of protective berms Increased inundation of Florida Keys and Ten Thousand Islands Habitat loss in low-lying areas in general, including coastal nurseries for important marine fish species	Plant communities, especially mangrove, freshwater marsh, saltwater marsh, etc. Coastal tidal flats Rare or endemic coastal plant species Sea turtles Wading birds Vertebrate species of the Florida Keys and other low-lying areas
Shift to more positive North Atlantic Oscillation	Extended droughts Increased evaporation Reduction of recharge in Everglades wetlands and aquifers Changes in fire patterns	Wetland vegetation communities Wetland-dependent wildlife species General plant and wildlife impacts from changes in fire regime and droughts
Increased atmospheric CO_2 concentration	Reduced pH in oceanic waters Photosynthetic pathways	Coral Fishes C3 vegetation

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FOREWORD

This report, "Potential Ecological Consequences of Climate Change in South Florida and the Everglades: 2008 Literature Synthesis," highlights current scientific literature on climate change trends and potential impacts to the ecosystems of south Florida and the Everglades. It represents one aspect of our continuing efforts to stay abreast of current scientific knowledge and projections of future changes to our environment.

Understanding the implications of climate change and the range of uncertainties in projections for climate change and associated impacts such as sea level rise and ocean acidification is critical to forward-looking natural resource management. The Intergovernmental Panel on Climate Change (IPCC) has documented substantial changes taking place in the Earth's climate systems and projects that decadal average warming by 2030 is likely to be at least twice as large as natural variability during the entire 20th century. The Committee on Independent Scientific Review of Everglades Restoration Progress (National Research Council of the National Academies) notes that we can no longer depend on past observations of natural variability to guide planning for the future.

The general IPCC climate change predictions for this area suggest a temperature increase of 2 to 5.5 ^{o}C by the end of the century and a 10 to 15 percent decrease in wet season rainfall that could lead to extended droughts and increased evaporation. These changes are particularly troubling to the numerous south Florida species that are at the edge of their physiological ranges. Projected sea level rise of at least 7 to 23 inches by 2100 along the Florida coastline will significantly impact coastal vegetative communities, which have a large proportion of rare and endemic species. Restoration efforts need to substantially increase water flows through the southern Everglades and Florida/Biscayne Bays to maintain the freshwater head necessary to offset projected saline transgressions. Everglades restoration components must be flexible and promote adaptation and resilience to changing conditions in the ecosystem and potentially greater climate variability.

It is our hope that the collective knowledge in this report will serve to inspire management and research directions for a changing ecosystem. Everglades National Park managers and scientists continue to work with our partner agencies, cooperators, local governments, and the public to promote a sustainable, natural Everglades for future generations and the long-term health of our environment.

Robert Johnson
Director
South Florida Natural Resources Center
Everglades National Park

June 2009

INTRODUCTION

Global climate changes are likely to have profound effects on the Earth's ecosystems and on our perspectives on ecological conservation. Although climate change is global in extent and effect, rates and directions of change are not uniform. Indeed, global and regional models project varying trends across the United States as well as between southern and northern Florida (IPCC 2007a). This literature compilation synthesizes current published scientific research pertinent to Florida south of Lake Okeechobee, and particularly the Everglades, relative to species and ecosystem vulnerabilities and capacity for adaptation to climate change. Most of this report focuses on direct ecological responses to current and future climate change. Social and economic responses to climate change have not been reviewed, although they are likely to have substantial impacts to ecological systems.

The Everglades (Fig. 1) have received international recognition for their exceptional conservation value. The area includes the largest congressionally designated wilderness area east of the Rocky Mountains, mandated to protect in perpetuity the wild and untamed nature of the Florida Everglades. Everglades National Park has been named a Wetland of International Importance under the Ramsar Convention of 1987, a UNESCO International Biosphere Reserve (1976), and a UNESCO World Heritage Site (1979). The unique position of the Everglades, at the interface between temperate and subtropical America and between fresh and brackish water, creates a complex of habitats that includes

- the largest protected stand of freshwater sawgrass (*Cladium jamaicense*) prairie in North America,
- the largest protected mangrove ecosystem in the Western Hemisphere,
- the most significant forage and breeding grounds for tropical wading birds in North America, and
- habitat for a high diversity of threatened, endangered, candidate, and endemic species, many with tropical affinities (IUCN 1979).

Twenty-eight terrestrial vertebrates, 3 marine vertebrates [West Indian manatee (*Trichechus manatus*), gulf sturgeon (*Acipenser oxyrinchus desotoi*), and smalltooth sawfish (*Pristis pectinata*)], 5 invertebrates [4 butterflies and the Stock Island tree snail (*Orthalicus reses reses*)], and 26 plants that are federally listed as threatened, endangered, or candidate species rely on habitat south of Lake Okeechobee (U.S. Fish and Wildlife Service, 2009). The landscapes surrounding the Everglades are essential to the integrity and biodiversity of the region and include expansive areas of cypress that grade to wet, mesic, and upland pinelands to the west, Biscayne Bay and coastal communities to the east, and the estuaries of Florida Bay to the south. Culturally, the area historically served as a refuge for a diverse assemblage of peoples, and the area remains the present homeland of the Miccosukee and Seminole Tribes of Indians. The world community, in general, and south Florida, in particular, benefit greatly from the landscape.

At a gradient of about 0.1 foot of elevation per mile, the Everglades rise from sea level at Florida Bay to a maximum elevation of approximately 14 feet above sea level at the northern end of Loxahatchee National Wildlife Refuge. The low topography and coastal proximity of the Everglades make natural areas in south Florida vulnerable to sea level rise and saltwater intrusion. Climate change also has particular potential for impacts to isolated species such as the Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*) and Key Largo woodrat (*Neotoma floridana smalli*) as a result of habitat fragmentation (such as in the pine rocklands, which contain the highest diversity of rare and endemic plant species in south Florida). Competing demands exist for water across a wet grassland sheetflow ecosystem that has been modified by about 2,600 miles of canals and levees. In addition, hundreds of water management structures provide water delivery and flood control for the built environment and approximately 6 million people that depend on it. In juxtaposition with dense coastal populations and agriculture are a multitude of Federal and State jurisdictions. Fifty-eight percent of the lands south of Lake Okeechobee are in ownership for conservation and water management. The Federal government owns 64 percent of southern Florida conservation lands (such as parks, refuges, and preserves) and the State owns 33 percent (parks, wildlife management areas, and water conservation areas). The remaining lands are in county, city, tribal, or private ownership. It is within these multiple agency authorities that coordinated policy and management decisions must be made in regard to climate change.

Because of rapidly increasing coverage of climate issues in the scientific literature, 30 percent of the articles cited in this report were written within the last 2 years. This report provides a baseline of literature for researchers integrating their science with other disciplines in natural resources.

Although this report illustrates potential for profound climate change impacts on much of the south Florida environment, clear uncertainties about the extent and direction of effects remain for many natural communities. This is in part because of the difficulties of scaling from global trend models to predictions of changes at the local physical environment, particularly given the climatic and meteorological interactions of a narrow land mass (south Florida) protruding into the Atlantic Ocean and Gulf of Mexico. Just as important are the unknowns surrounding natural community responses to those changes. Current literature addresses climate-related responses, and in some cases, adaptability, of some species to changes predominantly in single variables. Rarely are there syntheses of multiple effects, potentially with a high degree of variability, that are associated with landscape level inter-species interactions. Anticipated south Florida and Everglades-specific physical and biological modeling studies are the most likely source of information on multiple variable interactions in the near future.
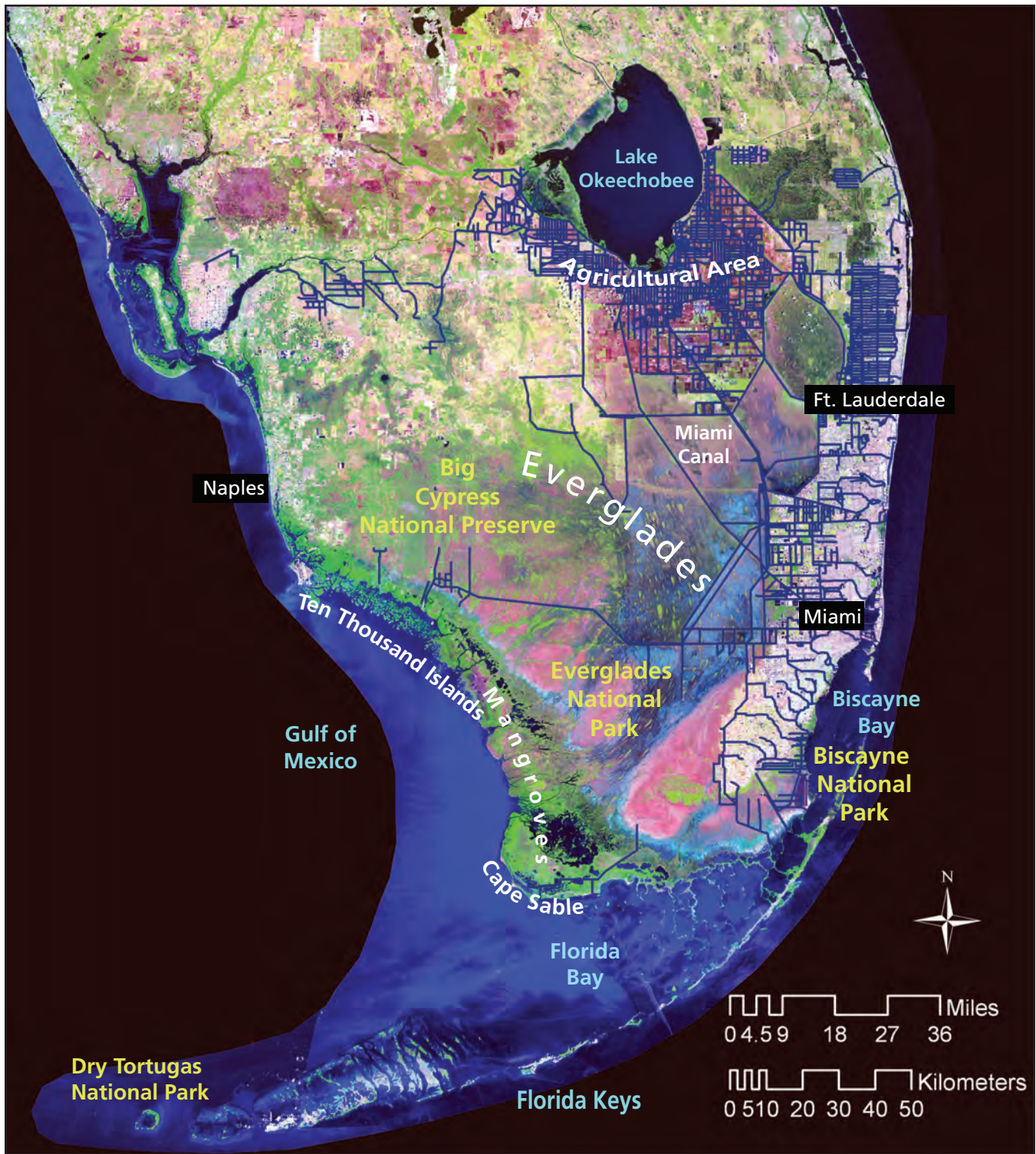
Figure 1. Location of the Everglades and surrounding environments in south Florida.

"In times of profound change, the learners inherit the earth, while the learned find themselves beautifully equipped to deal with a world that no longer exists."

Al Rogers

IPCC AND GLOBAL CLIMATE MODELS IN BRIEF

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body established in 1988 by the World Meteorological Organization and by the United Nations Environment Programme to provide an objective source of information about climate change. In 2007, the IPCC released its 4th Assessment Report (AR4), which includes probabilistic assessments of climate model simulations and projections through the end of this century using detailed atmosphere-ocean coupled models from 18 modeling centers around the world (IPCC 2007a). The multi-model approach to examining trends and variability among models, as well as alternative scenarios of continuing anthropogenic emissions (IPCC 2000), has established the IPCC assessment reports as the reference standard.

The IPCC (2000, 2007a) considers different radiative forcing agents due to anthropogenic greenhouse gases and aerosols that would be present in the atmosphere in 2100 as a result of a range of scenarios. The scenarios integrate different futures of global population growth and economic, social, and environmental stability. Current atmospheric CO_2 concentrations are approximately 380 parts per million. Scenarios B1, A1B, and A2 have been the focus of many of the multi-model comparisons and represent approximate CO_2 equivalent concentrations in 2100 of about 600, 850, and 1,250 parts per million, respectively. Scenario B1 represents a world with an emphasis on global solutions to economic, social, and environmental sustainability, including converging per capita income and cultural interaction, rapid economic growth, and rapid population growth to mid-century with declines thereafter. B1 is identified as a service and information economy with clean and resource-efficient technologies. Scenario A1B's economic and population growth and social convergence is similar, but without a substantial change to a service economy. Energy sources in A1B are a balance of fossil intensive and non-fossil energy systems with similar improvement rates applied to all energy supplies and technologies. Scenario A2 describes a very heterogeneous world with continuously increasing populations. Economic development is regionally oriented and economic per capita and technology change is fragmented and slower than the other scenarios.

The IPCC is unequivocal in its conclusion that the Earth's climate system is warming based on increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level over the last 100 years. Additionally, anthropogenic drivers of climate change have far more influence than natural drivers.

"Model experiments show that even if all radiative forcing agents were held constant at year 2000 levels, a further warming trend would occur in the next two decades at a rate of about 0.1 °C per decade, due mainly to the slow response of the oceans. About twice as much warming (0.2 °C per decade) would be expected if emissions are within the range of the [IPCC] scenarios. Best-estimate projections from models indicate that decadal average warming over each inhabited continent by 2030 is insensitive to the choice among [emission] scenarios and is very likely to be at least twice as large as the corresponding model-estimated natural variability during the 20th century" (IPCC 2007a, p. 12).

Meteorological instrumentation at the CO$_2$ flux monitoring station in Shark River Slough. Photo by Jordan Barr, ENP.

