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Committee on Independent Scientific Review of Everglades Restoration Progress

Water Science and Technology Board

Division on Earth and Life Studies

Consensus Study Report

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **George Hornberger** (NAE), Vanderbilt University and **Holly Greening**, CoastWise Partners. Appointed by the National Academies, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments received full consideration. Responsibility for the final content of this report rests entirely with the authoring committee and the National Academies.

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Preface

There are four remarkable things about the effort that this report describes. First, there are the innumerable and varied visions of the Everglades as an extraordinary ecosystem, from the vastness of a "River of Grass" to the incredible diversity of life that can be found in the smallest pocket of a hummock or beneath the seagrass blades in Florida Bay. There are the practical visions, too—its role in the very health and well-being of those who live near and those who visit from afar, to its powering of an economy and a way of life. Whatever vision we individually and/or collectively hold, we sense when it is at risk of being changed or lost. When many of us sense that loss, we do the second remarkable thing—we come together and willingly wrestle with the difficult question that asks what are we trying to restore and to what end. That leads us to the third remarkable thing, the sheer magnitude of the human endeavor to move large amounts of water, the very basis of life, across this vast and varied landscape that occupies most of the state of Florida, to restore it.

The use of the word "restore" dates back to the 14th century, defined as "a means of healing or restoring health, a cure; renewing of something lost." The word originated as a term applied to efforts directed to an individual or a single object. Now we find ourselves applying it to renewing a diverse and distinctive ecosystem that stretches from the meandering Kissimmee River and associated floodplain and chain of small lakes to the much larger Lake Okeechobee, and on to sawgrass plains, ridge-and-slough wetlands, tree islands, marl prairies, bays, and estuaries. To restore something lost means something far different in the 21st century than it might have in the 14th century because the context in which we restore—a changing climate, changing human needs—requires a diverse and unique set of skills, approaches, and philosophies to deal with both the pace of change and its consequences. The enormous passion, commitment, and collective intelligence of the people engaged in this effort to renew and restore the Everglades is the fourth remarkable thing, and it is an honor and privilege to be given the vantage point to review their efforts.

This document reports on the progress toward restoration of the Everglades natural system. The National Academies of Sciences, Engineering, and Medicine (National Academies) Committee on Independent Scientific Review of Everglades Restoration Progress, or CISRERP, was formed for this purpose in 2004. This report, which is the ninth in a series of biennial evaluations that are expected to continue for the duration of the Comprehensive Everglades Restoration Plan (CERP), reflects the concerted efforts of 12 committee members and 4 National Academies staff representing a wide range of scientific and engineering expertise. A fifth remarkable thing might be the circumstances under which the entire community of scientists, engineers, and stakeholders of the restoration effort helped the committee navigate the new landscape of remote meetings to provide a comprehensive picture of a work in progress unlike any other.

It has been my privilege to serve on this committee with some of the nation's leading experts in biological, hydrologic, and geographic sciences, hydrologic and systems engineering, project administration, law, and policy. I greatly appreciate the time, attention, and thought each committee member invested in understanding the complexity of the Everglades ecosystem and the corresponding scope of the CERP. I also appreciate the members' careful, rigorous analyses, expert judgment, constructive comments and reviews, and the professionalism, collegiality, and good humor with which they conducted their business, most notably over many hours on Zoom.

The committee is indebted to many individuals for their contributions of information and resources. Specifically, we appreciate the efforts of the committee's technical liaisons— Nafeeza Hooseinny (South Florida Water Management District), Robert Johnson (Department of Interior), and Gina Ralph (U.S. Army Corps of Engineers)—who responded to numerous information requests and helped the committee utilize the vast resources of agency expertise when needed. Many others educated the committee on the complexities of Everglades restoration through their presentations, field trips, and public comments (see Acknowledgments).

The committee had the good fortune to be assisted by dedicated and talented NRC staff: Stephanie Johnson, Sarah Haedrich, Jonathan Tucker, and Padraigh Hardin. Stephanie Johnson has served as senior project officer for all nine CISRERP panels and is a true Everglades expert. Her encyclopedic knowledge and understanding of the science, engineering, and administrative aspects of the CERP, ability to identify and synthesize the complex interrelationships among these aspects, deft management skills, and contacts were critical to the committee's success. She is intellectual shepherd, spiritual director, and choral master, blending voices and modulating rhythms as only she can. We literally can't thank her enough.

The CERP is a bold, challenging, and complex plan with great potential to provide benefits to the ecosystem and the public, and the progressively larger increments of restoration that have been achieved suggest that that potential can be realized. We offer this report in support of that endeavor.

Denice H. Wardrop, *Chair*
Committee on Independent Scientific
Review of Everglades Restoration Progress

Acronyms

A.R.M.	Arthur R. Marshall
AF	acre-feet
Alt-1BWR	Alternative 1BWR
AMO	Atlantic Multidecadal Oscillation
ASR	Aquifer Storage and Recovery
BBCW	Biscayne Bay Coastal Wetlands
BBSEER	Biscayne Bay-Southern Everglades Ecosystem Restoration
BBSM	Biscayne Bay Simulation Model
BISECT	Biscayne and Southern Everglades Coastal Transport
BMP	best management practice
C&SF	Central and South Florida Project
CBP	Chesapeake Bay Program
CEPP	Central Everglades Planning Project
CERP	Comprehensive Everglades Restoration Plan
CFR	Code of Federal Regulations
CISRERP	Committee on Independent Scientific Review of Everglades Restoration
CMIP5	Coupled Model Intercomparison Project Phase 5
COP	Combined Operational Plan
CRIDA	Climate Risk Informed Decision Analysis
CROGEE	Committee on the Restoration of the Greater Everglades Ecosystem
CSSS	Cape Sable Seaside Sparrows
CWA	Clean Water Act
DIP	dissolved inorganic phosphorous
DMSTA	Dynamic Model for Stormwater Treatment Areas
DOI	Department of the Interior
DOP	dissolved organic phosphorus
DRP	dissolved reactive phosphorus
EAA	Everglades Agricultural Area
EAV	emergent aquatic vegetation
ECB	existing conditions baseline
EIS	environmental impact statement
ENP	Everglades National Park
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
EPC_0	equilibrium phosphorus concentration
ERTP	Everglades Restoration Transition Plan

ET	evapotranspiration
FAV	floating aquatic vegetation
FDEP	Florida Department of Environmental Protection
FEB	Flow Equalization Basin
FW	Flow-way
FWMC	Flow-weighted mean concentration
FWO	future without
FY	fiscal year
GCM	General Circulation Model
GISTEMP	Goddard Institute for Space Studies Surface Temperature Analysis
HLR	hydraulic loading rate
IDS	Integrated Delivery Schedule
IMC	Interagency Modeling Center
IPCC	Intergovernmental Panel on Climate Change
IRL-S	Indian River Lagoon-South
IWR	Institute for Water Resources
LNWR	Arthur R. Marshall Loxahatchee National Wildlife Refuge
LORS	Lake Okeechobee Regulation Schedule
LOSOM	Lake Okeechobee System Operating Manual
LOWRP	Lake Okeechobee Watershed Restoration Project
LTER	Long-term Ecological Research
MAP	monitoring and assessment plan
NA	not applicable
NASEM	National Academies of Sciences, Engineering, and Medicine
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSM	Natural System Model
PDO	Pacific Decadal Oscillation
PDT	Project Delivery Team
PIP	particulate inorganic phosphorus
PIR	Project Implementation Report
PLR	phosphorus loading rate
POP	particulate organic phosphorus
PP	particulate phosphorus
PSTA	Periphyton-based STA
RCP	representative concentration pathway
RECOVER	Restoration, Coordination, and Verification
RSM	Regional Simulation Model
RSM-GL	Regional Simulation Model for the Glades and Lower East Coast Service Areas
SAV	submerged aquatic vegetation
SCG	Science Coordination Group
SCT	Science Coordination Team
SCW	Spreader Canal western
SFER	South Florida Ecosystem Restoration
SFER	South Florida Environmental Report

SFNRC	South Florida Natural Resources Center
SFRCCC	Southeast Florida Regional Climate Change Compact
SFWMD	South Florida Water Management District
SOM	System Operating Manual
SRP	soluble reactive phosphorus
SSG	Science Sub-Group
SSR	System Status Report
SSRF	Strategic Science and Research Framework
STA	Stormwater Treatment Area
STAC	Scientific and Technical Advisory Committee
STAR	Scientific, Technical Assessment and Reporting
STERTF	South Florida Ecosystem Restoration Task Force
TBD	To be determined
TE_P	phosphorus treatment efficiency
TIME	Tides and Inflows to the Mangrove Everglades
TMDL	Total maximum daily load
TN	total nitrogen
TP	total phosphorus
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WCA	Water Conservation Area
WERP	Western Everglades Restoration Project
WIIN Act	Water Infrastructure Improvements for the Nation Act
WPA	Water Preserve Areas
WQBEL	water quality–based effluent limit
WRDA	Water Resources Development Act
WY	water year

Contents

5
Restoration in the Context of Climate Change

Climate change represents an existential threat to many aspects of the South Florida ecosystem and the people who value and rely on it. The committee discussed the need to consider rise in sea level, change in precipitation patterns, and increasing temperature conditions in several previous reports (NASEM, 2016, 2018, 2021; NRC, 2014). In this chapter the committee reiterates many of the concerns expressed in previous reports and focuses on how climate change and variability can pose risks to the Comprehensive Everglades Restoration Plan (CERP) at various stages of its development and implementation. The committee offers the current Biscayne Bay Southern Everglades Ecosystem Restoration (BBSEER) project as an example of the critical need to consider climate change in planning. Next, the committee discusses how some aspects of climate change can influence the operations of CERP projects, highlighting the Lake Okeechobee operations, and reviews the role of System Operating Manuals in efforts to adapt to climate change. Finally, the committee describes the programmatic implications of recent and future changes in climate and how they influence the ecosystem if they are not meaningfully considered. As the CERP pivots from planning to operating projects to optimize ecosystem responses, both at a project and system scale, it becomes even more important to make climate change a central consideration in all aspects of the CERP to ensure that the nation's investments in restoration continue to reap benefits for decades to come.

CLIMATE CHANGE IN SOUTH FLORIDA

South Florida, a subtropical region surrounded by ocean with strong surface and deep water currents, is characterized by a distinct and highly variable climate regime. The climate is tropical and monsoonal, with variations manifested by large-scale phenomena (El Niño South Oscillation [ENSO], Atlantic Multidecadal Oscillation [AMO], and Pacific Decadal Oscillation [PDO]) that occur over multiple timescales with interspersed periodic extreme weather events. South Florida, like the rest of the world, is experiencing changes in climate and sea-level rise (Chassignet et al., 2017). The evolution of these climate phenomena will affect the CERP's context and success. South Florida is also periodically impacted by tropical cyclones, which can result in storm surge inundation, excessive rainfall, and wind damage to coastal forests (Han et al., 2018). During the past 20 years, the South Florida ecosystem has been impacted by Hurricanes Frances (2004), Jeanne (2004), Wilma (2005), Irma (2017), and Ian (2022) as well as numerous tropical storms. Although the science suggests that more intense tropical cyclones are associated with increased sea surface temperatures (Knutson et al., 2021), statistically significant trends are not yet apparent. A recent analysis in the U.S. Atlantic basin noted no significant overall trend in hurricane landfall or major hurricane landfall over 167 years of available data (Loehle and Staehling, 2020). Thus, the committee focuses here on effects of climate change on temperature, precipitation, and sea level.

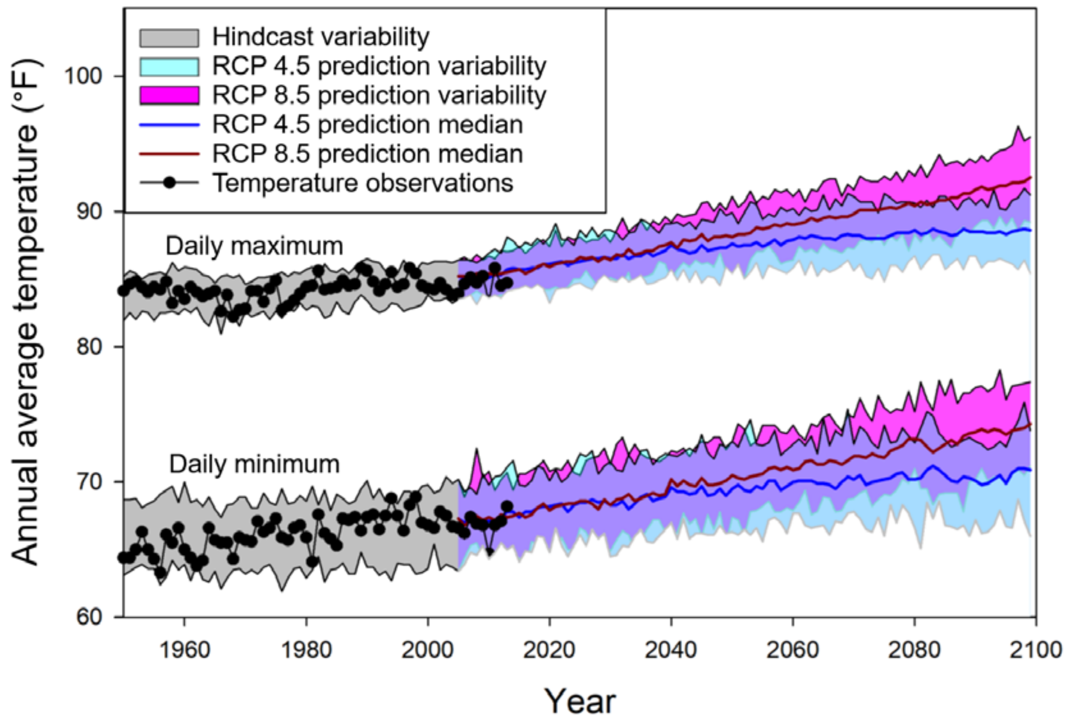

FIGURE 5-1 Historical measurements and future projections of annual average daily maximum and minimum air temperature for Miami-Dade County, Florida. Projections were generated by global climate models for the Coupled Model Intercomparison Project Phase 5 (CMIP5). Climate model data were statistically downscaled using the Localized Constructed Analogs method (Pierce et al., 2014). Shaded area shows uncertainty in general circulation model (GCM) hindcasts and forecasts. Two future emission scenarios are shown: higher emissions (RCP 8.5; red) and lower emissions (RCP 4.5; blue). The lines through the shaded areas represent the median value of GCM projections.
SOURCE: https://crt-climate-explorer.nemac.org.

