

Consideration of Climate Variability in Water Resources Planning & Operations – South Florida's Experience

Jayantha Obeysekera[1], Paul Trimble[2], Cal Neidrauer[3], and Luis Cadavid[4]

[1]Hydrologic & Environmental Systems Modeling Department; jobey@sfwmd.gov
[2]Hydrologic & Environmental Systems Modeling Department; prtimble@sfwmd.gov
[3]Operations Control & Engineering Department; cal@sfwmd.gov
[4]Hydrologic & Environmental Systems Modeling Department; cadavid@sfwmd.gov
South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, Florida 33406.

Abstract

Climate in any region is the result of both short- and long-term phenomena interacting at local, regional and global scales. In South Florida where major changes to the water resources infrastructure are being contemplated for facilitating the restoration of large-scale ecosystems such as the Kissimmee River Basin and the Everglades, consideration of climate variability on scales ranging from intra-seasonal to multi-decadal is extremely important in both water resources planning and regional operations. Correlations of hydro-climatology of South Florida to such global phenomena as El Nino-Southern Oscillation (ENSO) and Atlantic Multi-Decadal Oscillation (AMO) have been investigated extensively. This paper provides an overview of the climatic indicators and the teleconnections that are significant for south Florida. In particular, the application of the research to develop regulation schedules for the operation of Lake Okeechobee as well as the real-time implementation of rules based on climate outlook are discussed. The use of computer modeling as a tool for the design of operating rules as well as real-time operations is also included.

Introduction

In response to massive flooding that occurred in South Florida due to numerous hurricanes in the 1940s, the Central and Southern Florida Flood Control District (FCD), a state agency, was created as the local sponsor for an extensive federal flood control project developed and implemented by the U. S. Army Corps of Engineers (USACE). The FCD, renamed as the South Florida Water Management District (SFWMD), with a broader mission today, has the primary responsibility for management of water resources in a 16-county region that extends from just south of

Orlando to Florida Bay. Today's water management system with nearly 2,000 miles of canals and levees, 546 water control structures, and 51 pump stations is extremely complex, not only in its configuration, but also in its operation. The system will become even more complex as the State of Florida, in cooperation with USACE and other state/federal agencies, implements unprecedented changes to restore the Kissimmee and Everglades ecosystems.

Climate change and variability can influence large regional water management systems that include large lakes, storage reservoirs, extensive tributary watersheds, and large water-use basins. Climate in any region is the result of both short- and long-term phenomena interacting at local, regional and global scales. Reasons for long-term climatic shifts and changes are not completely understood and therefore significant uncertainties exist in climate forecasts. The relative influence of anthropogenic and natural factors on global weather patterns remains a highly debated topic but historical data can be analyzed to understand and potentially use climate regime shifts.

During the 1970s and 1980s, little was understood about global climate variability or how to apply relevant data to water resources planning or system operation. At that time, engineers and scientists at SFWMD were trying to comprehend a climate shift that occurred throughout the South Florida region during the late 1960s (Shih, 1983). Since that time, scientists in South Florida have conducted extensive research to identify climatic indicators and develop methodologies to use them in both water resources planning and operations (Trimble and Trimble, 1998, Trimble et al., 1998a-c, Obeysekera et. al, 2000, Trimble et. al, 2006, Enfield et. al, 2001). The remaining sections of this paper provide a summary of such research and their implementation for planning and operation of the South Florida water management system. The focus is on long-term natural climate variability (ranging from inter-annual to multi-decadal time scales) rather than climate changes due to such causes as global warming.

