SUMMARY REPORT

HYDROLOGY OF THE EVERGLADES IN THE CONTEXT OF CLIMATE CHANGE

March 29-30, 2012
Florida Atlantic University
Davie, Florida

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AND THE CENTER FOR ENVIRONMENTAL STUDIES AT FLORIDA ATLANTIC UNIVERSITY

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EXECUTIVE SUMMARY

Despite the dense data sets available for the Everglades there are substantial gaps and deficiencies in our understanding of Everglades hydrology. These become especially important as we attempt to assess the impact of climate change on components of the hydrological cycle. This workshop attempted to assess the state of knowledge on the hydrologic cycle, and on model projections of future change. In so doing, we identified critical knowledge gaps and made recommendations for future action.

A series of discussions on the complexity of downscaling from global models to this peninsular region revealed significant problems with projections of future precipitation patterns but better predictions of temperature change. Decadal variations involving El Niño and the Southern Oscillation complicate the picture. Urbanization and change in land use are also important.

Some conclusions are:

1. Statistical downscaling may be the most effective mechanism while the regional models improve, but the downscaling needs to be addressed in the temporal/spatial scales appropriate to the particular watershed.
2. While there are uncertainties, these need to be identified and quantified well.
3. Models need to test results at the local scale.
4. Historically-based management approaches must give way to adaptive management tools based on stochastic results.
5. Diurnal variations in temperature and rainfall are important.
6. Changes in the system are driven by extreme events rather than in a steadily evolving manner.

The Hydrologic Cycle

Research indicates that the hydrologic cycle will change in the future and water management must be modified to handle these changes. Current emperature projections show a rise of 1-2°C (1.8-3.6°F), precipitation change may be ±10% and evapotranspiration (ET) may increase 3-6 inches by 2050. North Florida will be warmer and South Florida, at the same latitude as the Sahara, will be drier.

Precipitation is the main driver of the Everglades hydrology. There are a number of research priorities that need to be examined to increase our understanding of precipitation events, and how future events will be affected by climate change:

- Understand trends in extreme precipitation events, like tropically-driven heavy rainfall systems and droughts.
- Develop a familiarity with spatial and temporal trends of precipitation in South Florida is critical to understanding how to manage the water budget in the Everglades and surrounding communities.
- Understand how spatial and temporal trends have changed throughout history and how they will evolve with a changing climate.
- Examine the relationship between precipitation trends of urban and natural systems.
- Develop models that incorporate future land use changes to accurately predict precipitation trends, critical to water management needs.
- Identify current and future urban heat islands and the local effects they may induce on regional precipitation trends.

Evapotranspiration is the second most important component of the Everglades' hydrology but is the most poorly understood. We have begun to build a wealth of information over the past 5-7 years regarding ET. Progress has been made in gathering data that are used for the evaluation of climate models. There are several points that are crucial to the understanding of how present and future ET rates relate to the evolution of the South Florida landscape:

- Build a firm understanding of ET rates among urban, suburban, and agricultural areas.
- Understand the related energy balance and effects on ET between urban and vegetative sites needs further investigation, as well as the effects of urban heat islands on non-stationarity in historic and present meteorological records.
- The alteration of land use patterns and increased urbanization will far outweigh the potential impacts of climate change on ET in South Florida for many years. The two need to be jointly and thoroughly assessed to improve predicted ET rates in the future.

Groundwater and **Sheetflow** are poorly understood components of the hydrology of the Everglades, especially regarding how they will be affected by climate change. The hydraulics of the Everglades is the only real world example of a genuine sheet flow system, which makes adaptive management and restoration an arduous and challenging task. Groundwater flow has undergone severe alteration as a result of the channelization and drainage of the Everglades, and several areas of research are needed:

- Practical modeling of sheet flow hydraulics to build a basis for future predications of sea level rise and climate change scenarios.
- Define critical regions throughout the Everglades and begin to integrate models, information, and people to acquire a more holistic approach to define where we are and where we should be going in terms of groundwater management.
- Examine the decomposition and subsidence of peat and marl throughout the Everglades as a result of groundwater alteration and its impact on flows.

INTRODUCTION

The Center for Environmental Studies (CES) at Florida Atlantic University (FAU) and the U.S. Geological Survey (USGS) held a workshop on March 29-30, 2012 at FAU in Davie, Florida. The purpose of this workshop was twofold:

- Assess the state of knowledge of the impacts of current and future climate change on the hydrological cycle in the Everglades including gaining a greater understanding of downscaled hydrologic global models for the Everglades.
- Examine each of the components of the cycle in the greater Everglades by identifying:
  - our understanding of potential changes in precipitation quantity and intensity, evapotranspiration, percolation to groundwater, runoff and drainage, and
  - critical knowledge gaps with respect to future patterns and their impact.

The plenary sessions opened with a series of presentations that set the stage by providing a common basis of information for the discussion groups to draw upon. The first group of speakers provided a "Big Picture Perspective" on the climate change implications for Florida, including the state of knowledge, downscaling global models, and changes in hydrology. This was followed by a review of selected components of the hydrological cycle, including precipitation, temperature, evapotranspiration, and groundwater and surface water flows.

As outlined in the introductory remarks of coordinators Leonard Berry, Florida Center for Environmental Studies, Florida Atlantic University (FAU), Ronnie Best, USGS, and Karl Havens, Florida Sea Grant, University of Florida (UF), the main objective of this 2-day workshop was to brainstorm and "open a conversation" among the 50 attendees on the climate change issues that impact South Florida. More importantly the idea of this workshop was to hone in on the impact of global climate change on rainfall variability and hydrologic variations, and their consequent implications on Everglades restoration and water management in south Florida in the near term (10-30 years) and long term (end of century). The issue of sea level rise was not part of this discussion since it was addressed by other workshops.

