Appendix 2-3: Consideration of Long-Term Climatic Variability in Regional Modeling for SFWMD Planning & Operations

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South Florida Water Management District

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EXECUTIVE SUMMARY

The South Florida Water Management District (SFWMD or District) is an agency of the state of Florida whose mission is to manage and protect water resources of the region by balancing and improving water quality, flood control, natural systems, and water supply. Planning of future facilities and their operations is a critical District function and for such efforts, regional-scale computer models are frequently used. A primary public concern is whether the SFWMD appropriately addresses future water management needs in computer modeling for both planning and operations. Long-term climatic variability due to natural causes and climate change due to anthropogenic causes are clearly important for planning of facilities and their operations.

During the past decade, the District initiated several investigative studies on the causes of climatic variability in southern Florida. In addition, methods have been developed to successfully incorporate climatic variability and climate outlooks into the water resource and operational planning (planning) modes of the central and southern Florida flood control system for today and into the future.

Regional climatic variability is the result of land/ocean/atmospheric processes interacting at various spatial (regional to global) and temporal (inter-annual to multidecadal) time scales. The correlation of atmospheric variables around the globe to the equatorial Pacific sea surface temperatures (SST) and atmospheric anomalies is one of the most well recognized teleconnections, known as El Niño-Southern Oscillation (ENSO). Teleconnections are statistically significant correlations between meteorologic variables in various places of the world. Two additional teleconnections recently identified as influencing climatic variability in South Florida include the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). The AMO and PDO can be recognized by SST anomalies in the north Atlantic and north Pacific oceans, respectively. All three of these oscillations are quasi-periodic, with varying periods and irregular amplitudes. This makes the prediction of a phase change of any of the three in advance very difficult. ENSO has a periodicity that ranges between 3 and 7 years, while the AMO and the PDO have periodicities that range between 10 to 60 and 5 to 20 years, respectively. Significant investment worldwide has been devoted to predicting the evolution of ENSO and its impacts on global climate. Still there is large uncertainty associated with the numerous statistical and dynamic models designed to predict the phase of the ENSO phenomenon.

This report presents an overview of the first three climate phenomena, to illustrate their influence on South Florida regional climatic conditions. Particular emphasis is placed on AMO, which has figured heavily in recent discussions regarding Lake Okeechobee operations and planning for the Comprehensive Everglades Restoration Plan (CERP). Along with analyses of period-of-record trends for both rainfall and Lake Okeechobee net inflow data, this report discusses the method for incorporating climatic variability into planning decisions. The South Florida Water Management Model (SFWMM), which has undergone multiple peer reviews to confirm its technical credibility, is the primary tool used for system simulation, planning, and performance forecasting. This model was also used for analysis of future projects proposed for CERP and for the development of regional water supply plans.

Currently, climatic variability and meteorological conditions that occurred during the 1965–2000 period are used to test various infrastructure or operational alternatives. The majority of this period represents an AMO cool phase that was in place from 1970 to 1994. Approximately 11 of the 36 years in this period (1965–1969 and 1995–2000) represent conditions from AMO warm phases, that include wet (having above-average seasonal rainfall) and some extreme dry events. Statistical analysis of the data from the 1965–2000 period indicates that the wet periods used in the model are similar to wet periods that may occur during a typical AMO warm phase.

The conclusion is that the historical period provides appropriate and reasonable estimates of the ranges of climatic conditions that are likely to occur in coming years.

The report recommends the continuing expansion of the period of simulation used in computer modeling, and a feasibility investigation for using historical data prior to 1965 and possibly synthetic rainfall data for evaluation of plan under a longer period of AMO warm phase. Future work should also include a more refined analysis of rainfall-runoff relationships in the Kissimmee Basin in order to separate those trends due to climatic variability from the effects of upper and lower basin water management. Adaptive management, already a cornerstone of CERP implementation, should be continued for re-evaluating facility plans and future operations as new data becomes available.

I. INTRODUCTION

BACKGROUND

The South Florida Water Management District (SFWMD or District) is an agency of the state of Florida that has primary responsibility for management of water resources in a 16-county region that extends from just south of Orlando to Florida Bay. Climate change and variability have been driving forces behind the growth and evolution of the District since its formation in 1949. The agency was created as the Central and Southern Florida Flood Control District, in response to massive flooding that occurred due to a 1948 hurricane, with the primary purpose to safely manage and dispose of excess floodwaters. The District was also the local sponsor for the federal Central and South Florida Project, developed by the U.S. Army Corps of Engineers (USACE). In 1968, this project was revised for greater emphasis on the development and enhancement of water supplies for public and agricultural uses. In response to this new definition of the project and widespread regional droughts that occurred in the 1950s, 1960s, and early 1970s, the District was renamed in 1973 by the Florida Legislature as the SFWMD and given an additional assignment to provide for environmental protection.

The agency's mission today is to manage and protect water resources of the region by balancing and improving water quality, flood control, natural systems, and water supply. To accomplish this mission, the District has broad authority and responsibility to operate and maintain a regional system of nearly 2,000 miles of canals and levees, 546 water control structures, and 51 pump stations; to conduct planning studies to assess present and future environmental, water supply and flood control needs; and to regulate water use and surface water management.

A major, relatively new initiative of the SFWMD, in cooperation with the USACE, U.S. Department of the Interior, other state and federal agencies, and local interests, is the ongoing effort to restore the Everglades ecosystem. Planning for this long-term restoration effort began in 1995 and resulted in development of the Comprehensive Everglades Restoration Plan (CERP) (USACE and SFWMD, 1999). The plan is designed to meet water management and environmental needs over the next 50 years and is expected to require more than 20 years to complete construction of facilities at an estimated cost of more than $8 billion. Since 1999, the District and USACE have conducted additional studies to develop details of this plan and initiate design and construction of project facilities to capture, store, and redistribute excess surface water to meet future needs. Early in the CERP planning process, it was recognized that long-term climatic variability due to natural or anthropogenic causes could cause significant changes to South Florida's hydrology across the 50-year lifetime of this program. Consequently, an effort was undertaken to assess the importance, impacts, and potential implications of climatic variability. The status of climate studies and research needed to address these critical issues were summarized in a District report in 1996 (SFWMD). Many of these issues and approaches remain relevant today.

Planning for the future is a critical District function. To conduct such analyses, the SFWMD uses state-of-the-art communications and engineering technology, combined with technical expertise in a wide range of scientific disciplines. Analysis of alternative planning and operations scenarios and planning for future conditions depends heavily on the collection of data concerning current and past conditions in the region and the use of computer-based simulation models to represent existing and potential future land use, population, environmental conditions, and alternative management scenarios.

The South Florida Water Management Model (SFWMM), a primary tool used to conduct these analyses, is a regional-scale computer model that simulates the hydrology and the management of the water resources system from Lake Okeechobee to Florida Bay. It covers an area of 7,600 square miles using a mesh of cells, each measuring 2 miles square; for this reason, the model is sometimes referred to as the “2x2 model.” The model simulates inflows from Kissimmee River, runoff and demands in the Caloosahatchee River and St. Lucie Canal basins, and major components of the hydrologic cycle in South Florida, including rainfall, evapotranspiration, infiltration, overland and groundwater flow, canal flow, canal-groundwater seepage, levee seepage, and groundwater pumping. It incorporates current or proposed water management control structures and current or proposed operational rules.

As a planning tool, the SFWMM can be used to predict the response of the water control system to climatic conditions and proposed changes in hydraulic infrastructure and/or operating rules. The model design takes into consideration distinct hydrologic and geologic features of subtropical South Florida, which include (1) the strong interaction between canals and the highly permeable surficial aquifer, especially in the eastern portion of the region and (2) the effects of rainfall, evapotranspiration, overland flow, and groundwater movement within the Water Conservation Areas (WCAs) and Everglades National Park (ENP). The SFWMM integrates hydrologic processes with the hydraulic infrastructure and associated policy-based rules and guidelines related to water management in South Florida. To develop CERP, the District used the SFWMM with historical environmental, land use, and hydrologic data along with the technical expertise of numerous scientists and engineers, to evaluate appropriate initial design features for regional facilities and operations.

CLIMATIC VARIABILITY AND CLIMATE CHANGE

Climate in any region is the result of both short- and long-term phenomena interacting at local, regional, and global scales. A weather anomaly that persists for extended periods is recognized as a climate shift or as long-term climatic variability. If the climate shift is likely to persist to the foreseeable future and is due to anthropogenic causes, it is defined here as a climate change. Reasons for climate patterns, shifts, and changes are not completely understood, therefore, significant uncertainties are associated with forecasting conditions.

The ongoing controversy over global warming underscores the challenge in distinguishing threshold points at which climate fluctuations become shifts or changes. Once a longer-term trend is established, the challenge is to determine whether the trend is due to effects of natural climatic variability, various thermal cycles in the oceans and atmosphere, variations in solar flux, changes in atmospheric chemical composition due to human activities, or a combination of factors. Therefore, the relative influence of anthropogenic and natural factors on global weather patterns remains a highly debated topic.

Not only are the causes of global warming uncertain, but also the effects. Increased thermal energy in the oceans and atmosphere does not necessarily lead to increased temperatures across the globe, or to increased rainfall in South Florida. In fact, some recent studies suggest that the increase in energy due to global warming may cause more extreme temperature fluctuations, more severe droughts, and increased storm activity. Wet regions of the earth could become much drier and dry regions could become much wetter. In view of the current uncertain state of science, this paper does not address the topic of climate change. However, the SFWMD has conducted sensitivity analysis of its plans through computer modeling for such climate change scenarios and sea-level rise and increased rainfall due to global warming.

Climate anomalies observed in South Florida during recent years may represent some combination of effects due to natural climatic variability and long-term shifts, and possibly an overall global warming trend, perhaps modified to some degree by effects of human activities. Small shifts in weather patterns can change the net rainfall (rainfall minus evapotranspiration) from a surplus to a deficit or vice versa without being noticed. However, if these weather patterns persist over the region for an extended period, they can produce significant excesses or deficits that water managers must deal with prudently. Decisions are typically based on minimizing impacts and/or maximizing benefits to natural systems, water supplies, and flood protection.

During the 1970s and 1980s, little was understood about global climatic variability or how to apply relevant data to water resource planning or systems operation. At that time, engineers and scientists at the SFWMD were trying to comprehend a climate shift that occurred throughout South Florida during the late 1960s (Shih, 1983). The cause of the shift was highly debated. Most scientists hypothesized that increased drainage and development or accumulation of greenhouse gases and global warming were the principal factors. Information now suggests that the climate shift in the late 1960s was associated with a phase change of the AMO (Trimble et al., 1998b; Enfield et al., 2001). Since that time, the District has been actively involved in conducting and supporting research and developing new technologies to incorporate of global, regional, and local climate factors into District planning and operations. The District has conducted multidecadal programs to implement some of these research findings and improve predictive capabilities and the efficiency of South Florida's complex water management systems. Many of these efforts are described in this report.

CURRENT MANAGEMENT ISSUES AND CONCERNS

A primary public concern is whether the SFWMD has appropriately addressed future water management needs in its operations, planning, and design efforts. Has the District has considered long-term climate variability, especially rainfall, in its planning and operations of future water management facilities, such as those associated with CERP? Most of the proposed CERP projects are evaluated based on model simulations that use a 36-year period (1965–2000) of rainfall, hydrologic and water management records. Recent data indicate that climatic conditions may be shifting in response to warmer North Atlantic sea surface temperatures that tend to produce greater annual rainfall in central and southern Florida, and greater variability in annual rainfall. This phenomenon, characterized by the AMO index, is long-term in nature, possibly lasting for multiple decades.

The effects of increased rainfall are nonlinear, that is, as the rainfall rate increases, soils become saturated, and storage facilities reach capacity, the proportion that becomes surface water runoff tends to increase rapidly. These conditions create a correspondingly greater need for additional water storage and/or disposal options during extended periods of high rainfall. This issue is of special concern for Lake Okeechobee, which is the largest natural reservoir for long-term water storage. During the past several years, the Lake has experienced consistently high water levels and levels of turbidity due to above-normal rainfall and several major hurricanes. These persistent high water and adverse water quality conditions have severely damaged Lake fisheries and littoral zone vegetation. Water managers were compelled to discharge large amounts of water to major outlets through the Caloosahatchee and St. Lucie rivers in 2004 and 2005, resulting in significant damage to downstream coastal and estuarine resources. Naturally, a climatic regime characterized by above normal rainfall and consequently runoff from tributary watersheds is a concern for management of the water resources system in South Florida.

Based on these considerations, several key questions concerning how SFWMD has dealt with long-term climatic variability in planning and operations were defined as follows:

1. Has the District adequately addressed the long-term wet and dry periods in modeling for (a) facility planning and (b) operational planning?
2. Is there compelling evidence that the volume of inflows to Lake Okeechobee will be as much as double during a wetter regime as they were in the dry regime?
3. In the current modeling efforts, has the District adequately addressed the variability of inflows into Lake Okeechobee?
4. Does the modeling approach used by the District for both CERP and the Water Supply and Environment (WSE) schedule design meet requirements of standard engineering and design practices?
5. Are the steps being taken in the adaptive management/modeling approach used by the District adequate to address the uncertainties in climate predictions and to assimilate new information?
6. Except for basic research approaches, are there other facility planning options that the District should consider to address the possibility of a continued wetter regime of the climate cycle?
7. Are the data and models used by the District appropriate (reasonable and adequate) for their intended applications?

The above questions were the basis of questions posed to a group of five independent peer reviewers who assessed them using an June 2006 version of this paper. The paper and the peer review reports are available at the District web site (www.sfwmd.gov), under the *Weather and Water Conditions, Long-Term Forecasts* section.

PURPOSE AND SCOPE

The purpose of this document is to describe climatic indicators that are likely to affect South Florida rainfall, the uncertainty associated with predicting the climatic variability, and the data available for modeling long-term hydrologic conditions and changes in South Florida, and apply this information to address key questions listed in the previous section. Detailed analyses of the trends in the long-term datasets on rainfall and net inflows to Lake Okeechobee are also presented, along with comparisons to those used in regional modeling. The long-term datasets were analyzed to determine whether the modeling dataset adequately represents climatic variability that is likely to occur during coming years. The use of climate outlooks based on known teleconnections for operational planning is also discussed. The document concludes with a set of recommendations for improving the current approaches to addressing long-term climate variability in planning and operations.

It is emphasized that this document focuses on long-term climate variability rather than climate change due to such causes as global warming. This focus reflects the recent emphasis on long-term climate shifts due to natural causes such as AMO and the lack of clear patterns and the considerable uncertainties concerning scientific understanding of climate changes that may be due to anthropogenic causes.

II. RELEVANT CLIMATIC INDICATORS

Teleconnections are statistical correlations between persistent shifts of atmospheric variables occurring in widely separated parts of the world. These statistical correlations generally result from shifts in atmospheric and ocean circulations. Of numerous teleconnections that have been investigated by the District, three are recognized to have significant impact on the regional climatic variability in South Florida. They are (1) the El Niño/Southern Oscillation (ENSO), (2) the Atlantic Multidecadal Oscillation (AMO), and (3) the Pacific Decadal Oscillation (PDO). These climatic indicators seem to be related to total annual or seasonal rainfall and hydrologic conditions across the South Florida region and within particular basins **(Figure 1)**.

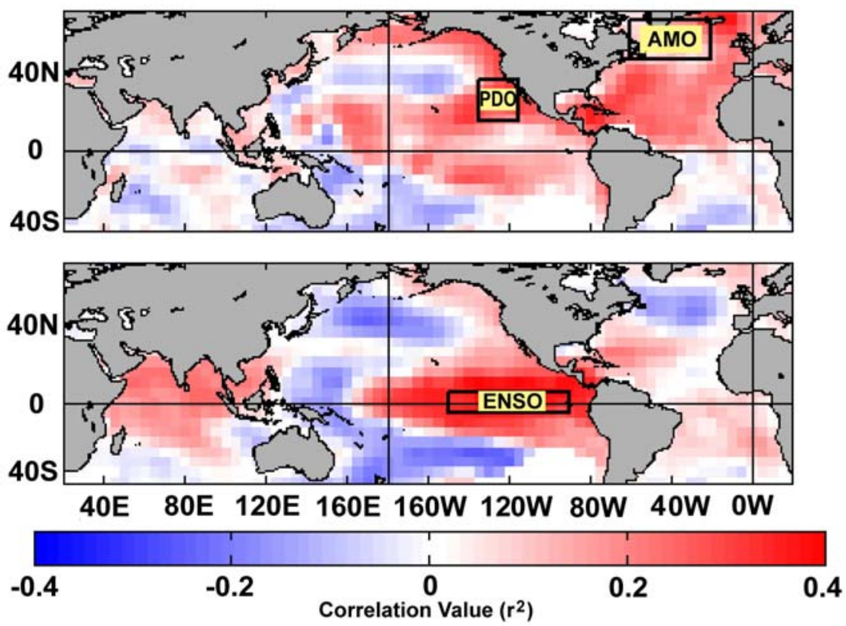


Figure 1. Geographical locations of AMO, PDO, and ENSO teleconnections related to climate in South Florida. The map shows the correlation (red for positive and blue for negative) between global monthly sea surface temperature (SST) anomalies and the Florida Climate Division 4 monthly precipitation. (Figure adapted from Mestas-Nunez and Enfield, 2003.)

EL NIÑO/SOUTHERN OSCILLATION

The ENSO is a slow oscillation in which the atmosphere and ocean in the tropical Pacific region interact to produce a slow, irregular variation between two extremes. The National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center and other El Niño web pages confirm that ENSO is a major source of interannual climatic variability in South Florida. (See http://www.cdc.noaa.gov/ENSO/enso.description.html and http://www.elnino.noaa.gov/.)