Relevant Climatic Indicators

Statistical correlations between persistent shifts of atmospheric variables occurring in widely separated parts of the globe (or the universe in some cases) are called teleconnections. The most well known set of teleconnections associated with climate variability world wide is those associated with the El Nino-Southern Oscillation (ENSO) phenomenon (Bjerkins, 1969). Two other teleconnections of relevance to climate in South Florida are (a) Atlantic Multidecadal Oscillation (AMO, Enfield et al., 2001); and (b) Pacific Decadal Oscillation (PDO, Mantua et al., 1997). The correlations associated with these teleconnections generally result from shifts in atmospheric and ocean circulations (for locations see Figure 1). Previous research (Zhang and Trimble, 1996, Trimble and Trimble, 1998) has revealed that fluctuations in south Florida hydrology may have associatons to various types of solar activity that in part can be estimated by the sunspot cycle and fluctuations in geomagnetic activity. NASA (2000) identified several mechanisms through which such solar-climate relationships may exist. A brief description of ENSO, AMO, and PDO and their relationship to South Florida Hydrology are described below.

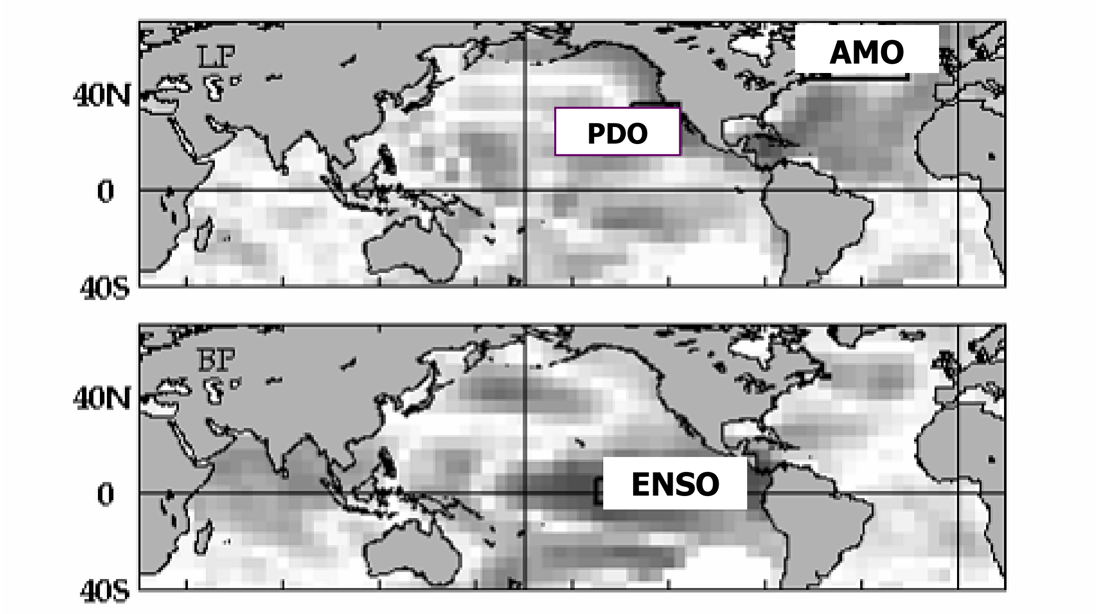

Figure 1. Geographical locations of AMO, PDO, and ENSO teleconnections related to climate in South Florida. (Figure adapted from Mestas-Nunez and Enfield, 2003.)

***El Nino-Southern Oscillation (ENSO)**:* The ENSO (http://www.cdc.noaa.gov/ENSO/) is a 2 to 7 year ocean-atmospheric oscillation in the tropical Pacific region that produces variation between two extremes (El Nino, the warm phase and the La Nina, the cool phase). During El Nino (La Nina) events South Florida tends to experience above (below) normal rainfall during the winter (Florida's dry season) months, Past SFWMD research has indicated that ENSO events have a significant correlation to net inflow into the Lake Okeechobee (Figure 2) during the dry season.