The State of Knowledge and Downscaling – DAY 1

There were three speakers for the morning session of the first day of the workshop: Ben Kirtman, Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami (UM), Vasu Misra, Center for Ocean Atmospheric Prediction Studies (COAPS), Florida State University (FSU), and Aris Georgakakos, Georgia Water Resources Institute. In the afternoon session there were four speakers: Aris Georgakakos, Wendy Graham, UF Water Institute, Tirusew Asefa, Tampa Bay Water, and Ramesh Teegavarapu, FAU. The title of each speaker's talk precedes their presentation summary.

Seasonal-to-Decadal Climate Prediction and Climate Projection

Ben Kirtman, who is heavily involved in global climate modeling from seasonal to decadal predictions and climate projections, gave a global context to the workshop participants. He made a subtle but important distinction between a prediction, which depends on the initial condition, and a projection, which is more dependent on forcings (e.g. the concentration of CO_2, aerosols, and other gases in the atmosphere). The science in decadal predictions is very young. Timescale and forcings are the main factors in uncertainty. The scientific basis for climate prediction stems from the ability of slowly varying boundary conditions (e.g. sea surface temperature modulation in the equatorial Pacific Ocean by El Niño and Southern Oscillation) to significantly modify the statistics (e.g. variance) of the daily weather globally, and more specifically over the southeastern United States. This optimism in seasonal climate prediction has translated into a national effort called the US National Multi-Model Ensemble project (NMME) where seven institutions are coordinating seasonal forecast experiments from 1982-2010. The initial results from this multi-model seasonal prediction effort (with over 80 ensemble members for each season) suggest that the forecast skill is very dependent on season and region. The models in NMME exhibit poor representation of the Gulf Stream, which consequently causes deterioration of the sea surface temperature (SST) forecasts in the northern Atlantic Ocean. On the other hand, the strong teleconnections emanating from the eastern equatorial Pacific Ocean due to El Niño/La Niña produces high correlations of forecasted seasonal precipitation with corresponding observations over the Gulf of Mexico and the southeastern United States (US). While the global mean trends and surface air temperature are well defined, the Atlantic Multi-decadal Oscillation (AMO) and Interdecadal Pacific Oscillation (IPO) are much less precise. The NMME clearly demonstrates a well-known fact that while pathological errors exist across models, there are substantial examples of model errors that are typical of each model as well. Therefore, despite prevailing systematic errors across all models, NMME clearly demonstrates the superiority of the multi-model prediction as opposed to a seasonal prediction from a single model.

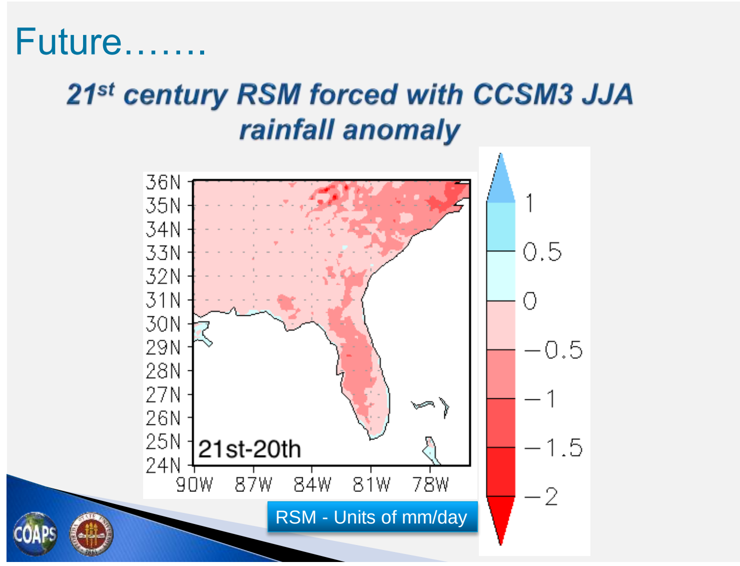
Kirtman made it clear in his talk that, although he was a Coordinating Lead Author of IPCC AR5 (Intergovernmental Panel on Climate Change, Fifth Assessment Report), he was not representing the IPCC in this workshop in any capacity. Therefore, his opinion should not be construed as that of the IPCC. The IPCC, as part of its AR5 effort, is also working on providing predictions of the near (decadal, 10-30 year) term. Because decadal predictability is a function of the initial conditions of the deep ocean, near term predictions must take this into account. The analysis of the decadal predictions from the IPCC AR5 suite of models so far have been sobering, with useful decadal prediction skill lasting up to only about 5 years. This useful skill is largely stemming from the persistence of the decadal variations over this time period from the initial time of the model integration. From these decadal predictions, there will be apparent cooling relative to the AR4 climate change projections in the next 5 years (2012-2016). In other words, these near term model projections are suggesting that the natural variability (e.g. AMO, PDO etc.) would prevail, reducing the rate of warming due to climate change as projected in the IPCC AR4 models. There is overwhelming evidence that warming is occurring at global scales, but it is just not happening as quickly as we thought due to natural variability. Regional actionable information is hard to obtain. The field of decadal prediction is quite nascent, and progress in improving these predictions is anticipated.

Understanding climate change in the southeast US from (recent) past, present and future

Vasu Misra, FSU, has worked extensively on regional climate modeling of the southeast US. He spoke about sources of climate change in this region and highlighted the influence of urbanization and irrigation on observed surface temperature trends in the southeast US. Land use, like urbanization and irrigation of cropland, modifies the surface interaction with radiation and therefore affects the surface temperature trend. The quantitative influence of urbanization on surface temperature trends was measured by examining its relationship with the Population Interaction Zone for Agriculture (PIZA) developed by the USDA Economic Research Service (ERS). This analysis revealed that as the PIZA index increases, i.e., as urbanization increases, there is a corresponding increase in the linear trend of the daily measured minimum temperatures. The fact that influence of PIZA is uniquely seen in the daily minimum temperature and not in the measured daily maximum temperature is suggestive of the urban heat island effect. The relationship of the temperature trends in the southeast US with the irrigation density index developed by the United Nations Food and Agricultural Organization likewise shows a warming trend in the measured daily minimum temperatures and cooling trends in the measured daily maximum temperature. As a result of wetting the soil during irrigation, there is an increased evaporation that leads to a cooling effect on the daily maximum temperature. On the other hand, wet soil increases the heat capacity of the soil, and under weak wind conditions leads to warming of the measured daily minimum temperature. The impact of irrigation is most pronounced in summer.