ENSO variations are more commonly known as El Niño (the warm phase) and La Niña (the cool phase). Although ENSO is centered in the tropics, the changes associated with El Niño and La Niña events affect climate around the world. ENSO events tend to form between April and June and typically reach full strength in December. During El Niño events, South Florida tends to experience above-normal rainfall during the winter (dry season) months, whereas dry-season rainfall tends be below normal during La Niña.

District research indicates that ENSO and other climate indices have significant potential to predict net inflow volumes into Lake Okeechobee (Trimble et al., 1998b). ENSO events typically have a three- to seven-year period and their climatic effects are more pronounced during the winter months than during the wet-season summer months. In recent years, artificial neural network (ANN) models have been employed by the District to help predict net inflow volumes into Lake Okeechobee using ENSO and other climatic indices (Zhang and Trimble, 1996; Trimble et al., 1998a,b; Trimble and Trimble, 1998). Using these techniques, scientists have gained a greater understanding of how ENSO and other factors affect South Florida weather and hydrology.

ATLANTIC MULTIDECADAL OSCILLATION

The AMO (http://www.aoml.noaa.gov/phod/amo_faq.php) is a long-range climatic oscillation that causes periodic changes in the surface temperature of the Atlantic Ocean, between the equator and Greenland, which may persist for several years or decades. AMO describes temperature deviations in the ocean surface that appear to be driving shifts ("warm" and "cool" phases) in South Florida's climate (Enfield et al., 2001). There are significant year-to-year fluctuations in the instrumental records of ocean temperature (**Figure 2**), but no clear indications of the exact years when AMO switches from a warm to cool phase. The transition between phases is generally determined by tracking a multi-year average (**Figure 2**).

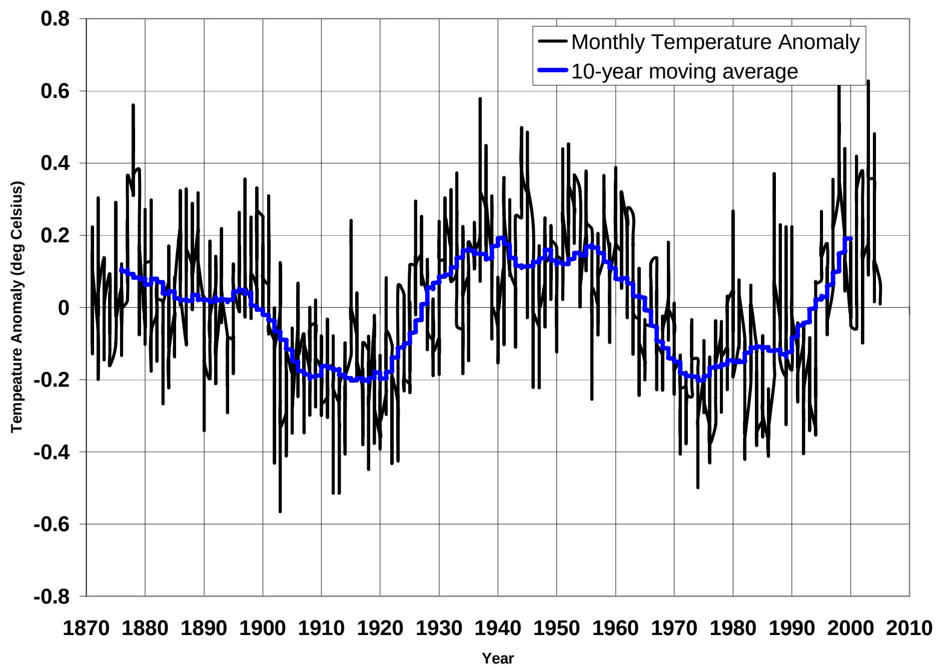


Figure 2. Interannual variability of detrended, monthly sea surface temperature anomalies (degrees Celsius) and the AMO index. Derived from a 10-year moving average.

During the twentieth century, the 1900–1925 period seems to have been dominated by a cool phase of the AMO, followed by a warm phase (1926–1969) and another cool phase (1970–1994). Since approximately 1995, the AMO index has been increasing. Although the exact years of warm and cool phases of AMO are difficult to identify and vary among researchers, the general conclusion drawn from the differing periods remain the same and is not critically important for ensuing discussions. Accordingly, the following four periods were used for this analysis:

AMO1 (cool)	1895–1925
AMO2 (warm)	1926–1969
AMO3 (cool)	1970–1994
AMO4 (warm)	1995–2005

The magnitude and duration of the current warm phase cannot be predicted solely based on historical trends, although Enfield and Cid-Serrano (2006) recently made some probabilistic predictions of when the current warm period might end. There is no overwhelming evidence to suggest that rainfall conditions during this warm phase will differ significantly from conditions experienced during the 1926–1969 warm phase. The duration and magnitude of the warm phase are major uncertainties that affect facility planning for such major programs as CERP.

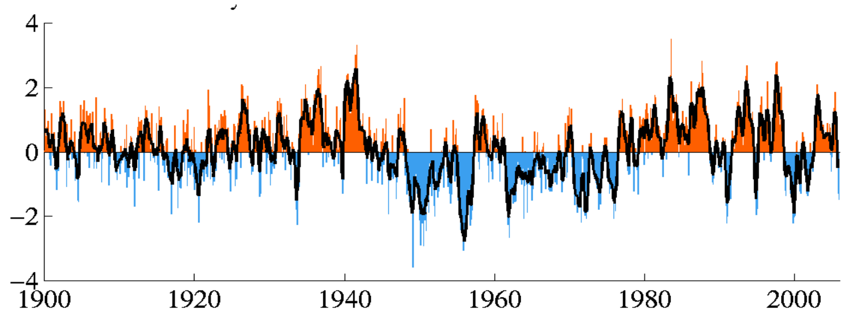
PACIFIC DECADAL OSCILLATION

The PDO (http://jisao.washington.edu/pdo/) is a pattern of Pacific climatic variability that somewhat resembles El Niño (**Figure 3 Panel A**). While the two climatic oscillations have similar spatial climate "fingerprints," they have very different behavior in time. Two main characteristics distinguish PDO from ENSO: (1) PDO events during the twentieth century have persisted for 20 to 30 years, while typical ENSO events last for only a few years, and (2) the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics. The opposite effects occur for ENSO.

Several independent studies find evidence for just two full PDO periods since the start of the twentieth century: PDO cool regimes prevailed from 1947 to 1976 and briefly during the latter half of 1999 through mid-2002, while warm regimes dominated from 1925 to 1946, from 1977 through 1998, and from late 2002 until the present. Several other shorter periods occurred within the longer ones, for example, the 1958–1961 warm phase and the 1988–1991 cool phase. Variations in South Florida rainfall data during the longer periods reflect these shorter episodes.

The PDO affects the South Florida climate much like El Niño except that the frequency of the oscillation is on decadal and multidecadal scales instead of the three to seven years of El Niño. Thus, during the warm phase of the PDO, South Florida tends to experience above-normal rainfall during the dry season (**Figure 3 Panel B**).

A Monthly Values for the PDO index: 1900–November 2005.



B Correlation of November–April precipitation with November–April PDO 1948–2004.

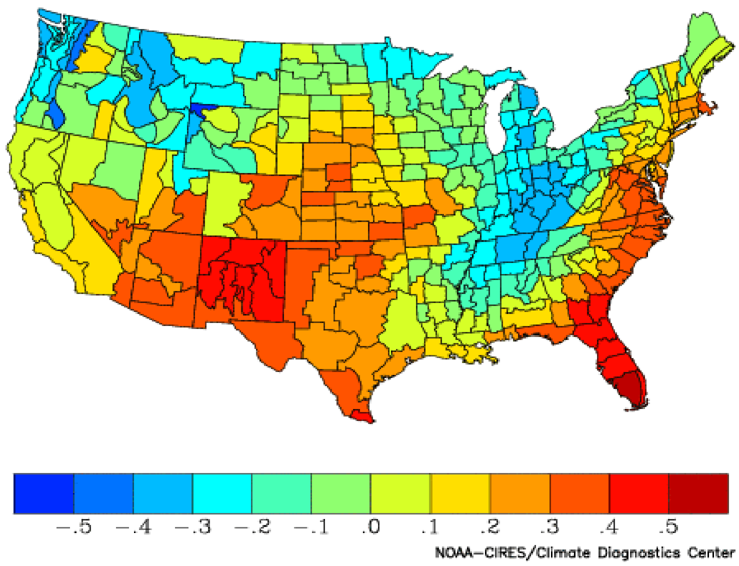


Figure 3. (A) PDO computed as the leading principal component of the monthly North Atlantic sea surface temperature anomalies. **(B)** Correlation map of U.S. precipitation to PDO shows that South Florida has a very high correlation between rainfall and PDO index during the dry-season months (November–April).

AMO AND SOUTH FLORIDA'S CLIMATE

The relationship between AMO cycles and rainfall patterns in South Florida is not well defined. **Figure 4** shows the historical time series of District-wide annual rainfall patterns and the forecast volumes of Lake Okeechobee Net Inflow (LONIN) plotted as a deviation from their overall statistical means. The variable LONIN is defined here as rainfall (RF) minus evapotranspiration (ET) plus inflows. It was computed using the continuity equation as LONIN = DS + Outflows, where DS represents Delta (change in) storage. Although no dramatic trends appear from these graphs, there are clearly periods of below- and above-normal rainfall and LONIN throughout the historical record. In particular, the wetter periods of 1940s, 1950s, and the years since 1995, can be identified from the rainfall pattern. These years generally correspond to the AMO warm phases. The LONIN shows similar patterns, and is further influenced by the nonlinear relationship between rainfall and runoff, the effect of antecedent conditions, and water management in the tributary basins of Lake Okeechobee. These influences will be discussed later in this paper.

Another way to identify trends in long-term data records is to inspect cumulative deviations from the statistical mean (**Figure 5**). The AMO1–AMO4 periods defined above correspond reasonably well with the increasing or decreasing trends of the cumulative deviations, which generally correspond to the below-normal or above-normal periods of the rainfall and/or LONIN time series, respectively.

PREDICTABILITY OF AMO

There is no known basis at present to estimate the exact duration, magnitude or return frequency of AMO phases. The short record of instrumental ocean temperature data show that the average length of the cycle is approximately 60 years, but individual cycles may vary considerably. As shown in **Figure 6**, a 450-year history of the AMO index was recently reconstructed using tree data (Gray et al., 2004). The average length of a warm phase during this period was about 34 years, but individual phases ranged from as short as 11 years to as long as 60 years. Similarly, cool phases averaged 21 years in length and ranged from 6 to 61 years (Enfield and Cid-Serrano, 2006). It is clear from this data that the exact length, and for that matter the strength of a warm or cool episode of AMO, may be extremely difficult to predict, while it is not clear whether the current warm phase will last as long as the last one (approximately 1926–1969).

Even during a warm phase of the AMO, multi-year droughts can occur in South Florida, associated with La Niña conditions or other phenomena. This was clearly demonstrated by occurrence of the most severe drought on record in 2000–2001, a year that was fully within the latest AMO warm phase. Multi-year drought periods occurred during each decade of the previous warm phase (1920s–1960s).

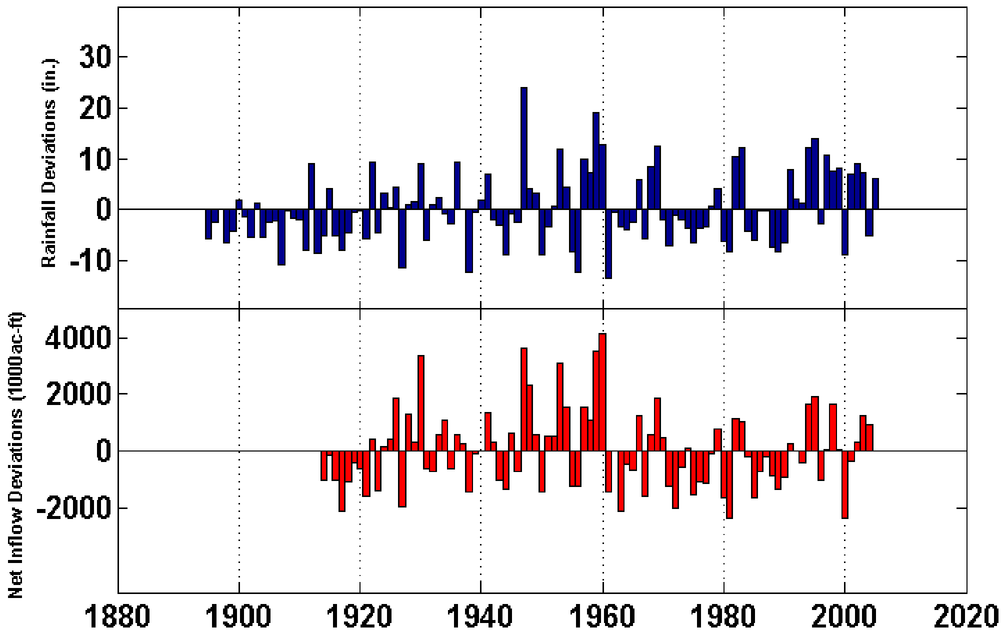


Figure 4. District-wide long-term rainfall patterns (top panel) and the Lake Okeechobee Net Inflow (LONIN) values plotted as deviations from the individual statistical means.

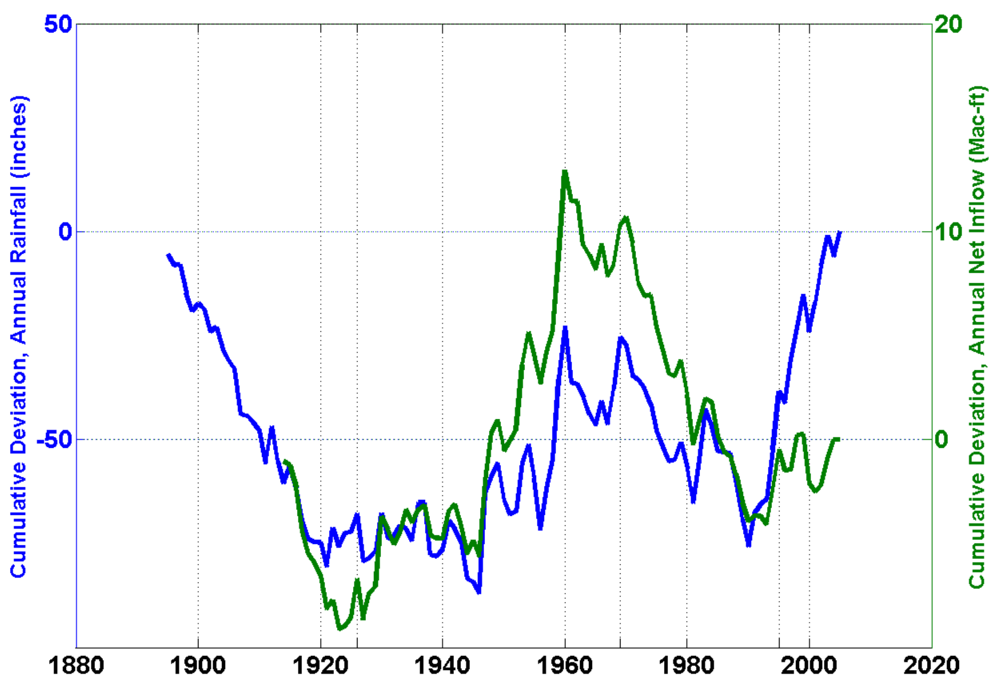


Figure 5. Cumulative deviation from the overall mean for district-wide rainfall and LONIN time series.

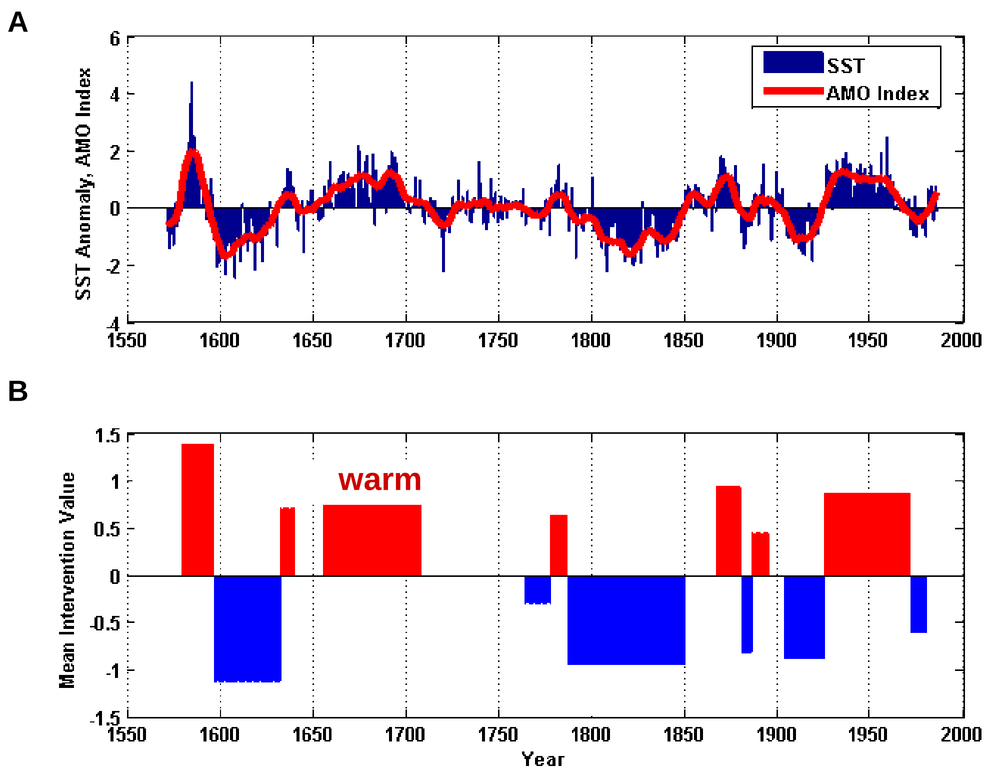


Figure 6. (A) Reconstructed values of North Atlantic Sea Surface Temperature (SST) anomalies (computed as the deviation from the mean in units of standard deviations, plotted as bars) using tree-ring technology and corresponding AMO index (10-year moving average plotted as a solid line). **(B)** Durations of significant warm (red) and cool (blue) AMO regimes identified from data in panel (A). (Data from Gray et al., 2004).