***Atlantic Multidecadal Oscillation (AMO)**:* The AMO is a secular climatic oscillation that is driven by quasi-periodic fluctuations in the sea surface temperature within the North Atlantic Ocean Basin (http://www.aoml.noaa.gov/phod/amo_faq.php). Each phase of these oscillations may persist for several years to several decades. There are significant year-to-year fluctuations in the instrumental records of ocean temperature that make it difficult to detect the exact period that AMO switches phases. The transition between phases is generally estimated by tracking a multi-year average of north Atlantic sea surface temperature anomalies (Figure 3). The AMO has been linked to spatial and temporal variability in precipitation and river flow throughout the United States (Enfield et al., 2001) and the world.(Knight et al, 2005; Goswami et al 2006; Lu et al 2006; Zhang and Delworth, 2006). The historical data also suggests (http://www.aoml.noaa.gov/phod/faq_fig3.php) that during the warm phases of the AMO, the number of tropical storms that mature into severe hurricanes can be at least twice as many as the number during cold phases.

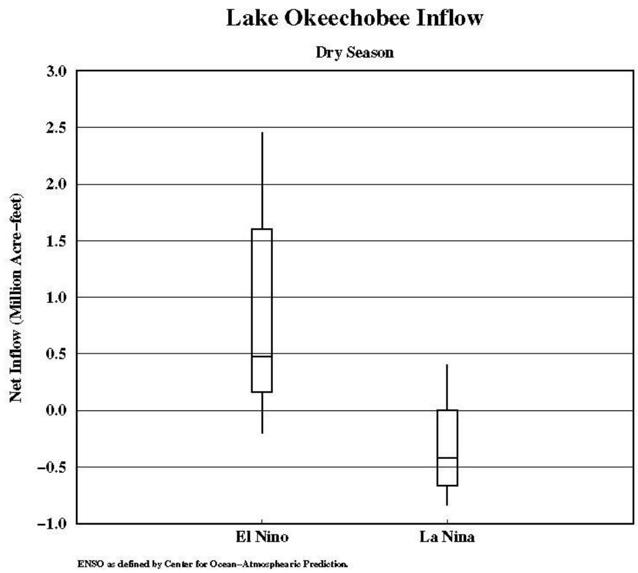

Figure 2. Box & Whisker plots of Lake Inflows during El Nino and La Nino conditions in the Pacific

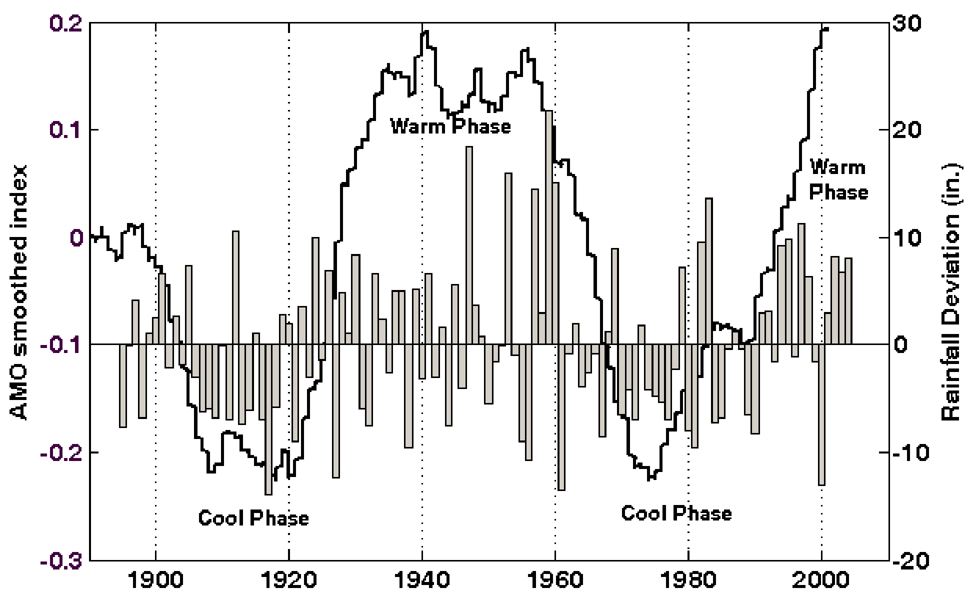

Figure 3. Time series of plot (solid line) of AMO (smoothed) index indicating “warm” and “cold” phases of AMO and their correspondence to rainfall deviations (from the long term mean shown as a bar chart) norh of Lake Okeechobee (Climate Division 4).