The second half of his talk focused on projections of rainfall change in the late 21st century in the Southeast. It was suggested that projections from global climate models especially for rainfall should be cautiously interpreted. The rainfall patterns in global climate models are unrealistic, raining too early, too frequently and too weakly. This likely stems from a poor resolution of the physical features and processes in the region, such as coastlines and topography. Using the Florida Climate Institute Florida State

University Regional Spectral Model (FCI-FSU RSM) at 10km grid resolution to dynamically downscale output from a global climate model ameliorates some of these issues to improve the credibility of the downscaled rainfall projection over the southeast US. Under the A2 climate scenario (of doubling the current CO_2 concentration to 750 ppm), one of the dynamically downscaled projections from Climate System Model, version 3 (CCSM3.0) shows a uniform drying of the Southeast in the future summer climate. This is primarily attributed to the reduction of the diurnal variation.



Joint Variable Spatial Downscaling - A New Statistical Downscaling Approach

Aris Georgakakos of the Georgia Water Resource Institute has worked extensively on the Apalachicola-Chattahoochee-Flint (ACF) river basin and other large basins across the US and in Africa. He talked about a new statistical downscaling approach called Joint Variable Spatial Downscaling (JVSD) and its merit over the more popular Bias Correction and Spatial Downscaling (BCSD). Despite the efficacy and appeal of using dynamic downscaling, statistical downscaling for hydrological studies continues to be popular for the ease and large ensembles of predictions and projections that can be generated without using intensive computing power. The BCSD uses quantile to quantile mapping between Global Climate Model (GCM) output and upscaled observations on a finer grid. The issue with the BCSD is that it gives a high spatially coherent distribution of precipitation and temperature, which is usually unobserved at watershed scales especially in the ACF basin. BCSD temporally disaggregates on a monthly scale by re-sampling the observed daily sequences, and spatially disaggregates by bias correcting all factors at the coarser resolution. JVSD uses a very different approach, first preferring to upscale observations, correct the biases therein, then use a historical analogue. Bias correction in JVSD is done using the Cumulative Distribution Functions (CDFs) of differences, as opposed to CDFs of raw data in JVSD. These differenced CDFs are chosen because they are shown to be relatively invariant through time, allowing a better association of control and projected CDFs, and a smoother transition to observed CDFs. As a result, JVSD preserves the relationship between the two variables (in this case, between temperature and precipitation) and produces less coherent distribution of temperature and precipitation on the watershed scale.

Climate Change Assessments for Georgia

Aris Georgakakos started the afternoon session with a presentation of the current climate change assessment of Georgia in the context of water management. As a community, there is a need to deliver climate change information in such a way that it can be employed by stakeholders and water managers alike. This requires that the global climate change information be customized for local application. At the same time, the water management policy needs to be developed with a bottom up approach and tested not only against historical climate events but also against future climate scenarios with respect to robustness and versatility. The major hurdles involve modeling the hydrology, groundwater table and estuary dynamics, and understanding the consequences on water resource management. One proposed method involves breaking the basins into sub-regions, and analyzing how runoff and evapotranspiration vary with latitude. Moving from the northern part of the ACF river basin toward the Gulf of Mexico, runoff decreases and evapotranspiration increases. This results from the subsoil moisture contribution to total rainfall. Under A2 and A1B future climate scenarios, the extensively calibrated "Sacramento" model with only two soil layers plus runoff, suggests the following impacts of climate change on all basins in Georgia:

a) Precipitation declines 9-16%
b) Potential evapotranspiration (PET) increases 1-3%
c) Soil moisture declines 3-6%
d) Runoff declines 16-27%
e) By 2050-2060, lakes will be completely drawn down (run out of water)

Furthermore, under a warming climate, Gulf-like conditions will move farther north. Positive trends in potential evapotranspiration and negative trends in total rainfall are noted to be statistically significant in a future climate. The take home message is that we need adaptive resource management strategies in order to handle uncertainties of the future climate.

Comparison of Statistical and Dynamic Downscaling methods for Hydrologic Applications in West Central Florida

Wendy Graham, of the UF Water Institute, compared the efficacy of statistical (and dynamic) downscaling techniques on rainfall in the context of streamflow simulation of the Tampa Bay watershed. One method examined was spatial downscaling, bias correction (SDBC), which is shown to over-predict streamflow events, but have a better representation of temporal variability. A second method, Bias Correction Spatial Downscaling (BCSD) was analyzed, and was seen to underestimate the spatial and temporal variance of rainfall, and overestimate the total number of low precipitation days. Her team also explored a third method that they developed, the Bias Correction Stochastic Analogue (BCSA). This method works by bias correcting data, downscaling them then feeding the mean rainfall into a stochastic rainfall distribution. This way, BCSA is able to capture variogram patterns of observed rainfall and does a good job of predicting chances of going from a dry-to-wet day and a wet-to-wet day. In short, downscaling shows promise, but predictions being made are generally poor. Dynamically downscaled RCM results show promise but must be driven by re-analysis data. Dynamically downscaled retrospective events from GCMs perform poorly and require bias correction.

Framework for Evaluating a Complex Water Resources System Performance under a Changing Climate

Tirusfew Asefa from Tampa Bay Water spoke about developing a framework for evaluating the consequences of meeting demand in 2050. Under a varying climate, it will be difficult to meet the water demands of an area under present withdrawal limits. To prepare for this, resource management districts need to define a new failure threshold and develop scenarios around this new threshold. The scenarios developed should include population size, possible changes in regulation and climate information. The scenarios should also assess the reliability and resilience of the system. Over the past 13 years, water withdrawal in the region has changed from an almost exclusively groundwater-based system to one that uses only 50% groundwater. Model projections of future change are very uncertain, showing either a slight decrease or massive increase in demand. The question is shifting toward how to meet an increased demand – perhaps by increasing the permit level for water withdrawal. The use of multiple resources improves the resilience of the whole system.