INTERACTING EFFECTS OF TELECONNECTIONS

Climatic variability and change are the result of complex and nonlinear interactions among a number of determining forces. Therefore, a single indicator cannot typically be used to represent the entire coupled oceanic-atmospheric weather generating system. For example, if varying ocean phases drive atmospheric circulation, then the response of the atmosphere may be delayed by a few years after an ocean phase indicator such as the AMO crosses a specific threshold. AMO sea surface temperatures may vary according to a sinusoidal wave pattern, while the atmospheric response follows a delayed-step function that is not immediately apparent when the AMO ocean index goes from negative to positive. For tropical weather and Florida hydrology, this seems to be the case. Similar delays also occur in the response of the atmosphere to El Niño events (Barnston et al., 1999). This delay in response to global-scale changes adds to the uncertainty in predictions.

The complexity underlying climatic indicators necessitates caution before using such information to make short- or long-range water management decisions. Finally, seemingly minor changes in spatial and temporal patterns of rainfall distribution may produce dramatic changes in hydrologic variables such as runoff.

Since there are at least three significant climatic indicators of importance for South Florida, it is important to understand and account for interacting effects of these teleconnections. As a part of the District's climate research program, Mestas-Nunez and Enfield (2003) made an exhaustive investigation of intra-seasonal to multidecadal variability in South Florida rainfall. From this analysis they concluded that the ENSO association with South Florida precipitation varies depending on the different phases (warm and cool) of AMO and PDO. For example, **Table 1** shows contingency tables of February–April rainfall and ENSO for AMO cool and warm phases, indicating how ENSO–rainfall relationships change depending on the AMO phase. For example, there is a 35 percent chance that February–April rainfall will be in the wetter tercile under El Niño conditions when AMO is in the cool phase. However, this increases to 81 percent when AMO is in the warm phase.

Table 1. Contingency table of ENSO–rainfall (February, March, and April [FMA]) relationship as a function of AMO.*

AMO Cool Phase				**AMO Warm Phase**			
Rainfall (FMA)	**ENSO Phase**			**Rainfall (FMA)**	**ENSO Phase**		
	La Niña	**Neutral**	**El Niño**		**La Niña**	**Neutral**	**El Niño**
Wet	0%	19%	35%	**Wet**	10%	35%	81%
Neutral	20%	50%	60%	**Neutral**	25%	35%	6%
Dry	80%	31%	5%	**Dry**	65%	10%	13%

* ENSO – El Niño-Southern Oscillation; AMO – Atlantic Multidecadal Oscillation

Correlations between South Florida climate and AMO/PDO patterns (the teleconnections mentioned above) have been seen in recent decades. For example, during the 1976–1995 period, the AMO was in the cool phase and the PDO was in the warm phase. This was a stressful time for the natural systems of south-central Florida, as the seasonality of rainfall tended to reverse the natural hydroperiod. That is, on average, wetter-than-normal dry seasons and drier-than-normal wet seasons occurred. Because evapotranspiration is much lower during the dry season, the 1976–1995 period brought frequent, very large dry-season surpluses of net rainfall. These surpluses led to large runoff volumes and rising water levels throughout the District.

Other examples include the 1970–1975 period, in which both the AMO and PDO were in their dry phases, resulting in extended dry periods, and 1995–1998, in which both oscillations were in their wet phases, producing very wet periods.

OTHER POTENTIAL INDICATORS

The SFWMD also uses the climate outlook forecasts developed by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) to aid operational planning efforts. Data sources and tools used for CPC forecasts include statistical interpretations of current and historical global sea surface temperatures (including the data that drive PDO and AMO periods), precipitation, soil moisture, solar radiation and trends, ENSO events, and outputs from various climate models. The CPC provides updated predictions of precipitation and temperature, including one-month and three-month outlooks.

The SFWMD has also conducted research to improve understanding of the effects of drainage and development on temporal and spatial distribution of rainfall (Mattocks et al., 1999; Mattocks and Trimble, 2000; Pielke et al., 1999; Chen et al., 2001) and potential effects of global warming, including sea level rise, on water resource planning (Trimble et al., 1998a). Several recent publications summarize the SFWMD experience in applying climate outlook methods to address water management issues in South Florida (IRI, 2002; Trimble et al., 2006).

DISTRICT EFFORTS TO UNDERSTAND TELECONNECTIONS

The District conducted numerous studies to understand the effects of teleconnections on South Florida and determine how climate forecasts could best be applied to improve Lake Okeechobee operations (Trimble et al, 1998b,c; Trimble and Trimble, 1998; Cadavid et al., 1999; Obeysekera et al., 2000). The work culminated in a landmark study describing the importance of the AMO to climatic variability (Enfield et al., 2001). The SFWMD has also investigated the application of ANN and data mining tools to characterize and hindcast Lake Okeechobee net inflows (Zhang and Trimble, 1996a,b; Trimble et al., 1998b;c Trimble and Trimble, 1998). These hindcasts are provided as input data to test the operational rules of the SFWMM (Trimble et al., 1998b,c) both for current operations and infrastructure and for performance of future alternatives.

A number of experts in the field of climatology have peer reviewed the SFWMD climate outlook methodology (Hewett, et al., 2000; Kolen and Hewitt, 2000; Mestas-Nunez and Enfield, 2003). More recently, recognizing the importance of long-term climatic regimes, the USACE formally approved and implemented the SFWMD recommendation to use AMO and ENSO climatic indicators to predict seasonal and multi-seasonal outlooks for use in the operational planning of Lake Okeechobee.

III. ROLE OF MODELS IN PLANNING AND OPERATION

Climatic indicators are used in the SFWMD planning process primarily through the application of regional models such as the South Florida Water Management Model (SFWMM). These tools provide a basis to assess water supply and flood control requirements, help determine the design and operation of future water management facilities, and determine environmental resource needs and impacts. Models used in conjunction with predictions of future climatic conditions are particularly important for planning, design and implementation of long-range activities such as CERP projects, which are expected to require many years to construct and have design life expectancies of 50 years or more.

In the design and analysis of water resources plans and projects for CERP, computer models are used to analyze existing and simulate possible future conditions (**Figure 7**). Planning processes then analyze these conditions to determine planning options that are likely to offer the greatest benefits or least impacts (Loucks, 1992). Models provide important information for planning, but such information is never complete. As a result, models cannot substitute for the judgment of experienced engineers, planners and managers (Loucks, 1992). Moreover, models are only one of a number of tools used to design project components.

More specifically, a particular modeling scenario is assumed to be static with respect to facility plans, operating criteria, land use/land cover conditions, and water demands (**Figure 8**). Consequently, this scenario is subject to a variety of hydrologic conditions as extracted from the most recent historical period of record, currently assumed to be 1965–2000. A regional-scale computer model (SFWMM) is used for evaluating the performance of the plan with respect to varying hydrologic conditions.

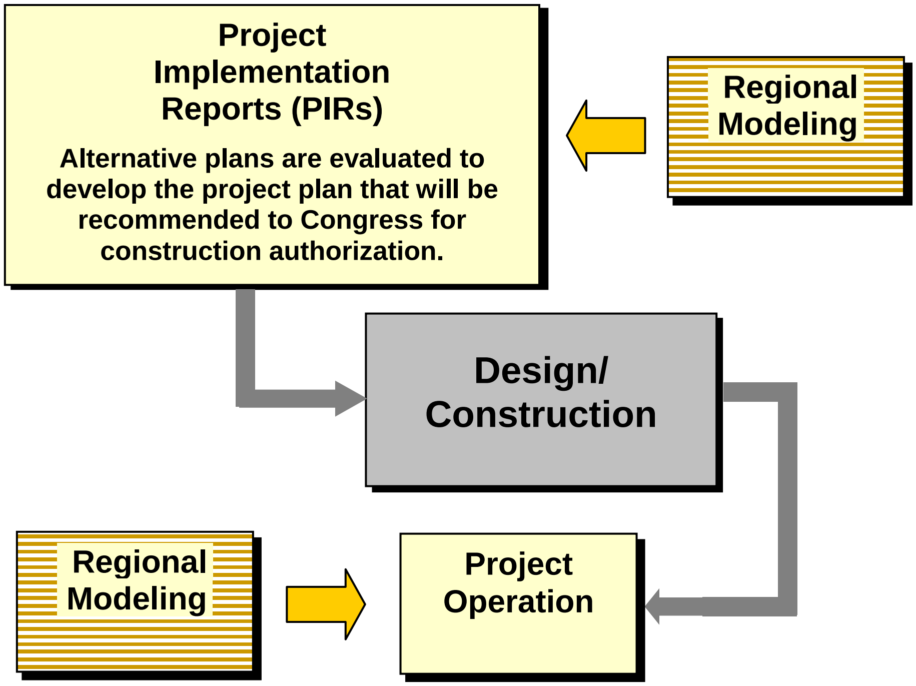


Figure 7. Planning, design, and construction phases of CERP process indicating where regional modeling plays a role.

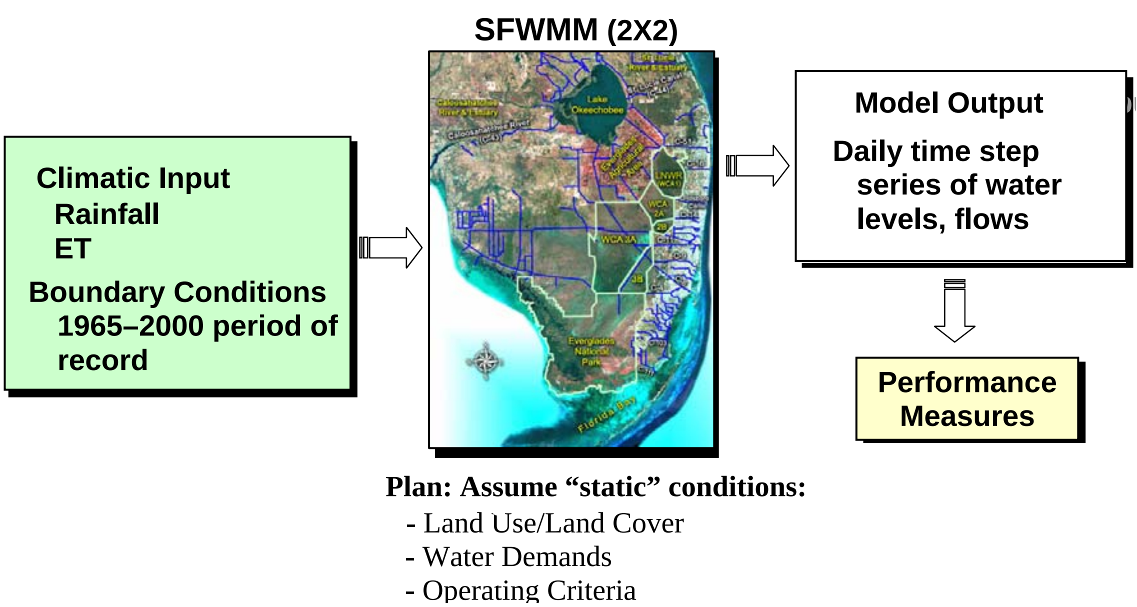


Figure 8. Scenario depicting South Florida Water Management Model (SFWMM) generalized inputs and outputs.

Analysis of project alternatives often relies on performance measures that represent project objectives in the form of quantitative criteria. Models allow quantification of hydrologic conditions (i.e., water levels and flows) that can be presented as performance measures and provided, along with other critical information such as costs and physical constraints, to decision makers.

The exact application of models in water resources planning and management depends on the project purposes. When modeling climatic variability and change, selection of an appropriate period of record is important. However, parameters that describe climatic variability (magnitude, duration, and return frequency) introduce uncertainties into water resources planning efforts, and can result in over-design, cost overruns, and poor project performance. Adaptive management offers an accepted approach to dealing with uncertainties in water resources modeling and planning processes. The basic elements of adaptive management are summarized in Section IV.

The South Florida Water Management Model (SFWMM) shown in **Figure 8** is a regional model developed by the SFWMD as a planning tool to help guide regional water supply and environmental restoration efforts for the District. A detailed description of this model can be found at the District web site (www.sfwmd.gov) under the S*imulation Modeling, Hydrologic & Environmental Systems Modeling* section. The model mathematically represents a physical system, and simulates the performance of the existing or proposed water management facilities and operations. Operating rules and input datasets can be modified to represent a range of planning and forecasting scenarios. The SFWMM is a continuous simulation model that is driven by historical hydrologic and meteorological data. Input datasets include daily spatial rainfall and evapotranspiration data, as well as local basin runoff and irrigation estimates for the relevant basins. The spatial domain of the SFWMM south of Lake Okeechobee is divided into grid cells, each 2 miles square. The model generates a description of hydrologic conditions throughout the region, which is then used to estimate effects on water supply, flood protection, and natural systems. A typical application of a planning tool such as the SFWMM uses an available period of reliable historical input data that includes a wide range of both dry and wet years. For Lake Okeechobee and its tributaries, the SFWMM uses estimates of inflows based on historical flow data or estimates of inflows based on prescribed changes to upstream water management. The combined inflows to Lake Okeechobee from the tributary basins may be referred to as net inflow.

Studies by Trimble et al. (1998b,c) have shown a significant potential for using ENSO and other indices to predict net inflow volumes into Lake Okeechobee for operational planning. Furthermore, use of ANN models has helped to bring a better understanding of these factors (Zhang and Trimble, 1996; Trimble et. al., 1998b,c; Trimble and Trimble, 1998).

IV. AMO TRENDS IN CLIMATE AND HYDROLOGIC DATA

Although the records at individual rain gauge locations vary in length, several long-term rainfall datasets have been constructed using such gauge records. These datasets typically begin in the year 1895. In addition, inflow records at key gauging locations of the Kissimmee Basin and a reconstructed time series of net inflow into Lake Okeechobee are also available. This exercise was intended to evaluate the long-term records to detect trends that may be associated with climate shifts, especially warm and cool phases of AMO.

DATA

Two sets of reconstructed monthly rainfall records were used for this analysis: (a) the PRISM dataset (Daly et al, 2004), and (b) National Climatic Data Center (NCDC) datasets for Climate divisions 4–7 in South Florida (http://www.ncdc.noaa.gov/oa/ncdc.html). This analysis used flow records for S-65 and S-65E gauge locations in the Kissimmee Basin as well as the LONIN dataset constructed using Lake water levels and outflow records. The grid-based PRISM dataset was spatially averaged to represent regions that cover the major basins in South Florida. Details of the data are shown in **Table 2**.

TRENDS IN WATER-YEAR DATA

In this study, annualized values were based on a water year, defined as the period from June 1 to May 31. This date range differs slightly from the standard period used by the SFWMD (May 1–April 30). The June–May span was used in this study because May represents the end of the dry season; therefore, the June–May span helped to minimize carryover of discharge data from one water year to the next.

Table 2. Monthly climatic data used for trend analysis.

	Variable	Region/Gauge Location	Dataset	Period of Record
Rainfall	Ukiss	Upper Kissimmee Basin	PRISM	1895–2005
Rainfall	Lkiss	Lower Kissimmee Basin	PRISM	1895–2005
Rainfall	KissRF	Entire Kissimmee Basin	PRISM	1895–2005
Rainfall	BigCyp	Big Cypress Basin	PRISM	1895–2005
Rainfall	EAA	Everglades Agricultural Area	PRISM	1895–2005
Rainfall	Everglades	Everglades National Park	PRISM	1895–2005
Rainfall	LOK	Lake Okeechobee	PRISM	1895–2005
Rainfall	WCA3	Water Conservation Area 3	PRISM	1895–2005
Rainfall	WCA12	Water Conservation Areas 1 and 2	PRISM	1895–2005
Rainfall	WestAG	Western Agricultural Areas	PRISM	1895–2005
Rainfall	Caloos	Caloosahatchee Basin	PRISM	1895–2005
Rainfall	SWCoast	South West Coast	PRISM	1895–2005
Rainfall	Browrd	Broward County	PRISM	1895–2005
Rainfall	Dade	Miami-Dade County	PRISM	1895–2005
Rainfall	MartSLC	Martin, St. Lucie Counties	PRISM	1895–2005
Rainfall	Pbeach	Palm Beach County	PRISM	1895–2005
Rainfall	Div4rf	South-central Florida	NCDC	1895–2005
Rainfall	Div5rf	Everglades and Southwest Coast	NCDC	1895–2005
Rainfall	Div6rf	Lower East Coast	NCDC	1895–2005
Rainfall	Div7rf	Florida Keys	NCDC	1895–2005
Flow	S-65E	S-65E gauge location	SFWMD	1928–2005
Flow	S-65	S-65 gauge location	SFWMD	1933–2005
Flow	LONIN	Lake Okeechobee net inflow	SFWMD	1914–2005

Note: All variables represent rainfall except S-65, S65-E, and LONIN, which represent flows.

Box plots of the water year data for variables for the four AMO periods (**Figure 9)** show a shift in distribution of both rainfall and flow between cool periods (AMO1 and AMO3) and warm periods (AMO2 and AMO4). Moreover, rainfall and flow amounts during the warm periods appear to shift upward compared to the cool periods. However, comparing of the means of all four periods using one-way analysis of variance (ANOVA) shows that not all of the shifts are significant. As shown in **Table 3**, shifts in rainfall for the Ukiss, KissRF, BigCyp, EAA, Everglades, LOK, WCA3, WestAG, and MartSCL basins are significant at the 5 percent level. Both S-65E and LONIN also show shifts in mean at the 5 percent level. Although rainfall data for NCDC Divisions 4–7 show visual shifts in the box plots, they are not significant at the 5 percent level. (The hypothesis testing is formulated in such a way that the percent chance of indicating a difference in means when in reality they are not is limited to 5 percent.)