Recent and Future Air Temperature Trends

Station data from Miami-Dade County for air temperature and precipitation from 1950 to 2013 show an increase in minimum and maximum annual average daily temperature (Figure 5-1) (Livneh et al., 2013, 2015).[1] The long-term average rate of minimum temperature increase was greater (0.23°C per decade) than the rate of maximum temperature increase (0.028°C per

[1] See also https://crt-climate-explorer.nemac.org.

decade), and annual minimum values have been more variable. Jones and Driscoll (2022) evaluated air and sea surface temperature anomaly (GISTEMP Team, 2020) from 1900 to 2020 and, for South Florida, reported a trend of accelerating increases in air temperature: from 0.11°C per decade for the period 1930-2020, to 0.14°C per decade for the period 1950-2020, to 0.21°C per decade for the period 1980-2020. They also found large relative changes in air temperature extremes, with many more extreme hot temperatures and far fewer extreme cold temperatures in recent decades than would be expected based on 20th century data. For example, in the 1990s and 2000s, South Florida had twice the number of months with extreme hot temperatures (defined as >90 percent the 20th century distribution of temperature values) compared to observations during the 20th century, and in the 2010s, it had 4.5 times the expected number of months with extreme hot temperatures. In contrast, in the 1990s and 2000s South Florida had only one-fourth of the expected number of months with extreme cold temperatures (<10 percent of the 20th century distribution of temperature values), and in the 2010s it had only one-half of the expected number of months with extreme cold temperatures based on the 20th century distribution of temperatures.

Future air temperature projections for two emission scenarios—Representative Concentration Pathway (RCP) 4.5, the lower emission scenario, and RCP 8.5, the higher emission scenario—suggest that temperature changes will continue to increase in South Florida through the 21st century (Figure 5-1). For the higher emission scenario, the annual average daily maximum and minimum temperatures are projected to change by 0.042°C and 0.04°C per year, respectively. These rates decrease to 0.036°C and 0.035°C for the lower emission scenario. Increases in air temperature cause increases in evapotranspiration, which would reduce surface-water availability under comparable precipitation conditions.

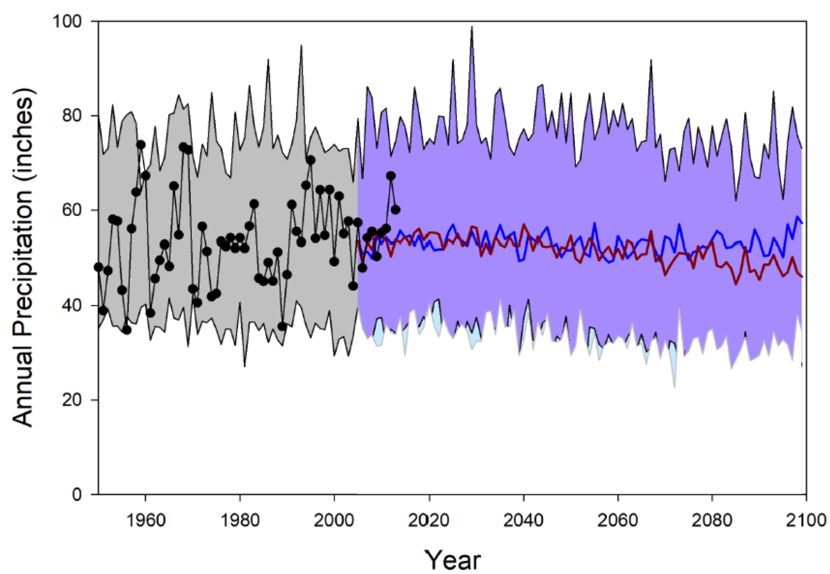

FIGURE 5-2 Historical measurements and future projections of annual precipitation for Miami-Dade County, Florida. Shaded area shows uncertainty in GCM hindcasts and forecasts. Two future emission scenarios are shown: higher emissions (RCP 8.5; red) and lower emissions (RCP 4.5; blue). The line through the shaded areas represents the median value of GCM projections.
SOURCE: https://crt-climate-explorer.nemac.org.

Recent and Future Evaporation and Precipitation Trends

Annual precipitation for South Florida is highly variable from year to year (Figure 5-2) with similar variation year to year in precipitation extremes (Figure 5-3). Future projections of precipitation for South Florida are highly uncertain and do not capture the variability evident in observations. Future projections do not indicate a clear future trend in annual precipitation, the number of dry days, or the annual number of precipitation events over 3 inches (7.6 cm) through the 21st century (Figures 5-2 and 5-3). Little difference in precipitation is projected between the higher and lower emission scenarios, except for a small projected decrease in annual precipitation and an increase in the number of dry days in the latter decades of the 21st century under higher emissions compared to a lower emissions scenario.

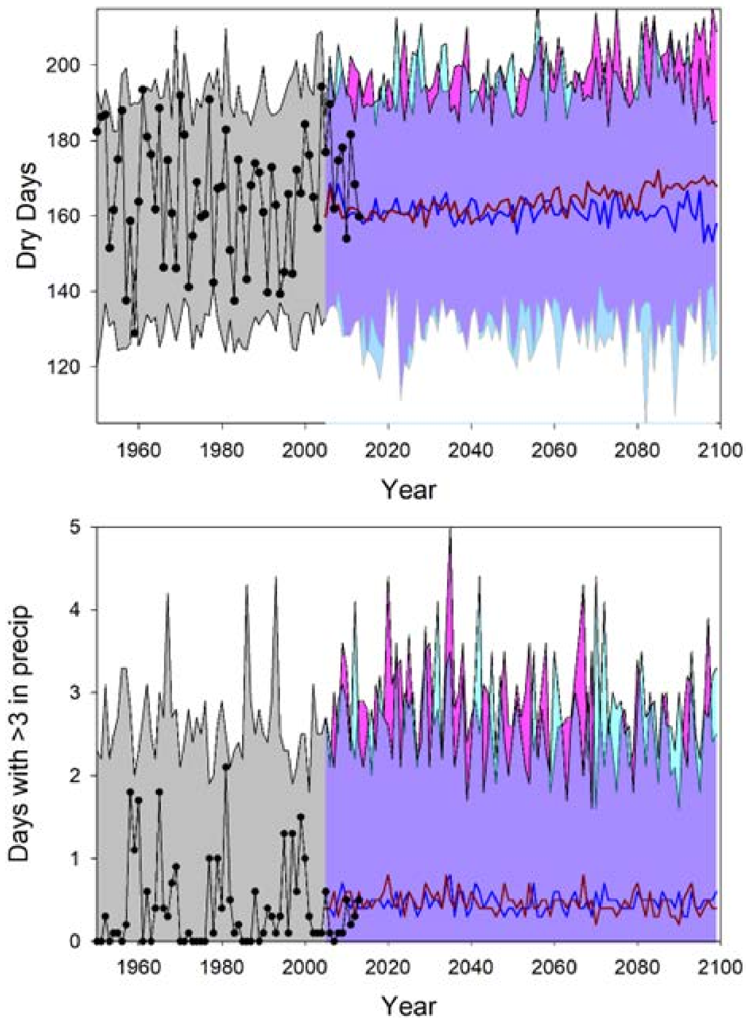

FIGURE 5-3 Historical measurements and future projections of annual dry days (top) and the number of precipitation events per year in which precipitation exceeded 3 inches (7.6 cm; bottom) for Miami-Dade County, Florida. Shaded area shows uncertainty in GCM hindcasts and forecasts. Two future emission scenarios are shown: higher emissions (RCP 8.5; red) and lower emissions (RCP 4.5; blue). The line through the shaded areas represents the median value of GCM projections.
SOURCE: https://crt-climate-explorer.nemac.org.

Similar projections are available for evapotranspiration and runoff.[2] Although future changes in precipitation are highly uncertain and projections of average annual precipitation currently appear relatively stable, it is quite certain that future climate will drive increases in rates of evapotranspiration due to projected increases in air temperature that will subsequently drive decreased runoff (Figure 5-4). For RCP 4.5, mean annual runoff for the ensemble of GCM projections is projected to decrease by 0.7 in/yr (1.8 cm/yr) over the period 2075-2099 relative to values for 1981-2010, while for RCP 8.5 runoff is projected to decrease by 3.6 in/yr (9.1 cm/yr) over the same conditions. The projected decreases in runoff are highly seasonal, with the largest relative changes occurring early in the wet season, during the months of June, July, and August (Figure 5-5). It is important to note that because future projections of precipitation are highly uncertain and variable, projections of runoff are also highly uncertain.

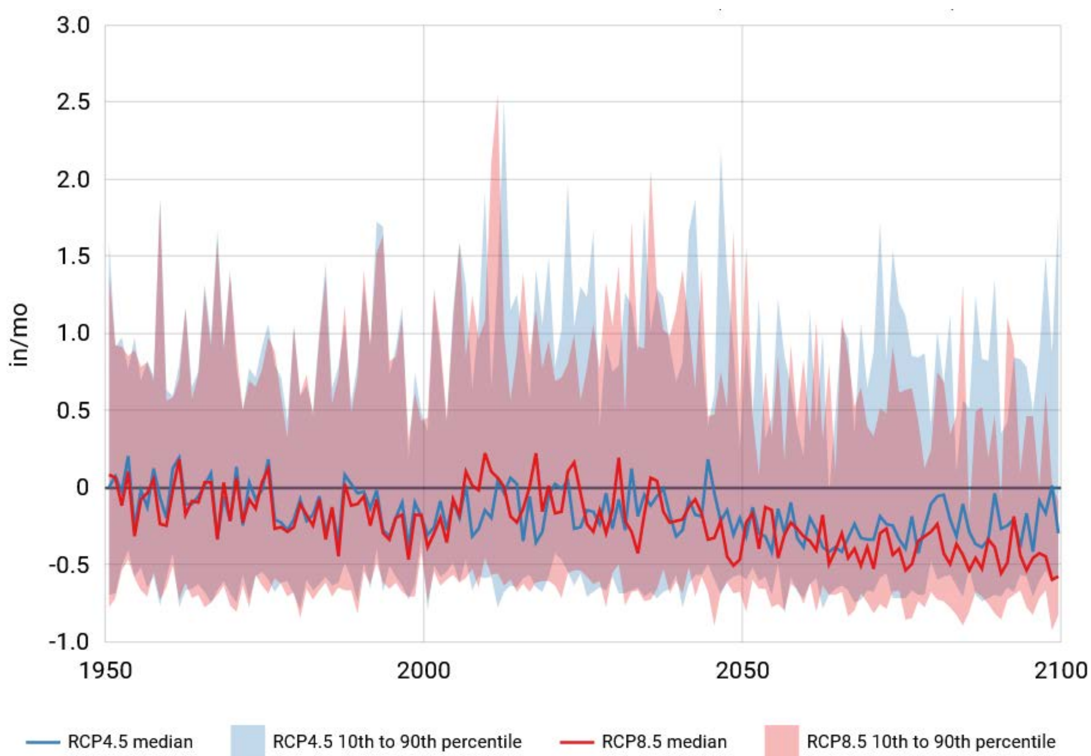

FIGURE 5-4 Historical and future projections of annual runoff (inches/month) relative to the mean of the historical period (1981-2010) for Miami-Dade County, Florida. The shaded area shows uncertainty in GCM hindcasts and forecasts. Two future emission scenarios are shown: higher emissions (RCP 8.5; red) and lower emissions (RCP 4.5; blue). The line through the shaded areas represents the median value of GCM projections.
SOURCE: https://www2.usgs.gov/landresources/lcs/nccv/maca2/maca2_counties.html.

[2] See https://www2.usgs.gov/landresources/lcs/nccv/maca2/maca2_counties.html.

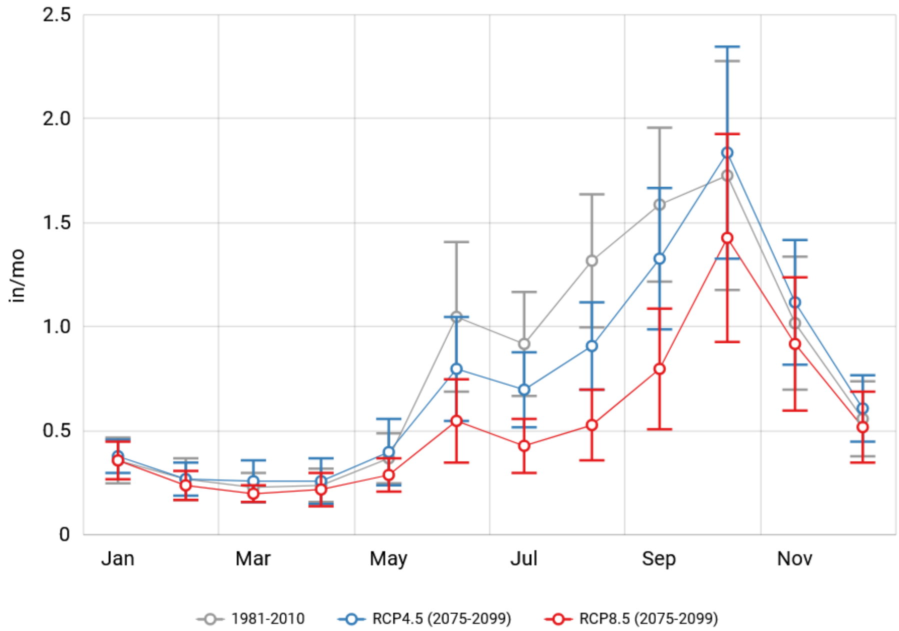

FIGURE 5-5 Historical simulations of monthly runoff (inches/month) for Miami-Dade County, Florida (1981-2010; grey) compared to future projections (2075-2099) of runoff under two emissions scenarios (higher emissions [RCP 8.5; red] and lower emissions [RCP 4.5; blue]), each with projected increases in air temperature and evapotranspiration combined with projected future rainfall. Error bars shows uncertainty in GCM hindcasts and forecasts. SOURCE: https://www2.usgs.gov/landresources/lcs/nccv/maca2/maca2_counties.html.