Experiments with Statistical Downscaling of Precipitation for South Florida Region: Issues & Observation

Ramesh Teegavaparu of FAU discussed current downscaling of rainfall in Florida and South Florida. The primary focus is to establish a functional relationship between the variable and the observation. Several transfer function methods were analyzed, including regression, nonlinear optimization, clusters and others. To analyze each of these, stationarity is assumed and a temporal analogue for events is sought. No models do well for rainfall predictions across Florida. To alleviate this, transfer functions linking the GCM scale to a National Center for Environmental Prediction (NCEP)-forced GCM must be found. Finding these transfer functions involves finding an optimal selection and number of predictors.

The panel discussion at the end of the day highlighted the following major points:

1. If you want to use statistical downscaling while regional models advance, you need to understand the spatial/temporal scales to create relevant products for the watershed in question.
2. Characterize/quantify uncertainties well then proceed because we can get useful information from models, especially groundwater models.
3. Don't be concerned that uncertainties are large, just document/quantify them; uncertainties may be sifted out by some models.
4. Heuristic/historically-based management will not work during times of climate change. Adaptive management tools based on stochastic results must be used.
5. Modelers need to test results at local scales.
6. Diurnal variations are important. Diurnal variability explains a significant fraction of the climate variations in Florida and the rest of the southeastern US.
7. Sustainable hydrologic design needs to take into account extreme events, but cannot assess extreme events with a low number of model ensembles.
8. Changes to the Everglades occur in pulses and are driven by extreme events (e.g., hurricanes) rather than a steadily evolving manner.
9. There is a need to integrate sea level rise into natural resource and regional planning.

Hydrology of Climate Change in Florida-Day 2

Review of the Hydrological Cycle and Change

Ronnie Best, USGS, Jayantha Obeysekera, South Florida Water Management District (SFWMD), Glenn Landers, US Army Corps of Engineers (USACE) and Robert Fennema, South Florida Natural Resources Center, SFEO Everglades National Park (ENP), presented their views of the most critical hydrological issues their organizations face.

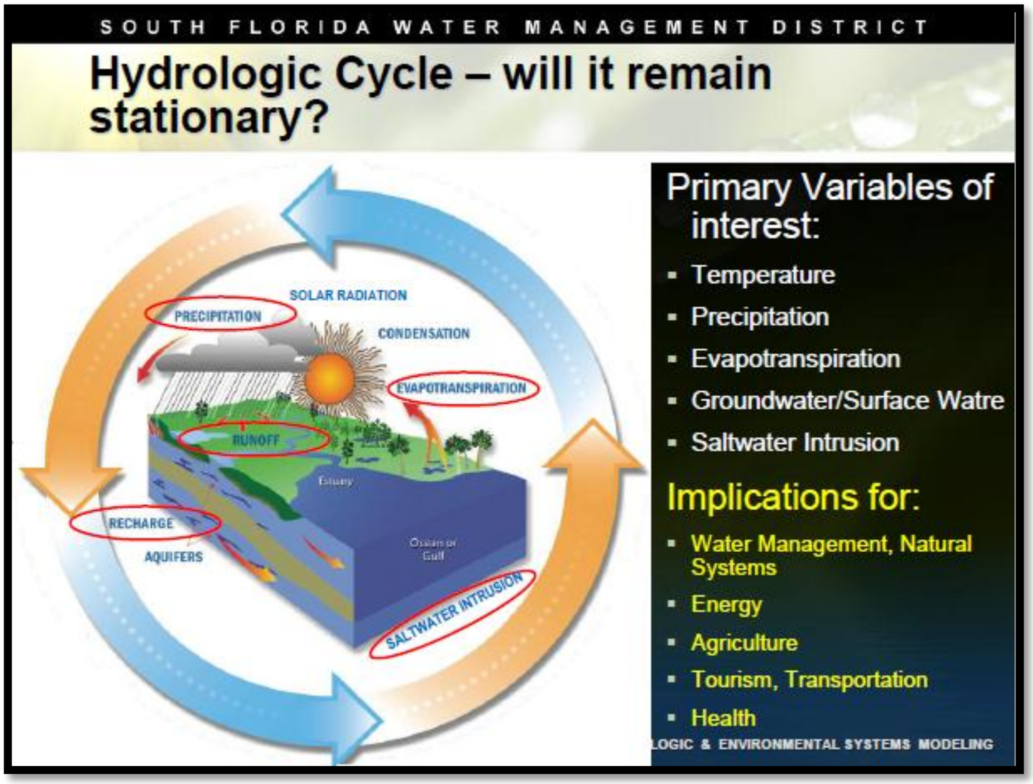
The Comprehensive Everglades Restoration Plan (CERP) is currently based on "stationarity," not on climate change. This needs to be modified to plan for the future. In Everglades National Park, SLR is a major concern. Because we have more water in South Florida, we need to optimize the delivery and storage of freshwater, thereby creating a temporal buffer to give species time to adapt. There are over 40 years of rainfall data being used for modeling but the system is no longer stationary and therefore the use of historical data alone may not be adequate. We must address climate change in future planning.

A 5-year plan was recommended – one that identifies the needs over the next 5 to 10 years, then begins to collect those data. There is a need for modelers to produce realistic and robust "What if...?" scenarios. For example, what happens if the volume of water in Water Conservation Area 3 increases? It does not automatically mean increased groundwater flow. Another need is for modelers to produce models with different levels of annual rainfall, e.g., 30, 50, 70 inches, etc. More intense science is needed for more useful information, but it must be actionable science.

Precipitation and Temperature

Hydrologic Cycle – will it remain stationary?