Overall, results show statistically significant shifts in mean values during different AMO periods for both rainfall and flow variables. Actual changes in the means and percent values are shown in **Table 4**.

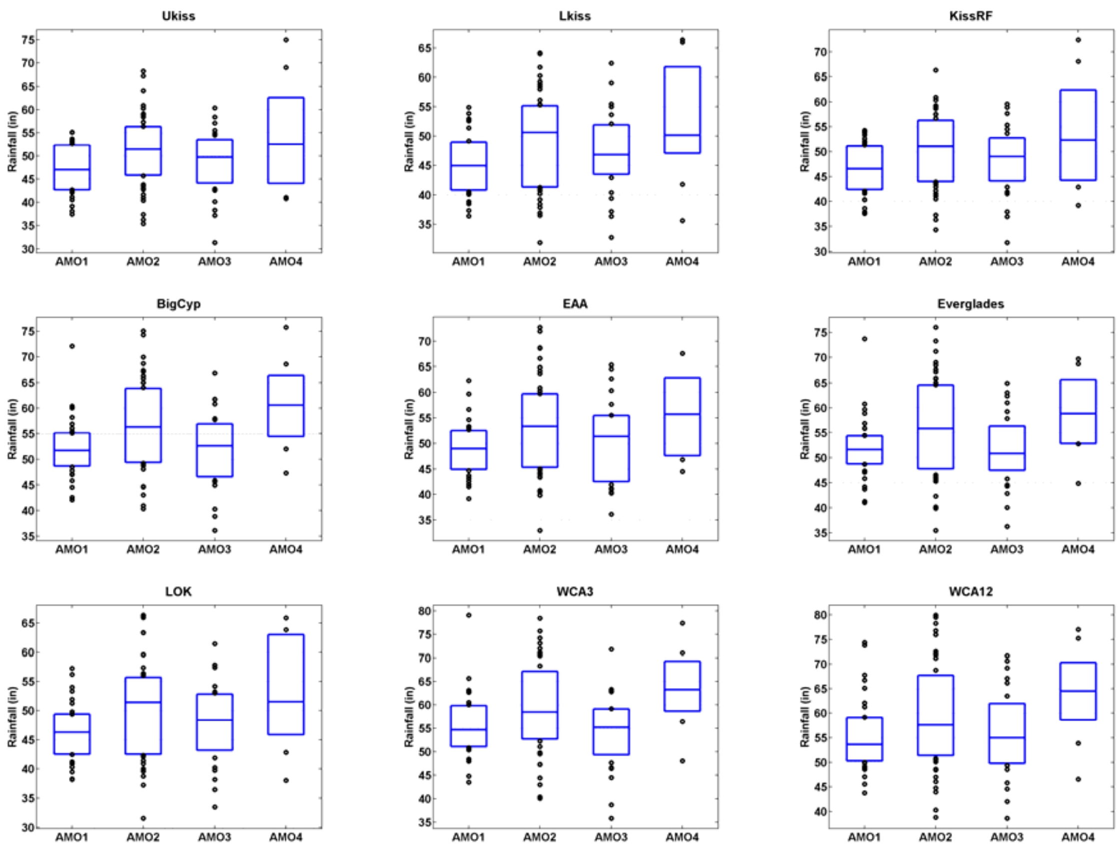


Figure 9. Box plots of water year (June–May) rainfall and flow variables for four AMO periods (1895–2005). Whiskers of the box plots were eliminated to show the actual distribution of points outside the interquartile range as indicated by each box. The line inside the box is the median value.

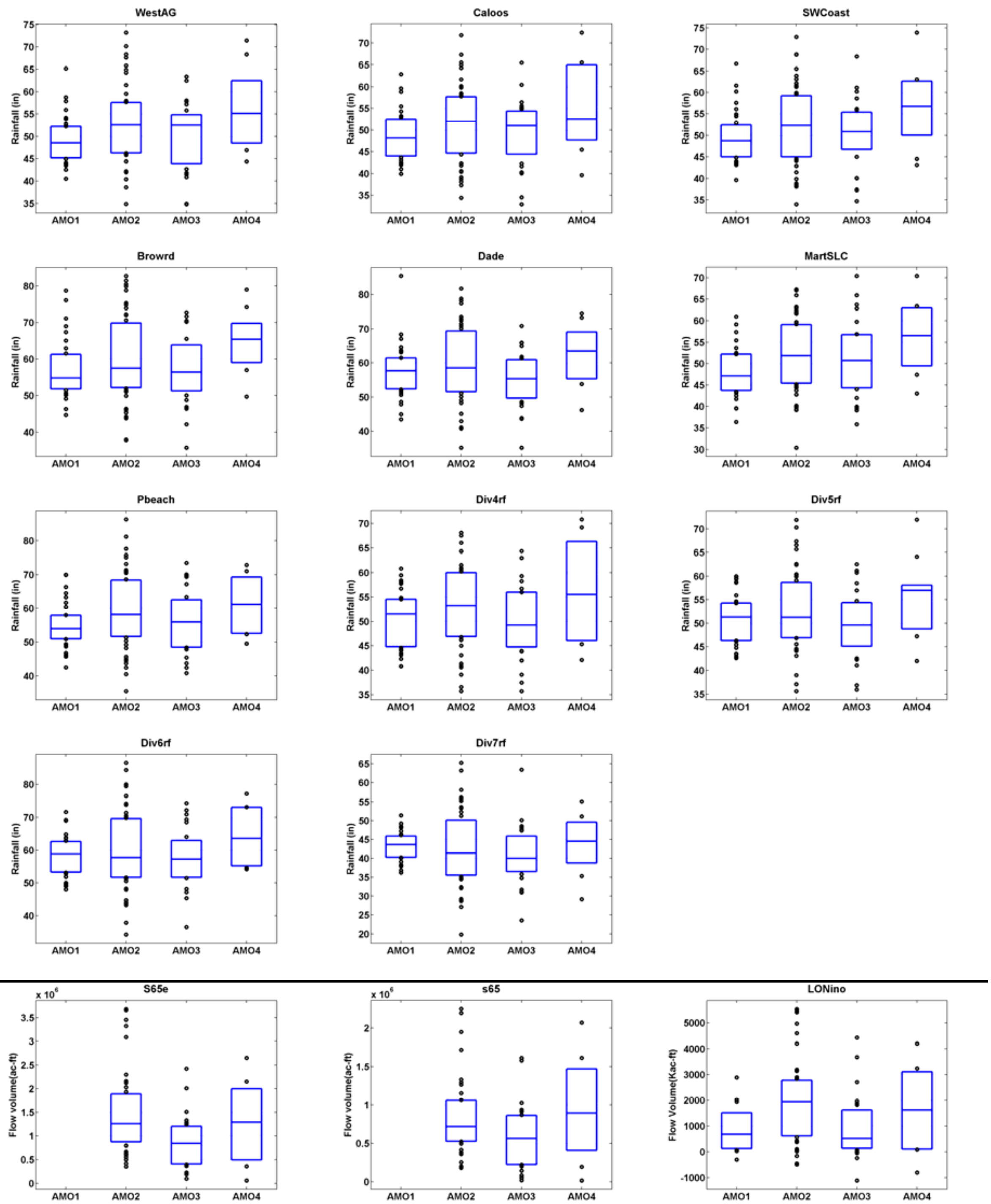


Figure 9. Continued.

Table 3. Probability value, p, for the null hypothesis that samples of different AMO periods were drawn from populations with the same mean. Also shown are the variables for which p-value exceeds the 5 percent significance level.

	Variable	ANOVA p-value	Significant at 5% level		Variable	ANOVA p-value	Significant at 5% level
Rainfall	Ukiss	0.027	Yes	Rainfall	Browrd	0.149	No
Rainfall	Lkiss	0.056	No	Rainfall	Dade	0.12	No
Rainfall	KissRF	0.028	Yes	Rainfall	MartSLC	0.038	Yes
Rainfall	BigCyp	0.003	Yes	Rainfall	Pbeach	0.186	No
Rainfall	EAA	0.038	Yes	Rainfall	Div4rf	0.104	No
Rainfall	Everglades	0.019	Yes	Rainfall	Div5rf	0.163	No
Rainfall	LOK	0.058	Yes	Rainfall	Div6rf	0.278	No
Rainfall	WCA3	0.012	Yes	Rainfall	Div7rf	0.672	No
Rainfall	WCA12	0.067	No	Flow	S-65E	0.014	Yes
Rainfall	WestAG	0.031	Yes	Flow	S-65	0.08	No
Rainfall	Caloos	0.137	No	Flow	LONIN	0.026	Yes
Rainfall	SWCoast	0.117	No				

TRENDS IN RAINFALL-RUNOFF RELATIONSHIPS

As shown in **Table 4,** the annual rainfall reduction in the last transition from an AMO warm period (AMO2) to an AMO cool period (AMO3) ranges from 2 to 9 percent. However, the percent reduction in the flow variables is much larger; the LONIN was the highest, at about 48 percent. Although increases in percent reductions in runoff are typically due to decreased rainfall, all of the following factors may contribute to this large reduction in the flow variables (S-65E, S-65, and LONIN), such as:

- Changes in rainfall between AMO periods
- Land use changes in the Kissimmee Basin
- Post-channelization water management in the Kissimmee Basin
- Non-homogeneity in long-term data used for trend analysis

With regard to the non-homogeneity, it is difficult to pinpoint inconsistency in the data, particularly from the 1920s and 1930s. In particular, the calculation of LONIN is based on changes in Lake stages and outflow variables. While it is challenging to determine whether decades-old measurements have inherent inaccuracies, review of rainfall-runoff relationships might provide useful for this analysis.

Table 4. Sample means for different AMO periods and percent change relative to other AMO periods.

			Mean				Percent Change		
	Area	**Unit**	**AMO1**	**AMO2**	**AMO3**	**AMO4**	**AMO2 to AMO3**	**AMO3 to AMO4**	**AMO2 to AMO4**
Rainfall	Ukiss	in.	46.89	50.93	48.61	54.48	-4.6	12.1	7.0
	Lkiss	in.	45.59	49.14	47.66	52.49	-3.0	10.1	6.8
	KissRF	in.	46.50	50.4	48.32	53.89	-4.1	11.5	6.9
	BigCyp	in.	52.27	56.54	52.00	60.82	-8.0	17.0	7.6
	EAA	in.	49.04	53.19	51.13	55.70	-3.9	8.9	4.7
	Everglades	in.	51.96	56.00	51.67	59.38	-7.7	14.9	6.0
	LOK	in.	46.44	50.11	48.39	52.58	-3.4	8.7	4.9
	WCA3	in.	55.94	59.21	54.20	63.33	-8.5	16.8	7.0
	WCA12	in.	55.86	59.07	56.28	63.32	-4.7	12.5	7.2
	WestAG	in.	49.31	52.90	50.40	56.38	-4.7	11.9	6.6
	Caloos	in.	48.58	51.12	49.94	54.91	-2.3	10.0	7.4
	SWCoast	in.	49.72	51.99	50.72	56.99	-2.4	12.4	9.6
	Browrd	in.	57.47	59.93	57.27	64.49	-4.4	12.6	7.6
	Dade	in.	57.38	59.9	55.22	62.66	-7.8	13.5	4.6
	MartSLC	in.	48.07	51.62	51.58	56.19	-0.1	8.9	8.9
	Pbeach	in.	55.06	58.82	56.81	60.58	-3.4	6.6	3.0
	Div4rf	in.	50.33	53.00	50.19	56.06	-5.3	11.7	5.8
	Div5rf	in.	51.09	52.81	50.41	56.07	-4.5	11.2	6.2
	Div6rf	in.	58.21	59.87	57.75	64.69	-3.5	12.0	8.1
	Div7rf	in.	43.02	42.56	40.79	44.38	-4.2	8.8	4.3
Flow	S-65E	ac-ft		1,399,271	890,342	1,386,436	-36.4	55.7	-0.9
	S-65	ac-ft		699,608	592,058	1,007,097	-15.4	70.1	44.0
	LONIN	ac-ft	319	1,966	1,031	1,619	-47.6	57.1	-17.6

Note: All variables represent water year (June–May) rainfall except S-65, S-65E, and LONIN, which represent annual flow volumes.

In **Figure 10,** the rainfall-runoff relationship (S-65E flow versus KissRF) for the Kissimmee Basin is presented. In this plot, the runoff volume (water year basis) at S-65E is expressed as a depth of water over the basin, by using a total area of 1,595 square miles for the upper basin plus 684 square miles for the lower basin. Based on the availability of flow data, only the scatter plots for AMO2, AMO3, and AMO4 periods are shown. Except for a group of "outliers" that are identified on the plot, it is difficult see a definite change between AMO cycles from this plot. Many of the outlier years correspond to well known times when South Florida experienced very wet periods due to tropical events. These years also occurred before the modern system of water control structures and improved canals was constructed in the Kissimmee Basin.

As is seen from the runoff coefficients (runoff as a fraction of rainfall) shown in **Figure 11**, the percentage of runoff due to rainfall was high (above 35 percent) during these seven outlier years. A further investigation of outlier years has shown that the wet-season rainfall, particularly the months of June and September, were much wetter during these years than normal (**Figure 12**). Under more natural basin conditions such as those that were present during the last AMO warm cycle (AMO2), such wet periods could result in long periods of wetter conditions in the basin with high runoff in the ensuing months. Occasional wetter-than-normal wet seasons, which could occur during an AMO warm cycle, may be responsible for large increases in runoff into Lake Okeechobee. The role of tropical storms and/or hurricanes as possible causes of the very wet antecedent conditions during wet seasons in these outlier years needs further investigation.

Monthly distributions of S-65 flow for the AMO2 and AMO3 periods are shown in **Figure 13**. The first box plot each month represents the wetter AMO2 period, while the second plot represents the drier AMO3 period. Clearly, there is a big difference between the monthly flow distributions. As seen from the box plots, during early dry-season months (September–December), the flow data at these key gauges in the Kissimmee Basin show a substantial reduction. This change is attributed to the regulation of the upper basin, which occurred during the 1963–1969 period, coincidentally around the same time (1960s) that the AMO appeared to switch from warm to cool. The change in flow regime, from a hydrograph characterized by slow recession to that of a managed flow regime typified by flow spikes, can be seen clearly in the daily flow hydrograph at S-65 (**Figure 14**). Consequently, the attribution of the drastic change in LONIN solely due to AMO change may not be warranted, particularly on a seasonal basis.

TRENDS IN MONTHLY DATA

To identify possible changes in seasonal patterns, monthly values of both rainfall and flow variables were analyzed. **Figures 15** and **16** present the mean monthly distributions of District-wide rainfall and LONIN for the four different AMO periods. A careful evaluation of the mean rainfall pattern indicates an apparent shift in the mean in June, with a more significant shift in September. Flow values also appear to show a similar shift in August through October. Once again, as discussed above, the flow values are impacted by causes other than the AMO.

Differences in the monthly means of AMO2 and AMO3 periods were tested using a standard t-test. **Table 5** shows the p-value associated with the t-statistic. In the table, values in bold type indicate instances where the p-value is less than the 5 percent significance level. In those instances, the null hypothesis that the means are the same between AMO2 and AMO3 may be rejected. **Table 6** shows the results of the Kolmogorov-Smirnov test, which was conducted to compare the empirical distributions of the AMO2 and AMO3 periods for each month. Again, bold type indicates instances where the null hypothesis that two distributions are identical may be rejected.

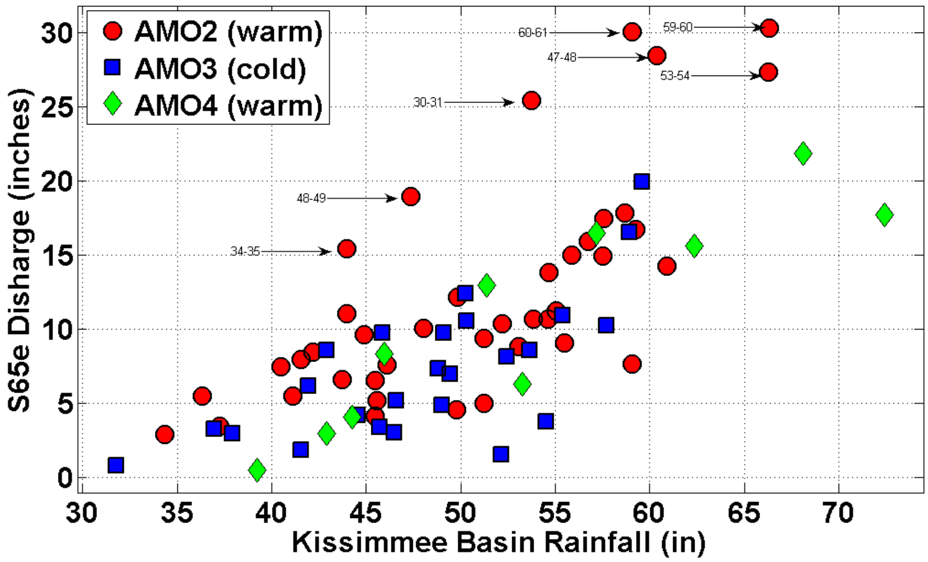


Figure 10. Rainfall-runoff relationship between S-65E and Kissimmee Basin rainfall (KissRF). Arrows indicate “outlier” years, which have unusually high discharge values.