GENERAL TRENDS FOR FLORIDA

Temperature

Temperature trends are variable temporally and spatially across the United States, where a cooling trend in the mid-1950s was followed by a mostly steady warming trend since 1970 (Fig. 2). According to the U.S. Climate Change Science Program (CCSP) of the National Oceanic and Atmospheric Administration, 7 of the 10 warmest years since 1951 have occurred since 1997 (CSSP 2008a). Greenland (2001) also observed this temporal pattern of cooling and then warming after the 1970s from a small sample of sites (n=5) across the southeastern United States.

The linear trend of annual surface temperature in most of the United States (1951 to 2006) is +0.90 ± 0.1 °C (1.6 ± 0.2 °F), but the trend has been less pronounced in the south-

east (CCSP 2008a). Reanalysis of historic climate data (CCSP 2008a) suggests that surface ocean temperatures appear to play an important role in temperature trends in the United States and that more than half of the warming is likely the result of anthropogenic greenhouse gas emissions. For the southeastern United States, Soule (2005) compared the differences in temperature normals for two time periods, 1961–90 and 1971–2000, and reported an increase of only 0.1 °C for the southeast as a whole, though the lower coastal plain physiographic region had significant increases. South Florida increased 0.25 to 1.4 °C (0.5 to 2.5 °F) when the 1971-2000 three-decade period was compared to the earlier period (with the exception of Miami Beach, which cooled by 0.06 °C).

Temperature changes anticipated by the end of this century, based on the mid-range IPCC A1B scenario, over North America are shown in Figure 3. General circulation models (GCMs) employed in these analyses are appropriate for global
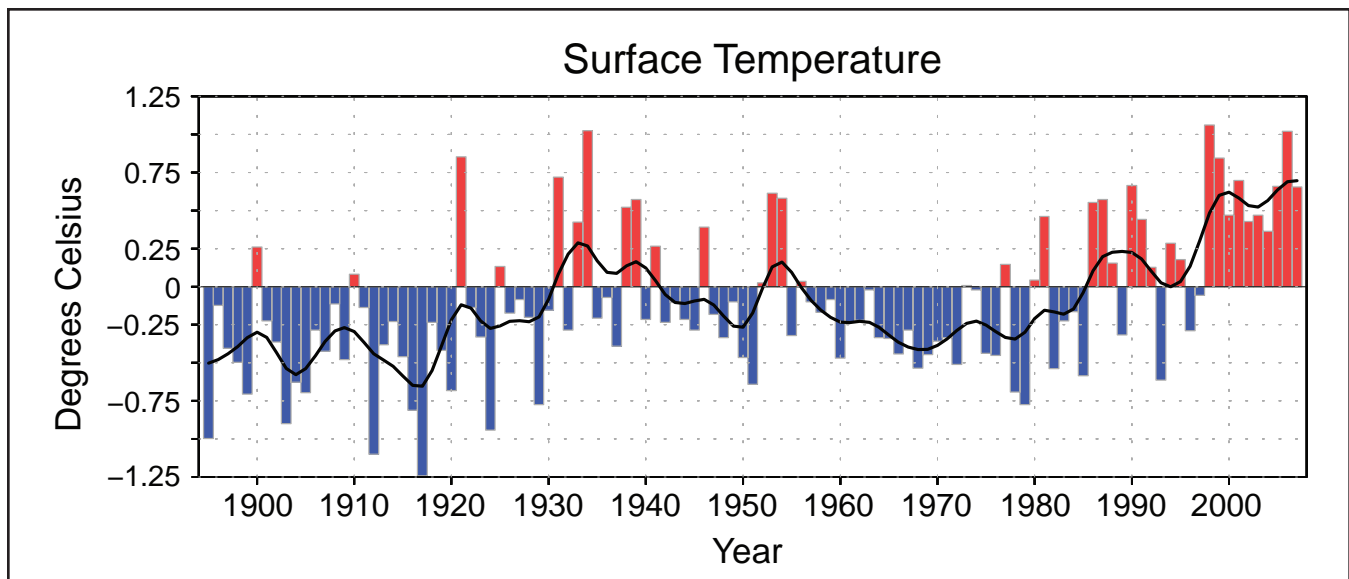
Figure 2. Time series of area-averaged and annually averaged surface air temperature in the United States for for 1895–2006 (CCSP 2008a p. 62). Curves are Gaussian smoothed annual values. Reprinted with permission.

Figure 3. Temperature change over North America from the multi-model A1B simulations: Annual mean, DJF (December, January, February) and JJA (June, July, August) temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Figure and caption from IPCC (2007a).

trends and patterns but are inappropriate for analyses much below the scale of continents. More-accurate forecasting of smaller regions is attempted by downscaling global models to obtain temperature trends in the southeastern United States (Fig. 4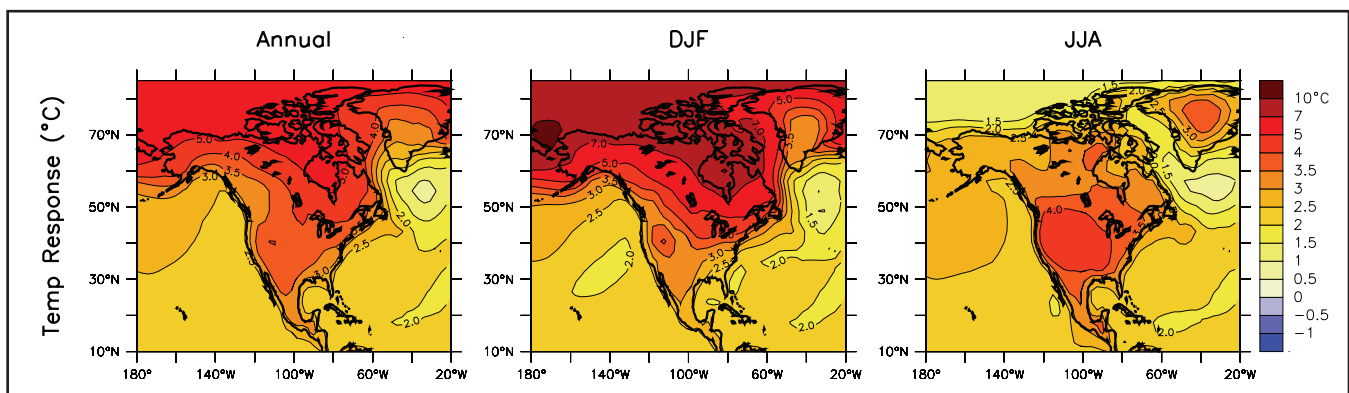). A variety of empirical and statistical methods of downscaling are being evaluated by researchers including statistical approaches that develop relations between large-scale climate variables resulting from GCMs and observed local climate variables.
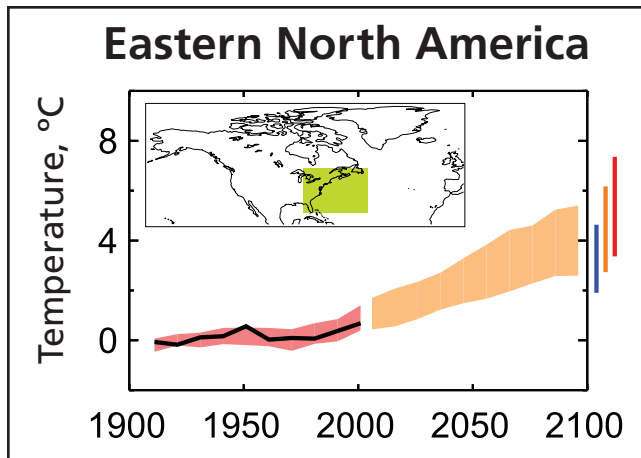

Figure 4. Temperature (°C) anomalies with respect to 1901 to 1950 for the Eastern North America region for 1906 to 2005 (black line) and as simulated (red envelope) by multi-model data set models incorporating known forcings; and as projected for 2001 to 2100 by MMD models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red). Figure and caption from IPCC (2007a).

Simulated average temperatures for Florida under the mid-range IPCC A1B scenario are estimated to increase 2 to 2.5 °C (3.5 to 4.5 °F) by the end of this century (Fig. 3). Stanton and Ackerman (2007) estimated Florida temperatures using the higher emissions scenario, A2, and averaging the IPCC A2 scenario results for the Eastern United States (Fig. 4) and the Caribbean. The higher emissions scenario, A2, results in increases in Florida's average annual temperatures of 3 °C (5 °F) in 2050 and 5.5 °C (10 °F) in 2100 relative to the 2000 annual average.

Simulations from multiple models of annual temperature increases for the A1B scenario in the Caribbean at the end of the 21st century range from 1.4 to 3.2 °C (2.5 to 5.8 °F), somewhat below the global average (IPCC 2007a). Fifty percent of the simulations give values differing from the median by only ±0.4 °C (0.7 °F). Statistical downscaling of several models for the Caribbean region gives approximately a 2.0 °C (3.6 °F) rise in temperature by the 2080s. The agreement between global circulation models and the statistical downscaling analysis (developed by Wilby et al. 2002) provides confidence in the temperature simulations.

Precipitation and Drought

Simulation of annual and seasonal precipitation changes using the mid-range A1B scenario is shown in Figure 5. The selected months for seasonal variation—June, July, and August (JJA) and December, January, and February (DJF)—correspond respectively to the height of the rainy season and the dry winter months in south Florida as illustrated in Figure 6 by a 58-year record of measured precipitation in Everglades National Park. IPCC models using the mid-range A1B scenario for CO_2 loading until the end of this century predict a slight decrease (less than 5 percent) in precipitation for DJF, but a 10- to 15-percent decrease during the wet season starting in June (Fig. 5). Most simulations indicate shifts to a more positive phase of the North Atlantic Oscillation (NAO) and an El Niño-like pattern with higher temperatures in the Pacific. These conditions are associated with drying in the Caribbean. The combined effect of even modest increases in temperatures along with modest reductions in rainfall during the historic wet season would be extended droughts with increased evaporation and uncertain recharge of Everglades' wetland ecosystems and surface aquifers during the wet season. These effects may produce dramatic changes to fire patterns and the composition of vegetation communities and utilization of the Everglades for wildlife habitat and forage. However, there is no consistent indication among climate models of future El Niño-Southern Oscillation (ENSO)-related amplitude and interannual variability. To develop a more accurate prediction of response would require continued downscaling of climate models to the level of south Florida landscapes and studies of faunal and floral response in the local environment. In addition to the IPCC model outputs for changes in precipitation, Allan and Soden (2008) used satellite observations of precipitation associated with warm El Niño events and cold La Niña events to suggest that precipitation extremes in the tropics are likely to be stronger than predicted in the current models.

Natural fire ignited by a lightning strike just north of Pa-hay-okee in southern Shark Slough. Photo by Lori Oberhofer, ENP.
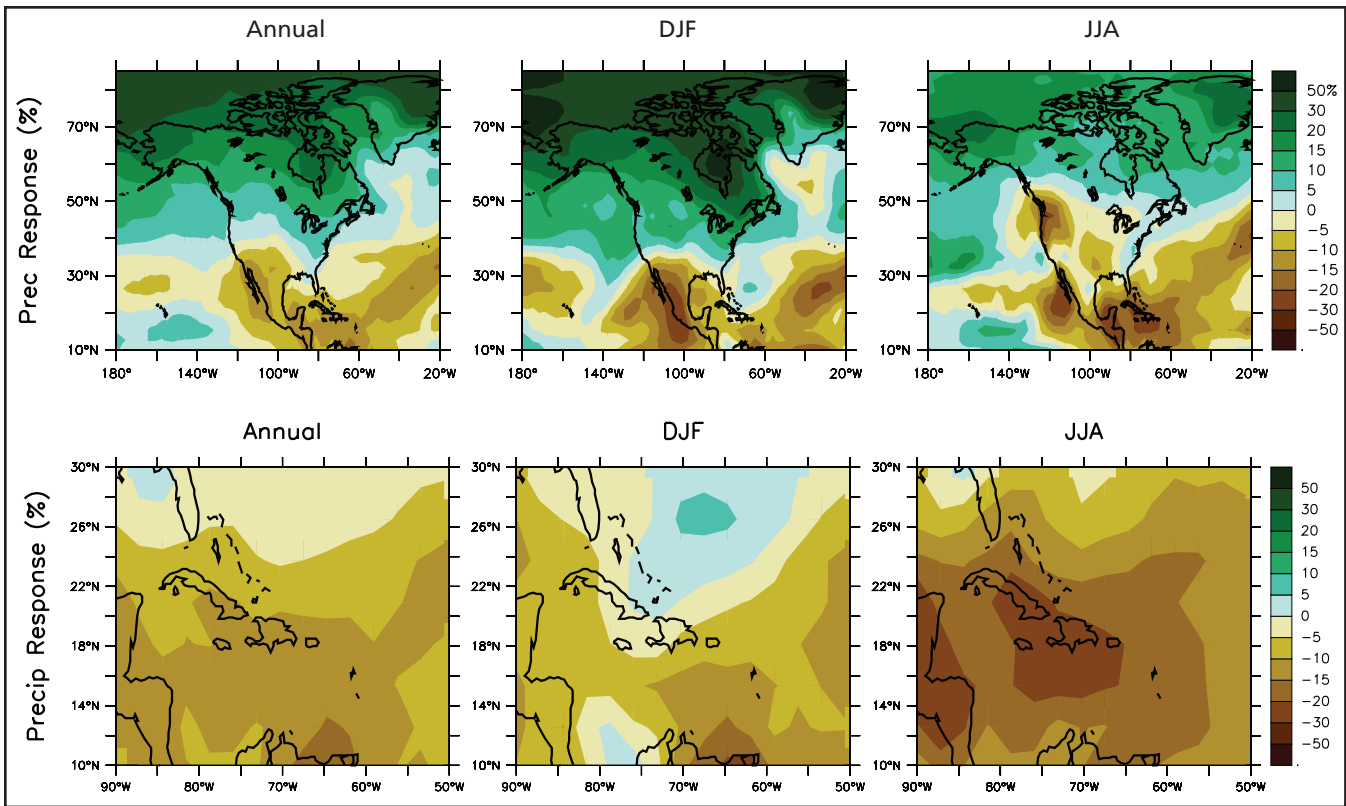
Figure 5. Precipitation changes over North America (top) and the Caribbean (bottom) from the MMD-A1B simulations. Annual mean, DJF (December, January, February), and JJA (June, July, August) precipitation change from 1980 to 1999 and 2080 to 2099 averaged over 21 models. Figure and caption from IPCC (2007a).
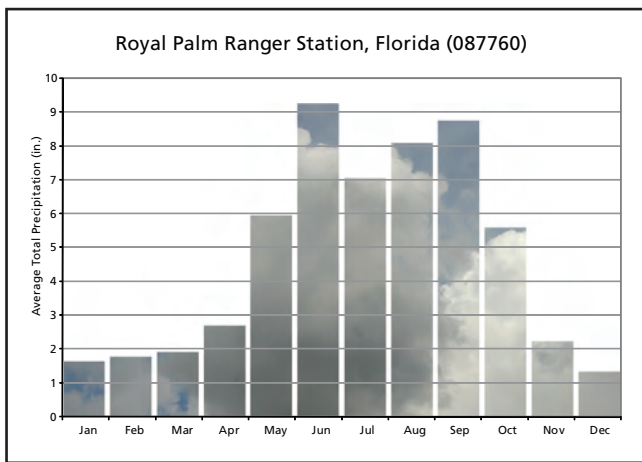

Figure 6. Average monthly precipitation for Royal Palm Ranger Station, Everglades National Park. Data from SERCC 2008.