Sea-Level Rise

Long-term data from Key West, FL (1913-2021) show an increasing sea-level trend of 0.10±0.006 in/yr (2.52+0.14 mm/yr; 95% confidence interval) based on monthly mean sea-level data, which is equivalent to a change of 10 inches (0.25 m) in 100 years.[3] Changes in the speed and thermodynamics of the Florida Current and the Gulf Stream have resulted in a notable regional increase in the rate of sea-level rise between 2010 and 2015 (Domingues et al., 2018; SFRCCC, 2019) (Figure 5-6).

The Southeast Florida Regional Climate Change Compact (SFRCCC, 2019) developed a suite of possible futures of sea-level rise based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014), as well as projections from the National Oceanic and Atmospheric Administration (NOAA) (Sweet et al., 2017). SFRCCC (2019) also accounted for regional effects, such as gravitational effects of ice melt, changes in ocean dynamics, vertical land movement, and thermal expansion from warming of the Florida Current. This analysis produced regional differences in the rate of sea-level rise for Southeast Florida compared to global projections. All projection curves developed by SFRCCC (2019) are based on the assumption that greenhouse gas emissions continue to increase until the end of the century, consistent with RCP 8.5 of IPCC (2014). Estimates of sea-level rise reflect a baseline year of 2000 and a planning horizon to 2120.

[3] See https://tidesandcurrents.noaa.gov.

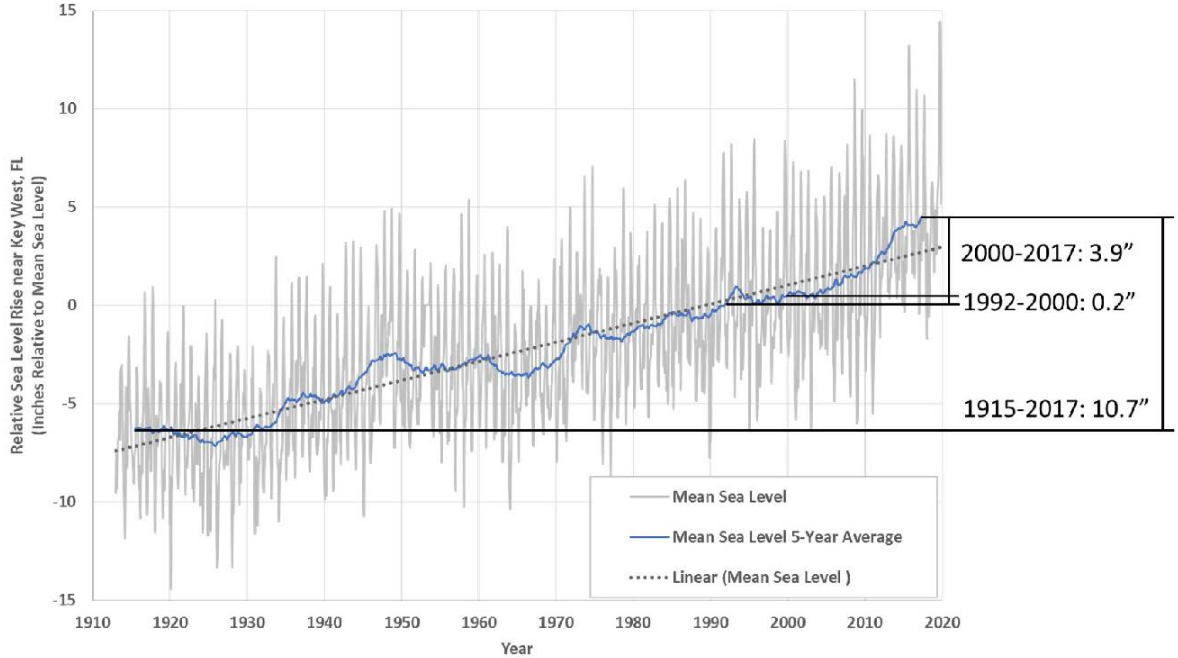

FIGURE 5-6 Relative sea-level rise in Key West, FL (NOAA Station ID 8724580) presented as monthly mean sea level, 5-year rolling average of monthly mean sea level, and linear trend of monthly mean sea level. Annotated measurements on right of figure are computed by subtracting the 5-year average mean sea levels for the years listed. The sea-level rise computed based on the linear trend will differ from the 5-year mean sea-level trend shown. SOURCE: SFRCCC, 2019.

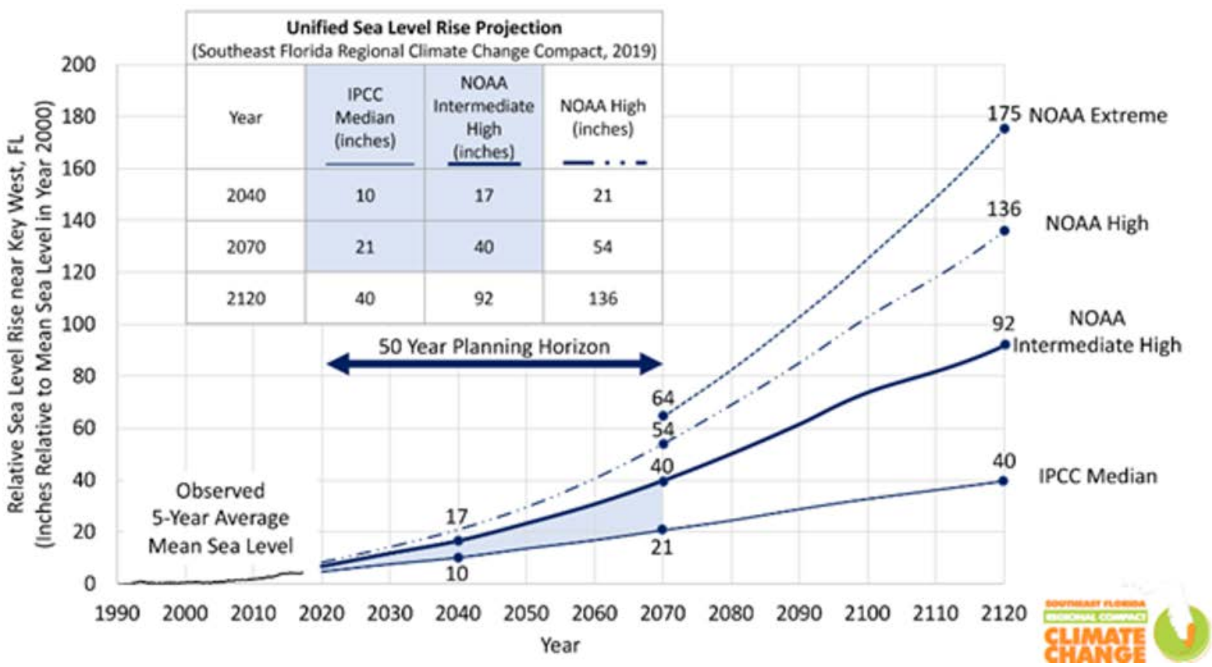

FIGURE 5-7 Unified projections of sea-level rise for South Florida
SOURCE: SFRCCC, 2019.

The 2019 Unified Sea Level Rise Projection includes three curves for application: the NOAA High Curve, the NOAA Intermediate High Curve, and the curve corresponding to the median of the IPCC (2014) RCP 8.5 scenario (Figure 5-7; SFRCCC, 2019). A fourth curve, the NOAA Extreme Curve, is included for informational purposes, not for application, illustrating the possible upper limit of sea-level rise in response to potential massive ice sheet collapse in the latter part of the century.

In the short term, sea-level rise for South Florida is projected to be 10-21 inches (0.25-0.53 m) by 2040 and 21-54 inches (0.53-1.37 m) by 2070 above the 2000 mean sea level in Key West, FL (Figure 5-5; SFRCCC 2019). Over the long term through 2120, sea-level rise is projected to be 40-136 inches (1.0-3.45 m). The range of variation in projected sea-level rise is substantial, especially beyond 2070, because of uncertainty in future greenhouse gas emissions reduction efforts and associated geophysical effects.

Implications for Everglades Restoration

Sea level is rising, which impacts coastal and estuarine zones in many ways, including inundation or exposure of low-lying coastal areas, changes in storm and flood damages, shifts in extent and distribution of wetlands and other coastal habitats, changes to groundwater levels, and alterations to salinity intrusion into estuaries and groundwater systems. Increasing temperatures and evapotranspiration will reduce runoff and impact water availability, unless precipitation increases to counter these effects. A central CERP objective is to increase water storage and provide additional dry season flows to the remnant Everglades and the southern coastal systems (Chapter 2), but increased air temperature and evapotranspiration will reduce the flows provided by new CERP storage. Such future changes have important implications for both the human system and the natural system.

Both sea-level rise and temperature and precipitation changes will influence the fate of the Everglades coastal wetlands. A critical question for the CERP is whether, and for how long, restoration of freshwater flows can mitigate salinity incursion related to sea-level rise, reduce associated peat collapse (Chambers et al., 2019), and facilitate a landward migration of coastal mangroves to counteract the effects of sea-level rise. Research is examining the factors that influence the relative rates of these processes and the role of freshwater flows to enhance the resilience of the Everglades coastal landscape (Charles et al., 2019; Ishtiaq et al., 2022; Wilson et al., 2018). For example, Wilson et al. (2018) found that dry-down events exacerbated peat loss in brackish wetlands. See NASEM (2018) for additional discussion of the role of sea-level rise on wetland peat and NASEM (2018, 2020) for a review of climate change effects on South Florida estuaries and their restoration goals. Understanding the potential effects of climate change and their relationships to CERP projects is necessary to ensure sound investments that enhance the resilience of the South Florida ecosystem.

USACE APPROACH TO CLIMATE CHANGE

U.S. Army Corps of Engineers (USACE) policy is to integrate climate change adaptation planning and actions into the Agency's missions, operations, programs, and projects. This concept is further developed in the USACE Climate Action Plan (USACE, 2021c), which includes a "commitment to integrate the best available observed and forward-looking climate information" into the agency's missions, programs, and management functions. Action 1 seeks to "ensure that new USACE-built projects are built to last and perform reliably for their intended design lives, despite uncertainty about future climatic conditions." Although updates to guidance are still in development, the Action Plan sets an expectation that USACE projects will be robust, resilient, and adaptable to future change.

USACE Sea-Level Change Guidance

In 1986 the USACE first developed a guidance letter requiring consideration of sea-level change in the planning and design of coastal flood control and erosion protection projects (USACE, 1986). The guidance followed the concepts outlined in the National Research Council's (NRC's) *Responding to Changes in Sea Level: Engineering Implications* (NRC, 1987), which covers multiple sea-level rise scenarios. USACE updated this guidance in its 2000 Planning Guidance Notebook (USACE, 2000), which informed early CERP planning studies, including the Biscayne Bay Coastal Wetlands. USACE (2000) called for an assessment of the sensitivity of project benefits to the historic and NRC high-rate scenario (equivalent to 4.9 feet [1.5 m] by 2100). In its current guidance, USACE (2019c) requires consideration of three scenarios (low, intermediate, and high rates of sea-level rise, calculated for local conditions based on equations in NRC, 1987). However, USACE planners can consider a higher rate of sea-level change if justified by project conditions to account for changes in statistically significant trends and new knowledge about sea-level change (USACE, 2019c). A subsequent USACE pamphlet (USACE, 2019a) describes procedures to evaluate sea-level change and calls for the use of multiple scenarios (consistent with USACE [2013]) in addition to a "single future," which must be used in National Environmental Policy Assessment evaluations. USACE (2019a) applies to USACE activities as far inland as the extent of estimated tidal influences. It provides options for how the scenarios should be used in USACE decision making, including

- When local conditions and plan performance are not considered highly sensitive to the rate of sea-level change, a single sea level–rise scenario could be used to develop and compare alternatives; the preferred alternative is then tested against other sea level–rise scenarios.
- When local conditions and plan performance are deemed to be very sensitive to the rate of sea-level change, alternatives could be formulated and then evaluated under all sea level–change scenarios.

USACE (2019a) also states the following:

> Alternative plan selection should explicitly provide a way to address uncertainty, describing a sequence of decisions allowing for adaptation based on evidence as the future unfolds. Decision-makers should not presume that the future will follow exactly any one of the SLC [sea level change] scenarios. Instead, analyses should determine how the SLC scenarios affect risk levels and plan performance, and identify the design or operations and maintenance measures that could be implemented to minimize adverse consequences while maximizing beneficial effects.

USACE guidance on the use of sea-level rise has evolved to allow for incorporation of scenario analysis and robust decision making into the planning process. However, the ability of any USACE team to fully embrace the approaches described may be limited by the availability of information (e.g., on the effects of sea-level rise on system dynamics), appropriate tools or models to explore alternatives across scenarios, and time and resources. In addition, for systems such as the Everglades, the interaction of sea-level rise with other climate stressors may be an important determinant of alternative benefits.