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). As seen from the rainfall deviations in Figure 3, South Florida appears to experience drier than normal rainfall during the “cool” phase of AMO. The opposite is true during the warm phase (eg. wetter years in the 40s and 50s) although this period is not consistently wetter and there are multi-year drought periods. 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. Interestingly, the AMO effect is opposite in North Florida (and elsewhere in US) in that when rivers in the peninsular Florida were in a multi-decadal period of higher flows, rivers in the north to northwestern part of Florida were in a low flow period (SWFWMD, 2004).

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 shows that the average length of the cycle is approximately 60 years, but individual cycles may vary considerably. 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). Enfield and Cid-Serrano (2006) recently made some probabilistic predictions of when the current warm period might end.

Pacific Decadal Oscillation (PDO)*:* The PDO (http://jisao.washington.edu/pdo/) is a pattern of Pacific climatic variability that somewhat resembles El Niño. 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.

The PDO affects the South Florida climate much like El Niño except that the frequency of the oscillation is on decadal 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.

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. For tropical weather and Florida hydrology, this seems to be the case. Similar but shorter lags may 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.

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. 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

Use of Climate Outlook in Operations

Advances in the ability to predict future climatic regimes have allowed this science to become a plausible mechanism for achieving more efficient regional water management in South Florida (Trimble et al., 2006; Cadavid et al., 2006). The best example of application of climate outlook for water management in South Florida is the operational schedule of Lake Okeechobee. Traditional rule curves (or regulation schedules) for operation of a typical reservoir are "static" in which decisions are made only when the reservoir level crosses a predetermined curve. In 1998, a climate-based regulation schedule for Lake Okeechobee was developed by incorporating not only the seasonal and multi-seasonal climate outlooks but also the near-term (two-week) forecasts of tributary inflows into the lake. The new schedule, known as the Water Supply and Environment (WSE), attempts to balance multiple objectives of managing Lake Okeechobee. Overall operational strategy in the development of the WSE schedule was to improve the performance with respect to five water management objectives associated with (a) maintain flood protection; (b) minimize urban and agricultural water supply shortages; (c) minimize damaging estuary discharges (c) improve Everglades hydroperiod; and (d) improve in-lake, littoral zone hydroperiod. Because of the competing nature of some of the objectives, a multi-objective trade-off analysis conducted by using a hydrologic simulation model which used the 1965-1995 period of record.

The final regulation schedule for Lake Okeechobee consisted of two main components: (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 (Figure 4). The climate-based operational guidelines as incorporated into the WSE regulation schedule have emerged as a highly desirable approach for Lake Okeechobee water management.

***<u>Implementation of climate based schedule</u>**:* The WSE schedule was adopted in July 2000. The weekly implementation of this operational schedule requires the following information: (a) current water level; (b) tributary hydrologic condition; (c) seasonal (6 months duration) and multi-seasonal (7-12 months in duration) climate outlook in terms of expected Lake Okeechobee Net Inflow. The USACE (2000) water control manual describes the methods which are used to estimate the required parameters to follow the decision trees. Every week on Tuesday, after the hydrologic and environmental data are collected and analyzed on Monday, an interdisciplinary team of scientists and engineers from the state and federal agencies meet to review the status of regional system and the implementation of WSE schedule.