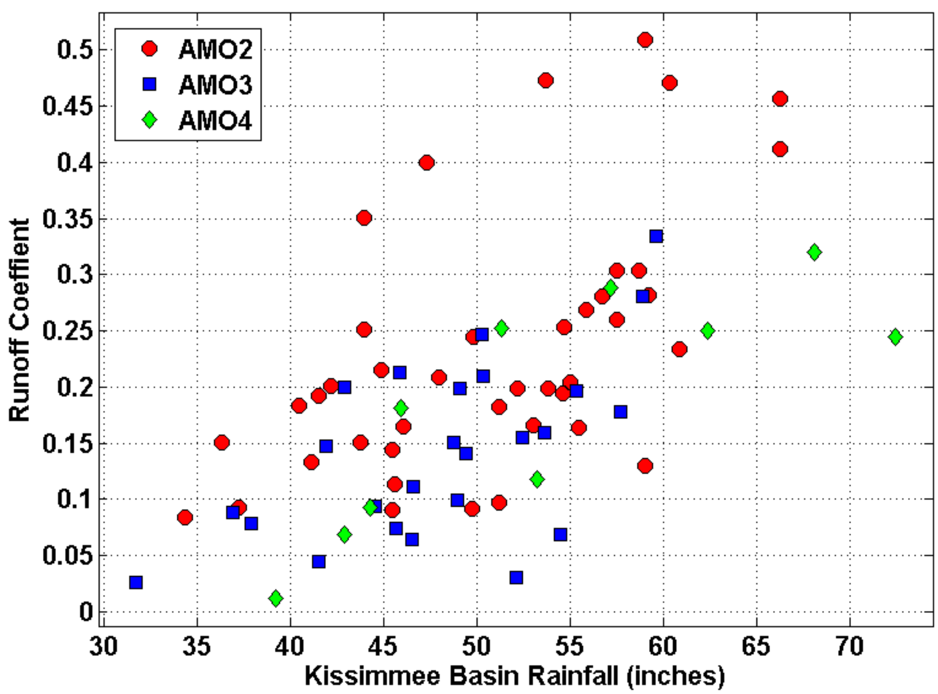


Figure 11. Runoff coefficient versus rainfall for the Kissimmee Basin.

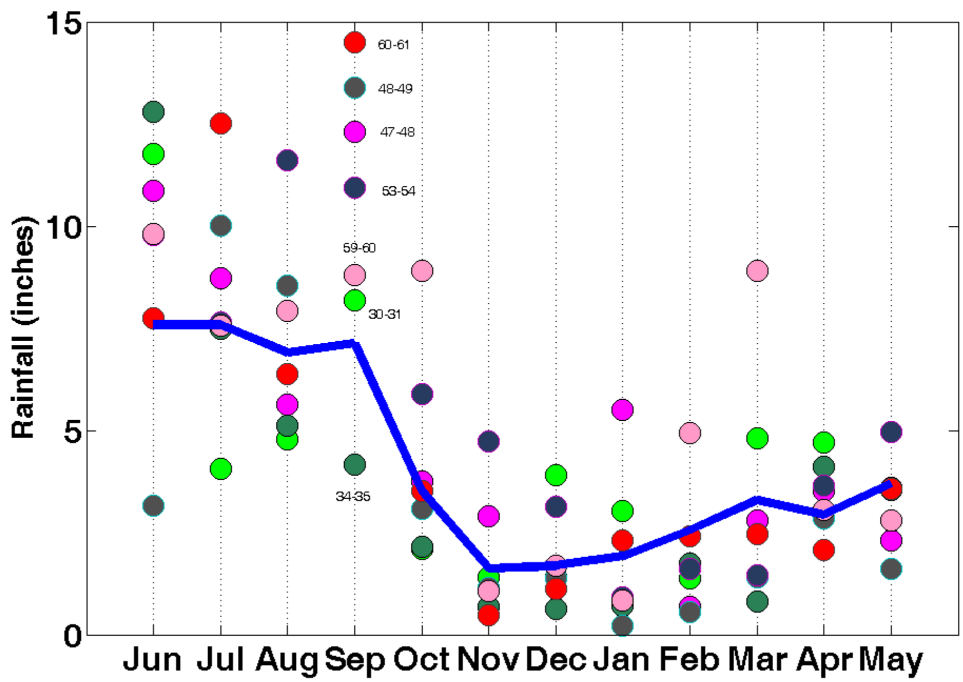


Figure 12. Monthly distribution of rainfall during the seven outlier years (34-35,48-49, 30-31, 47-48, 53-54, 60-61, and 59-60). Also plotted is the mean monthly rainfall (solid line) for the AMO2 period.

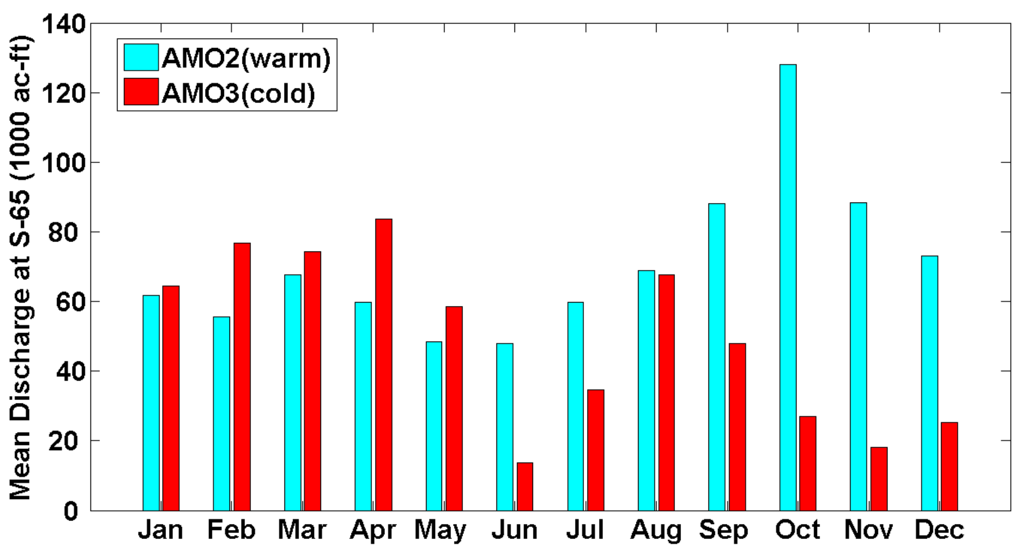


Figure 13. Mean monthly patterns of flows out of Lake Kissimmee at S-65 for AMO2 and AMO3 periods.

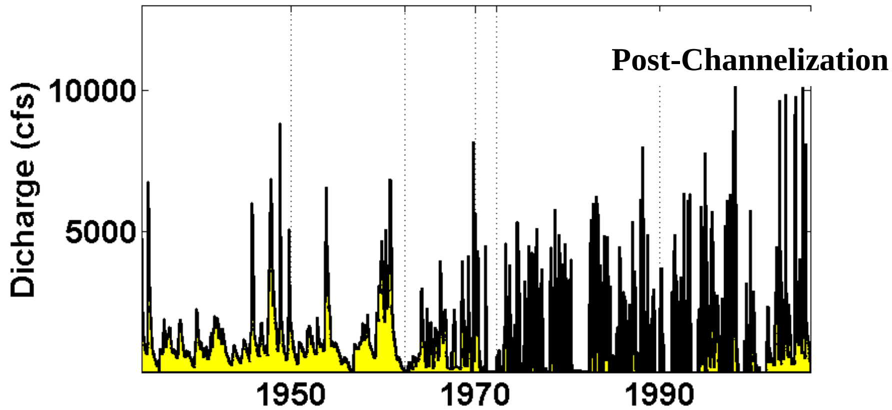


Figure 14. Daily flow hydrograph at S-65 indicating a change from natural recessions to flow spikes as a result of Upper Kissimmee Chain of Lakes regulation during the post-channelization period.

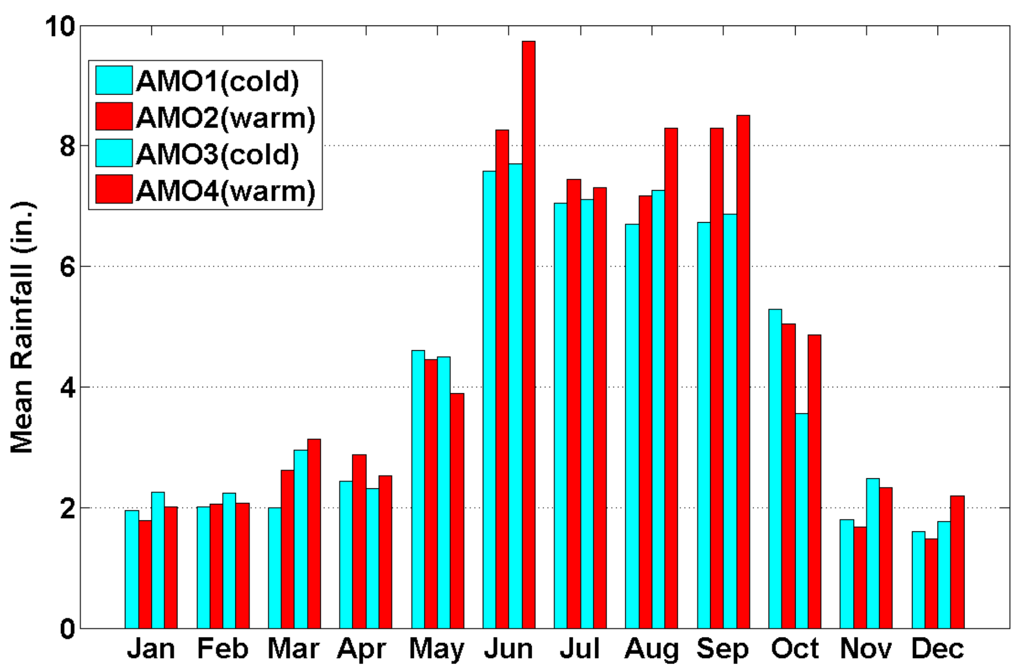


Figure 15. Mean monthly District-wide rainfall for different AMO periods.

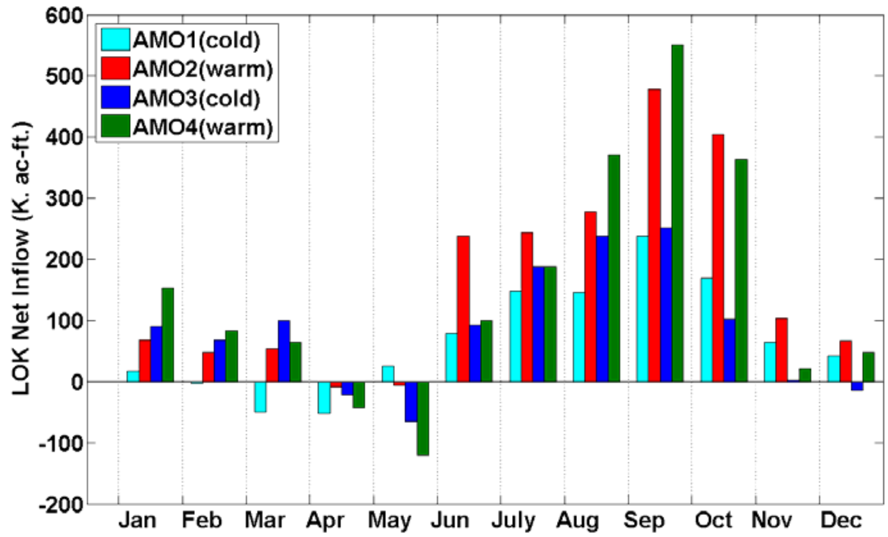


Figure 16. Mean monthly LOK net inflow volumes for different AMO periods.

Table 5. p-value for the t-statistic used for comparing means of AMO2 and AMO3. Values in bold type indicate variables for that month that have significant differences in mean at 5 percent level.

	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	Ukiss	0.35	0.94	0.94	0.07	0.33	0.29	0.42	0.63	0.13	0.34	0.18	0.72
	Lkiss	0.26	0.72	0.63	**0.04**	0.91	0.88	0.73	0.98	0.07	0.11	0.07	0.33
	KissRF	0.31	0.96	0.94	**0.05**	0.46	0.41	0.49	0.73	0.09	0.23	0.14	0.60
	BigCyp	0.50	0.50	0.60	0.50	0.21	0.42	0.19	0.70	**0.01**	**0.01**	**0.04**	0.10
	EAA	0.07	0.71	0.47	0.28	0.45	0.22	0.61	0.59	0.07	**0.01**	**0.02**	0.53
	Everglades	0.63	0.39	0.79	0.75	0.57	0.42	0.07	0.32	**0.01**	**0.00**	**0.05**	0.10
	LOK	0.13	0.76	0.41	**0.05**	0.87	0.45	0.58	0.88	0.06	0.07	**0.02**	0.40
	WCA3	0.61	0.31	0.61	0.60	0.65	0.32	0.17	0.95	**0.01**	**0.00**	**0.03**	0.21
	WCA12	0.25	0.32	0.29	0.61	0.51	0.34	0.54	0.67	0.07	**0.00**	**0.03**	0.78
	WestAG	0.20	0.68	0.41	0.29	0.62	0.40	0.34	0.97	**0.02**	**0.02**	**0.01**	0.32
	Caloos	0.15	0.86	0.29	0.07	0.82	0.65	0.44	0.52	0.08	0.11	**0.02**	0.41
	SWCoast	0.29	0.83	0.32	0.11	0.61	0.92	0.68	0.31	**0.05**	0.09	0.10	0.34
	Browrd	0.50	0.29	0.22	0.84	0.60	0.51	0.37	0.97	0.13	**0.00**	**0.03**	0.90
	Dade	0.84	0.25	0.95	0.83	0.92	0.33	**0.05**	0.27	0.06	**0.00**	**0.05**	0.18
	MartSLC	0.11	0.33	0.44	0.12	0.22	0.60	0.59	0.83	0.20	**0.01**	**0.01**	0.23
	Pbeach	0.10	0.57	0.33	0.60	0.24	0.33	0.72	0.25	0.15	**0.00**	**0.01**	0.53
	Div4rf	0.40	0.96	0.91	**0.02**	0.34	0.39	0.13	0.71	0.12	0.14	0.11	0.50
	Div5rf	0.16	0.86	0.42	0.08	0.83	0.36	0.14	0.60	**0.02**	**0.03**	**0.02**	0.43
	Div6rf	0.39	0.39	0.54	0.69	0.53	0.51	0.69	0.56	0.14	**0.00**	**0.01**	0.55
	Div7rf	0.28	0.46	0.57	0.72	0.20	0.70	0.15	0.34	0.11	**0.00**	0.38	0.63
Flow	S-65E	0.19	0.76	0.75	0.96	0.35	**0.05**	0.33	0.52	**0.02**	**0.00**	**0.00**	**0.00**
	S-65	0.84	0.09	0.67	0.13	0.28	**0.00**	0.14	0.94	**0.02**	**0.00**	**0.00**	**0.00**
	LONIN	0.62	0.62	0.39	0.72	**0.04**	0.09	0.42	0.53	**0.02**	**0.00**	**0.03**	**0.02**

Table 6. p-values for the Kolmogorov-Smirnov test for comparing distributions of AMO2 and AMO3. Values indicate variables for that month that have significant differences in distribution at 5 percent level.

	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	Ukiss	0.49	0.82	0.71	0.18	0.63	0.61	0.77	0.89	0.17	0.78	0.35	0.97
	Lkiss	0.38	0.60	0.85	0.12	1.00	0.53	0.87	0.44	0.19	0.45	0.32	0.59
	KissRF	0.25	0.75	0.78	0.18	0.97	0.59	0.60	0.48	0.27	0.78	0.27	0.93
	BigCyp	0.39	0.34	0.96	0.80	0.65	0.79	0.06	0.81	**0.01**	**0.01**	0.10	0.49
	EAA	0.13	0.29	0.45	0.12	0.57	0.15	0.76	0.67	0.24	**0.05**	**0.01**	0.59
	Everglades	0.49	0.48	0.90	0.92	0.98	0.85	0.03	0.77	**0.03**	**0.00**	0.20	0.41
	LOK	0.12	0.71	0.83	0.12	0.89	0.45	0.48	0.78	0.19	**0.05**	0.07	0.62
	WCA3	0.52	0.32	0.69	0.81	1.00	0.85	0.01	0.92	**0.04**	**0.00**	0.13	0.25
	WCA12	0.32	0.32	0.84	0.43	0.82	0.40	0.53	0.64	0.13	**0.01**	**0.04**	0.45
	WestAG	0.15	0.52	0.32	0.25	0.98	0.35	0.38	0.99	0.16	0.11	**0.02**	0.84
	Caloos	0.33	0.67	0.13	0.39	0.98	0.55	0.83	0.67	0.34	0.36	0.16	0.69
	SWCoast	0.53	0.75	0.64	0.34	0.55	0.93	0.63	0.10	0.08	0.46	0.55	0.54
	Browrd	0.80	0.63	0.61	0.57	0.68	0.52	0.41	0.67	0.60	**0.02**	0.06	0.45
	Dade	0.83	0.44	0.88	0.89	0.76	0.74	0.01	0.77	0.13	**0.00**	0.22	0.57
	MartSLC	0.11	0.18	0.91	0.22	0.27	0.71	0.99	0.97	0.27	**0.03**	0.06	0.41
	Pbeach	0.15	0.55	0.75	0.18	0.38	0.59	0.27	0.09	0.27	**0.01**	**0.02**	0.48
	Div4rf	0.45	0.75	0.56	0.12	0.84	0.59	0.35	0.55	0.37	0.25	0.20	0.99
	Div5rf	0.15	0.55	0.75	0.22	0.94	0.32	0.09	0.52	**0.04**	0.12	0.09	0.74
	Div6rf	0.69	0.92	0.79	0.77	0.45	0.71	0.38	0.96	0.54	**0.00**	**0.03**	0.72
	Div7rf	0.77	0.67	0.65	0.43	0.22	0.47	0.06	0.44	0.32	0.00	0.67	0.94
Flow	S-65E	**0.02**	0.23	0.30	0.35	0.34	**0.01**	0.06	**0.01**	0.06	**0.00**	**0.00**	**0.00**
	S-65	**0.00**	**0.02**	0.16	0.22	0.24	**0.00**	**0.00**	**0.01**	**0.01**	**0.00**	**0.00**	**0.00**
	LONIN	0.27	0.83	0.94	0.45	0.07	0.29	0.39	0.61	0.08	**0.00**	**0.00**	**0.00**

COMPARISON OF THE SFWMM MODELING PERIOD WITH THE PERIOD OF RECORD

Modeling an existing period of record allows continuous simulation that represents system responses on a daily basis to a wide variety of weather patterns actually experienced in South Florida. In addition, the 36-year period of record includes a wide range of extreme wet and dry events. The system's response to these extreme events has been documented and can be related to an expected frequency of occurrence or return period. The period includes a sample of the most likely weather-related impacts to the system and some very rare, extreme events. The likelihood of experiencing a weather pattern beyond the range represented in this period of record is very low.