Jayantha Obeysekera of SFWMD posed the question, “Will the hydrologic cycle remain stationary?” The answer is “no.” We must modify water management and consider climate change – a difficult process. Future changes to processes such as temperature, precipitation, evapotranspiration, groundwater, surface water, saltwater intrusions, and sea level rise need to be used. An overview of climate change scenarios from various models for greenhouse gas emissions, precipitation and temperature showed that there is both model and scenario uncertainty and significant natural variability. We need more scientific knowledge at a regional scale. Does observed climate data provide evidence of climate change trends? The seasonality of the GCM precipitation cycle for Florida is inaccurate. Overall, models show a warming of about 1.5°C to 2°C in the next 10-15 years, precipitation changes of ±10% by 2050, and a 3-6 inch increase in crop evapotranspiration (ET). Northern Florida will become warmer and southern Florida will become increasingly drier. The prediction of both a reduction in rainfall plus an increase in evapotranspiration creates a "double whammy" for water loss. The urban heat island effect modulates minimum temperatures, resulting in warmer nights. Natural variation will be more important in the next 10-20 years.



Spatial and Temporal Variability of Precipitation Extremes in Florida: Teleconnections and Implications for Hydrologic Design

Ramesh Teegavarapu, FAU, discussed the spatial and temporal variability of precipitation extremes in Florida for different durations. Will the tails of distributions increase under climate change? Multiple sources of data, including rain gauge data, NEXRAD precipitation, NCDC (National Climate Data Center) – UCF (University of Central Florida) subset, and SFWMD (DBHYDRO) data set show different durations of extreme precipitation events. The Atlantic multi-decadal oscillation (AMO) has a greater identifiable effect on climate and extremes. AMO warm phases are often associated with increased hurricane activity, have been attributed to increased variability in precipitation totals, and tend to have a bimodal distribution for June and September, especially with long temporal durations. Extremes during AMO warm phases are also associated with a drier western panhandle. Cool season landfalls have a less regular precipitation pattern. El Niño Southern Oscillation (ENSO) patterns in Florida typically have wetter and longer wet seasons and drier and shorter dry seasons. The question for implications in hydrological design is which window to look at. It is important to be careful with filling in data gaps in rainfall analysis. In-filled data can cause bias and reduce perceived impacts of extreme events.

Climate Change and Everglades Restoration

Tom J. Smith, USGS, began with a reminder that Florida is at the same latitude as the Sahara Desert. Florida State University's Regional Spectral Model (RSM) dynamically downscaled data predicts Florida will become hotter and drier. Non-tidal fresh surface water has been rising in the non-tidal Everglades for last 50 years. Stations in the Everglades match records at Key West. The groundwater in the southwest Everglades (Lostmans River) already has salt water readings. Decreased rainfall reduces freshwater outflows, resulting in saltwater intrusion. Western Shark River Slough is still fresh, but just barely. Mangroves are moving upslope and widening along the Harney River. Extended freezes (e.g., December 2010) caused massive die-off of mangroves and tree islands. Some mangrove forests have become mudflats. There are frequent wildfires throughout the Everglades. As it becomes hotter and drier, fires will burn peat soils with greater intensity. Hurricane storm surges have also washed away vegetation in some areas, causing peat collapse.

FSU's downscaled output data are being used as inputs to the USGS hydrology and ecology models. There are two hydrodynamic models developed by USGS: one for restoration scenarios for the Everglades and one for flow and salt transport for the Lower Suwannee River in the Big Bend area. Salinity is expected to increase in the coastal Everglades as sea levels rise. A variety of ecological models are being used depending on the flora and fauna in the area. Other threats from sea level rise include: potential range expansions for invasive exotics, such as *Lumnitzera racemosa* (a black mangrove from India), and loss of freshwater to salt water intrusion in the Navy well fields in southeast Miami-Dade County, the source of drinking water for Key West and the upper Keys.

Climate Uncertainties and Risk Informed Decision-Making for Everglades Restoration and South Florida

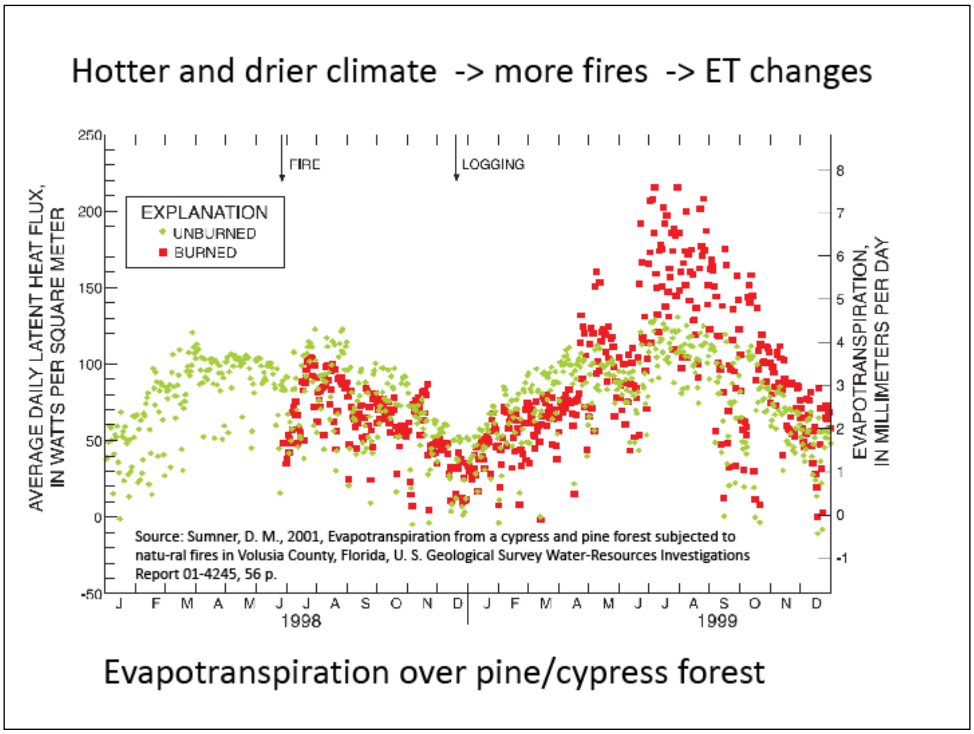
Glenn Landers, USACE, outlined climate uncertainties and risk assessment in decision-making for Everglades restoration and South Florida. He reviewed geological information on sea level changes over time, projections for South Florida, hydrologic and other uncertainties, which along with an understanding of combined risks, lead to informed decision-making. Most of Florida is very stable geologically, so sea level change is similar around the state. A 24-inch increase in sea level is predicted in the next 50 to 100 years. SLR will reduce the effectiveness of gravity-driven drainage canals. Droughts and salt water intrusion may be a bigger concern. Shallow wells are the primary source of fresh drinking water in South Florida. About 90% of Miami-Dade County has an elevation less than 10 feet, so vast areas would be flooded with a rise of 4 to 5 feet. There is also the risk of peat loss or collapse south of U.S. 41.