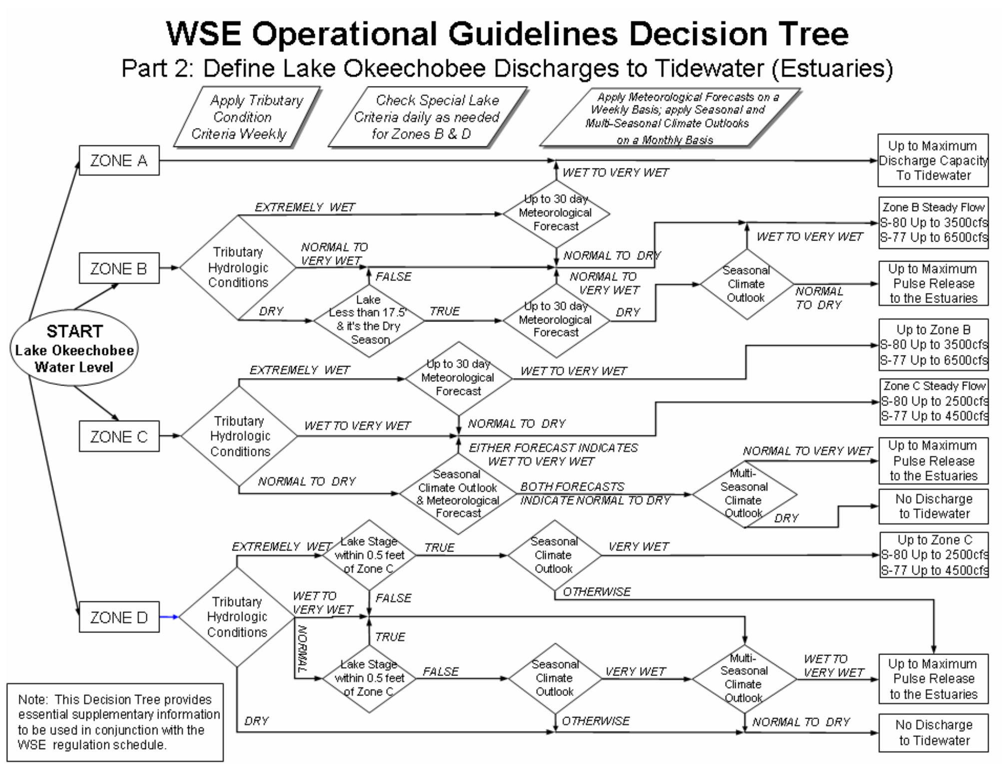

Figure 4. Part 2 of the Decision Trees associated with climate-based, WSE operational schedule for Lake Okeechobee

Climate Variability in Water Resources Planning

On a monthly basis, a form of Ensemble Streamflow Prediction (ESP) known as Position Analysis is used to provide probabilistic projections of Lake Okeechobee levels during the ensuing 12 month period given a specific operating plan but conditioned on the current state of the system (Hirsh, 1978; Cadavid et al., 1999; Cadavid et al., 2001). During the past decade, the Position Analysis concepts have been used with increasing effectiveness to assess risks associated with seasonal and multi-seasonal operations of the water management system and communicate them to decision makers, agencies partners, stakeholders, and the public.

Incorporating uncertain climatic tendencies into a long-range planning process calls for careful analysis to allow a balance among risks, costs, and benefits. There are many ways that the water resources planning for future changes to the system may account for uncertainties caused by natural climate variability such as those attributed to ENSO, AMO, and PDO. The methods that have been used for water resources planning in South Florida include, but are not limited to (a) sensitivity analysis of planning simulations; (b) continual expansion of the hydrologic simulation period to include more and more multi-decadal climate regimes; and (c) adaptive management of facility planning and implementation. To apply the adaptive management effectively, systems responses must be continually monitored and management actions adjusted to ensure that the desired outcomes are achieved. Adaptive management is a cornerstone of the implementation of the current Everglades Restoration projects which is expected to span decades. Future project designs and their actual operations 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 possibly global warming issues can play key role in those overall system reviews in the adaptive management framework.

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 predictions carry large uncertainties. ENSO, AMO, and PDO are large-scale climatic indicators that have implications for water resources planning and operations in South Florida. ENSO which follows a 3- to 7-year cycle has the strongest effect on dry season climate in South Florida. The PDO may last for decades and affects South Florida climate 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 cold phase is associated with below normal rainfall and lesser frequency of tropical storms which become major hurricanes. Conversely, the AMO warm phase is associated with slightly higher, but more variable conditions in South Florida. During this phase the number of tropical storms which become major hurricanes can be twice as many than the number during the cold phase. The AMO effects, although are significant, are not similar elsewhere in the country or even in North Florida.