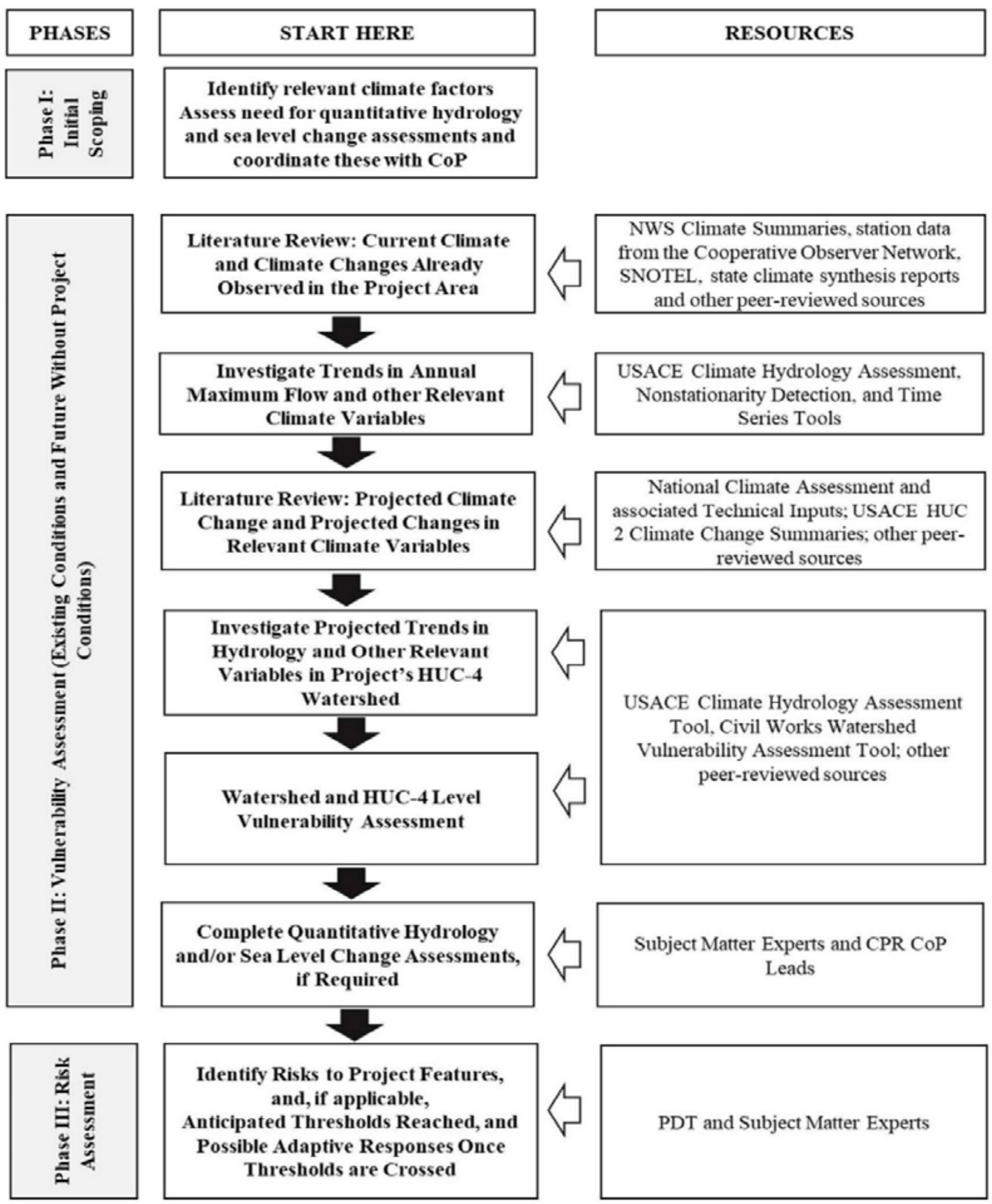

FIGURE 5-8 USACE process for qualitative analysis of climate change impacts on inland hydrology.
SOURCE: USACE, 2020e.

BOX 5-1
South Florida Water Management District Resiliency Planning

The South Florida Water Management District (SFWMD) has implemented programs specifically designed to assess and improve infrastructure resiliency and ensure function under the changing climate (SFWMD, 2021a). Recognizing that the current system will be stressed by climate change impacts such as sea-level rise and changing rainfall patterns, the SFWMD's Flood Protection Level of Service Program assesses the capacity of District flood control infrastructure to perform to both design specification and expected future conditions. Once areas for improvement are identified, Adaptation and Mitigation Planning studies are triggered. Since the program's inception in 2015, nine assessments have been or will be completed by 2022, and all flood control infrastructure will be assessed every 8-10 years (SFWMD, 2021a).

Through these and other assessments, the SFWMD's new Sea Level Rise and Flood Resiliency Plan identifies urgent improvement projects needed to address vulnerabilities to sea-level rise, storm surge, and extreme rainfall events (SFWMD, 2021b). Projects include both traditional "gray" infrastructure as well as nature-based solutions. The list of projects will be updated annually and serve as the basis for implementation priority.

USACE Guidance on Climate Change and Inland Hydrology

The current USACE Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects (USACE, 2020e) outlines the approach that the agency must follow to address climate change in its work related to runoff. The inland hydrology guidance (USACE, 2020e) requires incorporation of climate change into the assessment of all long-term planning and engineering decisions. It emphasizes understanding climate change impacts on plan selection and project objectives, the use of USACE tools and expert judgment, and communication of findings to the public. In particular, the guidance states that the risk of climate change must be identified, communicated, and managed in decision-making processes.

USACE (2020e) requires qualitative analysis of inland hydrology (Figure 5-8) and allows for quantitative analysis once USACE headquarters provides updated climate data and information, which has not yet occurred. The USACE qualitative analysis considers both past hydrologic changes and projected future hydrologic changes based on available modeling. The level of detail and complexity of this analysis will depend on the uncertainty and risks associated with the impact of climate on alternatives. This analysis is not expected to change the quantitative assessment of other factors that are part of project evaluation. However, it may influence future without project conditions, formulation and evaluation of alternative plans, and other aspects of the decision-making process. USACE (2020e) notes that the required qualitative inland hydrology analysis alone provides an insufficient basis for identifying or modifying a tentatively selected plan. However, it may be used by project partners, such as the South Florida Water Management District (SFWMD), to understand potential vulnerabilities and impacts so that they may be addressed outside the evaluation of the project itself. The SFWMD has established certain procedures to ensure the provision of service levels under climate change (see Box 5-1), and it could conduct additional analyses, in addition to the USACE qualitative analysis, to support a request for a "Locally Preferred Plan."

Although guidance is still pending, USACE (2020e) provides a preview of how future quantitative inland hydrology analysis will ultimately be conducted. Methods are expected to be flexible, with some requirements such as the use of USACE analytical tools for trend and non-stationarity detection and the use of a full ensemble of CMIP Phase 5 global climate model projections, stating that use of a subset is not supported. The level of effort for the analysis is expected to be scalable to the level of complexity of the project and its potential sensitivity to climate change. This flexibility will enable quantitative analyses in project evaluation under climate change in ways that could improve the future performance and resilience of the CERP once USACE guidance has been developed.

Approaches to Analyzing Precipitation and Temperature Change in Risk-based Planning

Consistent with the state of professional and scientific opinion, USACE (2020e) emphasizes that the historical record provides a relatively limited sampling of the conditions that will be experienced in the future. It cannot be assumed that the future climate will be well represented by historical conditions or that climate variability will occur over the same range as experienced in the past. Even if precipitation projections remain uncertain, increasing temperature and evapotranspiration trends (Figure 5-1) will affect future runoff and water availability (Figure 5-4 and 5-5), unless countered by increasing rainfall. Nonetheless, choosing an alternative to the historical record to inform planning and operations has been a vexing challenge for the water resources profession. However, methods have been developed, used, and documented that provide the basis for climate change analysis, and, if applied, would provide USACE partners with crucial information for improving the resilience of CERP investments.

For inland hydrology under climate change to be successfully addressed in project evaluation, expectations regarding the uncertainty of future climate must be appropriate. Most uncertainty associated with precipitation under a changing climate is irreducible in the short term. Therefore, there should be no expectation that a climate change analysis will narrow the range of possibilities or produce a single clear vision of future climate. Selecting a single mean estimate of future climate is like planning for each year to have the average annual precipitation, leaving a project unprepared for the risks of the wider range of possibilities. Instead, a pragmatic risk-based approach is necessary.

An objective of project evaluation under climate change is to improve understanding of the risks that climate change poses to the project, so that these risks can be better communicated and managed. A pragmatic approach to achieving this understanding uses modeling to simulate the effects of a wide range of plausible climate scenarios and future climate variability. In the case of precipitation and temperature changes, a well-established body of work in the scientific literature details methods for creating precipitation and temperature scenarios for this purpose (Herman et al., 2020; Kirsch et al., 2013; Mukundan et al., 2019; Seinschneider et al., 2013, 2015). These methods generally employ a set of equally probable stochastically generated time series of precipitation and air temperature that are then perturbed with plausible trends in the variable mean. This approach facilitates robust exploration of the effects of plausible changes to the mean climate state while accounting for the natural variability of the climate system. The futures can be conditioned on the specific climate phenomena that have the most influence in South Florida, such as ENSO, tropical cyclones, or seasonal precipitation, which enables assessment of risk levels based on expectations of changes in these phenomena. Simulations of plausible climate scenarios have been applied to water systems planning throughout the world and may be beneficial to CERP planning efforts. Several examples of successful approaches that could be highly appropriate for CERP project planning are described in Box 5-2.

Application of these methods in CERP planning would be straightforward in principle, notwithstanding the inevitable details of implementation in the existing suite of modeling tools. A systematic approach that uses these methods in CERP models to evaluate the risks posed by climate change to inland hydrology would align with USACE guidance and improve the likelihood of achieving the restoration goals while meeting other water system objectives.

RESTORATION PLANNING IN COASTAL SYSTEMS: THE BISCAYNE BAY AND SOUTHEASTERN EVERGLADES RESTORATION PROJECT

The BBSEER project focuses on ecosystem restoration of wetland and nearshore habitats in Biscayne Bay, Card Sound, and Barnes Sound and in the Model Lands, Southern Glades, and

BOX 5-2
Examples of Quantitative Climate Change Scenario Analysis for Inland Hydrology

A number of recent studies illustrate and, in some cases, provide guidance for applying "bottom-up" approaches to climate change assessment for water resources planning projects. They offer examples of methods that could be directly applied to Comprehensive Everglades Restoration Plan (CERP) planning. Each uses a climate stress testing approach, employing a wide range of stochastically generated climate scenarios that explore the plausible range of climate change. Thresholds on acceptable performance are used to define problematic climate scenarios or the degree of climate change that causes projects to either fail to meet their objectives. Climate projections from general circulation models (GCMs) can then be used to assess the level of concern associated with the vulnerabilities that are identified.

The California Department of Water Resources used this approach in *Decision Scaling Climate Vulnerability Assessment for the California Department of Water Resources* (Schwarz et al., 2019) to assess the vulnerability of the California Central Valley Water System using a regional planning model, Cal-Lite 3.0, to represent more than 30 water storage facilities and 700 miles of canals and pipelines that provide water for 25 million people and 750,000 acres of irrigated farmland. The San Francisco Public Utility Commission used a similar methodology, described in *Long Term Vulnerability Assessment and Adaptation Plan for the San Francisco Public Utilities Commission Water Enterprise* (Water Research Foundation, 2021), to understand the vulnerability of its water supply system to temperature and precipitation changes associated with climate change.

These methods have been documented and promoted by operational organizations including in reports by the World Bank, *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework* (Ray and Brown, 2015), and the USACE, UNESCO, and Deltares partnership, *Climate Risk Informed Decision Analysis (CRIDA): Collaborative Water Resources Planning for an Uncertain Future* (Mendoza et al., 2018). Deltares also developed the concept of Dynamic Adaptation Policy Pathways specifically addressing sea-level rise based on the Dutch experience (Werners, et al., 2021; Kwadijk et al., 2010). These reports provide implementation support based on decision making under deep uncertainty frameworks (Marchau et al., 2019), including decision scaling (Brown et al., 2012), robust decision making (Lempert et al., 2010; Weaver et al., 2013), and dynamic adaptive policy pathways (Mendoza et al., 2018).

other wetlands adjacent to these water bodies (see Figure 3-37). Canals and levees have reduced sheet flow to the coastal wetlands and estuaries and have concentrated discharge in drainage canals, altering nearshore salinity and coastal habitats. As discussed in more depth in Chapter 3, the project seeks to

- Restore ecological conditions in the Model Lands, Southern Glades, portions of Everglades National Park, and coastal wetlands;
- Restore conditions in the nearshore zones of Biscayne Bay, including Biscayne National Park, Card Sound, Barnes Sound, and Manatee Bay;
- Improve ecological and hydrologic connectivity between Biscayne Bay coastal wetlands, the Model Lands, and Southern Glades; and
- Increase resiliency of coastal habitats in southeastern Miami-Dade County to sea-level change (USACE and SFWMD, 2020c).

The BBSEER project builds on work conducted for the Biscayne Bay Coastal Wetlands (BBCW Phase 1) and the C-111 Spreader Canal West projects (see Chapter 3), which were each first increments of a larger regional project. To achieve these objectives, the CERP vision for the BBSEER project includes increasing water flows to the region through new water storage and/or wastewater reuse, improving sheet flow to the freshwater and coastal wetlands and the nearshore estuary ecosystem, and reducing seepage from Everglades wetlands.

In this low-elevation coastal system, the BBSEER project is on the front line of climate change effects. Because the project addresses coastal and near-shore issues and how they can be alleviated by increasing freshwater flows, it exemplifies the ways in which climate change effects on runoff and sea level can influence project performance. Further, because the planning is currently under way, BBSEER reflects the use of current climate change guidance for CERP agencies and provides the opportunity for the committee to review its use of information and tools in the planning process.

BBSEER Objectives and Challenges in Context of Climate Change

Climate change will have major effects on the estuaries (Figure 5-9; NASEM, 2021). Better understanding of these effects in the BBSEER footprint can help to inform management decisions and strategies that will provide long-term restoration benefits. The committee has previously noted that ongoing climate change, including changes in precipitation patterns, sea-level rise, and ocean warming, challenge the ability of many CERP restoration efforts to meet the "essential hydrological and biological characteristics that defined the undisturbed South Florida ecosystem" (NASEM, 2016). In light of sea level rise, the low-lying coastal wetlands of the Model Lands cannot be fully restored to their pre-drainage condition because ongoing sea-level rise is permanently altering the landscape and associated vegetation.