Risk assessment and management aid in systematic and flexible decision-making under uncertainty. The quality of the decision depends on the quality of the work to form alternative plans, weighing costs and societal benefits. The intent for Everglades restoration is to restore the characteristics of the natural system. A big part of the solution is to increase water flow through the Everglades. For this we need to establish SLR scenarios to facilitate planning. A 5-year planning initiative, released by the Florida Department of Economic Opportunity in March 2012, focused on community resiliency and hazard mitigation, including SLR. The USACE has three SLR scenarios: historic, intermediate and high.

Evapotranspiration

USGS evapotranspiration infrastructure in Florida

Why measure evapotranspiration? **David Sumner**, USGS Florida Water Science Center, explained that ET is a large component of the water budget and an important link between water and the energy budget. The eddy covariance method was used for ET measurements at 14 sites in peninsular Florida, including urban, wetland, swamp, open water, and pasture. Statewide estimates of daily potential and reference ET are being computed based on field-derived meteorological data and satellite-derived solar insolation data. Net radiation is the principal driver of ET fluctuations. If soil moisture is not available, then plant transpiration is inhibited ("choke effect"). Open water bodies are net sinks from the hydrologic system - evaporation exceeds precipitation over lakes. ET generally increases with higher solar radiation and shallower water levels. Depending on the site, ET is about 27 to 60 inches/year. The ET of the Everglades ridge vs. slough communities is unknown. Fires burn off dead material and other vegetation, so ET initially decreases following a burn. Later, growth of new plants is rapid due to nutrient release from burned biomass, resulting in increased ET. Flooding absorbs incoming solar radiation and lowers albedo, while drought conditions result in higher reflection of incoming solar radiation, causing a high albedo.
Most hydrological models use potential ET (PET), while most agricultural models use reference ET (RET). Cloud cover is a major factor in solar radiation. Radiation-based ET measurements are more accurate than temperature-based ET measurements. There is a need to standardize methods, because currently there are about 20 different versions of potential ET. The major need by hydrologists is to identify the amount of available water (= precipitation - ET). While coarse estimates are generally sufficient, when precipitation and ET are nearly equal, error is amplified. To prevent the problem of near-cancellation of terms, scientists may wish to downscale the combined quantity. The relative magnitude of ET is reduced with heavy precipitation, so ET errors are low during flooding events. Knowing the variability of rainfall is more critical than the variability of ET. As atmospheric CO_2 increases, plants open their stomata less to fix atmospheric CO_2 during photosynthesis, losing less water. This can result in a 20% reduction in ET; however, increased foliage cover might mitigate this effect. A negative correlation between precipitation and PET/RET is expected: when it is drier, less rain is associated with clearer skies and, therefore, higher radiation and higher PET/RET; dry conditions also reduce water availability and plants cut back on water use, tending to lower actual ET.



Remote Sensing of Evapotranspiration
Aaron Evans, FAU, described the use of remote sensing for ET in southern Florida. Thermal imagery and weather stations are mostly used for ET information. Cooler imagery indicates more evaporation. Because

remote sensing needs clear skies, there can be big gaps in imagery. Satellites cannot detect vertical differences in temperature between surface layer and above. If the atmosphere is less stable, then measuring land cover impacts closer to the station is important.

Evapotranspiration in the Everglades and its Watershed

Woosenu Abtew, SFWMD, provided an overview of ET in the Everglades, describing the difference between open water and wetland ET. Contour lines oriented from the southeast to the northwest, indicate an increased ET in the south. Lake ET in areas such as Lake Okeechobee and Everglades marshes ranges from 51.9 to 54 inches. ET is driven by solar radiation in South Florida so cloud cover is the key. Pan ET data are too variable and not useable for small changes. The trend of ET in South Florida appears to be increasing. With increased drought, there is less relative humidity. Dry years, e.g., when La Niña is engaged, results in higher ET, but it is reduced in forested wetlands. The maximum projected increase in ET due to climate change is 6 inches at the southwest tip of the Florida peninsula.

Projection of Evapotranspiration from Regional Climate Models: Challenges

Jayantha Obeysekera, presented the challenges of calculating ET from regional climate models. Next to precipitation, ET is perhaps the next most important variable. Regional climate models produce variables that can be used to compute ET. Reference ET is derived from the regional-scale, North American Regional Climate Change Assessment Program **(**NARCCAP) models using the Penman-Monteith equation, which includes not only temperature, but also solar radiation, pressure, relative humidity and wind. Data from FAWN (Florida automated weather network), USGS, and SFWMD were used to validate model predictions. Regarding seasonal patterns, clouds in the summer should reduce ET, but the summer solar radiation doesn't match,, perhaps because the simulated cloudiness in models is incorrect. Some NARCCAP produce relative humidity values greater than 100%. More accurate cloud simulations are needed. There are many indirect effects on solar radiation, such as aerosols, droplet size, etc.