Sea Level

Sea level is principally a function of ocean temperature and salinity. Seawater expands as it heats up, producing thermosteric sea level rise. Simulated changes in ocean temperature and salinity can be used over much of the ocean to forecast global average thermal expansion and sea level changes (Gregory et al. 2001, Lowe and Gregory 2006). However, amounts and timing of sea level rise are more uncertain than the projections for temperature and precipitation. Reasons for this greater uncertainty include (1) shorter and less exact observational records, (2) uncertainties in land ice projections, and (3) uncertainties in carbon cycle feedbacks and their relation to thermal expansion (IPCC 2007a).

Global variability in sea level trends as reconstructed from tide gages and altimetry data (IPCC 2007a updated from Church et al. 2004) for 1955 to 2003 is shown in Figure 7. Other methodologies and different time periods result in substantially different results. However, data from different sources emphasize the spatial variability common to results from all the reconstruction approaches (Fig. 7). The observed spatial variability in rates of sea level change is attributed primarily to El Niño-Southern Oscillation (ENSO)-related ocean variability and other ocean circulation patterns but also is influenced by regional gravitation and deformation of the Earth's surface in response to the ongoing change in loading by glaciers and ice sheets, atmospheric pressure changes, and regional and global salinity changes (IPCC 2007a). Higher-than-average historic sea level rise is modeled adjacent to Florida. Church et al. (2004) estimates observed sea level rise in the Caribbean to be near the global mean based on 1950 to 2000 observations (Fig. 7). Multi-model mean projections of sea level rise indicate that both Florida and the Caribbean appear to be near the global average during the 21st century
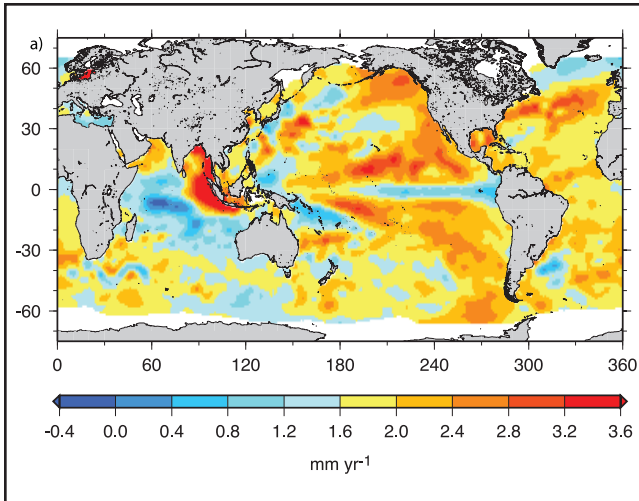
Figure 7. Geographic distribution of long-term linear trends in mean sea level (mm yr⁻¹) for 1955 to 2003 based on the past sea level reconstruction with tide gauges and altimetry data (updated from Church et al. 2004). Figure and caption from IPCC (2007a).
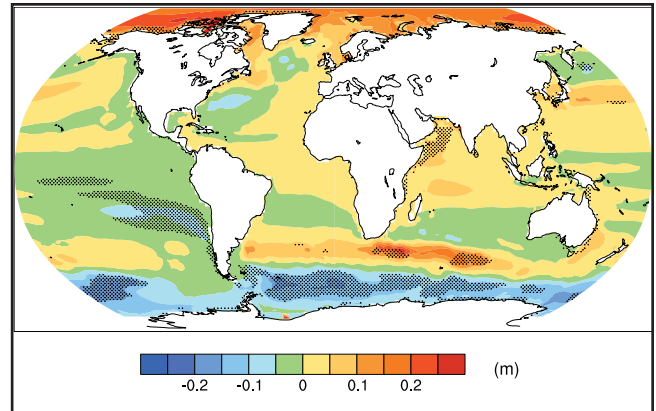

Figure 8. Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 Atmosphere-Ocean General Circulation Models forced with the A1B scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0. Figure and caption from IPCC (2007a).

(IPCC 2007a); however, large deviations among models make estimates of distribution uncertain, particularly across the Caribbean, Indian, and Pacific Oceans (IPCC 2007a) (Fig. 8).

The IPCC AR4 (IPCC 2007a) projects average global sea level rise to be from 0.18 to 0.59 meter (0.6 to 1.9 feet) by 2100. Walton (2007) estimated the same scale of sea level rise at Key West and St. Petersburg, Florida, by projecting a trend line over the historic data set of National Oceanic and Atmospheric Administration (NOAA) gages as shown in Figure 9. Walton adds, however, that if climate factors change, extrapolation of past trends can be misleading.

More-recent observations and new knowledge have led many scientists to believe the IPCC projection is conservative. For example, Rahmstorf (2007) proposed an improved model that projected a sea level rise in 2100 of 0.5 to 1.4 meters (1.6 to 4.6 feet) above the 1990 level. However, Rahmstorf (2007) stated that even these projections may be conservative because of the uncertainties associated with Antarctic and Greenland ice shelf modeling (for example, meltwater lubrication of the ice sheet bed, increased ice stream flow after the removal of buttressing ice shelves, and ocean warming at the
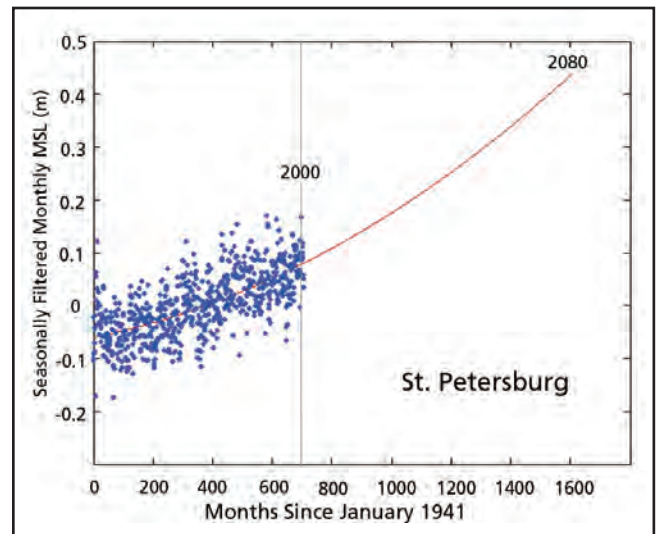
Figure 9. Forecast filtered sea level rise from two tide gages with sufficient historic record for sea level trend analysis: Key West, Florida (left) and St. Petersburg, FL (right) from the NOAA primary tide gage network. Seasonally filtered monthly MSL is the mean sea level with the seasonal (monthly) portion of the signal removed by subtraction of the monthly means. Walton (2007) used second order trend analysis (red line) to find a 0.31m relative sea level rise from 2006 to 2080 for Key West and 0.35m rise for St Petersburg. Figure from Walton (2007), used with permission.

grounding line of ice streams). Rapidly changing ice dynamics over land masses in Greenland and West Antarctic ice sheets (WAIS) are contributing to sea level rise and could result in substantial and abrupt rise in the future (Oppenheimer et al. 2007, Bell 2008). Because of the inadequacy of ice sheet models to predict events such as the Antarctica Larsen B ice shelf breakup by March of 2002 and the March 2008 breakup of the Wilkins ice shelf, WAIS dynamics were not considered in the AR4 projections (Oppenheimer et al. 2007). Pfeffer et al. (2008) modeled physical constraints on glacier and ice cap contributions to sea level rise from surface mass-balance losses and discharge of ice into oceans from marine-terminating glaciers. They predict a range in sea level rise of 0.8 to 2.0 meters (2.6 to 6.6 feet) by the end of the century, but the higher end of that range would require ice sheet velocities and other variables to accelerate to extremely high limits quickly and to maintain those high rates. Pfeffer et al. (2008) consider the lower end of the range to be more plausible. Another critical unknown is the amount of warming before the Arctic permafrost melts. Permafrost melting may release trapped methane gas that may have additional and substantial impacts on global climate (Brown 2008).

Detailed digital elevation models (DEMs) (Jones and Price 2007) can be used to map the potential extent of sea level intrusion into the Everglades (Fig. 10). DEM elevations are North American Vertical Datum 88 (NAVD88). The buttonwood embankment (not shown) is a berm south of the DEM area that may attenuate saltwater intrusion until the berm is transgressed. The Vegetation Communities and Landscapes section later in this report provides more details on the potential role of mangrove and buttonwood embankments.

Brown (2006) suggests a GIS rules-based approach for improved mapping of future sea level rise that can be implemented as better-resolution topographic surveys are extended south through the coastal areas. Titus and Richman (2001) caution that potential mapping of landward sea level rise based solely on current elevations is only a first approximation because it ignores processes such as future erosion, wetland accretion, and land use decisions.

Storms

Much uncertainty exists about predicted changes in the frequency and intensity of tropical cyclones (hurricanes) on a regional basis because the high resolution necessary to capture characteristics of tropical cyclones is rarely modeled in the context of global climate change. High-resolution models generally project increases in peak wind intensities with increased near-storm precipitation (IPCC 2007a). The IPCC (2007a) projected a decrease in the number of relatively weak tropical cyclones because of vertical stabilization of the troposphere, increased numbers of intense tropical cyclones because of increased sea surface temperatures, and a global decrease in total numbers of tropical cyclones. Larger sea surface temperature increases in the tropical North Atlantic

than in other basins are predicted to prevail over tropospheric stabilization and result in more storms as well as more intense storms (IPCC 2007a). Observational evidence supports increased tropical cyclone activity correlated with increases in sea surface temperature in the North Atlantic since about 1970 (IPCC 2007a). Oouchi et al. (2006) used a model that simulates tropical cyclone characteristics well against present day observations and determined that tropical cyclone frequency decreased about 30 percent globally but increased about 34 percent in the North Atlantic under the A1B scenario.
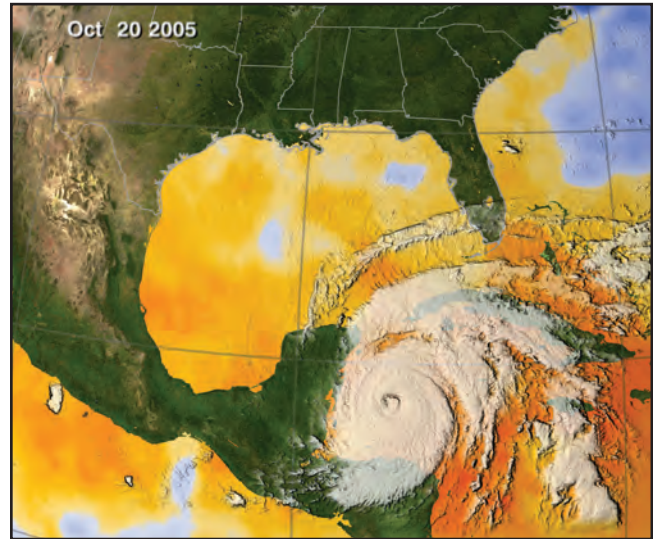
NASA image of Huricane Wilma on October 20, 2005. Yellow to red colors correspond to sea surface temperatures of 82–90 ˚F.

Ocean Circulation

The ENSO is the most important source of interannual variability in the tropics; however, there is no modeled indication of discernible changes in ENSO amplitude or frequency for the next 100 years. Changes in ENSO interannual variability differ from model to model.