The BBSEER project represents an important evolution in CERP project objectives, from projects that aim to re-create historic conditions to projects whose resilience to future change is a key metric to be evaluated in project planning, marking an important shift in thinking toward the future of the system, consistent with a recommendation in NASEM (2018). This resilience depends upon increased freshwater flows and appropriate salinity to support a resilient mangrove habitat that accretes peat and thereby builds land surface elevation. Although not the sole objective, coastal resilience is central to meeting other objectives over the long term, such as restoring ecological conditions in coastal wetlands and in the near shore. The project team added a specific resilience performance measure (see Box 5-3) to track progress toward this objective in the evaluation of project alternatives, although currently there is no plan to weight this measure more strongly than the other seven performance measures.[4] The BBSEER project also aims to maintain a 500-m nearshore zone within mesohaline conditions (5-18 psu); restore

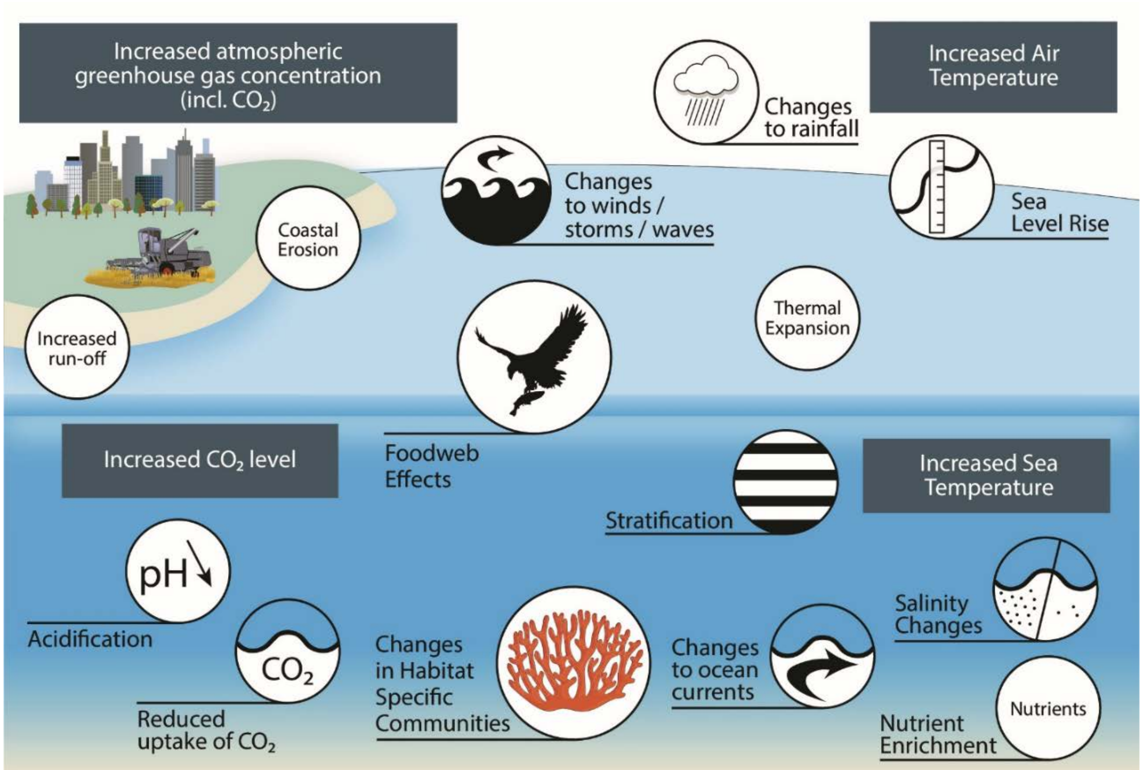

FIGURE 5-9 Conceptual model of impacts of global climate change on Florida estuaries.
SOURCE: Adapted from OSPAR, 2010.

BOX 5-3
The BBSEER Adaptive Foundational Resilience Performance Measure

Ecosystem changes within the Biscayne Bay Southern Everglades Ecosystem Restoration (BBSEER) footprint such as peat marsh degradation, replacement of coastal grasslands by mangrove forests, expansion of sparsely vegetated “white zones,” and introduction of invasive and exotic species have been accelerated by sea-level rise. In principle, increased freshwater flow to the area could promote restoration of peat-accreting vegetation, thereby resisting transgression due to sea-level rise.

[4] The performance measures are nearshore salinity, direct canal releases, timing and distribution of flow sources to Biscayne Bay, hydroperiods, water depth, wetland salinity, adaptive foundational resilience, and ecological connectivity. See https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll11/id/5760.

The new Adaptive Foundational Resilience performance measure (F. Sklar, SFWMD, personal communication, 2022) is an estimation of the peat accretion rate based on the hydrologic outputs of the Regional Simulation Model for the Glades and Lower East Coast Service Areas (RSM-GL) and the Biscayne and Southern Everglades Coastal Transport (BISECT) models. Specifically, estimates of porewater salinity, sheet flow volume, and depth duration at each model grid cell are translated into peat accretion rates based on sets of empirical conversions for freshwater and saline habitats (Figure 5-10). The peat accretion rates are integrated over the 52-year model duration and then normalized to the maximum possible peat accretion (based on the empirical formulations of peat accretion), yielding a normalized performance measure score from 0 to 100. The combined scores along various transects through indicator regions of the model domain will be used to directly compare the model-estimated peat accretion under the different flow regimes of existing conditions, future without project, and proposed project alternatives.

Although the Adaptive Foundational Resilience performance measure yields numerical estimates of peat accretion, the accuracy of these estimates is subject to significant uncertainty because of accelerating sea-level rise, other effects of climate change, and lack of dynamic feedback (i.e., vegetation succession), among others. However, because these uncertainties impact alternative measures similarly, the performance measure may still be useful as a relative scoring of the peat accretion potential under different project alternatives (F. Sklar, SFWMD, personal communication, 2022).

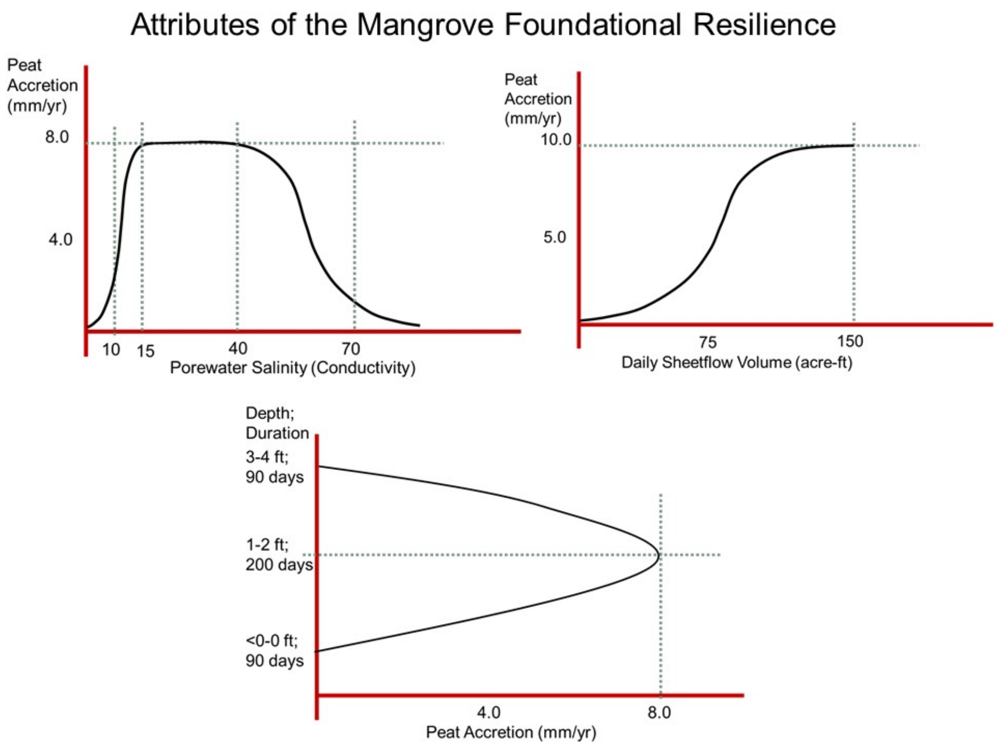

FIGURE 5-10 Graphical functions of the relationship of porewater salinity, sheet flow volume, and water depth and duration, which control peat accumulation in mangroves. These functions will be used in the Adaptive Foundational Resilience performance measure to calculate peat accretion based on various project alternatives that affect flow and salinity. Different graphical functions are used for peat accumulation in freshwater wetlands.
SOURCE: F. Sklar, SFWMD, personal communication, 2022.

freshwater depths, hydroperiods, and flows in terrestrial wetlands; and connect habitats from the sawgrass marsh through saltwater wetlands to open water across a 0-35 psu gradient.[5]

Many of the desired outcomes of the BBSEER project depend upon increased freshwater flow (by volume) in the southern Everglades afforded by new storage and/or wastewater reuse. The collection and delivery of water through the ecosystem for restoration purposes is impacted by climate change through altered precipitation regimes, increased evapotranspiration, increased salinization of coastal surface and subsurface waters, and decreased gravitational drainage as sea levels rise. It is important that all the assumptions being made about the availability and use of these water sources are reasonable given climate change and that effects of potential climate stressors on different water sources (e.g., surface storage, water reuse) are understood. Evaluation of whether alternatives produce meaningfully different outcomes when uncertainty posed by climate change is considered seems consistent with USACE policy and should be an explicit part of the decision process for BBSEER given the reliance on limited sources of freshwater under existing and future conditions.

Modeling Tools and Their Applications for BBSEER Planning in the Context of Climate Change

Previous committee reports have noted the difficulty of using the Regional Simulation Model (RSM) to understand the effects of projects near the coast, and the need for models that can assess the effects of sea-level rise. NASEM (2018) identified advancement of tools to better characterize and quantify the effects of sea-level rise as a critical need and noted that, despite the value of the RSM in understanding changes in water stages and flows, the lack of a coupled connection to the coastal systems and the ability to simulate salinity dynamics and variable density flows was a drawback. Thus, it is not surprising that BBSEER project planning has required a number of model refinements. Three models are being used to evaluate various project alternatives and to determine the effects of the eight performance measures:

- Regional Simulation Model for the Glades and Lower East Coast Service Areas (RSM-GL), which provides an integrated simulation of surface and groundwater from the Water Conservation Areas (WCAs) through Everglades National Park, the lower east coast, and the Model Lands, using a daily time step over a 52-year period (1965-2016) (Bras et al, 2019). The RSM-GL will be used to simulate water depths, hydroperiod, and flows.
- The Biscayne Bay Simulation Model (BBSM), which is a 2D model that uses vertically integrated hydrodynamic equations to simulate water flow and salinity dynamics (Wang et al., 2003; Stabenau et al., 2015). BBSM will be used to simulate nearshore salinity.[6]
- Biscayne and Southern Everglades Coastal Transport (BISECT), which was developed to evaluate South Florida surface-water stages and flows, groundwater levels, and salinity in response to changes in water-management practices and sea-level rise by combining the Tides and Inflows to the Mangrove Everglades (TIME) and FTLOADDS simulator (Swain et al., 2019). In BBSEER, BISECT will not directly simulate project features;

[5] See also https://www.saj.usace.army.mil/BBSEER/.

[6] Following release of the prepublication report, this text was edited to provide an accurate description of the BBSM.

instead, it will utilize RSM-GL structure flows and stages at canals and project features. The model evaluation will use a 2007-2016 record of coastal forcing and will be used to simulate marsh salinity.

Figure 5-11 summarizes the proposed use of the various models in an early evaluation of project alternatives. Several ecological models are also available to elucidate the ecological implications of various project alternatives, and these models are used in parallel with the process to evaluate performance measures.

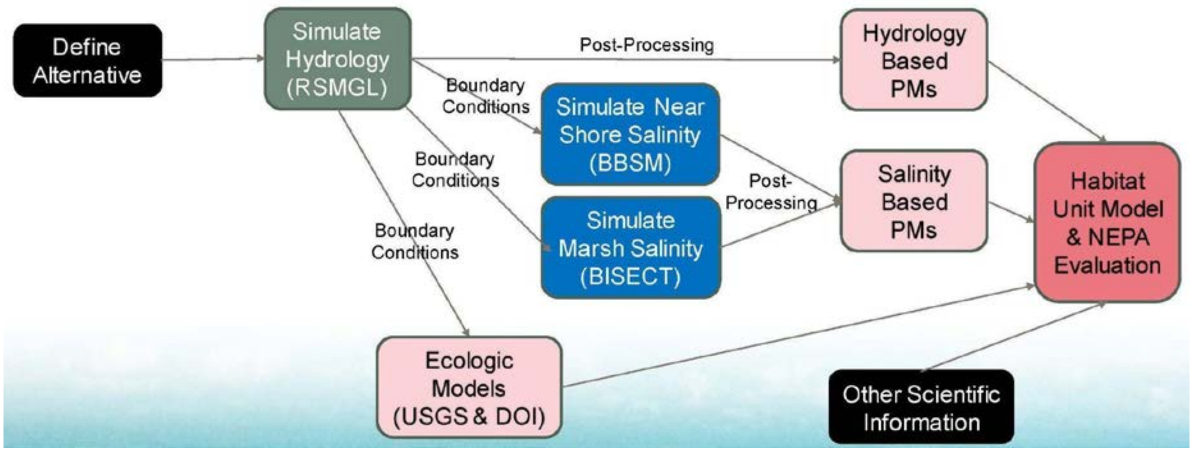

FIGURE 5-11 BBSEER model processing steps for round 1 of plan formulation.
NOTE: DOI=Department of Interior, NEPA=National Environmental Policy Act, PM=performance measure, USGS=U.S. Geological Survey.
SOURCE: Wilcox, 2022.

Significant efforts are under way to refine these hydrologic models to increase compatibility. For example, remeshing has extended the RSM-GL boundary seaward to improve representations of the coastal area. Extensive work has been undertaken to generate the tidal boundary forcing for RSM-GL based on long-term data sets. A limited recalibration was conducted on the BBSM, with added diffusion coefficient zones so that it would better align with the RSM-GL and adjustments to groundwater flow. These models employ slightly inconsistent approaches to assessing salinity changes, and how this plays out in the project planning remains to be seen. The models influence separate salinity-based performance measures. Because all applicable performance measures for any given grid cell will ultimately be combined in project alternative evaluation, the different models should ideally respond to common forcing.