Groundwater and Surface Water Flows

Climate Change Considerations for Surface Water and Groundwater Flows in the Everglades

Bob Johnson, South Florida Natural Resources Center, addressed climate change considerations for surface water and groundwater flows in the Everglades. The main consideration for South Florida is how we manage rainfall events. The current system of draining water out to tide is poor at retaining water, so it is crucial that we find better water storage alternatives. South Florida's alternating wet and dry periods are also difficult to manage. Climate change predictions suggest slightly drier wet seasons, increased rainfall variability and stronger hurricanes. The three viable options for water storage are: Lake Okeechobee, Water Conservation Areas (WCA) and seepage management which reduces groundwater seepage to the lower east coast. Trade-offs are water quality, water supply and flood control. Average groundwater levels declined by 1 to 3 feet from 1940s to 1990s due to increased water use. Water management is driven by rainfall events and hurricanes. About 3.5 million acre feet of water is lost per year that could be retained by marshes in order to maintain low water levels and dry land for human development. Lake Okeechobee's water levels were lowered in 2007 to accommodate failing dikes and damage to littoral zone.

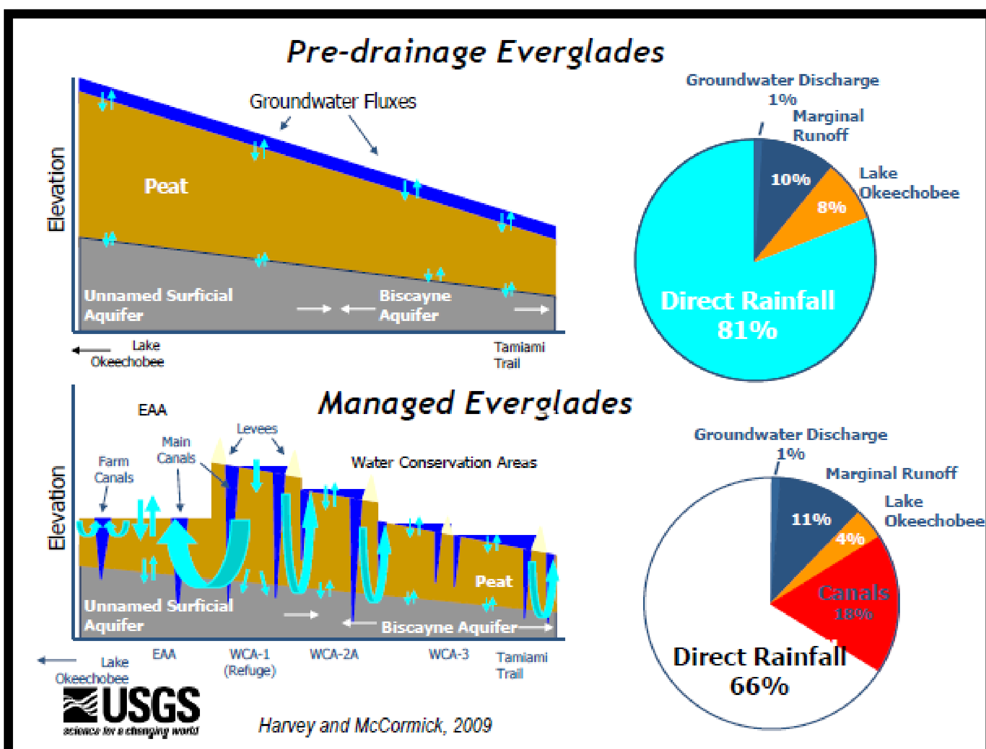
The natural system received twice as much water as the currently managed system today. The Comprehensive Everglades Restoration Plan (CERP) would increase lake outflows into the Everglades Protection Area by only 20% because there is a 750 cubic feet per second (cfs) cap on how much water can flow south to maintain the integrity of canals. Many CERP plans that would have stored more freshwater have been abandoned due to budget cuts. Due to technical problems, only strategic, small scale use of aquifer storage and recovery (ASR) as in-ground reservoirs will be maintained. There are two approaches to reducing seepage losses from the Everglades: reduce and reuse the draw from the regional system, and install seepage barriers for groundwater. A pilot program is underway. A projected 6-inch increase in ET equates to 250,000 acre feet of water in Lake Okeechobee. Priorities include: greater outflow flexibility and development of optimal long term operations for sustainability for Lake Okeechobee; improved conveyance for sheet flow and rainfall-driven operations in the Everglades; and new storage approaches for Lake Okeechobee, WCAs, Everglades Agricultural Area (EAA) and north of the lake. New optimization tools are needed to maximize restoration benefits.

Southern Everglades Impacts from Changes in Water Level

Robert Fennema, ENP, gave an overview of impacts in the southern Everglades due to changes in water levels. The amount of peat in Shark and Taylor Sloughs has been declining. The advantage of peat is that it has low vertical permeability which allows for water storage. We need to maintain the flow to maintain the peat. Flows are the driving force to lower salinities. As water levels change, the composition of flora and fauna will also change with new and shifting vegetation communities. Some species' tolerances may be impacted by temperature, hydroperiod, or sea level. The Cape Sable Seaside sparrow has already disappeared in some areas. Between 1992 -1997, there was increased rainfall during a warm phase of AMO, and widespread changes from prairie to marsh. More recent periods have been well-balanced. Wanless and Vlaswinkel at UM-RSMAS studied coastal landscape and channel evolution at Cape Sable, where current sea level rise is 30 cm per 100 years. The upper limit for mangroves may be 15 cm/ 100 years. There are rapid changes occurring in peat decay and subsidence. With sea levels rising, why restore the Everglades? The restoration of proper groundwater flows will slow down saltwater intrusion. Slowing down the process will allow some species to adapt or migrate. Abrupt changes tend to be less stable and diverse than a gradual change.

Managing Sheetflow to Restore a High-Functioning Everglades Ecosystem

Jud Harvey, USGS, spoke about sheet flow management to restore a high functioning Everglades system. Natural sheet flow formed the ridge and slough system, but the Everglades is currently human-controlled, and 50% of the ridge and slough portion of the system has been degraded under our management. The system was once well-connected by a broad sheetflow through the wetlands but the flow is now discontinuous, having been broken up into separate compartments by levees and canals.