Table 7 compares the SFWMM modeling period with the AMO phases in the entire period of record. About one-third of the 36 years within the SFWMM dataset represents AMO positive (warm phase) years and the remaining two-thirds represent AMO neutral or negative (cool phase) years. Efforts are ongoing to update the model data through 2005. This will provide 41-year simulations that include at least 15 years from the AMO warm phase. The variability and range of extremes in the datasets that drive the model are much more important than the AMO phase for a given year.

Table 7. Comparison of AMO periods with the SFWMM period of simulation.

AMO Period Name	AMO Phase	Selected year Range within the period of record	Number of Years	Number of years in current SFWMM modeling period (1965–2000)
AMO1	cool	1895–1925	31	Not used
AMO2	warm	1926–1969	44	5
AMO3	cool	1970–1994	25	25
AMO4	warm	1995–2005	11	6

The current SFWMM input rainfall dataset covers the geographic region south of Lake Okeechobee. The dataset uses hundreds of rain gauges to define the 36-year (1965–2000) daily time series for each of the model's 4-square-mile grid cells. The dataset and SFWMM model simulations have not been extended to include years before 1965 because of the relatively low density of rain gauges prior to that year, lack of other hydrologic and management data for the system, and the fact that many of the Central and Southern Florida Flood Control (C&SF) Project facilities were not constructed then.

For this document, PRISM rainfall data were compared to ascertain how well the 36-year "sample" represents the 111-year "population" The 36-year sample is the 1965–2000 period currently simulated by the SFWMM; and the population is taken as the entire 1895–2005 period of the PRISM dataset. Annual and wet-season rainfall for the entire SFWMD region was evaluated. **Figure 17 Panel A** shows the annual PRISM rainfall data (May–April water year) series for the SFWMD region as departures from the mean. In the figure, values are ranked from highest to lowest and the 36 years used in the current SFWMM are highlighted. **Figure 17 Panel B** is formatted similarly but uses wet-season (May–October) rainfall data. These figures show many wet years in the 36-year dataset, and the distribution is representative of the range that occurred during the entire 111-year period. In fact, several of the 36 years in the dataset were considerably wetter than were the years 2002–2005.

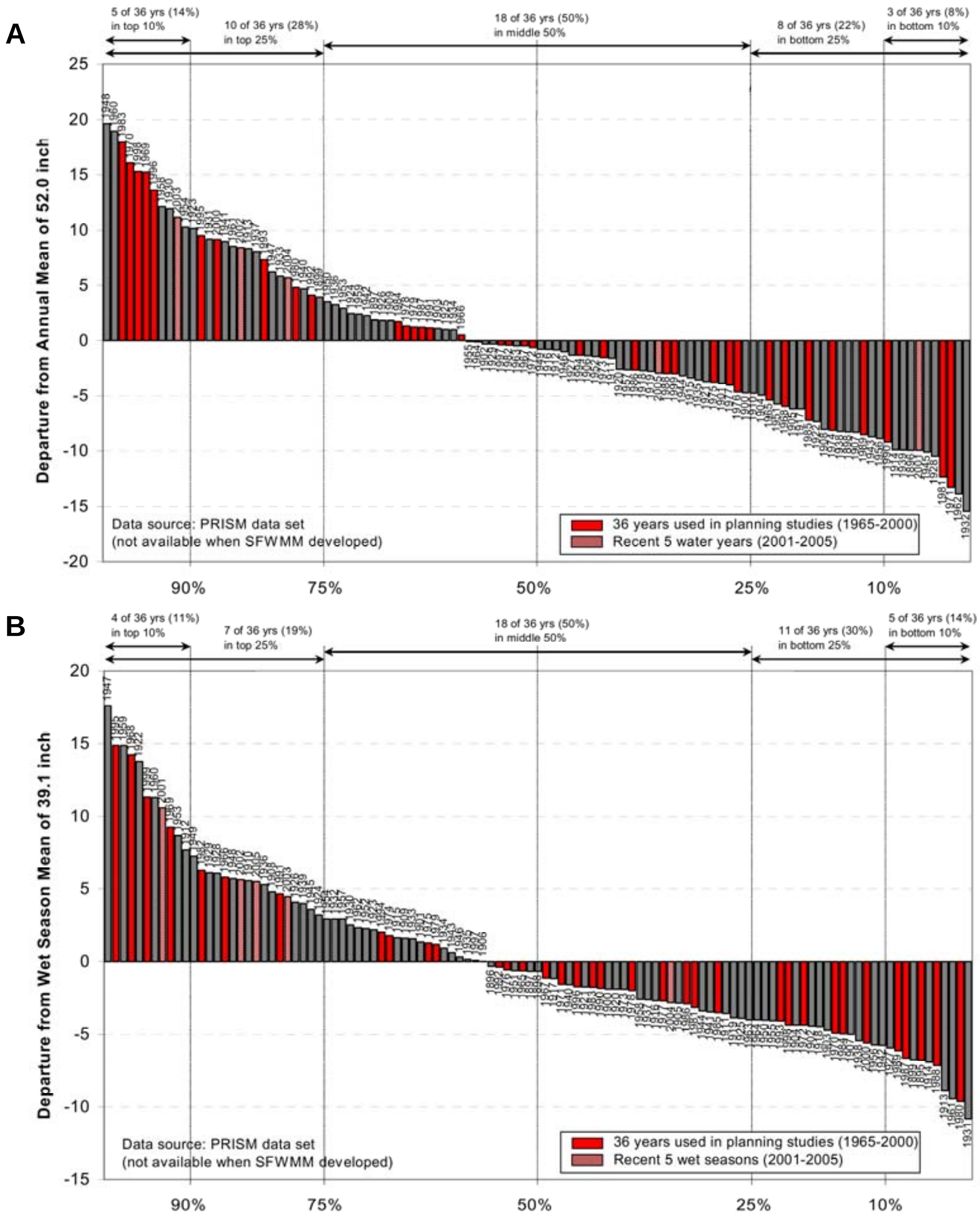


Figure 17. (A) Distribution of annual rainfall for the SFWMD (May–April water years, 1895–2005). **(B)** Distribution of wet-season rainfall (May–October, 1895–2005).

LAKE OKEECHOBEE NET INFLOW

An important aspect of determining potential effects of increased rainfall on water management decisions is the relationship between rainfall rates and the resulting amount of surface water flow. This is an issue of special concern in the Lake Okeechobee watershed. In recent years, excessive rainfall has produced both sustained high water levels in the Lake and consequential large releases of excess water to tide. CERP projects have been proposed and initially designed to provide additional capacity throughout the regional system to capture and store more of this "excess" water. This added capacity will help to lower Lake levels and reduce discharges of water to tide. The concern has been raised that the climatic conditions used to design CERP and other projects may not represent a sufficiently wide range of Lake runoff conditions. Therefore, an initial analysis was conducted to determine whether the period of record used for SFWMM simulations represented a broad-enough range, relative to historical conditions, to provide a technically sound basis for future planning efforts.

Figure 18 illustrates the distribution of historical net inflow to Lake Okeechobee available from 1914 through 2005. The solid bars represent the 36-year span used in the current SFWMM simulation period (1965–2000), and the striped bars represent the recent, relatively wet five years (2001–2005).

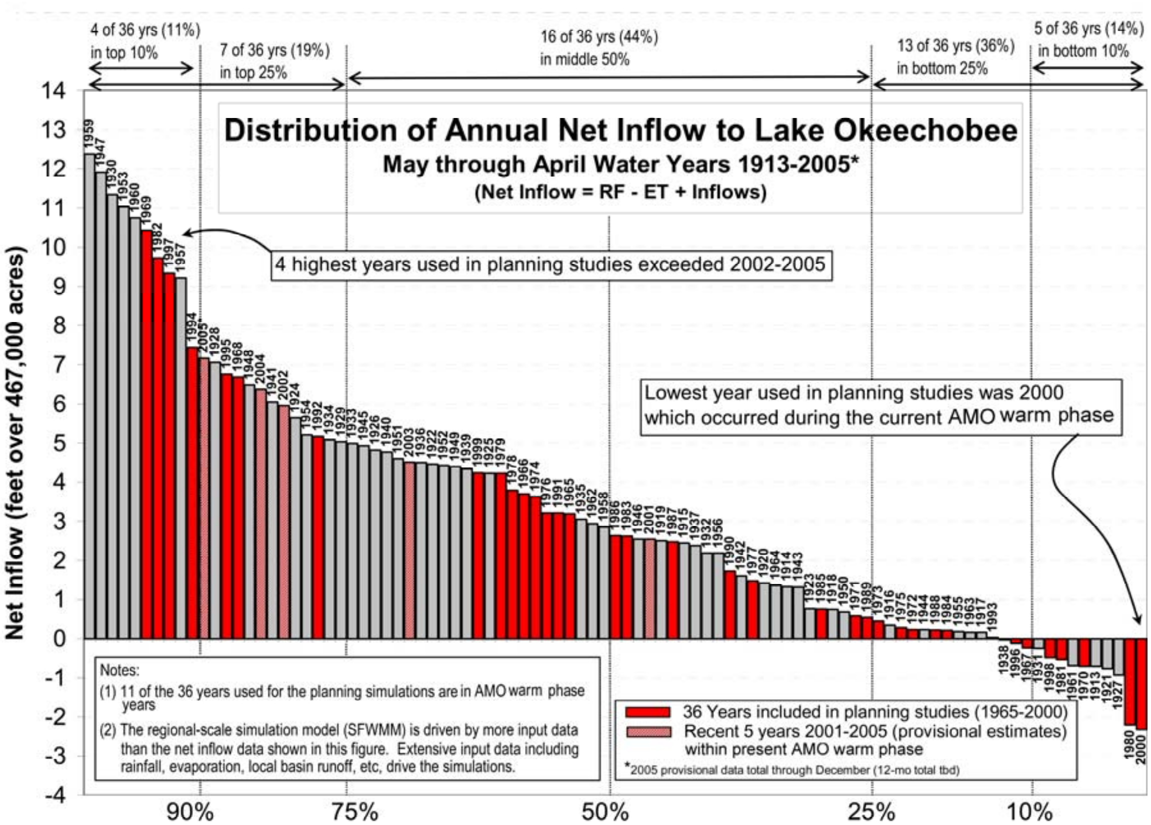


Figure 18. Distribution of annual net inflow to Lake Okeechobee, water years 1913–2005 (May–April), where NI = RF – ET + inflows.

These data indicate that the four wettest years used in the 1965–2000 simulation period all have larger net inflow than any of the recent very wet, AMO warm-phase years (2001–2005). Furthermore, the smallest net inflow year (2000), occurred during the current AMO warm phase. This helps to confirm that the SFWMM distribution represents a range of net inflow conditions sufficiently broad to evaluate the performance of proposed structural and operational plans.

Questions have been raised as to whether the dataset used for the SFWMM adequately represents conditions likely to occur during the current AMO warm period. Because it is unclear how long such a warm period may last, it is important to include both cool and warm period data in the modeling period. The period of simulation for the SFWMM is 36 years long, from 1965 to 2000. Plans are under way to extend this period through 2005. If one applies the same criteria that were used to define the AMO phases (AMO1–AMO4), then the current SFWMM simulation period includes 11 years of warm-period data, which represents about one-third of the entire period.

A statistical analysis was performed to compare the 1965–2000 period to the previous 36-year period (1929–1964). Both the t-test for mean and the Kolmogorov-Smirnov test for distributions were conducted to characterize significant differences between the two periods. The results of this analysis are shown in **Table 7** and **Table 8**.

In the case of rainfall variables, the SFWMM 36-year simulation period was not significantly different from the previous AMO warm period. An exception may have occurred during the month of April, when many of variables indicated differences between the two AMO periods. Flows at S-65 and S-65E show significant differences during most of the wet season and in the early dry-season month of November. This difference may be partly due to regulation of the Kissimmee Basin. However, such a change due to management is not relevant for the issue of 2x2 modeling since the current modeling approach already accounts for hydrologic changes due to regulation of the Kissimmee Basin lakes and Kissimmee River.

Table 7. p-values for t-statistic for comparison of means of rainfall and flow values between the 2x2 simulation period (1965–2000) and the preceding period (1929–1964). Values in bold type indicate variables for that month that have significant differences in mean at 5 percent level.

	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	Ukiss	0.29	0.74	0.61	**0.01**	0.71	0.76	0.55	0.87	0.11	0.52	0.39	0.41
	Lkiss	0.25	0.66	0.87	**0.01**	0.43	0.60	0.48	0.69	0.10	0.45	0.18	0.43
	KissRF	0.26	0.71	0.74	**0.01**	0.62	0.95	0.52	0.81	0.09	0.48	0.31	0.40
	BigCyp	0.20	0.41	0.98	0.28	0.26	0.30	0.26	0.72	**0.02**	0.37	0.16	0.23
	EAA	0.07	0.27	0.67	0.10	0.88	0.74	0.96	0.70	0.10	0.29	0.19	0.86
	Everglades	0.28	0.41	0.99	0.33	0.66	0.18	0.06	0.36	0.06	0.25	0.30	0.27
	LOK	0.15	0.57	0.66	**0.01**	0.66	0.75	0.61	0.87	0.09	0.46	0.12	0.56
	WCA3	0.14	0.19	0.72	0.24	0.69	0.27	0.15	0.61	0.06	0.36	0.18	0.45
	WCA12	0.06	0.10	0.36	0.15	0.67	0.22	0.95	0.82	0.16	0.41	0.23	0.62
	WestAG	0.12	0.36	0.71	0.14	0.40	0.43	0.66	0.93	**0.03**	0.54	0.08	0.44
	Caloos	0.14	0.75	0.60	**0.03**	0.50	0.53	0.82	0.16	0.07	0.68	0.08	0.45
	SWCoast	0.25	0.85	0.71	0.08	0.38	0.42	0.88	**0.04**	**0.05**	0.61	0.16	0.36
	Browrd	0.12	0.10	0.24	0.25	0.70	0.12	0.74	0.50	0.29	0.51	0.23	0.48
	Dade	0.27	0.28	0.97	0.26	0.90	0.18	**0.02**	0.26	0.26	0.17	0.32	0.43
	MartSLC	0.08	0.20	0.48	**0.03**	0.86	0.59	0.32	0.69	0.14	0.13	0.07	0.72
	Pbeach	**0.05**	0.21	0.54	0.12	0.60	0.37	0.91	0.59	0.19	0.17	0.08	0.81
	Div4rf	0.32	0.98	0.68	**0.00**	0.98	0.88	0.26	0.94	0.06	0.43	0.24	0.45
	Div5rf	0.17	0.62	0.71	**0.04**	0.95	0.76	0.27	0.61	**0.03**	0.61	0.14	0.69
	Div6rf	0.18	0.18	0.60	0.21	0.69	0.14	0.93	0.32	0.26	0.18	0.10	0.80
	Div7rf	0.20	0.92	0.37	0.42	0.31	**0.05**	0.10	0.51	0.41	0.35	1.00	0.99
Flow	S-65E	0.24	0.93	0.70	0.85	0.19	**0.04**	0.25	0.77	**0.01**	**0.00**	**0.00**	**0.00**
	S-65	0.79	0.20	0.23	0.08	0.41	**0.00**	0.16	0.56	0.08	**0.00**	**0.00**	**0.02**
	LONIN	0.74	0.57	0.34	0.21	**0.01**	0.19	0.77	0.91	**0.00**	**0.03**	**0.04**	**0.03**

Table 8. p-value for the Kolmogorov-Smirnov test for comparing rainfall and flow distributions of **2x2** simulation period (1965–2000) and the previous 36-year period (1929–1964). Values in bold type indicate variables for that month that have significant differences in mean at 5 percent level.