As of July 2022, modeling efforts for project alternative evaluation were still at early stages. These efforts are expected to include development of a 2022 existing conditions baseline (ECB) run (including the Lake Okeechobee Systems Operating Manual [LOSOM] and the 2020 Combined Operational Plan [see Chapter 3]) and evaluation of a “future without project” (FWO) for 2085. The FWO will capture the effect of a step increase in sea level without BBSEER but including authorized CERP projects, including the Central Everglades Planning Project (CEPP) and the Everglades Agricultural Area (EAA) Reservoir. For the various project alternatives, eight performance measures will be examined under the 2085 conditions with projected sea-level rise, and the results will be compared to the ECB and FWO scenarios to evaluate the degree to which the alternatives meet project objectives.

Modeling the Effects of Sea-Level Change on Project Outcomes

One complication with the current approach is that sea-level rise effects are assessed using a step-change in the coastal boundary, whereas the rate of sea-level rise changes incrementally over time (Figure 5-7). Several important aspects of the system, such as mangrove transgression, are responsive to the rate of change in addition to the amount of change. If the rate of sea-level rise exceeds the capacity for mangroves to accrete peat, then vegetated wetlands will be replaced by open estuarine waters. The extent of mangroves may increase as the salt-freshwater transition moves inland, potentially leading to the conversion of sawgrass to mangroves. The modeling team recognizes that the future landscape and the performance of the project can be influenced by the interplay of a higher tidal boundary, adjustments in landscape definition, and topographic change. The current assumption is that accretion rates (and thus topographic change) are based on relationships between accretion, flow, and salinity, which vary by vegetation community (Box 5-3). These relationships have been established based on data from the system as it is now or has recently been. Sensitivity analyses need to be conducted to understand how much these assumptions drive the performance of the project. Uncertainty in soil accretion has been shown in other coastal wetland models to be an important driver of future landscape change (Meselhe et al., 2021). Further, coastal wetland accretion has been shown to be responsive to changes in relative sea-level rise rate (Davis et al., 2005; Saintilan et al., 2022); thus, if the rate of sea-level rise increases, assumptions about accretion rates may need to be adjusted. Plant-soil feedbacks are complex (Wimmler et al., 2021) and physical conditions, including storm effects, can have important implications for mangroves (Chambers et al., 2021; Xie et al., 2022). Including all aspects of coastal wetland dynamics in time-dependent modeling can be complex. However, in coastal Louisiana, focused effort and investment in the development of tools to support planning has yielded a relatively simple model in which simulations show change over time in coastal wetlands in response to changes in sea-level, freshwater inflows, and some storm effects (Reed et al., 2020a).

Further, the survival in place of the mangroves depends on their ability to maintain their relative elevation as sea level progressively rises. Changes in wetland condition may be gradual until thresholds for tolerance of flooding or salinity are exceeded (Chambers et al., 2021). Such thresholds may be exceeded by the gradual encroachment of saline waters, for example, or during extreme events, such as hurricanes. Understanding when the rates of sea-level rise exceed the ability of mangroves to accrete, and the rapidity with which transgression and associated vegetative transitions occur due to both chronic and acute stresses (with and without the project), is key to understanding project performance over the USACE-prescribed 50-year planning period. The step-change approach to sea-level modeling fails to encompass the types of transitions that occur and may provide misleading information about project performance over time.

Modeling the Effects of Variations in Precipitation and Climate Change on Project Outcomes

The only aspect of climate change included in the BBSEER analysis is sea-level rise. Despite ongoing collaborative efforts between SFWMD and Florida International University (FIU) to develop new scenarios of precipitation under climate change to support restoration decision making, future precipitation scenarios will not be incorporated into the BBSEER analysis. The BBSEER modeling for the evaluation of project alternatives will be based on the prior climate record, which assumes that the historical time series of precipitation and air temperature provide an adequate set of conditions to fully test the robustness of the candidate plans to future climate conditions. The drawback of this approach is that the results will not reflect the range of possible future weather conditions that the recommended design is likely to face.

At the spatial scale of BBSEER and for a planning horizon of 50 years, the natural variability of the local climate will be a significant source of variability, while trends in climate due to anthropogenic climate change, including changing air temperature and evapotranspiration (Figures 5-1 to 5-5), are likely have a more subdued effect, at least in the next few decades. Thus, the key question is whether and to what degree the historical observed weather record provides a reasonable simulation of the conditions under which the restoration project will take place. It is worth noting that in the practice of water planning, it is not uncommon that the historical record retains a primacy for project evaluation. Nonetheless, a general conclusion in water resources planning has been that the historical record provides a relatively limited sampling of the conditions that will be experienced. Although the range of variability may not significantly differ, the specific sequence of weather events certainly will. For example, the sequence of above and below normal precipitation years and the magnitude of the departure from mean conditions will likely be unprecedented. There may be years with more intense precipitation or more intense drought simply due to natural variability, or multiple extreme years may occur back to back in ways that have not occurred in the precipitation record. The specific effects of anthropogenic climate changes are difficult to anticipate but they do increase motivation to consider more variation than has been evident in the historical record during evaluation of restoration designs.

A rich literature describes methods to generate climate scenarios for water project design evaluation that precedes more recent concerns related to climate change (Cioffi et al., 2020; Kwon et al., 2007, 2009). Interest in using GCM projections as the basis for such simulations is common. However, alternative methods that do not require GCM projections may better elucidate the sensitivity of a particular project, such as BBSEER, to climate change (Brown et al., 2012; Steinschneider and Brown, 2013; Whateley et al., 2014). Such methods range from incrementally shifting the historical precipitation and air temperature time series to systematically explore plausible climate changes (e.g., ±5 and ±10 percent mean annual rainfall and +1, +2, +3℃ mean annual temperature) to applying climate shifts to stochastically generated new time series that reflect possible variability. Either way, the scenarios can be used with existing models to unveil the robustness or vulnerability of various designs to climate change.

With an understanding of the sensitivity of performance measures to key assumptions and a more rigorous approach to exploring effects of precipitation and temperature change in project evaluation, confidence in the ability of the selected restoration measures to provide the anticipated benefits will increase. Project managers could then select an alternative plan that reflects robustness to future climate uncertainty—thereby increasing the probability of project success. Further, the issue of robustness to future uncertainty can be extended beyond questions of climate uncertainty.

Lessons Learned for Future Coastal Planning

The approach to model alignment and the consideration of sea-level rise represents important steps forward in CERP planning for coastal projects. The committee appreciates the challenges that the modeling team faces in working with existing tools with limited time to make adjustments, as well as the complexities of predicting future change in coastal wetland and nearshore systems, especially one with complex surface-nearshore-groundwater interactions. However, key questions remain regarding the analysis as currently planned, which have implications both for the BBSEER project and for future coastal planning efforts under the CERP.

The committee is concerned that the current analysis could lead to misleading conclusions about the likelihood of project success under any of the alternatives, and therefore ill-informed restoration decisions. The benefits of including climate change in project planning could take many forms, such as the incorporation of project features that better accommodate extremes in runoff or project objectives that reflect an array of potentially desirable outcomes rather than a fixed target condition. Project plans could also include staged implementation that recognizes that features that provide benefit in the near term may need to be replaced by other features in future years. Climate change in South Florida will have a myriad of effects, including monotonic sea-level rise, temperature change, and the potential for increased variability and extremes of precipitation and temperature that will impact not only the surface-water budget but also the ecological dynamics of the system. Project alternatives could be impacted in different ways. For example, nearshore fishes may be influenced by changes in sea surface temperature, while sawgrass is more susceptible to salinity changes, which could be caused by salinity incursion from sea-level rise, rising soil salinity associated with extended drought, and/or more intense tropical storms. Considering only the effects of sea-level rise rather than its effects in combination with other climate-related stressors makes the project planning process vulnerable. Unless these interacting factors are explored in some way, the nature of that vulnerability remains unknown. Ignoring a known risk is problematic. Although the exact future conditions cannot be known, the potential for impacts can be explored.

Rather than redesigning an entire planning process that is already under way, a near-term solution may be to conduct parallel exploratory analyses of some of these potential climate impacts, using modeling tools available from the research community to assess the potential sensitivity of project outcomes to climate change factors, such as more variable rainfall and increasing air temperature and evapotranspiration. Such analyses could inform the planning process, for example by identifying which performance measures are most sensitive to climate change or the range of potential variability in performance metrics associated with climate changes.

The larger question is how to promote the development of a set of integrated predictive models for use in project planning that are broad enough to consider an array of climate change effects on systems dynamics, are nimble enough to enable exploration of a range of plausible conditions, and can show progressive changes over time. The current "pragmatic" approach is to introduce a model developed outside of the CERP, either in agencies or universities, into the project planning process when it can be approved for use in USACE planning and when it serves a need that no other existing model can support. Model development needs should be identified well before project planning starts to ensure the availability of the tools needed to fully support planning.

A dedicated focus on models that can more fully consider climate change effects, including the combined effects of climate stressors, will reduce the risks exemplified in the BBSEER planning discussed above and will ensure project planning can identify measures that will perform under an array of plausible future conditions. Such an initiative will take focused effort, time, financial support, and dedicated expertise. How and where these resources should be aligned is beyond the scope of the committee's charge, but the lack of such tools seems to be a major constraint on effective planning of the CERP for the future of the coastal ecosystem. Project planning will need to continue while such models are being developed—this statement is not a call for a delay. Rather, it is intended to emphasize the need for model development work to support future planning efforts to begin in parallel with ongoing planning. Otherwise, future project planning efforts, especially for the coastal ecosystem (e.g., the Southern Everglades project), will continue to be vulnerable to climate change effects.

MANAGING OPERATIONS

The effects of climate change on the frequency of more extreme conditions, especially a change in the number of dry days, has been described previously in this chapter. Although long-term planning requires thinking about decades into the future, system operation to achieve restoration goals must react to the conditions encountered in terms of runoff and the balance between reducing flood risk and providing water to people and the ecosystem. Here the committee explores the implications of climate change effects on temperature and precipitation on operations through the recent work on the LOSOM. Because this work is recent, the committee expects it to reflect current approaches to the consideration of climate change in inland operations.

Lake Okeechobee Systems Operating Manual

In 2022, the USACE released a draft environmental impact statement for LOSOM (USACE, 2022a) as an update to the 2007 Lake Okeechobee Regulation Schedule in response to the construction of additional CERP projects and rehabilitation of the Herbert Hoover Dike (see Chapter 3). Implementation of LOSOM is anticipated in 2023. LOSOM has an explicit goal to incorporate flexibility into Lake Okeechobee operations while balancing congressionally authorized project purposes. The development of LOSOM included analyses of numerous scenarios based on correlation matrices of performance metrics and use of multi-criteria decision analysis to identify an optimal balance to minimize impacts and/or maximize benefits to the lake itself, the connecting northern estuaries, the remnant Everglades, and water supply to the region. This was not a trivial task, and considerable effort was devoted to both the analyses and the synthesis of the results to better meet the competing demands of the South Florida ecosystem.

LOSOM was evaluated in accordance with USACE climate guidance. LOSOM was based on an analysis of scenarios using the climate record of the past 52 years (1965-2016). That the record was expanded to end in 2016 rather than 2005, and includes the 2006-2008 drought and Tropical Storm Isaac's rainfall in 2012, is a positive step, but the evaluation of how well the alternatives will perform still does not account for the possibility that conditions during the next 50 years will vastly differ from the past record. Indeed, most climate modelers expect the future climate to differ, possibly in unpredictable ways, from that of the past 50 years. In particular, it is surprising that the analysis did not use multiple and equally likely stochastically generated time series of precipitation. Doing so would enable more robust assessment of alternative operating plans over the range of possible weather and climate conditions that may be experienced in the future (e.g., Kwon et al., 2007, 2009). Furthermore, the stochastic time series can be coupled with plausible climate trends to create a set of scenarios that evaluates performance under both future climate variability and climate change (Brown et al., 2012; Steinschneider and Brown, 2013; Whateley et al., 2014). The USACE evaluated non-stationarity (Hirsch, 2011; Milly et al., 2008) with its non-stationarity detection tool, which enables assessment of whether and when the statistical characteristics of a hydrologic data series are not constant through time (USACE, 2022a). The non-stationarity detection tool was applied to a single site, Fisheating Creek, because of its long unregulated period of record, but with the caveat that this tool is not a substitute for engineering judgment. Based its established criteria, the USACE concluded that there was insufficient evidence to support the presence of non-stationarity. However, this conclusion does not rule out the possibility of non-stationarity in the future as the climate continues to evolve under the influence of increasing greenhouse gas concentrations.

The importance of examining climatic conditions that may extend beyond those that have been observed in the past cannot be overstated given the drastic effect of high and low water levels on the Lake Okeechobee ecosystem, as well as the other systems that are hydrologically connected to Lake Okeechobee. For example, stakeholders throughout South Florida have expressed serious concerns about Lake Okeechobee operations. In the northern estuaries, excess releases from Lake Okeechobee result in high nutrient loads and changes in salinity, leading to losses in the shellfish and pinfish communities; loss of *Vallisneria* (Doering et al., 2002), a key food source for the Florida manatee (Bengston, 1983); and proliferation of harmful algal blooms (NASEM, 2021; Phlips et al., 2020). Extreme water levels in the lake itself can lead to the loss of submerged aquatic vegetation and proliferation of invasive species (Havens et al., 2004). The effects of very low water levels due to drought (Steinman et al., 2002b) and very high water levels due to hurricanes (Havens et al., 2016; Kramer et al., 2018) on Lake Okeechobee and its connecting estuaries have been documented. Record water levels have been established in the past few decades, and because of concerns about changing climate and non-stationarity, there is no reason to expect climate conditions to stabilize. Hence, it is prudent to run models that include water levels that transcend past historical bounds.