All climate model projections show an increase in high-latitude temperature and precipitation. Both of these effects tend to make the high-latitude surface waters less dense. The increase in ocean surface buoyancy inhibits convective processes and weakens the Meridional Overturning Circulation (MOC). A weakening of the MOC causes reduced ocean surface temperature and salinity in the region of the Gulf Stream and North Atlantic Current (Dai et al. 2005). This effect may increase northward heat transport north of 60° N, but decrease northward heat transport south of 60° N, (Hu et al. 2004). South Florida is between 25.5 and 26.5° N. Models of the MOC response vary considerably, but none show an increase in the MOC. One model indicates that the changes are not distinguishable from natural variability, and others show as much as a 50-percent weakening by the end of the century (IPCC 2007a). No model simulates an abrupt shutdown of the MOC within the 21st century.
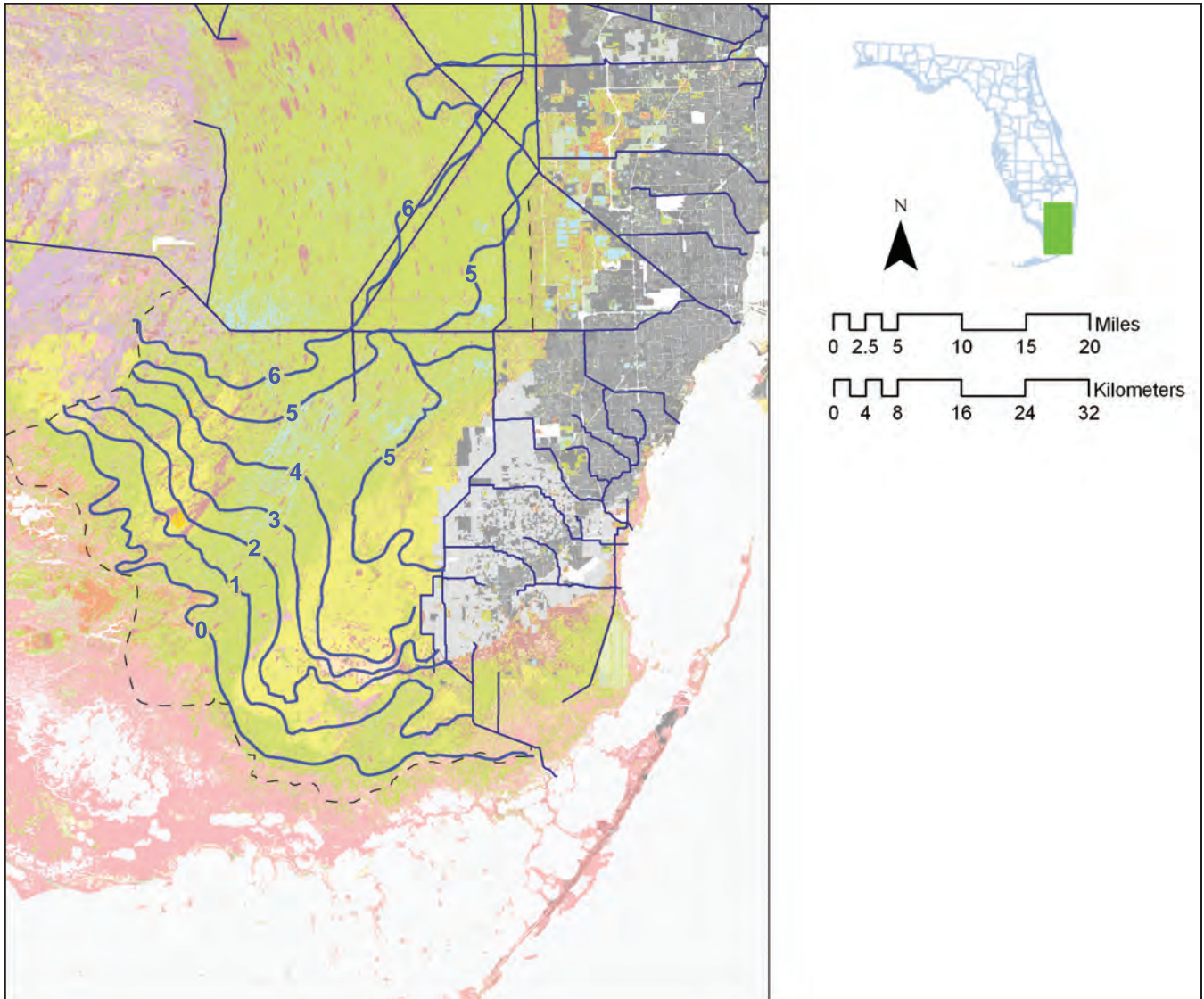
Figure 10. Contours (blue lines) of approximate mean high water shoreline in the Everglades with sea level rise of 0 to 6 feet relative to Florida Bay. Contours are based only on current elevations in the Everglades. The dashed line is the Digital Elevation Model (DEM) boundary. To find elevations above mean high water (MHW) the difference in NAVD88 and MHW at 5 National Geodetic Survey tidal benchmarks along the Florida Keys (PID# AC1028, AA0934, AA0383, AA0815, and AA0352) was calculated and the average difference (0.568 ft) was added to the DEM elevation. The background is the Florida GAP vegetation classification (Pearlstine et al. 2002). The major communities in the classification are: marsh (green), marl prairie (yellow), mangrove and buttonwood (pink), swamp forest and cypress (purple), hammock and tree island (brown), and urban and agriculture (shades of grey). DEM from Jones and Price (2007).

"The Everglades are unique: they have no counterpart anywhere on earth. Although the region is almost perfectly flat, few landscapes anywhere have a more intricate interplay of physical and biological factors."

Archie Carr, The Everglades, Time Life Books, 1973

Road sign in Everglades National Park. Photo by Joy Brunk, ENP.

POTENTIAL EVERGLADES ECOLOGICAL EFFECTS

Studies of species responses to potential climate change impacts in the unique environments of the south Florida Everglades are limited. Potential effects resulting from climate change include:

1. Direct responses to the changing climate envelope. Species may have linear and nonlinear responses to the interaction of changing environmental conditions including changes in CO_2, temperature, precipitation, storms, run-off, waves, and sea level in coastal communities (IPCC 2007a, IPCC 2007b). Tolerances to, for example, temperature increases or droughts may be exceeded for some species, particularly those on the edge of their physiological range. Many species are resilient and may adapt to changes; however; rapid climatic change may limit adaptation for some species.

2. Loss of species synchronization. Species depend on timing of physical events such as wading bird nesting during periods of water recession, or trophic interactions such as pollinator emergence during flowering (Memmott et al. 2007). These interactions are often critical to the maintenance of stable populations and likely will be affected by climate change effects.

3. Habitat change or loss. Climate change-induced habitat succession to new vegetation communities

and promotion of opportunistic invasive species may create local population extinctions or force native species that can disperse to find replacement habitat. Dispersal is likely to be restricted or blocked in many cases by habitat fragmentation and development (Alley et al. 2003, Hughes et al. 2007). If large-scale disturbances such as fire, hurricanes, and storm surge become more intense, abrupt habitat loss may increase in extent.

In a meta-analysis of 203 species from the northern hemisphere, Parmesan (2007) catalogued differing phenological responses to climate change over the last decade in 9 taxonomic groups (Fig. 11). Shifts in timing of breeding responses by amphibians were more than twice those of trees, birds, and butterflies. Butterfly emergence or migratory arrival has advanced three times faster than the first flowering of herbs and may forecast an increasing decoupling of insect-plant interactions. Many individual species within a taxonomic group (20 to 70 percent) showed no phenological response to climate warming to date (Parmesan and Yohe 2003). Latitude explained less than 4 percent of the response, but as warming trends continue to affect northern latitudes the most, it can be expected that phenological responses will be more pronounced at higher latitudes.

The implications of Parmesan's meta-analysis for south Florida are not clear. Information about the phenology of south Florida plant-dependent species is scarce. An increasing number of Everglades' butterflies are rare or extirpated, such as the candidate species Bartram's scrub hairstreak (*Strymon acis bartrami*) and the Florida leafwing (*Anaea troglodyte floridalis*), in part because of their dependence on specific host

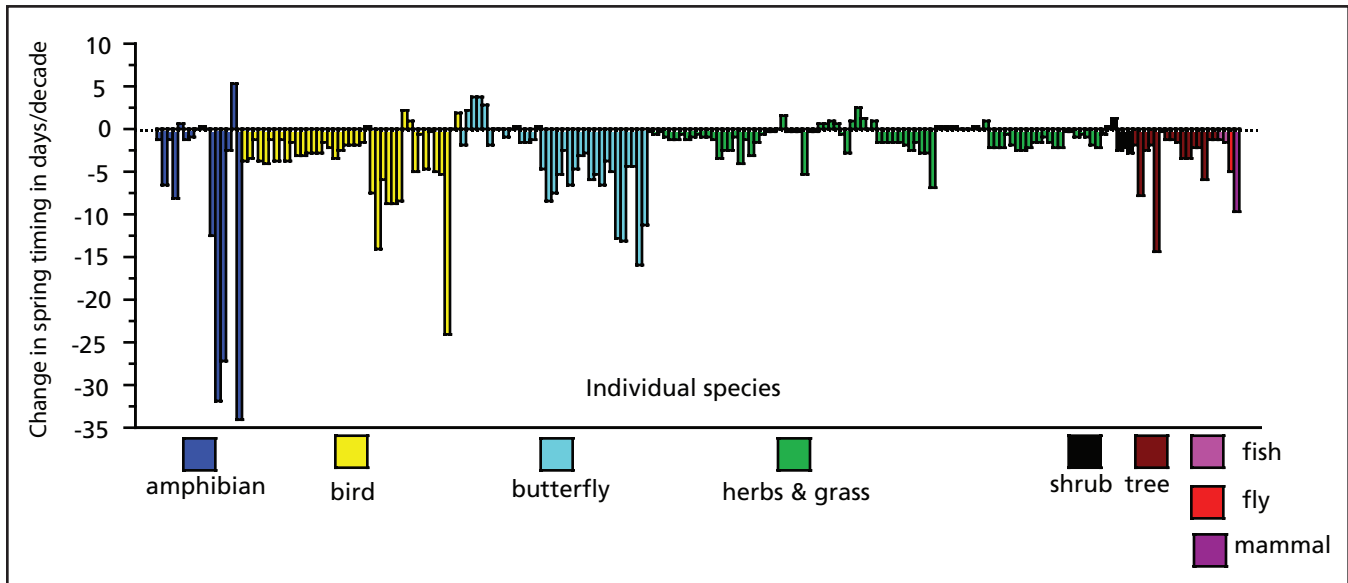**Figure 11. Changes in timing of spring events in days decade^{-1} for individual species grouped by taxonomy or functional type for the combined dataset. Each bar represents a separate, independent species. Negative values indicate advancement (earlier phenology through time) while positive values indicate delay (later phenology through time). Figure and caption from Parmesan (2007), used with permission.**

species and habitats such as pine rocklands that are becoming increasingly isolated (Susan Perry, Everglades National Park, pers. comm., 2008). Phenological disconnects of species local to the Everglades may or may not be less common; however, south Florida is contained within the Atlantic flyway and also is important wintering habitat for migratory and neotropical birds that may be responding to more northern environmental clues. Migratory butterflies may follow the same pattern.

In spite of limited specific information about effects on south Florida, some general concerns have been recognized in the literature that may be critical to understanding the responses of south Florida species to climate change. It is important to understand these patterns in order to inform future management decisions. Distributional responses of species likely will be most pronounced in northern latitudes with shifts in species ranges farther northward and contracting or remaining unchanged on the southern extremes. These patterns already are being observed in European studies (birds – Sparks 1999, trees and shrubs – Menzel 2000, butterflies – Roy and Sparks 2000, Franco et al. 2006) and in modeling results (mammals – Levinsky et al. 2007) and North American studies of birds (Peterson et al. 2002, Hitch and Leberg 2007), trees and shrubs (Crumpacker et al. 2001), and butterflies (Crozier 2004). The number of frost days for plants and animals has been identified as a primary determinant in producing these shifts (Inouye 2008).

Many species are likely to mitigate impacts of climate change with genetic variation in critical traits and localized evolutionary responses (Conover and Schultz 1995, Stockwell et al. 2003, Pelletier et al. 2007) that allow them to adapt to new conditions. For some species, however, time lags and limits on genetic variation are potential constraints to evolutionary response (Schiedek et al. 2007). Some species will not be able to respond quickly enough to changing conditions (Davis et al. 2005), and although others may initially produce a rapid response to changes, the rate of evolution can decay over time (Kinnison and Hendry 2001) as habitat continues to change in response to climate. Schiedek et al. (2007) also emphasize the effect of climate change on small populations, suggesting the potential for low initial genetic variation and large influences from genetic drift, which may limit natural selection (Burger and Lynch 1995, Willi et al. 2006).

Little is currently known about the genetic makeup of species that may or may not provide them with the ability to respond to climate change (Holt 1999), south Florida species included. However, it can be supposed that lack of genetic variation in some species may limit their ability to respond to climate change (Holt 1999). The endangered Florida panther (*Puma concolor coryi*) is an example of a species that despite generalist habitat requirements may have limited ability to adapt if climate change further restricts its environment. The panther has contemporary (1980s) microsatellite heterozygosity that is only 0.3 of that measured in museum samples from the 1890s and only has 0.4 the heterozygosity of Idaho pumas (Hedrick et al. 2008). Hedrick et al. (2008) determined that the estimated diversities in mitochondrial DNA in the

museum and contemporary Florida panther samples were 0.600 and 0.000, respectively. Species best adapted to dealing genetically with climate change are those very species least at risk of extinction in any scenario; they generally have large geographical distributions, short generation times, and high dispersal rates thus leading to a larger genetic pool from which to draw (Holt 1999). Even in those species that exhibit genetic or phenotypic change in response to seasonal change, some populations are declining in response to their inability to keep pace with environmental change (Bradshaw and Holzapfel 2006). Genetic traits on the same chromosome vary together such that favorable changes in one trait may have more than one outcome. Correlation among genetic traits that would respond to environmental variation may not match the direction of environmental change or may not be present (Hellman and Pineda-Krch 2007).

Florida panther (*Puma concolor coryi*). Photo by Connie Toops, NPS.

Ecosystem response will also vary depending on interactions among species within the physical and chemical characteristics of the environment (Davis et al. 1998, Shaver et al. 2000, Wilmers et al. 2007), making significant errors in predictions likely where ecosystem processes are not specifically considered. The effects of increased CO_2 concentration and temperature on ecosystems depend, to a large extent, on a web of indirect effects on process interactions and feedbacks. Shaver et al. (2000) use the example of net primary production (NPP) and heterotrophic respiration (Rh), which are both directly affected by temperature. Temperature also impacts factors such as nitrogen mineralization, species composition, moisture, litter quantity and quality, and soil organic matter quality, which in turn feed back to NPP and Rh (Shaver et al. 2000).