The South Florida Water Management District (SFWMD), jointly with USACE, has successfully incorporated climate trends into its seasonal and multi-seasonal operations decision making process. A notable example of these efforts includes the development and application of the WSE schedule and position analysis techniques to guide the management of water levels and discharges form Lake Okeechobee. By periodically extending the simulation period in hydrologic models, the SFWMD continually incorporates recent climate trends for the re-evaluation of proposed infrastructure changes, particularly those associated with Everglades restoration. This adaptive approach follows standard engineering and operational planning practices and provides a means to manage the risks of facility implementation when climatic changes are inherently uncertain.

References

Barnston, A.G., M.H. Glantz and Y. He. (1999). “Predictive Skill of Statistical and Dynamical Climate Models in SST Forecasts During the 1997-1998 El Niño Episode and the 1998 La Niña Onset”. *Bulletin of the American Meteorological Society,* 80(2):217-243.

Bjerknes, Jacob. (1969). “Atmospheric teleconnections from the Equatorial Pacific.” *Mon. Weather Rev.* **97**(3):163-72

Cadavid L.G., R. Van Zee, C. White, P. Trimble and J. Obeysekera. (1999). Operational Hydrology in South Florida Using Climate Forecasts. American Geophysical Union, 19th Annual Hydrology Days. Colorado State University, August 16-20, 1999. ed. H.J. Morel Seytoux. Hydrology Days Pub.

Cadavid L. G., P. Trimble, R Santee, C. White, A. Ali, J.T.B. Obeysekera (2001). “Use of Regional Simulation Models in Operational Hydrology in South Florida”, in proceedings of the specialty symposium in “Integrated Surface and Ground Water Management" held in conjunction with the World Water and Environmental Resources Congress, edited by B.K. Panigraphi, J. Obeysekera and M. Krishnamurthy, ASCE.

Cadavid, L. G., Neidrauer, C. J., Obeysekera, J. T. B., Santee, E. R., Trimble, P., and Wilcox, W. (2006). “Lake Okeechobee operations by means of the water supply and environment (WSE) regulation schedule”, in Operating Reservoirs in Changing Conditions, Edited by D. Zimbelman and W. C. Loehlein, ASCE.

Enfield, D.B. and L. Cid-Serrano. (2006). “Projecting the Risk of Future Climate Shifts.” *International Journal of Climatology* 26(7): 885-895.

Enfield, D.B., A. Mestas Nunez, and P.J. Trimble. (2001). “The AMO and Its Relationship to Rainfall and River Flow in the Continental U.S.” *Geophysical Research Letter*, vol. 28, May.

Goswami, B.N., M.S. Madhusoodanan, C.P. Neema, and D. Sengupta. (2006). “A Physical mechanism for North Atlantic SST influence on the Indian summer monsoon.” Geophysical Research Letters, Vol. 33, L02706, doi:10.1029/2005GL024803

Gray, S.T., L.J. Graumlich, J.L. Betancourt and G.D. Pederson. (2004). “A Tree-Ring Based Reconstruction of the Atlantic Multidecadal Oscillation Since 1567 A.D.” *Geophysical Research Letters*, 31:L12205, doi:10.1029/2004GL019932.

Hirsch, R. M. (1978). “Risk Anal. for a Water-Supply System – Occoquan Reservoir, Fairfax and Prince William counties, Virginia.”, *HydroL Sci B* **23**(4), 476-505.

Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M., Mann, M.E., A signature of persistent natural thermohaline circulation cycles in observed climate, Geophysical Research Letters, 32, L20708, doi:10.1029/2005GL024233, 2005.

Li, S., and G. Bates, 2006: Influence of the Atlantic Multidecadal Oscillation on the winter climate of East China. *Adv. Atmos. Sci.* (in press)

Mantua, Nathan J., S. R. Hare, Y. Zhang, J. M. Wallace, R. C. Francis (1997) "A Pacific interdecadal climate oscillation with impacts on salmon production." Bulletin of the American Meteorological Society, 78, 1069-1079.