	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	Ukiss	0.46	0.46	0.30	**0.01**	0.66	0.85	0.97	0.30	0.30	0.46	0.30	0.85
	Lkiss	0.46	0.66	0.85	0.10	0.66	0.85	0.85	0.66	0.18	0.66	0.66	0.85
	KissRF	0.46	0.46	0.46	0.06	0.66	0.85	0.97	0.46	0.46	0.85	0.18	0.85
	BigCyp	0.18	0.18	0.85	0.66	0.30	0.30	0.30	0.85	0.10	0.30	0.46	0.85
	EAA	0.18	0.10	0.46	**0.03**	0.85	0.66	0.85	0.97	0.30	0.18	0.10	0.66
	Everglades	0.10	0.46	0.97	0.66	0.66	0.66	**0.01**	0.85	0.30	0.18	0.85	0.66
	LOK	0.10	0.46	1.00	0.10	0.30	0.85	0.66	0.97	0.18	0.46	0.46	0.66
	WCA3	0.10	0.10	0.85	0.46	0.85	0.66	**0.03**	0.85	0.18	0.10	0.46	0.85
	WCA12	0.10	0.10	0.85	0.10	0.85	0.66	0.85	0.85	0.66	0.46	0.66	0.66
	WestAG	0.10	0.18	0.66	0.18	0.66	0.46	0.97	0.66	0.18	0.46	0.18	0.66
	Caloos	0.30	0.46	0.46	0.30	0.66	0.97	0.97	0.18	0.18	0.85	0.66	0.85
	SWCoast	0.30	0.85	0.85	0.30	0.46	0.66	0.85	**0.01**	0.18	0.85	0.85	0.66
	Browrd	0.18	0.30	0.30	0.30	0.66	0.30	0.85	0.46	0.66	0.30	0.66	0.97
	Dade	0.30	0.30	0.30	0.30	1.00	0.46	**0.01**	0.85	0.85	0.18	0.66	0.97
	MartSLC	**0.03**	0.18	0.66	0.06	0.66	1.00	0.85	1.00	0.30	0.18	0.66	0.66
	Pbeach	0.10	0.18	0.97	0.10	0.97	0.46	0.66	0.46	0.46	0.30	0.18	1.00
	Div4rf	0.66	0.46	0.30	**0.01**	0.85	0.97	0.66	0.85	0.10	0.46	0.18	0.97
	Div5rf	0.30	0.18	0.85	0.18	0.85	0.97	0.30	0.97	0.10	0.46	0.66	0.46
	Div6rf	0.10	0.46	0.85	0.18	0.46	0.30	0.46	0.85	0.46	0.18	0.46	1.00
	Div7rf	0.46	0.85	0.85	0.18	0.66	0.46	0.06	0.66	0.46	0.18	0.97	0.97
Flow	S-65E	**0.01**	0.18	0.06	0.46	0.46	**0.03**	**0.01**	0.18	0.10	**0.00**	**0.00**	**0.00**
	S-65	**0.02**	**0.04**	**0.04**	0.08	0.21	**0.00**	**0.00**	**0.02**	**0.02**	**0.00**	**0.00**	**0.00**
	LONIN	**0.03**	0.85	0.85	0.18	0.10	0.46	0.46	0.85	**0.03**	0.10	**0.01**	**0.00**

V. USE OF CLIMATE OUTLOOK IN OPERATIONS

Lake Okeechobee Regulation Schedule Development

Seasonal and multi-seasonal climate outlooks have also been incorporated into the federal operational rules for Lake Okeechobee. Traditional rule curves (or regulation schedules) for reservoir operations are "static" in the sense that operational decisions are made only when the reservoir stage crosses a predetermined curve. In 1998, the SFWMD developed a "dynamic" regulation schedule for Lake Okeechobee known as Water Supply and Environment (WSE) that incorporates not only the seasonal and multi-seasonal climate outlooks, but also the near-term (two-week) forecasts of tributary inflows into the Lake. The schedule, adopted by the USACE in July 2000, consists of (a) a set of regulation schedule lines that define different operational zones; and (b) decision trees that support the process for making discharges based on forecasts of inflows and climate outlook. The climate-based operational guidelines as incorporated into the WSE regulation schedule have emerged as a highly desirable approach for Lake Okeechobee water management.

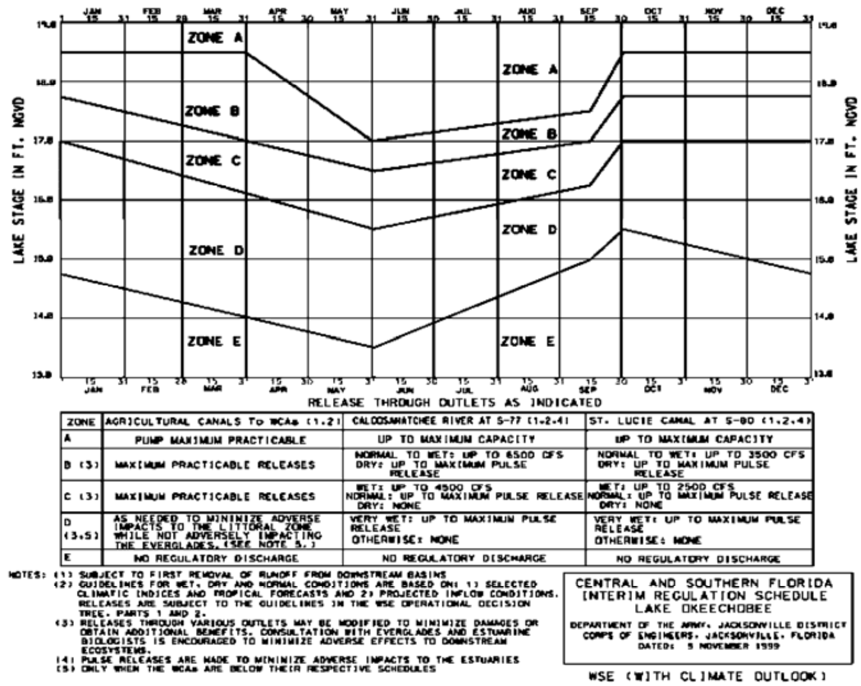
Diagrams representing the two parts of the WSE schedule are presented in **Figure 19**. The decision to hold water in the Lake or make releases to tide is primarily determined by Lake water levels, the time of year, and conditions in other parts of the regional systems (**Figure 19 Panel A**). These water levels were established primarily based on historical data and experience with Lake operations over the past several decades. Meteorological conditions, including forecasts and long-term trends, are considered in the operational decision tree (**Figure 19 Panel B**) to determine whether discharges to tide are necessary.

WSE was the first regulation schedule in South Florida that formally and explicitly utilized seasonal and multi-seasonal climate outlooks as guidance for regulatory release decisions. The WSE schedule has been modified recently to use the AMO and ENSO states in estimating the Lake Okeechobee Net Inflow Outlook (LONINO) for the future 6 to 12 months. Adoption of a decision tree with climate outlook as a component of the WSE schedule was a unique feature in the operation of Lake Okeechobee, and was a major shift from the traditional rule curves that are used to operate large reservoirs elsewhere in the country and the world.

During WSE development, the SFWMD conducted a performance test using available Lake net inflow data beginning in 1914. The results of that effort were presented at public meetings prior to the adoption of WSE. Although the 1914–1964 period appeared to be somewhat wetter than the 1965–2000 period documented in the Environmental Impact Statement (EIS), the WSE schedule still outperformed other regulation schedules considered at that time. This evaluation was based on the analyses of the type shown in **Figure 20**, which consider effects on water supply, flood protection, and environmental systems.

Overall operational strategy was simulated to improve conditions with respect to five major competing water management objectives (**Figure 20**). This improvement was estimated for the climatological regime during the 1965–1995 period by five performance measures: (1) a decrease by 3 percent in the undesirable Lake Okeechobee water level events for the Lake littoral zone, (2) an increase by approximately 4 percent of the Lake Okeechobee Service Area water supply needs being met during drought years, (3) improved hydropattern for the Everglades, (4) a decrease in the number of times undesirable high discharge criteria were exceeded for the estuaries, and (5) lower Lake water levels during the peak of the hurricane season.

A



B

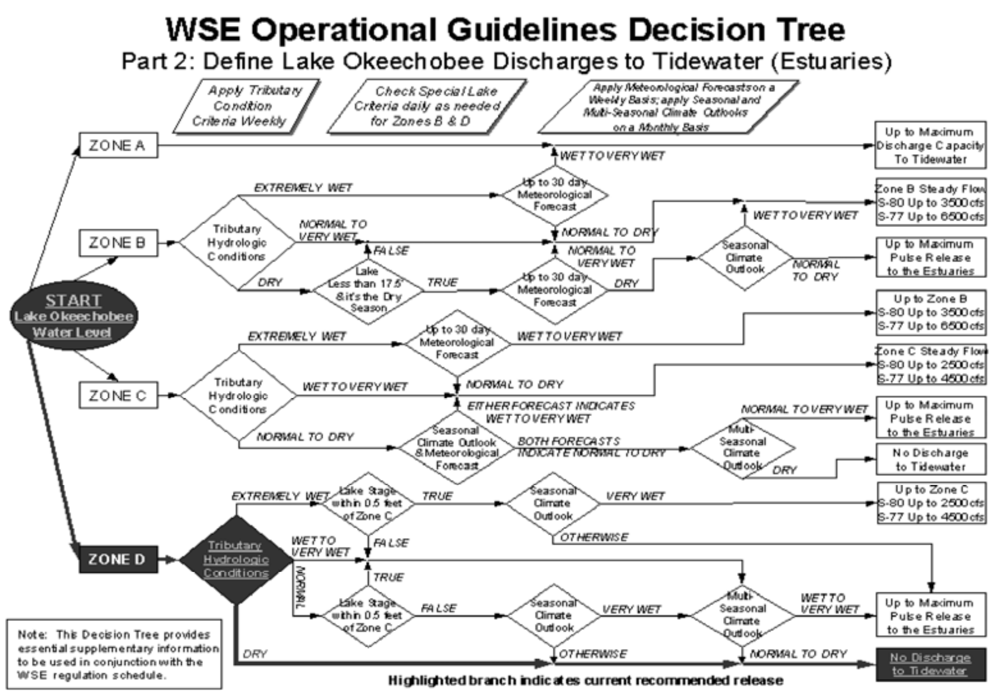


Figure 19. (A) Water level criteria used to identify different lake management zones and potential needs for water releases based on water supply, flood control, and environmental considerations. **(B)** Operational decision tree used to help determine timing and volume of water releases based on water levels, estimated inflows, and climate forecasts.

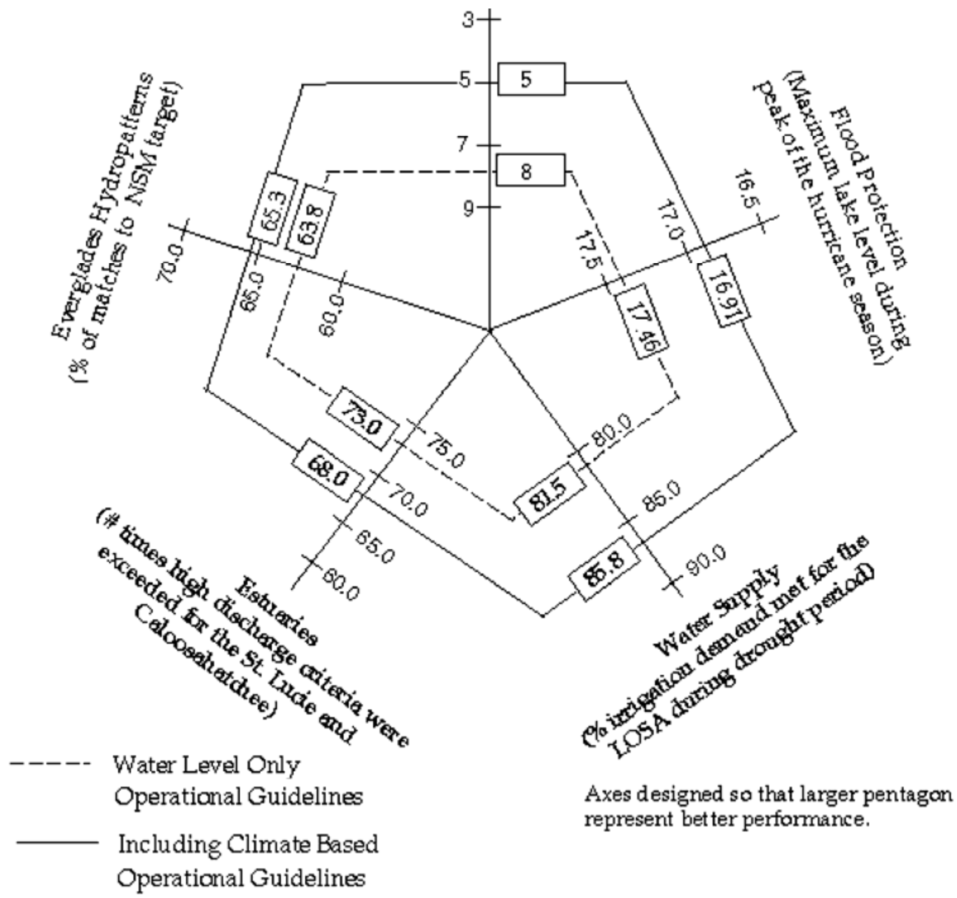


Figure 20. Multi-objective tradeoff analysis showing improvement with climate-based operation of Lake Okeechobee.

When the regulation schedule was evaluated, it was unclear whether the apparent trend to a drier hydrologic condition was due to changes in regional-scale precipitation patterns associated with drainage and development in South Florida (Chen et al., 2001; Mattocks and Trimble, 2000; Mattocks et al., 1999; Pielke et al., 1999), natural climatic variability (Enfield et al., 2001; Zhang and Trimble, 1996a,b; Trimble et al., 1998b,c; Trimble and Trimble, 1998), long-term global climate change, or rainfall–runoff relationships altered by infrastructure changes. As data were much sparser before 1965, it was not clear whether wetter periods such as the 1940s and 1950s would re-occur or whether South Florida's declining rainfall trend would continue.

During the 1970s and 1980s, the remnant Everglades experienced prolonged undesirable dry conditions. From an ecological perspective, it seemed highly desirable for any new Lake schedule to route regulatory discharges southward to the Everglades at lower Lake water levels for the benefit of the littoral zone, the Everglades, and the Caloosahatchee and St. Lucie estuaries. WSE was designed to achieve these goals. To account for a possible return to persistent, much wetter conditions, WSE was designed to allow regulatory releases to tidewater at stages that were almost 2 feet lower than the previous schedule allowed.

The SFWMD and USACE have further modified the WSE schedule to incorporate the potential presence of a wetter climatic regime that appears to have begun in the mid-1990s. In 2003, after four years of WSE operation, the WSE decision trees were adjusted to improve performance during wet periods. The re-evaluation led to adjustments of several WSE parameters including the LONINO (USACE, December 2004).

The USACE secured several other minor temporary deviations (2004, 2005, and 2006) to the Water Control Plan to allow releases in pulses up to Level 1, if necessary, under conditions that the WSE decision tree called for no releases. These temporary deviations are identified in the plan as tools that can be used as adaptive management strategies to address unusual conditions.

Completion of the 1999 C&SF Project Comprehensive Review Study (Restudy) led to the development of CERP (USACE and SFWMD, 1999). When CERP planning began in the mid-1990s, there was little published information on relationships between global climate states and South Florida rainfall. As CERP planning continued through the late 1990s and predictive relationships were developed, it was suggested that climate outlook information should be used to help guide the design and operation of some CERP components. Those components included the regional Lake Okeechobee Aquifer Storage and Recovery (ASR), the Everglades Agricultural Area (EAA) Storage Area, and the Lake Okeechobee Regulation Schedule study.

POSITION ANALYSIS

Seasonal and multi-seasonal operational planning of major water resources systems requires a careful evaluation of likely future scenarios of water and environmental conditions that influence management objectives. It is common practice to use computer simulation models to determine likely outcomes of both short- and long-term management options. The SFWMD uses position analysis as a form of risk analysis that can forecast uncertainties associated with a specific operating plan for a basin over a period of many months conditioned on the current state (e.g., reservoir storages) of the system (Hirsh, 1978; Smith et al., 1992; Tasker and Dunne, 1997; Cadavid et al., 1999). The District relies on generating a large number of possible traces with durations of one or more seasons for the hydrologic variable of interest (e.g., reservoir stages or flows), using the same initial conditions and broad ranges of meteorological conditions that may occur in the future but cannot be forecast accurately. Future likely meteorological conditions may be derived using such methods as extended streamflow prediction (Day, 1985), historical data, and stochastic simulation models (Tasker and Dunne, 1997).

Ideally, to include effects of long-term climate cycles such as AMO and PDO, the dataset should span 100 years or more. The 36-year dataset that is generally available for the South Florida system allows consideration of only shorter-term phenomena, such as ENSO and sunspot cycles, that have return frequencies of 10 years or fewer.

Cadavid et al. (1999) defined the terms Conditional Position Analysis (CPA) and the Unconditional Position Analysis (UPA) depending on whether or not the estimated risks incorporate climate outlook (e.g., La Niña conditions that affect the likely inflows to the reservoir system). The objective of the CPA is to estimate the risks of the future response of the system given both the current state and the future climate forecast. The methodology adopted for CPA (Cadavid et al., 1999) follows a procedure described by Croley (1996). Croley's method includes an optimization procedure that provides a set of weights for different traces, and these weights reflect information provided by the climate forecasts. For example, if an El Niño condition is predicted and larger reservoir inflows are possible during this condition, the traces that are associated with El Niño years would have larger weights.

During the past decade, position analysis concepts developed by the District have been used with increasing effectiveness to assess risks associated with seasonal and multi-seasonal operations of the water management system and communicate the projected outlook to decision makers, agency partners, stakeholders, and the public. While the District has used position analysis chiefly to project the expected stage of Lake Okeechobee, it has also used the technique for other impoundments, including the WCAs. Monthly position analysis has become an important tool for making operational decisions that may have implications for multiple seasons.

VI. INCORPORATION OF CLIMATIC VARIABILITY IN WATER RESOURCES PLANNING

Incorporating uncertain climatic tendencies into a long-range planning process calls for careful analysis to allow balance among risks, costs, and benefits. It may be expensive to provide areas for open storage for flood control, for example, based on an expectation that the next several decades will be wetter. Construction and operation of such storage facilities may also cause significant long-term environmental impacts. Plans must also consider the possibility that droughts may occur during an overall wetter climatic regime and, therefore, include provisions for long-term carryover water storage capacity.