Ferriter et al. (2008) identify 80 nonindigenous terrestrial vertebrates (amphibians, reptiles, birds, and mammals), 32 nonindigenous fishes, 81 nonindigenous invertebrates (including ants, bees, ticks, mussels, and others), and 25 nonindigenous priority plant species present in southern Florida south of Lake Okeechobee. Invasive plant and animal species are typically opportunistic over a range of environmental conditions (Qian and Ricklefs 2006). Changing climates are unlikely to negatively impact current invasive species and

may increase the successful colonization and competitiveness of new species (Hellmann et al. 2008). For example, of the 23 exotic freshwater fishes considered to be permanently established in Florida waters, many, including the banded cichlid (*Heros severus*) and spotfin spiny eel (*Macrognathus siamensis*), have been temperature-restricted to south Florida (Shafland et al. 2008). Invasive species typically are first found in canal networks, but they are increasingly spreading to more natural ecosystems, including Everglades National Park and Big Cypress National Preserve (Shafland et al. 2008). Increasing minimum temperatures associated with climate change may facilitate their spread north. A stratified random sample of 10 percent of harmful invasive species in the United States, both plant and animal, determined that almost half are likely to benefit from a warming trend. A small percentage was likely to contract their range, and effects were difficult to predict for the remaining species (Zavaleta and Royval 2002). Five potential consequences have been identified relative to changes in invasive species characteristics as a result of climate change: (1) altered mechanisms for introduction, (2) potential for new species to establish, (3) altered impacts from existing invasive species, (4) altered distribution of existing invasive species, and (5) altered effectiveness of control strategies (Hellmann et al. 2008). It is necessary to consider the consequences of expansion of exotic invasive and native species into new areas when developing informed adaptive management and monitoring programs.

Landscapes and Vegetation Communities

The Everglades is a depression filled with freshwater peat and, in some locations, calcitic mud deposits. The depression is bounded east and west by limestone ridges — the limestone and quartz sand Atlantic Coastal Ridge to the east and Big Cypress limestone ridge to the west. On the south and southwestern sides of the Everglades, extensive natural berms protect the Everglades depression from saline intrusion. Because of slow sea level rise and a low-energy coast for the past 3,000 years, the mangrove and marl berm has been able to establish and continue upward accretion (Wanless et al. 1997). Although natural drainages cut through the mangrove berm, freshwater head generally is sufficient to inhibit saline intrusion to the transitional and freshwater marshes of the Everglades depression.

Seawater moves inland a great distance where multiple tidal riverine fingers lower the hydrologic head on the west coast (Fitterman and Deszcz-Pan 2001). Under natural conditions along the east coast, saltwater was present only close to the shoreline and freshwater was discharged from springs on the floor of Biscayne Bay, where the aquifer is hydrologically connected to the Atlantic Ocean (Renken et al. 2005, Parker et al. 1955). Construction in the 1880s and continuing into the 1990s has created an extensive network of Everglades drainage and flood-protection canals. Uncontrolled Everglades drainage resulted in oxidation-compaction loss of peat and muck soils and associated lowering of the water table. Along the coast, lower water tables along with well-field withdrawals and droughts created saltwater intrusion several miles inland by the 1930s and 1940s, particularly along the Miami Canal (Renken et al. 2005). Saltwater intrusion has been substantially reduced since the 1950s and 1960s by surface-water control structures in the canals and improved water management practices. The issue has not been completely mitigated, however, particularly along the southern Biscayne Bay coast and continuing south (Renken et al. 2005), and sea level rise exacerbates saltwater intrusion. Within Biscayne Bay, most present-day ground-water discharge is recirculated saltwater. Only a limited portion of ground-water discharge to the bay is fresh (Langevin 2001).

As discussed previously, rates of sea level rise are continuing to increase and are projected to be anywhere from 20 to more than 150 centimeters per 100 years. From geological records of past events, Wanless (1989) and Wanless et al. (1997) show that since about 1930, sea level rise has increased from 4 centimeters per 100 years over the last 3,000 years to 20–40 centimeters per 100 years, and they believe that mangroves will continue maintaining a dam to saltwater intrusion at 30 centimeters per 100 years or less, but with an erosional coastline and the mangrove migrating landward. At higher rates of sea level rise, they predict the mangrove berm will increasingly be overstepped in numerous places with saline water. Freshwater wetlands are predicted to be rapidly lost and bay and estuaries are projected to deepen, eventually to the point of catastrophic inundation of south Florida and loss of freshwater resources.

Intense storm impacts on soil subsidence and accretion affect local calculations of relative sea level rise (Cahoon 2006). Storm disruption of coastal wetlands may result from the creation of breaks that allow abrupt changes from saltwater intrusion into freshwater wetland or freshwater flushing of estuaries. For mangrove forests, both Whelan et al. (2005) in southwestern Florida and McKee et al. (2007) in the Caribbean determined that subsurface processes are the primary source of elevation change in mangrove communities with minimal influence from above-ground organic inputs. Changes in ground-water movement are related to mangrove elevations through shrinking and swelling of peat deposits in the Florida study (Whelan et al. 2005). In the Caribbean, McKee et al. (2007) determined that the accumulation of subsurface mangrove roots is primarily responsible for maintaining mangrove elevations and determined that fringe mangrove sites in Belize can accommodate sea level rise of as much as 4 millimeters per year, a similar range to that predicted by Wanless et al. (1997). Because of low root production in interior sites, however, interior mangrove accretion could not keep up with subsidence at this rate. At southwestern Florida mangrove sites, mostly within Everglades National Park, Smith et al. (2009) also determined that basin mangroves were more likely to suffer storm surge damage than either riverine or island mangroves. Tom Smith (U.S. Geological Survey., pers. comm., 2008) has not observed any increase in mangrove site elevation in re-

sponse to below-ground root production. Elevation increases were observed at several sites entirely in response to sediment deposition from Hurricane Wilma. Some sites, including one with accretion from the storm, have since decreased in elevation in response to continued mortality of mangrove trees (Smith et al. 2009). The impacts of several storms on one site have reduced it to intertidal mudflat. Because of rapid sea level rise and previous simulation modeling of recovery rates (Teh et al. 2008), Smith et al. (2009) expect that recovery of the site to a mangrove ecosystem is unlikely and that other mangroves impacted by the storm may continue to decline. In Louisiana marshes, Nyman et al. (2006) determined that accretion was primarily the result of organic accumulation rather than mineral sedimentation. Flooding stimulated fibrous root networks to grow just above the marsh surface, becoming the new surface.

Increases in temperature and direct effects of increased CO_2 concentrations are expected to increase mangrove net primary productivity and change the timing of flowering and fruiting. However, decreased precipitation and rising sea level can lead to increased salinities resulting in decreased productivity and seedling survival (Snedaker 1995). Salinity increases also may cause a net loss of peat as anaerobic decomposition increases (Snedaker 1995).

Mangroves provide habitat along a gradient of salinity from riverine mangroves growing alongside coastal rivers that may contain freshwater for part of the year to ocean fringe communities that are completely saline. Two aspects of these mangrove forests are important for wildlife: the structure of

the trees and roots and the leaf detritus. The intricate tangles of mangrove roots provide nursery habitat for many Florida fishes as well as habitat for other vertebrate groups. Leaves that fall into the ocean and rivers form the base of the detritivore food web in these habitats. Odum (1982) and Meshaka et al. (2000) document 217 species of fish, 18 to 24 species of amphibians and reptiles, 180 species of birds, and 21 species of mammals living in the various mangrove communities of Florida, including native as well as non-native species.

Although mangroves are the first responders to sea level rise and intense storms, Everglades graminoid communities may be among the first to change broadly in response to changing temperature, precipitation, drought, and floods. The photosynthetic pathway used by a plant species may contribute substantially to community successional responses. Graminoid communities in Everglades' marshes and prairies include C3 plants (such as *Typha* spp., *Scirpus* spp., *Cladium jamaicense*, *Carex* spp., and *Phragmites australis*) as well as C4 species (such as *Schizachyrium rhizomatum* and *Paspalum monostachium*). Some genera can be either C3 or C4 depending on the species (for example *Eleocharis* and *Rhynchospora*) (Soros and Bruhl 2000, Vorster 1996, Bruhl 1995, Bruhl 1993). Graminoids using the C3 pathway have been shown to assimilate CO_2 at a greater rate than those using the C4 pathway (Kimbell 1983). This may favor a shift in species toward those using the C3 pathway. However, species using the C4 pathway have a physiological advantage in hot environments (Bjorkman et al. 1974), dry environments, and during droughts (Raven 2001). Long-term response to elevated

Aerial view of North River looking south toward Whitewater Bay, which is just out of view at the top of the photo. Photo by Lori Oberhofer, ENP.

atmospheric CO_2 concentration also may differ substantially from short-term responses (Soussana and Lüscher 2007).

Interactions among CO_2, water availability, nutrients, and temperature can be positive or negative depending on the species (Jifon and Wolfe 2005). Experimental elevated CO_2 concentrations significantly increased proportions of dicotyledonous species (forbs and legumes) and reduced the proportion of monocotyledons (grasses) in temperate grasslands (Teyssonneyre et al. 2002a). Grass responses varied, however, with leaf light-capturing efficiency (Teyssonneyre et al. 2002b) and nitrogen-use efficiency (legumes) (Soussana et al. 2005). Accelerated flowering times in forbs and delayed flowering in co-occurring C3 and C4 grasses at 680 parts per million CO_2 (Cleland et al. 2006) also may be contributing to differing productivity responses. Little is known about photosynthetic pathway responses of Everglades species and their competitive interactions; however, elevated CO_2 concentration has also been significantly associated with altering germination (Thurig et al. 2003, Mohan et al. 2004), leaf development (Ainsworth et al. 2006), senescence (Rae et al. 2006), and for some wetland species, increased salinity tolerance (Rozema et al. 1991), thereby increasing the potential for evolutionary changes in community composition with climate change (Springer and Ward 2007).

Iverson et al. (1999) used statistical regression tree analysis to model the distribution of 80 common tree species in the southeastern United States and project distribution shifts in response to climate change. However, none of the modeled species had ranges extending through south Florida. A climate envelope model of 125 native Florida woody plant species was used by Box et al. (1993) to successfully explain broad species distribution on the basis of climate variables alone. A climatic space for each species is defined in terms of available climatic data, mainly temperature and moisture variables, for which relatively long-term records are available. Thirty-seven of the modeled species were subtropical from south Florida and the Keys. To model species presence at local scales would require consideration of additional factors such as substrate, topography, fire, and competition (Box et al. 1993). Unlike the Iverson et al. (1999) analysis, results under moderate climate change for individual species were not published; however, winter temperature variables were most often the limiting factor for species rejected at a site by only one variable (Box et al. 1993). It is possible that many of the indigenous south Florida woody species would expand their range under climate warming scenarios. Conversely, the projections of increased periods of drought may restrict many species. Upland plant communities in the Everglades that may be impacted by such events include tree islands, coastal hardwood hammocks, and pine rocklands. These unique communities are often critical habitat for a diversity of wildlife species in south Florida ranging from mammals seeking shelter to butterflies seeking nectar plants. Most emergent wetland plants benefit from droughts reducing water levels so that seeds can germinate and the new plants can obtain a sufficient height to avoid complete inundation. Severe droughts, however, can drop the water table below the roots and cause plant mortality (Duever et al. 1997).

Coastal plant communities of Everglades National Park are likely to experience increased salinity intrusion and flooding from sea level rise. Everglades National Park and The Institute

Hurricane damage to mangroves in Whitewater Bay, Everglades National Park. Photo by Jordan Barr, ENP.

for Regional Conservation (IRC) have identified 27 rare plant species — in most cases designated as critically imperiled by the IRC (Gann et al. 2002) — that they believe will be affected by sea level rise on the basis of their primarily or entirely coastal distribution. Of these, 22 have tropical distributions, 4 are endemic, and 1 is temperate.

Fishes

Climate change in south Florida may affect the quality of freshwater fish habitat by altering hydrologic regimes and increasing surface water temperatures, resulting in decreased dissolved oxygen concentration and increased toxicity of pollutants (Loftus et al. 1986, Ficke et al. 2007). The same impacts are expected in estuarine and coastal marine fish habitat, along with acidification and changes in salinity patterns associated with changing rainfall and increased evaporation rates. In response, species range shifts are likely to change fish community composition. Genetic change is also possible for many species that are unable to migrate or acclimate (Ficke et al. 2007).

Climate change impacts south Florida bays and estuaries through the timing and quantity of freshwater delivery, increased water temperature, decreased pH and carbonate saturation, and changes in storm intensity (IPCC 2007a, Scavia et al. 2002). Temperature and precipitation changes that result in extreme precipitation events becoming more common may produce flashier runoff that increases nutrient and sediment load delivered to the coast, which, in combination with other climate change impacts, can have complex interacting effects on salinity patterns, water clarity, phytoplankton abundance, and impacts to benthic organisms and aquatic vegetation (Scavia et al. 2002).

Little is known about the physiology and ecology of marine and estuarine fishes inhabiting marine tropical waters and how they will react to impacts from global climate change (Roessig et al. 2005). In south Florida, many shallow-water habitats including coastal tidal flats and mangrove communities may be lost if climate change continues at the predicted rates. Most tropical and temperate marine fish species that inhabit shallow water, tidal flats, seagrass banks, and mudflats in Florida Bay clearly respond to changes in water level (Sogard et al. 1989). Loss of nursery function (fish shelter and sustenance) of tidal flats is likely if increases in sea level continue at the projected rate, leading to increased levels of turbidity from resuspension of sediment materials over tidal flats and mud banks. Loss of this habitat could lead to the displacement or population shift of recreationally and ecologically important marine fish species including tarpon (*Megalops atlanticus*), red drum (*Scianenops ocellatus*), snook (*Centropomus undecimalis*), mullet (*Mugil cephalus*), and small epibenthic forage species such as silver jenny (*Eucinostomus gula*), pinfish (*Lagodin rhomboids*), and rainwater killifish (*Lucania parva*). Saltwater intrusion in coastal nursery habitats also may result in changes in near-shore fish abundance and diversity as well as changes

in critical cues for spawning and recruitment. In addition, decreased oxygen concentration in Florida Bay associated with increases in water temperatures (thermal stress) are expected to exacerbate the occurrence and intensity of anoxia-hypoxia conditions leading to more massive fish kills and algal blooms (Schmidt and Robblee 1994). Paerl and Huisman (2008) report that cyanobacteria outcompetes other phytoplankton species at higher temperatures, particularly in near-coastal waters with nutrient runoff. Cyanobacteria blooms increase the turbidity of aquatic environments, thereby stressing or killing seagrasses, which results in reductions of invertebrates and important fish habitat. As blooms die off, oxygen depletion may kill fish.