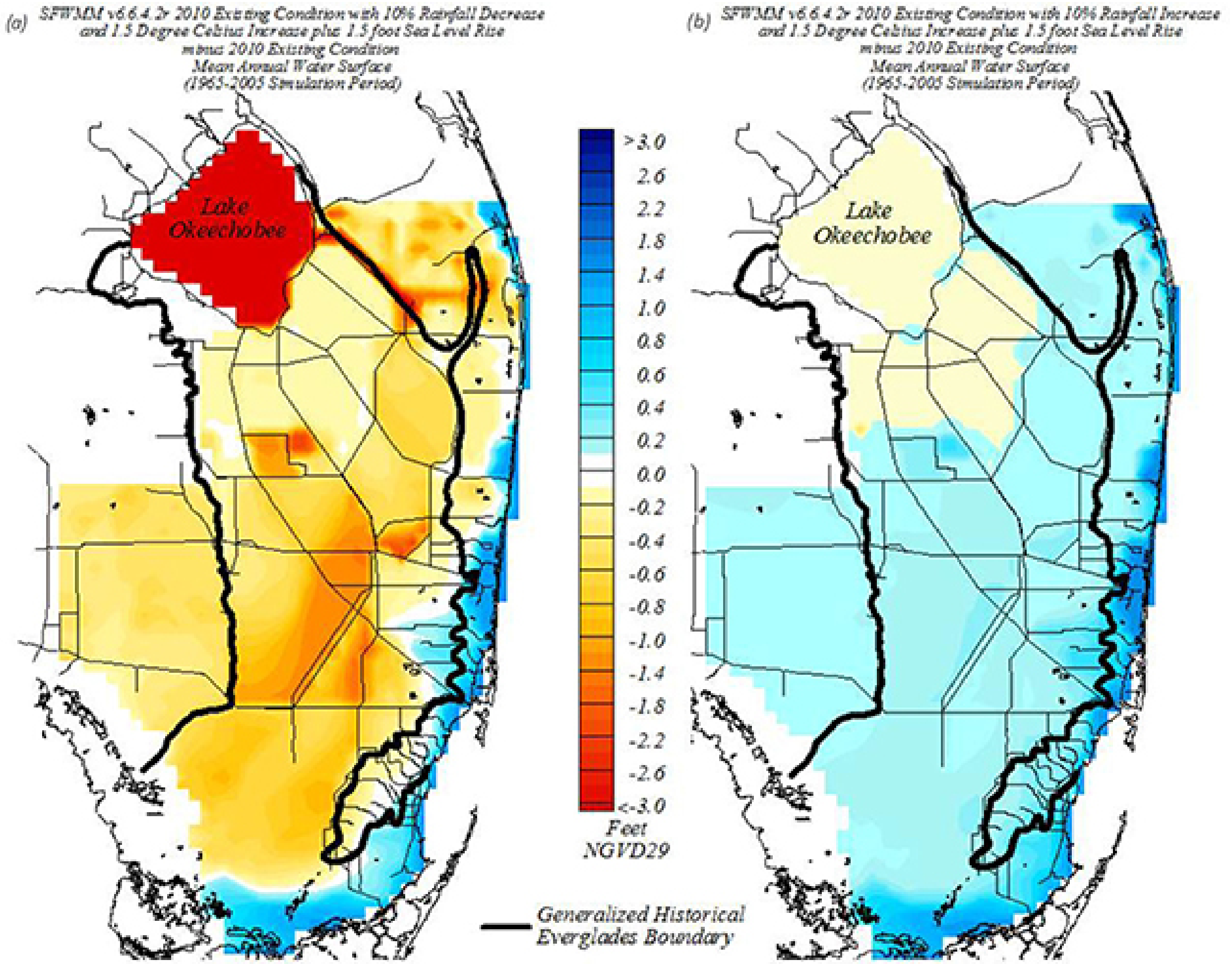

FIGURE 5-12 Differences in annual average water stage between scenarios of: a) a 10% decrease in average annual rainfall, and b) a 10% increase in average annual rainfall. Both scenarios include 1.5 ˚C temperature increase and 1.5 feet of sea-level rise and changes in rainfall were equally distributed across the year.
SOURCE: J. Obeysekera, SFWMD, personal communication, 2014.

Indeed, a set of future scenarios for year 2060 that were developed based on outputs from the South Florida Water Management Model (Obeysekera et al., 2015) examined potential impacts associated with changing rainfall (±10 percent) combined with increasing air temperature and evapotranspiration rates. Analyses of these scenarios show that mean outflows from the lake declined by 11 percent through evapotranspiration increases alone. Under the 10 percent decrease in rainfall scenario, outflows decreased by 26 percent and the median lake level decreased by approximately 4 feet (Figure 5-12). The scenario with a 10 percent increase in rainfall condition plus increasing evapotranspiration showed a 4.5 percent increase in outflows compared to the base scenario (Table 5-1) (Havens and Steinman, 2015).

Under the relatively modest change of a 10 percent reduction in future rainfall combined with increasing evapotranspiration, some elements of the water budget show dramatic changes, including a substantial reduction of inflows from the watershed north of Lake Okeechobee. The largest relative reduction of lake outflows was projected in regulatory releases to the northern estuaries and to the L-8 Basin for agricultural uses (Table 5-1). Another potentially significant impact is the reduction in environmental releases to the Caloosahatchee River, which may impact the health of *Vallisneria* beds, which require freshwater releases from the lake to maintain an optimal salinity regime (Doering et al., 1999; NASEM, 2021). In the scenario with 1.5℃ increase in air temperature and an associated increase in evapotranspiration with no difference in rainfall, surface elevations in Lake Okeechobee were projected to decrease to an elevation of 6.9 feet (2.1 m) NGVD29[7] or below for 20 percent of the simulation and to a minimum lake stage of 4.9 feet (1.5 m), exposing the littoral and nearshore zones, which support emergent and submerged vegetation respectively. Under this condition, the surface area of the lake is reduced to less than half of its full area (Figure 5-13). This scenario could result in a reduction in lake stage of more than 6 feet (2 m). When increased evapotranspiration is combined with reduced rainfall, the scenario predicted that the littoral and nearshore zones were dry 55 percent of the time compared to less than 4 percent in the base run with no change in temperature or precipitation (Havens and Steinman, 2015). Conversely, the modest 5 percent increase in outflows under the 10 percent increase in rainfall scenario has relatively small effects on outflows relative to the base condition (Table 5-1), because of offsets from greater evapotranspiration.

Although the committee recognizes the considerable uncertainty about long-term changes in climate and precipitation, this uncertainty should not preclude, and in fact elevates, the need for broad exploratory analysis to understand the possible implications of a changing and variable climate. These "what if" model runs could be used to consider a more expansive view of climate change variables. It is likely that LOSOM, with its expanded zone D that permits greater latitude in operational decision making, will accommodate changing climatic conditions when lake stage is between ~12 and 17 feet NGVD. However, the flexibility in zone D operations does not extend to the extremes that may occur with greater frequency in the future. It would be useful to project how frequent those extremes could occur in the future, which could increase understanding of the challenges associated with operating lake discharges during extended droughts or intense precipitation.

As stated in previous reports, uncertainty about the direction and magnitude of future climate is not an impediment to a comprehensive understanding of how the Everglades ecosystem responds to climate changes. This consideration applies to LOSOM as well. The use of large ensembles of climate simulations or, often more effectively, stochastically generated climate change scenarios facilitates the ability to sample and infer the system response to a wide range of possible changes. Indeed, this approach is an extension of the well-established methods of synthetic hydrologic simulations that are commonly used in engineering practice to evaluate the performance of designs in the face of new hydrologic variability. The USACE Institute for Water Resources has applied and contributed to the development of these methods (e.g., Mendoza et al., 2018; Poff et al., 2016; Spence and Brown, 2018). Restoration leaders would be well served by applying them to future revisions of the Lake Okeechobee operating schedule.

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[7] National Geodetic Vertical Datum of 1929.

TABLE 5-1 Comparison of the Mean Water Budgets for Lake Okeechobee (1965-2006) under Four Future Climate Scenarios

Water Budget Element	**Scenario**			
	Base Condition	+1.5℃	+ 1.5℃ /+10% Avg. Rainfall	+1.5℃ /-10% Avg. Rainfall
Inflows (ha-m/yr)				
Rainfall	197	198	217	178
Kissimmee River	128	99	133	**66**
Others	102	85	96	**70**
TOTAL INFLOW	427	382	446	**314**
Outflows (ha-m/yr)				
Evapotranspiration	252	258	268	241
St. Lucie (regulatory)	21	**8**	22	**1**
Caloosahatchee River (regulatory)	58	**26**	60	**6**
Caloosahatchee (environmental)	5	4	5	**1**
Water supply to EAA	33	34	35	25
Water supply to Lower East Coast Service Area	4	5	3	**6**
L8 agricultural demands	6	**4**	5	**2**
Others	46	41	46	**33**
TOTAL OUTFLOW	425	380	444	**315**

NOTE: The four scenarios included (1) base: a future condition that assumes no change in climatic conditions; (2) a future with an increase in air temperature of 1.5°C and associated evapotranspiration; (3) a future with an increase in air temperature of 1.5°C and associated evapotranspiration plus a 10 percent increase in average rainfall; and (4) a future with an increase in air temperature of 1.5°C and associated evapotranspiration and a 10 percent decrease in average rainfall. Numbers in bold indicate a >25% change from Base Scenario conditions.
SOURCE: Havens and Steinman, 2015.

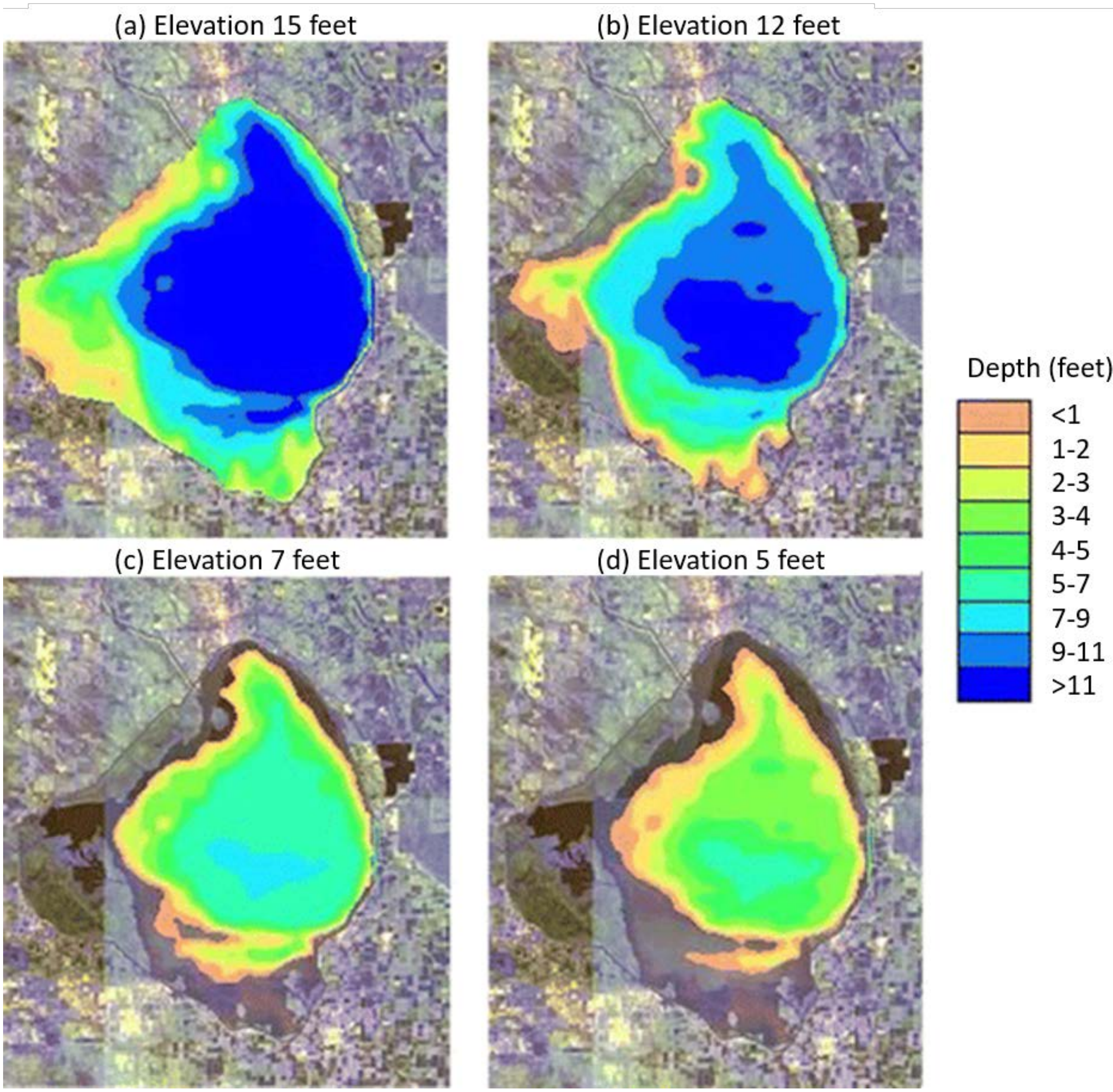

FIGURE 5-13 Water depths and spatial extent of Lake Okeechobee inside its levee at four different lake levels (surface elevations relative to NGVD29). Lake surface elevations of 12 feet (3.7 m) (b) to 15 feet (4.6 m) (a) fully hydrate the littoral marsh, and then allows it to dry out but leaves sufficient water in the nearshore zone for submerged aquatic vegetation to flourish. At 15 feet (4.6 m), the water surface extends to the edge of the levee, and at 12 feet (3.7 m), the nearshore zone and part of the littoral zone remain hydrated. At a lake surface elevation of 7 feet (2.1 m) (c), an elevation reached nearly 20 percent of the time in the -10% rainfall + evapotranspiration scenario, submergent vegetation is dry; and (d) at 5 feet (1.5 m), approximately the lowest elevation reached in that same scenario, large areas of emergent vegetation are dry.
SOURCE: Modified from Havens and Steinman, 2015.