Mestas-Nunez, A.M. and Enfield, D.B. (2003). "Investigation of Intra-seasonal to Multi-decadal Variability in South Florida Rainfall." Atlantic Oceanographic and Meteorological Laboratory (83 pp). Online at http://www.aoml.noaa.gov/phod/docs/Mestas_Enfield_FR_2003.pdf,

NASA (2000). "NASA Workshop on Sun - Climate Connections Summary Report" Universitity of Arizonia, March 6-8, 2000. Online at: http://www.atmo.arizona.edu/faculty/research/sunclimate/sunclimate.pdf

Obeysekera J., P. Trimble, L. Cadavid and C. White. (2000). "Use of Climate Outlook for Water Management in South Florida." U.S.A. Proceedings of the Engineering Jubilee Conference. University of Peradeniya, Sri Lanka, June.

Shih, G. (1983). "Data Analysis to Detect Rainfall Changes in South Florida." Technical Memorandum #DRE-165, South Florida Water Management District, West Palm Beach, FL.

SWFWMD (2004). "Florida River Flow Patterns and the Atlantic MultiDecadal Oscillations." Ecological Evaluation Section, Southwest Florida Water Management District.

Trimble, P. (1997). Workshop on Climate Variability and Water Resource Management in Southeastern United States. Vanderbilt University. Nashville, TN, June 25-27 (74 pp). Online at http://www.ghcc.msfc.nasa.gov/regional/jun97/wkshp.pdf.

Trimble, P.J. and B.M. Trimble. (1998). "Recognition and Predictability of Climate Variability within South-Central Florida." 23rd Annual Climate Diagnostic and Prediction workshop, Rosenstiel School of Marine and Atmospheric Science. University of Miami, Florida, October 26-30. Online at http://www.sfwmd.gov/org/pld/hsm/pubs/ptrimble/solar/workshop/cpc_paper.htm.

Trimble, P.J., E.R. Santee and C.J. Neidrauer. (1998a). "Preliminary Estimate of Impacts of Sea-Level Rise on Regional Water Resources of Southeastern Florida." Proceedings of the International Coastal Symposium, Journal of Coastal Research. Special Issue, No. 26.

Trimble, P.J., E.R. Santee and C.J. Neidrauer. (1998b). "A Refined Approach to Lake Okeechobee Water Management: An Application of Climate Forecasts. South Florida Water Management District" (73 pp). Online at http://www.sfwmd.gov/org/pld/hsm/pubs/ptrimble/solar/report/report.pdf.

Trimble, P.J., E.R. Santee and C.J. Neidrauer. (1998c). Including the Effects of Solar Activity for More Efficient Water Management: An Application of Neural Networks. Second International Workshop on Artificial Intelligence Applications in Solar-Terrestrial Physics. Sweden, July. Online at http://www.sfwmd.gov/org/pld/hsm/pubs/ptrimble/solar/final_dec3.pdf, October 24, 2006.

Trimble, P.J., T.B. Obeysekera, L.G. Cadavid and E.R. Santee. (2006). Applications of Climate Outlooks for Water Management in South Florida. In *Climate*

Variations, Climate Change, and Water Resources Engineering. Edited by Jurgen D. Garbrecht and Thomas C. Piechota.ASCE/EWRI. Reston, VA.

U.S. Army Corps of Engineers. (2000) "Water Control Plan for Lake Okeechobee and the Everglades Agricultural Area", Jacksonville District, Florida

Zhang, E. and P.J. Trimble. (1996). "Predicting Effects of Climate Fluctuations for Water Management by Applying Neural Networks". *World Resource Review*, 8(3) (17 pp).
Online at http://www.sfwmd.gov/org/pld/hsm/pubs/ptrimble/prediction/prediction.htm, October 24, 2006.

Zhang, R., and T. Delworth, 2006. Impact of Atlantic Multidecadal Oscillation on India/Sahel rainfall and Atlantic hurricanes. *Geophysical Research Letters*, 33, **L17712**, doi:10.1029/2006GL026267