Figure 18, which shows the distribution of annual net inflow to Lake Okeechobee for the period from 1913 to 2005, provides a general indication of relative inflows to the major regional storage facilities planned in CERP, and can be used as a basis to estimate how cost effectively the proposed CERP projects may address hydrometeorological extremes. This figure indicates that during the 1913–2005 period of record, there are only five years (roughly 5 percent of this period) when the volumes of inflow had the potential to exceed the inflow extremes reflected in the 1965–2000 period of record that was used in CERP planning studies. These five years experienced extreme inflows, which exceeded the highest flows of the 1965–2000 period, and ranged from approximately 5.0 to 5.9 million acre-feet (ac-ft). These values were up to 20 percent greater than the maximum inflow of 4.9 million ac-ft that occurred during 1969 within the 1965–2000 planning period. As previously noted, these extreme flows occurred before major water control facilities were completed in the Upper Kissimmee Basin and Kissimmee River floodplain. These facilities provide improved capability to control water levels and flows, and could have allowed water managers to better regulate the rate of inflow to Lake Okeechobee, providing more time for redistribution, evaporation, and infiltration of excess surface water.

Recent cost estimates for the three largest reservoirs contemplated in CERP total approximately $1 billion. For discussion purposes, assuming that capturing this additional peak inflow would require a linear increase in reservoir capacity and construction costs, then it would cost approximately $200 million more to accommodate an additional inflow that could be reasonably expected to occur once every 20 years (USACE and SFWMD, 1999). Facilities proposed in CERP typically have a design life span between 50 and 75 years. Therefore, such extreme inflow conditions may occur only two to three times over the life of the project. In this example, regional facility planning should balance the cost ($200 million) for this protection from two or three extreme inflow events against potential damages or losses. The planning and design process could involve engineers and water managers in a public process, with input from concerned citizens and stakeholders, to determine whether the increased capacity would be cost effective over the life cycle of the project.

There are many ways that water resources planning for future changes to the system may account for uncertainties caused by natural climatic variability such as those attributed to AMO. The methods that are being used by the District are:

1. Sensitivity analysis of planning simulations
2. Continual expansion of the simulation period to include more AMO warm-phase years
3. Adaptive management in facility planning and implementation

SENSITIVITY ANALYSIS

Several efforts have been undertaken to investigate the implications of climate shifts in South Florida. This section explains a sensitivity analysis that was conducted to ascertain the impacts of climate shifts. The District used the SFWMM in 1996 to simulate system performance for precipitation values that were 10 percent higher and lower than the base values. Results are shown in **Figure 21**. A 10 percent shift in average rainfall (i.e., ± 5 inches) is considered as an extreme change. The average rainfall District-wide is approximately 52.1 inches. The District-wide mean increases during the AMO warm phase by 1.8 inches to about 53.9 inches and decreases during the cool phase by 1.5 inches to 50.6 inches. The change of ±10 percent, therefore, represents a shift approximately three times greater than can be expected to occur due to temperature cycle effects.

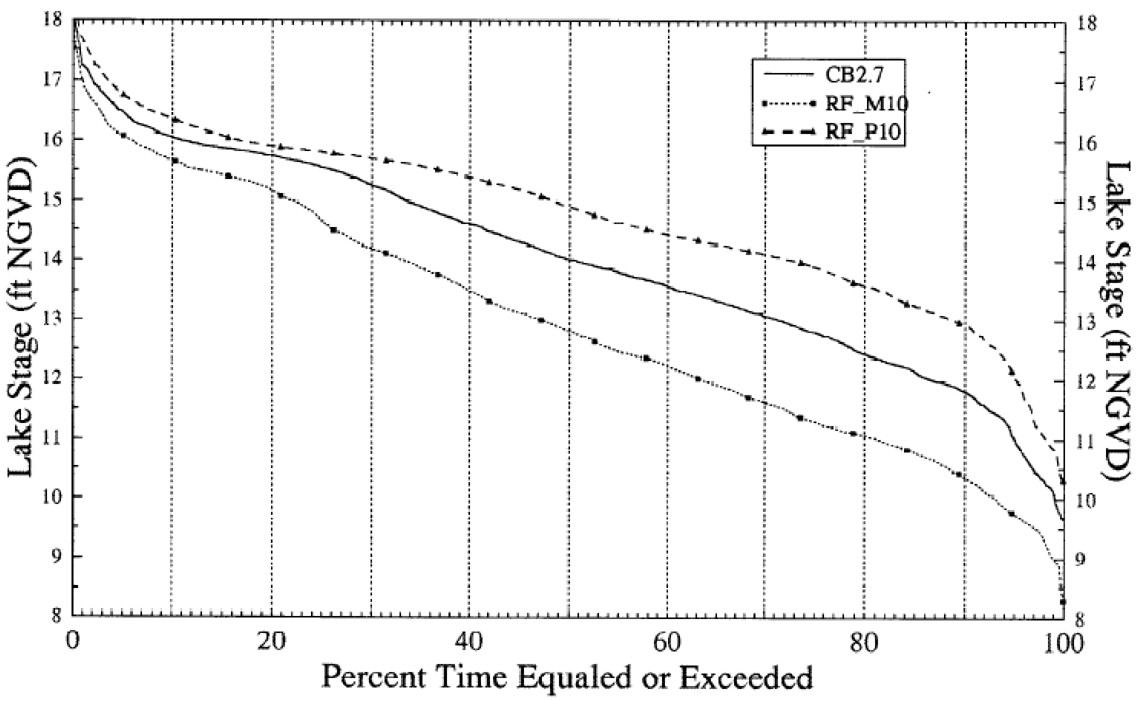


Figure 21. Results of SFWMM model simulation to estimate lake stage in Lake Okeechobee using actual precipitation data for the period from 1965 to 1995 (CB2.7), precipitation data increased by 10 percent (RF_M10), and precipitation decreased by 10 percent (RF_P10).

In this simulation, the base alternative (CB2.7) included the 1990 land uses. A second alternative (RF_M10) was based on the same period of simulation with the rainfall decreased by 10 percent, whereas the third alternative (RF_P10) had rainfall increased by 10 percent. This study substantiated the importance of including climate forecasts and climate shift indicators in future model development. As a result, subsequent model development integrated climatic variability as a key parameter and sensitivity analyses as a standard of performance. While this study shows the system responses to large changes in rainfall in the tributary basin, it may not be practical or feasible to plan for such changes that have large uncertainties. A similar sensitivity analysis has been conducted to investigate implications of potential sea level rise.

CONTINUAL EXPANSION OF SIMULATION PERIOD OF SFWMM

The choice of a period of simulation in any hydrologic model requires careful analysis of temporal and spatial density of data for rainfall, evapotranspiration, and required discharges at the boundaries of the model. Sparseness in the data, both temporally and spatially, can introduce unrealistic trends in long-term modeling results. Therefore, modelers typically evaluate the modeling objectives with respect to data availability to determine reasonable beginning and end dates for historical information.

During the early 1980s, the SFWMM model developers originally chose to use an input dataset from the 1969–1982 period to simulate alternative structural and operational changes to the system, because the period represented the most accurate and complete combination of hydrological, meteorological, and physical system information available at the time. The model datasets for the Lower East Coast Regional Water Supply Plan during the early 1990s were increased to allow simulations for rainfall years 1965–1990. Before the start of Everglades Restudy modeling in the mid-1990s, the 1991–1995 period was added. Further evaluations of the WSE schedule and CERP have used the current 36-year simulation period (1965–2000).

Lack of sufficient spatial coverage of rain gauges and weather stations makes it impractical expand the range of years used in simulations to earlier years (prior to 1965). However, District modelers are continually investigating methods that allow simulations to include more years during both drier and wetter periods. Because proposed infrastructure changes will be implemented over decades, the District will be able to evaluate future system changes with datasets that include more wet years, if the current AMO warm phase and above-normal rainfall conditions continue.

ROLE OF ADAPTIVE MANAGEMENT IN PLAN IMPLEMENTATION

The SFWMD uses an adaptive management approach to incorporate new information about climate and hydrologic conditions in South Florida into regional modeling for facility planning and operations. Information obtained from scientific research and monitoring is evaluated by District scientists and managers, and used as a basis to modify or adjust operational policies and procedures and potentially to redesign projects and facilities. Water managers use adaptive principles as a means to test or experiment with new concepts and effectively "learn by doing." The planning and implementation of projects associated with CERP over a period of decades makes adaptive management an effective means for incorporating climatic variability.

To apply adaptive management effectively, system responses must be continually monitored and management actions adjusted to ensure that the desired outcomes are achieved. Application of adaptive management principles is especially appropriate, and often required, in situations where there is a substantial amount of uncertainty regarding how management activities affect hydrologic conditions.

Effective adaptive management involves a sequenced approach to information types and analysis procedures, including:

- Develop hypotheses about ecosystem structure and function, and relationships between particular management goals and actions and anticipated system responses.
- Identify information needed to test hypotheses and assess overall system responses.
- Conduct field operations or tests to manipulate/control/or modify water management system features.
- Perform effective monitoring and evaluation of hydrologic and system responses in response to natural or induced changes.
- Conduct research necessary to investigate/define/redefine hypotheses.
- Implement a process to systematically modify plans features or operations based on monitoring data and measured outcomes.

Modeling, an important tool used by the SFWMD throughout the adaptive management process, provides a means to rapidly and relatively inexpensively develop, test, and screen hypotheses that can help identify modifications or design features most likely to produce the desired results, and determine which aspects are best tested in field-scale experiments, which features of the system may be most important to monitor, and what are the likely effects of proposed changes on system components or operations. In the case of climatic variability, models can be used to simulate alternative future rainfall conditions of higher rainfall or to effectively extend the period of hydrologic simulations backward in time to include additional years in an AMO warm phase.

Adaptive management is a cornerstone of CERP, whose implementation will span decades. Projects designed and constructed under CERP are required to incorporate adaptive management considerations within their operating rules. The CERP project designs and their actual operation are evaluated as a composite on a five-year cycle, to test the assumptions that were originally used in their development and determine whether changing conditions or improved knowledge identify the need for change. Climatic indicators, trends, and global warming issues will play a key role in these overall system reviews.

Modeling is central to CERP adaptive management, as shown in **Figure 22**. System-wide performance measures are defined by scientists participating in the restoration process and expressed in quantitative hydrologic terms. These performance measures are provided to the modelers and translated into a form that can be generated by output files from the regional computer models. Performance measures may be further refined based on results of research or monitoring studies. The regional models are used to simulate the effects of various CERP projects and alternative scenarios. The consequent model results, expressed in terms of the hydrologic performance measures, are then evaluated by Everglades scientists. The final step is an overall assessment through the RECOVER process to determine whether the goals of CERP are being achieved by the completed projects. This assessment may result in suggested changes to the projects themselves, to the monitoring program, and/or to the models and performance measures.

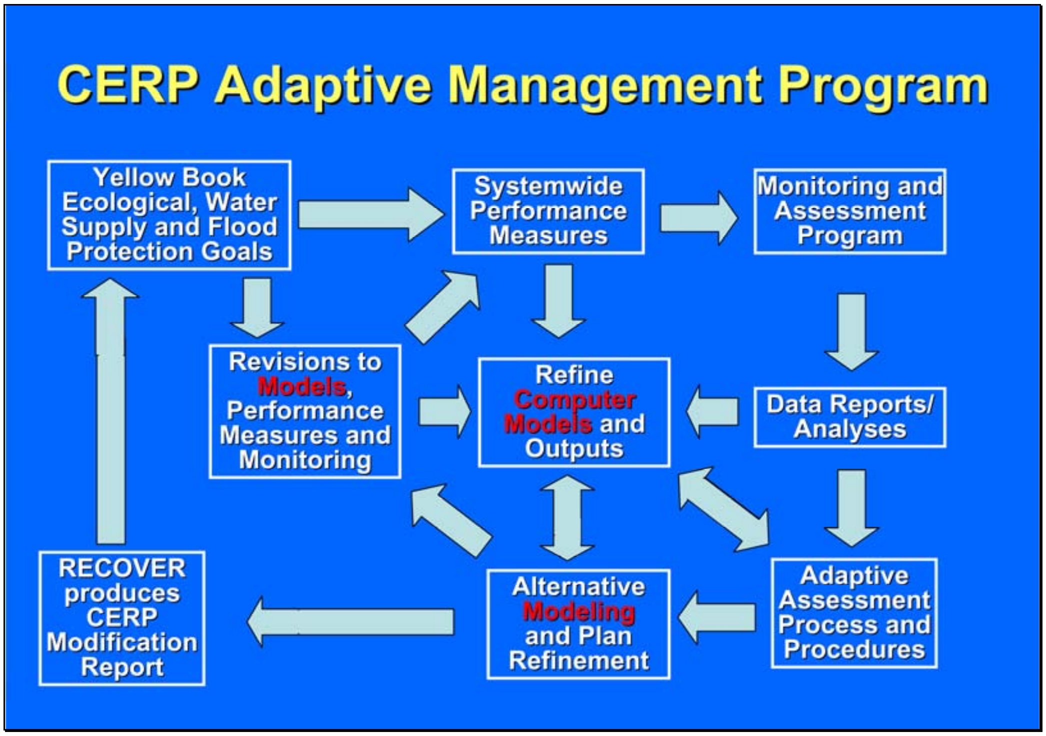


Figure 22. Geographical locations of AMO, PDO, and ENSO teleconnections related to schematic diagram of CERP adaptive management, indicating the central role of modeling in this process.

V. SUMMARY AND CONCLUSIONS

The choice of climatic conditions used for planning and operations of complex water resources systems involving multiple objectives is an important consideration for success of future projects. Climate change and variability due to natural and anthropogenic causes are not fully understood and their prediction carries considerable uncertainties. Climate change and variability, which always have been of interest to the SFWMD, have become increasingly important during the last two decades. Applied research conducted and supported by the SFWMD has been published in peer-reviewed literature and has been widely recognized by other researchers, agencies, and institutions. Results from these studies have been selectively incorporated into SFWMD water resource modeling, planning, and operational programs.

ENSO, AMO, and PDO are large-scale climatic indicators that have implications for water resources and planning in South Florida. Of these three indicators, ENSO, which follows a three- to seven-year cycle, has the strongest effect on South Florida climatic conditions, and has received the most study. The PDO may last for decades and affects South Florida weather in a manner similar to ENSO, but with much less influence. The AMO has weaker effects than ENSO, but the cycles could span several decades. The AMO warm phase is associated with slightly higher, but more variable, rainfall conditions in South Florida.

Research on AMO and PDO influences indicates a significant variability in the periodicity, duration, and magnitude of these multidecadal climatic indicators and their effects on South Florida weather. Furthermore, the relationships between these indicators and regional weather patterns or rainfall conditions in South Florida cannot be accurately predicted. Hydrologic variation not only changes the amount of rainfall but also the spatial and temporal distribution.

The SFWMD has incorporated consideration of climate trends into its modeling and operations decision-making processes. Notable examples include application of the WSE schedule and position analysis techniques to guide the regulation of water releases into and out of Lake Okeechobee. The SFWMD is also proceeding cautiously to address long-term climate changes in its planning processes through an adaptive management approach, collecting new data and periodically reviewing project designs and operations based on new information.

The SFWMD uses complex regional models effectively as tools to aid in water resources planning and management in conjunction with standard engineering practices. Its regional model, the SFWMM, incorporates a period of the South Florida hydrologic record (1965–2000) that includes a broad range of wet and dry years. This period of record is shown to include years with both excess and deficient rainfall that are comparable in magnitude and duration to extreme conditions that occurred prior to 1965. Although it would be desirable to expand the hydrologic basis of the SFWMM to include more years from the AMO warm phase, especially during the period from 1927 to 1964, there is a lack of hydrologic data and operational parameters for the water management system before 1965. The SFWMD will continue to expand the modeling period forward to include the current AMO warm period as new data become available.

By periodically extending the simulation period, the SFWMD can continually incorporate recent climate trends and re-evaluate proposed infrastructure changes, including CERP projects, that will be designed and constructed over a period of several decades. This adaptive approach follows standard engineering and operational planning practices and provides a means to reduce the risks of facility implementation when climate changes are inherently uncertain.

The SFWMD has also effectively incorporated the potential effects of future climate shifts and variability into operations of the regional water management system. The use of climate outlooks as a consideration for regulation of water levels in Lake Okeechobee is an example of this effort. Moreover, the SFWMD continuously re-evaluates the implementation of this WSE regulation schedule to include adjustments that account for changes in climatic indicators such as ENSO and AMO.

The SFWMD continues to rely on timely information about climate patterns and change for planning, design, and operations to meet its mission to manage and protect water resources of the region by balancing and improving water quality, flood control, natural systems, and water supply.

VI. RECOMMENDATIONS

Specific recommendations using long-term climate forecasts in District planning and operations, not necessarily in order of importance, are as follows:

1. Continue to incorporate new climatologic data into its modeling efforts to reflect developing trends in climate change.
2. Investigate alternative methods that can be used to extend the modeling period backward to incorporate climatic conditions that existed before 1965.
3. Further refine the analysis of rainfall relationships to the volume of runoff into Lake Okeechobee, especially to examine specific antecedent conditions that occurred prior to large inflow events during the 1930s, 1940s, and 1950s, and the relative roles of tropical storms/hurricanes and water management practices.
4. Review the adaptive management approach to ensure that climatic variability is adequately addressed in CERP implementation. Careful monitoring and evaluation during their design, construction, and operational phases, in conjunction with information derived from continued hydrologic monitoring and improved climate change predictions methods, will be used to refine and modify these projects as necessary to address changing conditions.
5. Explore the use of synthetically generated rainfall data that account for climate shifts due to accepted teleconnections such as AMO and ENSO.
6. Continue the SWFMD climate research program to investigate further the utility of global climate teleconnections for improving the management of existing and proposed water resources facilities. Results of this applied research should be included, as appropriate, in the development of operating plans.

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