Opportunities to Incorporate Climate Change in System Operations

The 2021 Integrated Delivery Schedule (USACE, 2021c) includes a schedule for the development of updates for the regional System Operating Manual. The System Operating Manual consists of seven volumes, organized according to geographical regions, that are designed to collectively provide a system-wide framework for the operation of components of the Central & Southern Florida Project and CERP projects to ensure that they function in a coordinated, systematic way. The Programmatic Regulations (33 CFR §385.3) call for the System Operating Manual to plan for flooding events to minimize the need for short-term deviations and establish a drought contingency plan. The System Operating Manual is considered the "critical last step in getting the water right and achieving system-wide benefits" (USACE, 2021c). The focus on the System Operating Manual, and associated Project Operating Manuals, reflects the pivot in the CERP from project planning to operations discussed in NASEM (2021). Work to update several volumes of the System Operating Manual is scheduled for completion by October 2025 (USACE, 2021c).

According to the Programmatic Regulations, the System Operating Manual should be revised whenever deemed necessary by the agencies to ensure that the goals and purposes of the CERP are achieved. This provision recognizes that changes can occur between project planning and operations of the final projects, because of changes not only in individual project features but also in other aspects of the system. Because CERP principles dictate the use of adaptive management based on the best available science, it is appropriate that the System Operating Manual be viewed as a vehicle to modify system operations based on evolving understanding of climate change and its effects to achieve CERP goals. For example, updates to the System Operating Manual may incorporate new knowledge of rainfall-runoff relationships and rising sea levels. Further, because the Project Operating Manuals are updated throughout the project life (Figure 5-14), they can incorporate new information that arises, for example, during engineering and design and during the operation, testing, and monitoring of project phases as they come on line. Project Operating Manuals can also be updated as understanding improves about climate change effects on the management of the South Florida ecosystem, including the influence of extreme events. The latter may be an especially useful way to incorporate new information on progressive change in the ecosystem due to climate change when there is an extended period between the end of project planning and project operation.

Periodic revisions to the System Operating Manual will ensure that an updated climate record, reflecting recent records of climate variability and trends (which may differ from the patterns shown in longer-term records), is used to operate the system and plan for droughts and floods. As more CERP projects are completed, updates to Project Operating Manuals may increase in frequency to capture the effects of project interactions, which will further consideration of climate trends and variability.

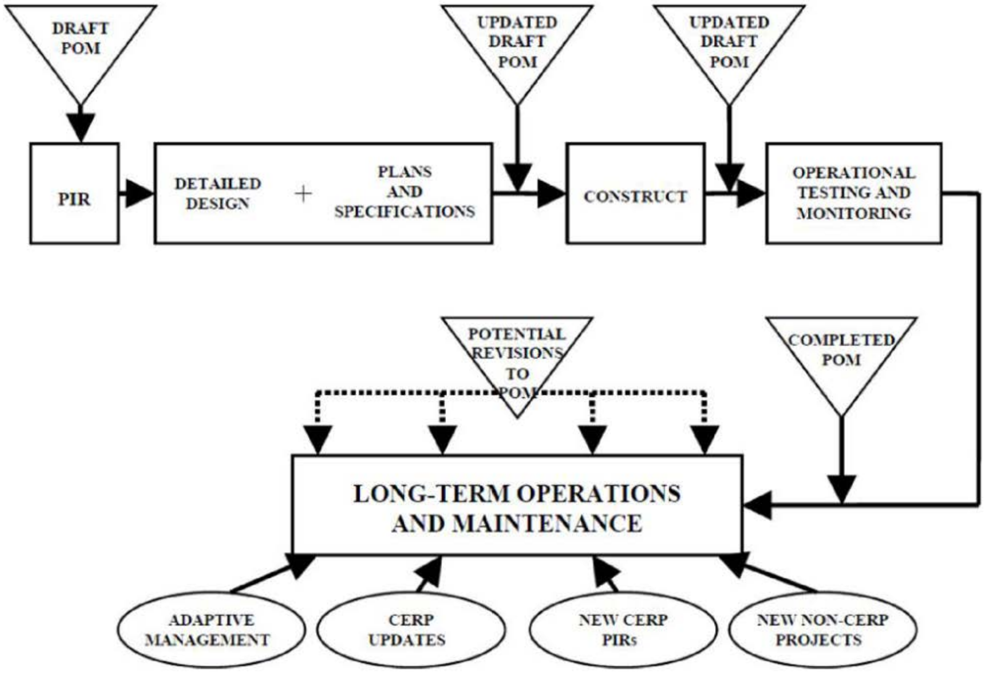

FIGURE 5-14. Evolution of the Project Operating Manual.
NOTE: POM= Project Operating Manual, PIR=project implementation report.
SOURCE: SFWMD, 2018a.

PROGRAM MANAGEMENT

NASEM (2018) called for a systemwide, program-level assessment of the resilience and robustness of the CERP to the changing conditions that will drive the Everglades of the future. The time and resources needed to move a project from planning through to construction and operation are extensive. Therefore, it is essential to consider the risk posed by climate change as early in the process as possible, at both the project and system scales, considering the long time scales of implementation relative to those of ongoing change. Identifying opportunities and risks at the program scale in the face of a changing climate can inform ways in which adaptive management or a change in project sequencing can be applied to better meet CERP goals. Further, a program-level analysis of climate change effects could help determine the need for additional actions beyond those envisaged in the Yellow Book (USACE and SFWMD, 1999).

A review of the 2021 draft Integrated Delivery Schedule (USACE, 2021c) shows the considerable progress that has been made on project planning. Of the 68 projects originally outlined in the Yellow Book, only 18 are still pending for project planning (13 of these are in the Greater Everglades). This pattern suggests that only a few project planning efforts remain, with the largest of these being the Southern Everglades project, although efforts are also under way to update the System Operating Manual, which could provide important opportunities for adaptive management at the system scale in the context of climate change. Understanding the systemwide outcomes of the CERP in the context of its original goals and the programmatic risks associated with climate change would improve the capacity to develop the System Operating Manual and plan these final projects.

The USACE has announced that it is moving forward with a Periodic CERP Update, as required by the Programmatic Regulations (33 CFR Part 385), although no timetable for its completion has been announced. The CERP Update will provide a vehicle for evaluating the ways in which current and planned projects will alter the system compared to original CERP expectations (USACE and SFWMD, 1999).[8] However, it remains unclear whether or how these analyses will consider climate change and examine the robustness of the proposed plan to future climate effects. The Committee reiterates its discussion of NASEM (2016): "Climate change has the potential for marked effects on the structure and functioning of the Everglades, increasing the need for CERP benefits that are robust in the face of climate change uncertainties or outcomes that help mitigate the effects of changing climate and sea level rise." The CERP Update will provide an important assessment of how and where restoration progress may be made with the current projects. but unless climate change is considered, the utility of those results for communicating the future state of the system will be limited, and an unrealistic view of future success could be presented. Now that such a large portion of the CERP has been planned, this is an opportune time to stress test the current program against selected climate change scenarios. CERP agencies will then have a solid foundation for considering the objectives, implementation schedules, and operating manuals of pending projects. In addition, CERP agencies can work with the Science Coordination Group and others to identify what additional projects may be needed, within or outside of the CERP, to ensure a sustainable ecosystem. If the CERP update does not include an analysis of climate change, additional system-level analyses should be conducted. These analyses are outlined in NASEM (2018).

RECOMMENDATIONS AND CONCLUSIONS

The one near certainty regarding Florida climate change is that temperature and sea level will continue to rise. Increases in sea level will alter the salinity and habitats in coastal and near coastal regions, and increases in air temperature will drive increases in evapotranspiration and decreases in runoff, unless compensatory changes in precipitation occur. However, changes in precipitation and resulting discharge will remain uncertain and highly variable during CERP planning and implementation. Progress is under way to increase the rigor in which sea-level–rise scenarios are considered in CERP project planning (e.g., coastal wetland and estuarine salinity changes), but analytical capabilities are limited by the tools presently available. In contrast, minimal progress is being made in the use of precipitation and temperature scenarios in project planning. No clear signal of the direction of change is not equivalent to an expectation of no change. The committee reviewed examples of how climate change is being incorporated into CERP planning and operations and offers the following conclusions and recommendations.

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[8] According to the Programmatic Regulations, "The periodic CERP updates will be accomplished by the Corps of Engineers and the South Florida Water Management District, in consultation with Tribes, Federal, State, and local agencies, to conduct an evaluation of the Plan using new or updated modeling that includes the latest scientific, technical, and planning information. The periodic CERP updates will provide a basis for determining if management actions are necessary to seek improvements in the Plan based upon new information resulting from changed or unforeseen circumstances, new scientific and technical information, new or updated modeling; information developed through the assessment principles contained in the Plan; and future authorized changes to the Plan." The periodic CERP update will also "determine the total quantity of water that is expected to be generated by implementation of the Plan, including the quantity needed for the natural system and human environment."

The USACE and SFWMD should proactively develop scenarios of future precipitation and temperature change, including changes in variability, and a strategy to use them to inform future project planning decisions and ensure more reliable project performance. USACE project planning efforts seek to identify justifiable solutions to current problems that will ensure performance for the next 50 years at minimum, and USACE policy requires that restoration planning must meaningfully consider climate change trends and potentially increasing climate variability. Past CERP evaluations of climate change effects have been inconsistent and often limited to a step increase in sea-level rise. Meaningful consideration of climate for restoration decision making would include selection of appropriate performance measures and focused analysis and assessment of risk using multiple plausible scenarios of the future. The impacts of changes in interannual variability could be examined based on the historical record (e.g., by using a Monte Carlo approach), which would provide valuable insight into potential project performance. Exploring the effects of trends in air temperature and precipitation—individually, in combination, and with sea-level rise—during the planning process will help ensure that projects that perform reliably under future change move forward. If appropriate, additional data collection and further analysis can be conducted in preconstruction engineering and design.

Existing modeling tools, although effective for many CERP-related purposes, constrain the ability to improve planning to consider the effects of sea-level rise and other climate change impacts. Current models have limited flexibility to incorporate alternative climate futures, especially those that reflect increased variability and non-stationarity. Such limitations introduce risks into the project planning process because projects may not perform as anticipated. The USACE and SFWMD should develop improved tools and analytical approaches that enable the examination of progressive change over time, rather than time slices of future conditions, to enable identification of environmental conditions when ecological thresholds are crossed. Examination of progressive change is especially important for the assessment of sea-level rise. Improved tools are needed to assess the project-related effects of various rates of sea-level rise and its interaction with hydrologic changes, and to examine sensitivity to the magnitude, frequency, and sequence of episodic events. In addition, hydrologic models should be able to readily accommodate a range of plausible future conditions that differ from historical conditions. Development of a modeling and analysis framework to plan for climate change in a system as complex as the Everglades will be a challenging endeavor but should be initiated as soon as possible to provide appropriate tools for future planning and evaluation efforts.

Inadequate consideration of water availability under future conditions and potential variations in the rate of sea-level rise could cause a project to move forward that is not viable under future climate change. The BBSEER planning process is a step in the right direction, especially in its novel consideration of resilience. However, it is constrained by the capacity of the models that support it. Climate change analysis should not be based on a single performance metric; rather, it should underlie all aspects of project planning, and all performance measures should be evaluated for outcomes under different climate conditions. BBSEER provides lessons to inform future CERP planning efforts. Planning should consider the effects of a range of plausible future conditions (precipitation and air temperature) on freshwater availability, including, for example, extended droughts or wet years, to understand the vulnerability of project outcomes to climate change and to avoid delays and additional costs as the project moves forward. Further, progressive change over time due to sea level rise should be considered, rather than just time slices, so that potential tipping points in habitat change can be identified and project alternatives adjusted as needed.

Each revision to LOSOM and the System Operating Manual should incorporate the latest information on climate change and variability to ensure anticipation of and planning for a wide range of conditions. Regular revisions to the System Operating Manual and other major operational plans, such as LOSOM or the Combined Operational Plan, provide an opportunity to incorporate evolving understanding of climate variability and change into Everglades restoration. Several recent major operational planning efforts, such as LOSOM, have proceeded based on analysis of a prior 52-year climate record, with limited assessment of potential changes in future air temperature or precipitation, providing an incomplete view of their performance under potential future conditions. Efforts to update these operational manuals should identify data collection and information needs to ensure the manuals reflect the current dynamics of the system and its variability.

Systemwide analysis of climate change on CERP performance is essential to assess the robustness of the restoration effort to possible futures and support program-level decision making. The work being conducted for the CERP Update provides a critical opportunity to examine the functionality of the system as a whole, but whether or how climate change analyses will be included in this work remains unclear. If not included as part of the CERP Update, additional analyses should be conducted outside of this process. These system-level climate change analyses will inform priorities for the remaining unplanned CERP projects and adjustments to system operations and will illuminate potential restoration actions that may be needed to enhance ecosystem resilience, either within or outside the CERP.

The lack of USACE guidance on the use of accepted information related to changes in precipitation and air temperature in quantitative analysis as part of project planning leads to future vulnerabilities to climate change and variability as CERP projects come on line. The science of global climate change is mature and rigorous and many other water resources planning projects, in the United States and globally, routinely use climate change scenarios to examine project performance under a range of future conditions. The USACE has progressively advanced guidance on the consideration of sea-level change in its activities, but the success of the CERP also relies on understanding the effects of other climate change impacts. To reduce future vulnerabilities, the committee urges the USACE to develop guidance on the use of climate-affected hydrology data for Civil Works studies discussed in the USACE Climate Action Plan, which was anticipated in 2021. This guidance is critical to support Action 1 of the USACE Climate Action Plan to "[e]nsure that new USACE-built projects are built to last and perform reliably for their intended design lives, despite uncertainty about future climatic conditions." Providing the USACE Districts with the tools and guidance needed to effectively plan for future conditions is an urgent priority. The lack of guidance on the use of quantitative approaches to consider climate change and variability in hydrologic analyses fundamentally limits the potential success of CERP investments in ecosystem restoration.