Increased water temperature effects on freshwater and marine fishes already are being observed, primarily in higher latitudes, and are accompanied by invasive species and pathogens (Beaugrand et al. 2002, Brander 2007). Increasing CO_2 concentrations are producing a decrease in ocean pH with unknown impacts to marine species (Feely et al. 2004). Temperature increases and pH reductions in the ocean also reduce structural complexity of coral reefs, resulting in a loss of fish biodiversity (Graham et al. 2006).

Duarte (2007) used metabolic theory to calculate an average 45-percent reduction in planktonic marine larvae dispersal distances with a 4 °C increase in ocean temperature. Reduced dispersal combined with mortality and fecundity impacts of climate change may impede connectivity as already fragmented populations become more disjointed (Duarte 2007). Fishing pressures on many fish populations cause changes in fish distribution, age, and size structure (fishing is size-selective) that are expected to interact with climate change and thereby affect the sustainability and resilience of fish communities (Berkeley et al. 2004, Ottersen et al. 2006, Brander 2007).


The karst topography of much of the Everglades contains characteristic solution holes where fish concentrate during low water. The small fish in this picture are primarily mosquitofish (*Gambusia holbrooki*). Photo by ©Jennifer Brown, used with permission.

Within freshwater Everglades landscapes, extended and more severe droughts are a possible consequence of climate change and may have substantial impacts on freshwater fishes. Fish competition models (DeAngelis et al. 2005) indicate that sites with hydroperiods of less than 6 months accumulate negligible fish biomass and match observations of low fish biomass in short-hydroperiod wetlands and observations of fish biomass increasing with lengthening hydroperiod (Trexler et al. 2002). During periods of low water levels, shallow karst solution holes are critical refugia for small freshwater fishes (Kobza et al. 2004). Deeper holes may be dominated by predatory, often non-native, species that make it unlikely for smaller native fishes to survive. Kobza et al. (2004) observed very high losses of fish biomass when water levels in solution holes declined more than 46 centimeters below the ground surface.

Coral

South Florida living coral is the third largest reef tract in the world (behind Australia and Belize) and is particularly prolific in a 150-mile-long and 4-mile-wide system of approximately 6,000 coral reefs extending from Key Biscayne, continuing along the seaward side of the Florida Keys, and west to the Dry Tortugas in the Gulf of Mexico. Biodiversity estimates for species using coral reefs as habitat range from 1 to 9 million species (Reaka-Kudla 1997). Coral are obligatory dependents on zooxanthellae microalgae. Zooxanthellae live in symbiosis with coral and assist the coral in nutrient production through its photosynthetic activities. The coloration of coral comes from zooxanthellae. Since the 1980s, there has been increased frequency of coral bleaching caused by declines of 60–90 percent in zooxanthellae on the coral surface (Glynn 1993, Le Tissier and Brown 1996). Multiple causes have been suspected for coral bleaching, including increased UV exposure, sedimentation, inorganic nutrients, pathogens, and increased temperature with combinations of stressors often present (Glynn 1996). However, large-scale, mass bleaching events have been exclusively linked to unusually high sea-surface temperatures (Glynn and D'Croz 1990, Brown 1997, Hoegh-Guldberg 1999). A 1 °C increase in temperature can cause severe coral bleaching (Glynn 1993). Global warming changes of this magnitude are projected to occur in south Florida and the Caribbean within the next 25 to 50 years. If stony coral reefs are subjected to a continual temperature increase over this century, they may respond with an increased frequency, scale, and severity of coral dysfunction and death (Glynn 1996). It is also possible, through physiological acclimatization and species replacements, that the zooxanthellae will develop tolerances to higher temperatures given their diverse species composition and genetic diversity (Rowan 1998, Knowlton 2001).

Should sea level rise occur faster than reef formation, lower light levels on the reef may result in coral zooxanthellae death, and subsequently, death of the coral polyp (Glynn 1993). In a circular fashion, global warming may contribute
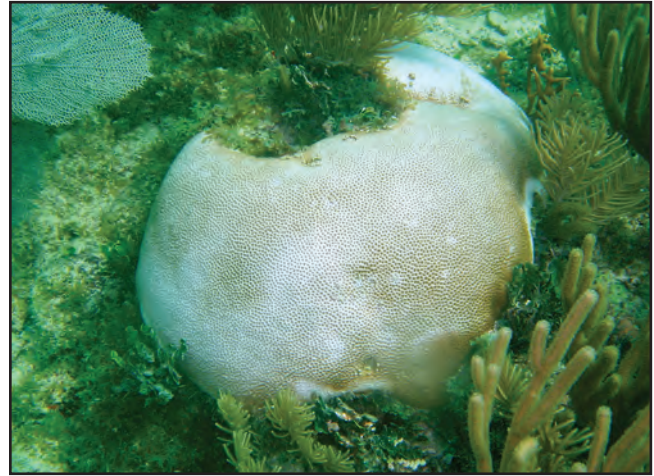
Coral bleaching of the species *Siderastrea siderea*. Photo by William Fit, University of Georgia.

to slowing coral growth. Coral also may be susceptible to the demographic "Allee Effect" sometimes exhibited in small populations. The Allee Effect refers to a decrease in survival and reproductive success of individuals of some species when population size decreases. Reef building coral typically broadcast their gametes into the water column and depend on eggs from one colony reaching sperm from another for reproduction to be successful. Temporal isolation of more than a few hours or spatial isolation of more than tens of meters can cause reproductive failure (Knowlton 2001).

In 2005, the National Park Service monitored coral reef bleaching in the Caribbean following unusually high water temperatures. An average of 90 percent of the sites in the U.S. Virgin Islands had bleaching, and depth of bleaching was much greater than in past events. Some signs of recovery were observed as water temperatures declined, but recovery was hampered by disease following the bleaching. Mortality of the corals is estimated at 50 percent from the combination of bleaching and disease (Patterson et al. 2006). In the Florida Keys, 2005 high temperatures appear to have caused coral bleaching; however, hurricanes Katrina and Rita lowered water temperatures and may have prevented massive bleaching (Manzello et al. 2007), suggesting that increased storm activity predicted with climate change could help slow the impacts of temperature increases. As in the Virgin Islands, where bleaching did occur, it was followed by disease (Brandt and McManus in press).

Corals also are sensitive to acidification of the oceans. The availability of calcium carbonate for coral reef building (and other calcifying organisms) is pH-dependent. Increased CO_2 concentration in the atmosphere leads to increased acidity of oceans as CO_2 is hydrolyzed in the surface waters, leading to decreases in biologically available calcium carbonate (Orr et al. 2005, Yates and Halley 2006, Hoegh-Guldberg et al. 2007). Experiments have suggested that CO_2 concentrations of 560 parts per million (approximately equal to the conservative IPCC scenario B1) will reduce coral calcification and growth by as much as 40 percent (Kleypas and Langdon 2006).

Hoegh-Guldberg et al. (2007) suggest several possible coral reef responses to decreased carbonate availability: (1) decrease in growth rate and skeletal density as observed on the Great Barrier Reef (Cooper et al. 2008), (2) maintenance of growth rates by reducing skeletal density further, or (3) maintenance of growth rates and density by investing more energy in calcification. Reduced skeletal density results in increasingly brittle coral at greater risk of storm damage. Allocating more energy to calcification diverts energy from reproduction and other important processes (Cooper et al. 2008). Ongoing stress from continuously shifting adaptive pressure leaves coral susceptible to competition and replacement by macroalgae-dominated ecosystems (Hoegh-Guldberg et al. 2007). The lower Florida Keys were formed from once-living coral and provide a barrier from the open ocean, protecting Florida Bay. As sea level continues to rise and new coral growth is increasingly compromised, Florida Bay may be increasingly exposed to open ocean waves and currents, impacting the ability of the bay to protect estuarine species.

Following broad regional bleaching of the Great Barrier Reef in 1998, coral steadily recovered in areas with large herbivorous fishes present. However, the quantity of macroalgae dramatically increased, suppressing coral growth and survival where herbivorous fishes were experimentally excluded (Hughes et al. 2007). Invertebrate herbivores such as sea urchins play a similar role (Edmunds and Carpenter 2001). Hughes et al. (2007) and Hoegh-Guldberg et al. (2007) both stress that local management policies and stewardship of fish and invertebrate herbivores, including reductions in local stressors such as declining water quality and fishery overexploitation, can play an important conservation role in the resilience of reefs to larger-scale disturbances that cannot be managed directly.

Amphibians and Reptiles

Amphibians in the Everglades consist of a diverse group that includes toads, treefrogs, frogs, sirens, newts, and amphiuma (Meshaka et al. 2000). The matrix of upland hammocks and freshwater habitats characteristic of the ecosystem are necessary for the life cycle of amphibians and, as in most places, can be an indicator of the health of the system. Amphibians appear to be among the most sensitive species to changes in temperature and precipitation (Corn 2005). Meta-analysis studies already have confirmed shifts in breeding for some species (Parmesan 2007; Fig. 11). Recent amphibian mortality has been linked to increases in the frequency of El Niño events; however, the mechanisms are not understood. The impact of reduced soil moisture on prey species and habitat has been identified as one possible factor (Corn 2005). Because the amphibian immune system is highly temperature dependent (Raffel et al. 2006), changes in temperature can adversely affect resistance to diseases. An example is the differing temperature-dependent interactions between the infectious *Batrachochytrium dendrobatidis* (a chytrid fungus that causes the amphibian disease chytridiomycosis) and various amphibian hosts (Woodhams et al. 2007). An amphibian species with an immune system that has evolved to cope successfully with pathogens adapted to specific temperature ranges may not be able to respond as quickly to new pathogens in a changed climate (Fisher 2007).

More than 50 distinct kinds of reptiles inhabit Everglades National Park, including the easily recognizable American alligator, the endangered eastern indigo snake (*Drymarchon corais*), and a suite of endangered and threatened sea turtles (Meshaka et al. 2000). Although related, the American alligator (*Alligator mississippiensis*) and American crocodile

Alligator hatchling in nest with eggs. Photo by Lori Oberhofer, ENP.

(*Crocodylus acutus*) are expected to respond differently to climate change. Alligators in the Everglades are at the southern end of their tolerance range and grow more slowly, take longer to reach sexual maturity, and have higher metabolic costs than alligators in other areas (Mazzotti and Brandt 1997). Temperature increases may further decrease their physiological well-being, but changes in hydropattern, habitat, and prey availability may be just as, or more, important. Alligators in Louisiana also are at the southern end of their range, but they grow faster and reach sexual maturity sooner. Their diet of primarily waterfowl and small mammals is in contrast to that of alligators in the Everglades, which consists of fish and snails. Diet may be a substantial cause of the differences in growth and reproduction rates between the two populations (Mazzotti and Brandt 1997). Prolonged droughts resulting from global climate change that decrease aquatic faunal densities and biomass (Loftus et al. 1986) may further exaggerate the growth and reproductive rates of alligator populations that inhabit the Everglades.

American crocodiles in south Florida are at the northern end of their range. Temperature increases are not expected to be problematic for this subpopulation (Mazzotti and Cherkiss 2003). However, indirect adverse effects to this species from global climate change may result from the potential for rapid to complete loss of existing coastal wetland and shore habitat (Wanless et al. 1997), as well as increased salinities (Mazzotti and Cherkiss 2003). Habitat loss from salt water transgression of the mangrove berms may be alleviated by nesting habitat shifting landward into the Everglades as long as elevated berms suitable for nesting remain alongside water with relatively low salinity.

The sex of crocodilians such as the American alligator and American crocodile is determined by temperature during incubation of the embryo (Ferguson and Joanen 1982, Lang and Andrews 1994). This same process may have acted in the selective extinction of groups of archosaurs (dinosaurs) during relatively sudden, continuous change in climate (Ferguson and Joanen 1982). Other reptiles, including sea turtles and mangrove terrapin (*Malaclemys terrapin*) that use coastal southwestern Florida and Florida Bay habitat extensively, also exhibit this characteristic. They may be among the groups most sensitive to global climate change and likely will act as early indicators of change (Janzen 1994).

Loss of sea turtle nesting habitat is likely where beaches are inundated by rising seas and enhanced beach erosion occurs from landward shifts in beaches being blocked by hard structures and developed land uses (Klein and Nicholls 1999). In the Ten Thousand Islands area in southwestern Florida, success of loggerhead sea turtle (*Caretta caretta*) hatchlings decreased as inundations, sand water content, and sand water salinity increased on low-relief mangrove islands (Foley et al. 2006). Hobe Sound National Wildlife Refuge and Juno Beach and are examples on the east coast of Florida with high densities of sea turtle nesting that are at risk from extensive development in the coastal zone (Engeman et al. 2002, Stewart and Wyneken 2004).

Birds

Since the earliest history of the Everglades, birds have been an integral, recognizable, and critical part of the ecosystem. From the wading birds that were hunted for their plumes to those birds designated as critical species for restoration, a functioning and healthy ecosystem is necessary for the continued presence of the more than 360 species listed in the Everglades National Park bird checklist. South Florida also provides a variety of habitats for migratory birds on their way to Central or South America as well as wintering birds that stay in south Florida. According to Maehr and Kale (2005), 143 bird species migrate through and/or winter in south Florida. Of these, 17 are ducks and other water birds and 30 are shorebirds of which 5 migrate through and 25 winter to some extent in south Florida. Sixteen warbler species migrate through and an additional 10 spend the winter in south Florida. The remaining 70 species include various songbirds, gulls or terns, raptors, and pelagic species. Birds, like amphibians, already are responding to climate changes with shifts in phenological timing (Brown et al. 1999, Parmesan 2007), including migratory phenology (Cotton 2003).

Many migratory bird species are now leaving for breeding grounds earlier and initiating migration earlier (Cotton 2003). Because many of these migrants are predatory or may compete for food, it is unclear how this trend will affect resident birds that often nest during the late winter and early spring, a period that may overlap with early spring migrants heading north. For example, the wintering Rufous Hummingbird (*Selasphorus rufus*), who in the past primarily wintered in Mexico, is appearing more frequently in Florida to spend the winter (Parmesan 2006). Hitch and Leberg (2007) examined the breeding bird survey data for North American birds (U.S. Geological Survey 2001) and determined that of 27 bird species selected with a southern distribution, 9 showed a significant shift northward and 2 shifted south (average 2.35 kilometers per year northward). There was no southward expansion of birds with northern distributions. Jiguet et al. (2007) identified habitat and life history traits in birds that appear to predict recent population trends in France and are likely to be relevant to identifying responses of bird species elsewhere. The factors most associated with declines in populations were (1) specialist considerably more than generalist, (2) birds that experience lower temperatures at the southern edge of their climate envelope regardless of the thermal range over which these species exist, (3) fewer number of brood per year, which Jiguet et al. (2007) suggest may reflect more capacity to respond to shifts in food peaks in response to climate change, (4) higher annual fecundity, and (5) lower natal dispersal.

Wading birds and shorebirds, resident as well as migratory, are expected to be affected by an increase in the rate of sea level rise with an accompanying loss of coastal marshes. Marsh areas are predicted to advance landward with modest sea level rise, but the landward response will likely be too slow to be successful in establishing new marsh habitat during periods of rapidly rising sea levels. These habitat losses

could be especially important in areas where seawalls or construction impede the development of new marshes farther inland (Butler and Vennesland 2000, Galbraith et al. 2002). The southeastern United States is an area of special concern (Butler and Vennesland 2000). Although wading birds have evolved in conditions of environmental variability, loss of habitat and connectivity increases the difficulties of responding to decreases in prey or suitable nesting habitat (Butler and Vennesland 2000).

Birds that breed in the Everglades time their breeding cycle with hydrologic events and depend on finding suitable water conditions for foraging and nesting. The nests of the federally endangered Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*) are flooded when water depths are too high (Nott et al. 1998), but the driest nesting sites tend to have lower nest success, possibly because food availability depends on the presence of water (Baiser et al. 2008). As water depths increase, however, nest predation increases (Lockwood et al. 1997). Hence, because this species is so sensitive to water levels, it is likely to be dramatically affected by sea level rise, increased drought, and increased storm intensities predicted with climate change. Changes may include loss of habitat, loss of breeding windows, species movement, or extinction.

Wading birds such as the White Ibis (*Eudocimus albus*) and Wood Stork (*Mycteria americana*) initiate nesting as water recedes in the dry season. Sudden reversals in water levels can cause widespread nest abandonment (Frederick and Collopy 1989). Snail Kites (*Rostrhamus sociabilis*) require wetland habitat that experiences drying and flooding events that are not too frequent or severe. Apple snails (*Pomacea paludosa*), their primary food, are maintained by nearly continuous, but shallow, flooding of wetlands. Generally one year of flooded conditions is required to sustain large populations

of the snails and to allow them to remain active and available as a food source. If water recedes from under Snail Kite nests, however, predation risk is increased and droughts drastically affect apple snail availability. Changes in hydrology may cause loss of habitat through conversion to uplands, adverse impacts to apple snail populations, reproductive failure, and change in habitat structure leading to loss of nesting substrate (Sykes et al. 1995, Martin 2007). Although droughts in the natural marsh system may be an important organizing force, a climate-related increase in drought frequency and extent in wetlands occupied by Snail Kites in the spring-summer could be a greater threat to Snail Kites than a lack of droughts (Martin et al. 2008). The Roseate Spoonbill (*Platalea ajaja*) times its nesting in Florida Bay to closely coincide with low-water depths that occur during the dry season, thus ensuring appropriate quality and quantity of prey. One predicted result of climate change is alteration of the flow of nutrients and fresh water to the coast, which is predicted to have a strong influence on Roseate Spoonbill nest success.

Of special interest to Everglades restoration issues is a suite of birds that includes the Snail Kite, Wood Stork, Roseate Spoonbill, and the Cape Sable Seaside Sparrow (Sustainable Ecosystems Institute 2007). In workshop settings with south Florida biologists, the Sustainable Ecosystems Institute (2007) panel concluded that all four avian species require similar cycles of rising water and dry down to produce hydrologic conditions favorable to the four species. The Comprehensive Everglades Restoration Plan (CERP) must result in freshwater levels that peak in the water conservation areas during the wet season (June–September) followed by dry down beginning as early as October and release of water through Shark River Slough. With the impacts of present and projected sea level rise, the importance of freshwater flows to the south-

Roseate Spoonbill (*Platalea ajaja*), Wood Stork (*Mycteria americana*), White Ibis (*Eudocimus albus*), and Great Egret (*Ardea alba*) foraging together in shallow water. Photo by Elise Pearlstine, University of Florida.

West Indian manatee swimming among mangrove islands in the Taylor River, Everglades National Park. Photo by William Perry, ENP.

ern Everglades for the gradual adaptation and sustainability of coastal brackish and freshwater habitats will increase (Sustainable Ecosystems Institute 2007). The Sustainable Ecosystems Institute (2007) also reported that climate change is likely to affect these four species, in common with other south Florida avian species such as wading birds in general, by increased frequency and severity of fires and storms (both tropical and hurricane), loss of freshwater marsh habitat in response to saltwater intrusion, thermal stress, and changes in phenology that decouple life cycles of avian species and their prey. Birds that require woody vegetation for nesting are likely to experience reduced amounts of suitable nesting substrate. Many birds rely on aquatic fauna as prey items and these communities will be altered through reduced oxygen concentrations and higher water temperature. Although the direction of change can be predicted for some variables related to climate change, predictions involving biological systems are very difficult to make because of the potential for interactions and the uncertainty of thresholds in physical processes.

Mammals

According to current (2008) mammal checklists available at Everglades National Park, Everglades ecosystems support a variety of mammals including bats, rabbits, river otters (*Lontra canadensis*), Florida panther (*Puma concolor coryi*), and a sea mammal — the West Indian (Florida) manatee (*Trichechus manatus latirostris*). Mammals are less likely than other groups to have direct phenological or distributional responses to climate change but will respond to changes in habitat and prey availability. The low-lying islands of the Florida Keys and Ten Thousand Islands region are particularly vulnerable to sea level rise. Expected sea level rise in conjunction with storm surges would inundate large proportions of habitat, either permanently or episodically (Backland et al. 2008) occupied by endemic Florida Keys federally endangered species such as the Key deer (*Odocoileus virginianus clavium*), Key Largo woodrat (*Neotoma floridana smalli*), Key Largo cotton mouse (*Peromyscus gossypinus allapaticola*), silver rice rat (*Oryzomys palustris natator*), and Lower Keys marsh rabbit (*Sylvilagus palustris hefneri*) (U.S. Fish and Wildlife Service 1999).

Lower regional survival probabilities for West Indian manatee coincide with years having strong hurricanes (Langtimm and Beck 2003). Increased and more-intense storms predicted to accompany climate change, along with potential coastal impacts to seagrass habitats, could increase survival pressures on this endangered species.

Insects

Insects provide waste management (decomposition), food for wildlife, pest control (Losey and Vaughan 2006) and pollination services for three-quarters of the world's flowering plants (Inouye 2007). Shifts in distribution and phenology of many insects are already being observed in apparent response to climate change (Parmesan 2006). Bale et al. (2002) cite research that suggests some insects may rapidly evolve physiological adaptation (Masaki 1967, Tauber et al. 1986, Pullin 1986), but many will migrate to avoid the effects of climate change (Coope 1978, Butterfield 1996, Hill et al. 1998). Synchrony with host-plant availability may be critical (Hodkinson 1997, MacLean 1983). On the basis of current experimental evidence, the direct effect of temperature — more so than increased CO_2 concentration, UVA, or precipitation — is likely to be the largest factor impacting insect species (Bale et al. 2002). Although warming trends are predicted to be less severe for south Florida as compared to northern latitudes, Tewksbury et al. (2008) summarize literature that suggests that insects and other ectothermal animals (such as fish, reptiles, and amphibians) living in tropical climates are likely to be less tolerant of climate warming. Many tropical ectotherms are already living in environments near the upper limits of their optimal temperature range (Deutsch et al. 2008), and relatively small increases in temperature throughout the year may be beyond their ability to acclimate.

The migration of butterflies is correlated with spring temperatures. Researchers have documented northward and higher-altitude distributional shifts as well as southern contractions of their historic range (Pollard et al. 1995, Parmesan et al. 1999, Crozier 2004). Increasing variability in precipitation associated with climate change was modeled to be the cause of population decline in one species of butterfly in California, the checkerspot butterfly, where distribution shifts were not possible because of habitat fragmentation (McLaughlin et al. 2002).

Five new species of tropical dragonfly were observed to have established themselves in Florida in 2000. This appeared to be a natural invasion from the Bahamas and Cuba (Parmesan 2006). Two species of butterfly, Florida leafwing (*Anaea troglodyte floridalis*) and Bartram's hairstreak (*Strymon acis bartrami*), were listed as federal candidate species in 2005 and are listed as threatened by the Florida Committee on Rare and Endangered Plants and Animals (Dreyrup and Franz 1994). The Florida leafwing occurs only on Long Pine Key in Everglades National Park and the population is rapidly declining (Cech and Tudor 2005). The

Dragonfly (*Brachymesia gravida*). Photo by Leonard Pearlstine, ENP.

population of Bartram's hairstreak is very small and is limited to south Florida and the Florida Keys; the species is one of the most imperiled butterflies in the Eastern United States (Susan Perry, Everglades National Park, pers. comm., 2008). Additionally, seven or more butterfly species that inhabit the park are imperiled. Butterflies are highly sensitive to a critical range of temperature, humidity, and light levels (Murphy et al. 1990) and their dependence on specific host plants ties them to specific habitats (Ehrlich and Raven 1965). Adequate rainfall is necessary for the health of butterflies and the plants they depend on; however, heavy storms or extended rainfall and temperature-rainfall interactions can cause direct or indirect mortality (Susan Perry, Everglades National Park, pers. comm., 2008). The Florida leafwing occurs only within pine rocklands in which grow its host plant, pineland croton. Bartram's hairstreak is a similar specialist in the larval stage, but because it has a wider range of plant nectar sources, its chances of survival are greater should the plant community shift (Susan Perry, Everglades National Park, pers. comm., 2008). Global climate change is expected to bring hotter and drier conditions, more frequent storms, and sea level rise. The hydrologic and ecologic effects on low-elevation habitats and on insect-plant phenology could cause major physiological disruptions for these insect species.

Bartram's hairstreak (*Strymon acis bartrami*). Photo by William Perry, ENP.

NATURAL RESOURCE MANAGEMENT IMPLICATIONS

Observed and anticipated climate change effects on southern Florida provide strong motivation for examining the goals and objectives of greater Everglades restoration. The Everglades is a dynamic landscape of ecosystems. Change occurs in response to drivers at temporal and spatial scales ranging from seasonal variation to abrupt, regional disturbances such as hurricanes and fire, and to long-term climate trends (which may include both gradual and abrupt events).

Present and future climate change scenarios in conjunction with irreversible human alteration of the landscape lead to the conclusion that restoration efforts can no longer be considered a program to return the Everglades to the past. The Department of Interior Task Force on Climate Change (DOI 2009a) and The National Research Council (NRC 2008) agree that historic conditions are no longer adequate as the sole basis for future resource management decisions. Multiple impacts from climate change, sea level rise, and the effects of human adaptations to climate change that compete with natural systems for resources and further fragment the landscape interact to produce ecological effects that cannot be fully predicted. Even if human interventions are successful in stabilizing climate regimes, they will be different from recent historic climate regimes and many species will not survive (Ruhl 2008). South Florida species most at risk are likely to be those dependent on isolated or fragmented habitats or species on the edge of their climatic tolerance ranges that are unable to respond quickly enough to changing climate trends by migration or adaptation. As a next step, recommendations for addressing climate change should consider species and habitats most at risk along with locally specific management options for their conservation. Some species are likely to thrive under climate change conditions and others can survive with assistance through a focused application of ecosystem-level management of habitat and other resources vital to sustainability (Ruhl 2008). Natural resource managers also must be open to the potential for a rich, biodiverse, functioning Everglades ecosystem that may include a new mix of habitat and species. The Everglades can be characterized as a complex of systems that are self-organizing, adaptive, and heterogeneous (Casti 1997)—not closed and predictable, but open, evolving, and in constant change (Pahl-Wostl 2007). Restoration under climate change may be most properly defined in terms of reducing ecosystem vulnerability and promoting adaptation and resilience.

This management section addresses broad topics of science-based understanding and management response to climate change impacts in the Everglades. Most of the focal topics echo natural resources policy and management guidance published in reports by the Intergovernmental Panel on Climate Change (IPCC 2007b), the U.S. Climate Change Science Program (CCSP 2008b), the Department of Interior Task Force on Climate Change (DOI 2009a, 2009b),

the National Research Council's second biennial review of Everglades restoration progress (NRC 2008), the Miami-Dade Climate Change Task Force (MDCCATF 2008), and others. In addition, Heller and Zavaleta (2009) provide a systematic review of published journal articles recommending measures to adapt conservation to climate change. Issues of climatic variability and extreme events, species and habitat migrations, and adaptability are common to most of the reports, as are management issues of monitoring, integrated database management, and modeling. NRC (2008) observes that dynamic aquatic and terrestrial habitats likely will continue to be a part of south Florida and impending climate change should be a motivation to avoid irreversible losses and to restore resilience of the ecosystem.

The current broad level of published recommendations for natural resource climate change policy and management must now be directed to specific goals, needs, and actions in south Florida and the Everglades. Focus groups within a structured risk-analysis and decision-support approach (van der Heijden 1996, Goodwin and Wright 1998, Mowrer 2000, Pyke et al. 2007) may be used to develop specific short- and long-term strategies along with climate change research and monitoring needs for Everglades natural resource management. These set clear, achievable goals that include auditing of their achievements (Rogers 1998).

Bridging the gap between science and policy is not typically as straightforward as a linear and one-way transfer of scientific knowledge to policy implementation. Moss (2007) identifies global scale, systems complexity, long time lags, lack of experimental controls, and the multiple disciplines involved as particularly challenging in the assessments of climate change uncertainties. Communication among many intermediaries, policy-brokers, lay shareholders, and multiple levels of governance and knowledge production is the key to successful integration of science into policy (Vogel et al. 2007). Climate change imposes long-term variably continuous change on systems, making management goals a moving target and observable systems response to actions under current conditions only a partial indicator of success. An adaptive management strategy must commit to long-term, often gradual, changes with potential for large abrupt changes, and requires ecological and physical modeling in the development of hypotheses and goals (Fussel and Klein 2006).

Goals for Resilience in Everglades Restoration

1. Maintain or restore multiple areas of habitat to facilitate population stability and recovery following disturbances.

2. Maintain or restore large-scale connectivity (ecological network of core areas, corridors, buffer zones, and restoration areas) to facilitate habitat potential,

maintain viable populations, and respond to habitat shifts resulting from climate changes and sea level rise. Jones-Walters (2007) reports that in Europe, the science of ecological connectivity has been successfully linked with policy considerations in natural resource protection.

3. Minimize diversity and abundance of habitat-homogenizing exotic species.

4. Maintain coral reef and coastal mangrove ecotones as natural barriers to storm surge and critical habitat for maintaining coastal biodiversity.

5. Consider assisted colonization (Hunter 2007, McLachlan et al. 2007) (migration or relocation of species) where present habitat is no longer sustainable and species are not able to adapt or migrate unassisted.

6. Engage in social, group decision, support building techniques that promote stakeholder and political understanding of Everglades complex adaptive systems and increase support for adaptive learning and management.

Broad Monitoring and Research Needs

Existing Everglades monitoring systems range from Earth observing satellites to hydrologic gage networks. Existing systems, however, are not optimized for detecting key biological and physical indicators of the consequences of climate change and may be monitored haphazardly or with incomplete spatial information (Backland et al. 2008). The CERP Monitoring and Assessment Plan (MAP) for Everglades restoration proposes a hypothesis-based ecological monitoring plan that links acquisition of monitoring and research data to system-wide assessments of ecological indicators that are essential to reducing uncertainty in decisions and evaluating CERP success (RECOVER 2008).

Baseline biotic and environmental monitoring should use standardized methods and common formats and may link to regional and national biological and physical databases to draw information from multiple sources (Lee et al. 2008). Information from disparate sources often is not well integrated. Recently, the Everglades Depth Estimation Network provided a successful example of agencies cooperating to bring water-stage gage data and analyses together into a common datum, format, and distribution network (http://www.sofia.usgs.gov/eden/). The USA National Phenological Network (http://www.usanpn.org/) provides another important example. A continued, long-term commitment of support is required for these and other monitoring networks to assist early

warning and more accurate forecasts of potential ecosystem changes.

Region-wide spatial databases of the greater Everglades and adjacent landscape for existing and potential faunal communities, key indicator species, vegetation communities, land use, elevation, hydrology, and water quality are fundamental components that provide the baseline spatial data for forecasting potential future conditions. The South Florida Water Management District is developing detailed vegetation classifications for the Everglades with an unknown completion date (Ken Rutchey, South Florida Water Management District, pers. comm., 2008). To bring this critical spatial data layer more quickly to researchers and to the decision process will require increased interagency involvement. A completed base map could be updated relatively frequently by identifying and mapping only areas of change and by integrating the mapping effort with permanent field monitoring sites. High-accuracy topographic surveys (Desmond 2003) and continuous mapped surfaces from the observations (Jones and Price 2007) have been completed for the freshwater marsh systems of the Everglades but need to be extended to include Everglades coastal areas, the Big Cypress landscapes, and the Florida Keys (not just the populated, higher-elevation outer keys). Hansen and Dewitt's (2000) bathymetry of Florida Bay also should be extended to include observations in the shallows of the bay. Combined, the elevation products will provide information needed for adequate forecasting of the spatial dimensions of sea level rise and potential for saltwater intrusion under scenarios of Everglades hydrologic restoration. The South Florida Water Management District is developing Everglades hydrologic model scenarios incorporating climate change and the University of Florida is preparing a downscaled climate model for Florida (Danny Coenen, University of Florida, pers. comm., 2008).

The ability of Everglades native and non-native species to adapt to climate change within their geographic range and to compete with invasive species depends in part on their ability to move into new locations and niches. Discrimination of these movements can be aided by monitoring and research that partitions four stages of invasion as presented by Theoharides and Dukes (2007) because of the different factors affecting each stage: 1) Movement into new geographic areas is facilitated by multiple introductions and high genetic variation, 2) colonization depends on environmental conditions (such as soil, temperature, and hydrologic factors), phenologic plasticity, and reproductive rates, 3) establishment depends on competitiveness, niche overlap, and interactions with enemies and disease, and 4) connections with other populations may increase genetic variability and reduce lag times from establishment to spread. Dispersal and linking of meta-communities across the heterogeneous landscape depends on the species' dispersal mechanisms, as well as the factors from all three previous stages. An understanding of species and community differential response to climate change in each of the four stages aids policy decisions in targeting management goals and actions (Theoharides and Dukes 2007).

Current Everglades restoration efforts to increase water flow to Shark River Slough, Taylor Slough, and Florida Bay may be particularly important in the coming decade for the freshwater head provided to offset saline transgressions with increasing sea level.

Comparative studies, physiological studies, and modeling could help to address climate change and restoration interactions on:

1. Area and distributional shifts in estuarine and freshwater wetland habitats,

2. Changing habitat and trophic linkages,

3. South Florida species phenology and distribution shifts and disruptions in interactions and synchronization among species,

4. Short and long-term adaptive capacity of south Florida species, and

5. Vegetation (and thus, habitat) responses specific to south Florida.

Managers should be aware that climate extremes and variability are likely to be more important to species responses than the expected mean climate changes. Further, species responses are frequently not linear relations with a single environmental trend (such as temperature and CO_2), but a complex, nonlinear relation to multiple environmental factors including geographic and hydrologic patterns, interactions with other species, and restriction to migration (natural and anthropomorphic) (Burkett et al. 2005).

Management decisions also need to incorporate evolutionary assessment into restoration and conservation practices keeping in mind that intraspecific genetic variation is critical to microevolution in response to rapid climate change (Rice and Emery 2004). Simulations of nonlinear ecosystem dynamics and adaptive variation are needed to support adaptive climate change management strategies, but predictive models will never be as advanced as management desires. Application of the precautionary principle (see sidebar) will remain a critical safety net for maintaining ecosystem structure and function (Burkett et al. 2005).

Carbon sequestration or "carbon farming" is gaining attention as a method of offsetting carbon emissions. The U.S. Department of the Interior has recognized its potential to play a key national role in reducing atmospheric CO_2 concentration through carbon sequestration (DOI 2009a). To this end, carbon is stored in plant material such as in forests, or in the soil. There has been recent interest in whether farming Everglades marsh in a flow-way being proposed for Everglades restoration would be effective to build peat and, subsequently, sequester carbon. Coastal wetlands contain about 10 percent of the total soil carbon in the world (Choi et al. 2001). Wetlands in general represent the largest portion of the terrestrial biological carbon pool (Chmura et al. 2003) and are thus important in global carbon cycles. In addition, much of the biomass in these systems is below ground and contributes to vertically extensive deposits (Chmura et al. 2003). However, these same systems are known to produce methane, an important greenhouse gas that derives from the decomposition of peat soils. Methane concentration may increase in wetlands at higher temperatures (Bartlett and Harris 1993), leading to a net production of greenhouse gases. It is also true, however, that southern latitude wetlands continue to be productive for longer periods of time and thus continue their uptake of CO_2, thereby reducing their overall CH_4/CO_2 ratio (Whiting and Chanton 2001). When considered over time periods of 100 years or greater, tropical wetlands may have potential to act as a carbon sink because of the shorter persistence of CH_4 in the atmosphere than CO_2 (Whiting and Chanton 2001). Tidal saline wetlands may be negligible sources of CH_4 because of likely effects of higher sulfate reduction in these soils (Chmura et al. 2003). The relation between soil carbon, greenhouse gas production, and other considerations such as in wetlands is complex, and currently there is no clear formula to determine whether natural wetlands in south Florida have the potential to act as a carbon sink.

A central idea within the U.S. Endangered Species Act, the United Nations Framework Convention on Climate Change, Kyoto Protocol, and the U.S. National Environmental Policy Act is the Precautionary Principle (Prato 2008). The precautionary principle states that if a condition creates the potential for a serious threat to human or environmental health, then precautionary measures should be taken to alleviate the condition. Scientific uncertainty is not to be used as a reason for postponing cost-effective measures to prevent environmental degradation (United Nations 1992). However, Prato (2008) (using fuzzy set operators with minimax regret criterion), and Nicholson and Possingham (2007) (using information-gap decision theory) provide two examples of quantitative evaluation methods that a decision-maker may use to help select a preferred adaptive strategy that represents minimum loss in adapting an ecosystem to future climate change under conditions of uncertainty and risk.

Although not reviewed by this report, ecosystem services link conservation to human benefits by relating environmental health to human health, security, and material goods (Brauman et al. 2007). Ecosystem services and resources such as storm and flood protection, freshwater quality, seafood, recreation, and tourism that are provided by the Everglades and adjacent natural areas will be important to identify as discussions with shareholders and local communities progress on managing the future of the Everglades.

The effects of global climate change are likely to have profound and widespread consequences on Earth's ecosystems. In south Florida, anticipated sea level rise (0.8 to 2 meters predicted) is predicted to overstep natural protective berms, allowing saline water intrusion into fresh marshes as well as flooding beaches, mangrove forests, and salt marshes. These habitats are critical for south Florida's native wildlife, especially those that serve as fish breeding and nursery grounds and wading bird and shorebird foraging and breeding areas. Increased weather uncertainty and lower rainfall levels in both dry and wet seasons are predicted to lead to droughts, hydrologic changes, increased fire, and other disturbances. Nearly all of south Florida's native wildlife species and plant communities are highly adapted to the cycles of wet and dry season and to particular hydrologic patterns. Loss of breeding and dispersal habitat for wildlife species are two likely effects in addition to direct mortality as a result of more intense tropical storms. Predicted temperature rise in the range of 2 to 5.5 °C by the end of the century is likely to directly impact species at the edges of their range like the American alligator, or thermal-dependent species like amphibians, and will likely lead to a turnover and alteration of many vegetation communities. To the detriment of native plant and animal species, invasive species are more likely to benefit from alterations to the environment that result from climate change. Endangered and threatened species as well as south Florida endemic species are predicted to suffer as all scenarios potentially result in habitat loss, phenological disturbance, increased hydrologic and weather uncertainty, range shifts, and other widespread habitat and life-cycle disruptions. Identification of those species and habitats most at risk and potentials for increasing habitat and landscape resilience to changes in climate will be critical next steps in a heightened focus within Everglades restoration.

Endangered Wood Stork (*Mycteria americana*) fishing at dawn. Photo by Elise Pearlstine, University of Florida.

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APPENDIX: ADDITIONAL RESOURCES

Assessment Reports

Intergovernmental Panel on Climate Change (IPCC)

http://www.ipcc.ch/ipccreports/assessments-reports.htm

U.S. Climate Change Science Program

http://www.climatescience.gov/Library/sap/sap-summary.php
21 reports at press time of this report

DOI Climate Change Task Force Draft Subcommittee Reports

http://www.usgs.gov/global_change/doi_taskforce.asp

State of Florida Action Team on Energy and Climate Change

http://www.flclimatechange.us/documents.cfm

Wildlife 2060

http://www.myfwc.com/docs/RecreationActivities/FWC2060.pdf
Florida Fish and Wildlife Conservation Commission report on wildlife trends

Florida 2060

http://www.1000friendsofflorida.org/PUBS/2060/Florida-2060-Report-Final.pdf
A Population Distribution Scenario for the State of Florida prepared for 1000 Friends of Florida

Miami-Dade Climate Change Advisory Task Force (CCATF)

http://www.miamidade.gov/derm/climate_change.asp

Florida Coastal and Ocean Coalition

http://www.flcoastalandocean.org/PreparingforaSeaChange/
Preparing for a Sea Change in Florida

Tufts University

http://ase.tufts.edu/gdae/Pubs/rp/Florida_lr.pdf

http://ase.tufts.edu/gdae/Pubs/rp/Caribbean-full-Eng.pdf
Climate change in Florida and the Caribbean: The costs of inaction

Data

Global Historical Climate Network (GHCN)

http://cdiac.ornl.gov/epubs/ndp/ndp041/ndp041.html

http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php
Windows utility that allows users to search and retrieve data for specific areas from the original GHCN files:
http://fuzzo.com/ghcn/index.htm

Everglades Depth Estimation Network

http://www.sofia.usgs.gov/eden/
Daily water stage, NexRAD rainfall data and ground elevation

National Climatic Data Center

http://www.ncdc.noaa.gov/oa/ncdc.html

NASA Global Change Master Directory

http://gcmd.nasa.gov/

Southeast Regional Climate Center

http://www.sercc.com/
Climate Data including historic and current precipitation, temperature, drought, and storms

Modeling

Climate Envelope Modeling Algorithms

http://openmodeller.sourceforge.net

North American Regional Climate Change Assessment Program (NARCCAP)

http://www.narccap.ucar.edu/data/status.html
High resolution climate change simulations

More Resources

USA National Phenology Network

http://www.usanpn.org/

Ecosystem Marketplace

http://ecosystemmarketplace.com/
Markets and Payment Schemes for Ecosystem Services

Florida's Wildlife: On the Frontline of Climate Change

http://www.ces.fau.edu/floc/updates.php
Summaries from October 2008 Workshop

Conference on Ecosystem Services, Naples, Florida 2008

www.conference.ifas.ufl.edu/aces
Includes abstracts, speaker Powerpoint presentations, and plenary session webcasts

U.S. Geological Survey Global Change Science

http://www.usgs.gov/global_change/
USGS Climate Change Activities

South Florida Regional Planning Council Climate Change Community Toolbox

http://www.sfrpc.com/climatechange.htm
Fact sheets, sea level rise maps, and adaptation resources

U.S. Geological Survey National Climate Change and Wildlife Science Center

http://nccw.usgs.gov/
Assess, synthesize, and share current information on climate change

The Nature Conservancy Climate Wizard

http://www.climatewizard.org/
View historic and predicted temperature and rainfall maps for anywhere in the world

Wildlife Management Institute

http://www.seasonsend.org/
Global Warming's Threat to Hunting and Fishing