Normally 1/3 ridge and 2/3 slough, the lower water levels have created conditions favorable for expansion of sawgrass and wet prairie species into sloughs that in some cases leads to a complete disappearance of sloughs. There is usually an accompanying loss of microtopography for which the subtle differences in ground surface elevation create conditions favorable for the coexistence of ridge and slough vegetation. Together, lowered water levels and loss of microtopography have exacerbated the loss in directional connectivity of sloughs. Water velocity has a less well understood effect in redistribution of fine sediment from sloughs to ridges. The result of degradation is a decrease in functional integrity through loss of habitat diversity and well-connected animal migration pathways, which are maximized in a well-functioning ridge and slough ecosystem.

DISCUSSION GROUPS

Following the plenary sessions on day two, attendees participated in discussion groups that concentrated on the three primary influences of hydrology of the Greater Everglades: evapotranspiration, groundwater, and precipitation. The discussion groups' goals were:

- to describe the current state of knowledge of its subject,
- identify the key gaps in our current and future knowledge of each subject,
- describe the anticipated effects of climate change on research goals,
- deliberate on what can be done to widen our understanding of the hydrologic cycle in the Everglades, and
- confer what steps should be taken to prepare South Florida and the Everglades for a climate change event.

The discussion groups were composed of a wide variety of individuals including hydrologists, modelers, meteorologists, and biologists. Discussion leaders guided the dialog to answer the above inquiries. The results were presented to the entire workshop to discover commonalties in knowledge gaps and to discuss any potential items that may have been overlooked by the groups.

Precipitation

Leader- Karl Havens

Precipitation is the main driver of the Everglades hydrology. There are a number of research priorities that need to be examined to increase our current and future understanding of precipitation events and how future events will be affected by climate change. Understanding trends in extreme precipitation events, like tropically driven systems and droughts, should become a top priority as changes to extreme events from seasonal climate variations have already been noted. Developing a familiarity with the spatial and temporal trends of precipitation in South Florida is a demanding procedure but critical to understanding how to manage the water budget in the Everglades and surrounding communities. Priority should be given to understanding how spatial and temporal trends have changed throughout history and how they will evolve with a changing climate. Close examination of the relationship between the precipitation trends of urban and natural systems is crucial. The development of models that incorporate land use changes in the future to accurately predict precipitation trends is critical to water management needs. We need to identify current and future urban heat islands and the local effects they may induce on regional precipitation trends, which may become exacerbated as a result of climate change.

We have a wealth of information and data regarding historic and present precipitation events throughout South Florida. We need to ensure the quality of historic data. Investigation of data inaccuracies, such as changes when a station location is moved, must be identified to provide -modelers with quality data to ensure accurate predictions of future events. Further inquiry into the recovery of historic data and the construction of a digital dataset in which to store archived data for easy retrieval is essential to ensure that data quality is maintained. Construction of new rain stations to augment current numbers will benefit data collection and extrapolation of point data to estimate total rainfall. Evaluations of NEXRAD radar data should be explored to ensure quality and accuracy against observed and modeled data.

Regional downscaling of precipitation events is a necessary but complicated task to predict future changes of precipitation trends. Refinement of downscaling procedures that infuse meteorological intelligence, physics, and processes is vital. Relying only on observed data can create bias throughout many models. There is a need to define the minimal scales required for the regional downscaling needs of South Florida in order to create more accurate models that can be replicated. Spatial resolution often suffers during downscaling procedures. It is important to include realistic spatial patterns in downscaled products. A reevaluation of the downscaling procedures for extreme events should be pursued. Downscaling is an important tool in the predication of future variations to precipitation trends during climate change events and should be a priority for climatologists, meteorologists, and modelers.

Evapotranspiration

Leader- Ronnie Best

Evapotranspiration is the second most important component of the Everglades' hydrology, but is the most poorly understood. We have begun to build a wealth of information over the past 5-7 years regarding ET with the information and progress that has been made in gathering data that is used in the construction of the GCM. There are a number of points that are crucial to the understanding of present and future ET rates to understand the evolution of the South Florida landscape. First, it is vital that we build a firm understanding of ET rates among urban, suburban, and agricultural areas; just measuring natural systems negates the potential impacts embedded within mixed landscapes (microclimate). Secondly, the related energy balance and effects on ET between urban and vegetative sites needs further investigation as well as urban heat islands and their effects on non-stationarity in historic and present meteorological records. Finally, the alteration of the land usage patterns, compared with changing ET rates in South Florida, through increased urbanization will far outweigh the potential impacts of climate change for many years and should be assessed thoroughly to improve predicted ET rates in the future.

Up to 15% of total rainfall in the Everglades is induced by ET and most rainfall in the Everglades is returned locally to the atmosphere. Isotopic studies of water could help to distinguish between the rates of evaporation and transpiration leading to more accurate estimations of ET. Although it is viewed as a meteorological event, ET must also be examined as a biological route for water to enter the atmosphere. An understanding of plant response to climate change must be factored in to determine ET rates in the future. A firmer understanding of the effects of seasonal variations and the physiological differences of plant species throughout the Everglades is imperative in understanding ET rates. Although wetland species may be less affected by increased CO_2 levels, it is critical that we examine stomatal response to elevated CO_2 levels and determine how CO_2 levels affect transpiration pathways.

There is a need for more measurement towers that measure ET rates in both urban and rural areas. The largest hindrances we face today with the installation of new towers is the cost and that towers are often limited in their functionality, meaning they serve a single purpose (measuring ET) rather than performing a wide variety of meteorological data collection. A future possibility to reduce the cost of ET data collection is to engineer semi-permanent collection towers which house a variety of instruments to measure the numerous variables that play a role in ET. Another possibility to reduce the research cost of ET while increasing our understanding is to implement the usage of remote technologies. Remote sensing techniques and satellite technology can be used to accurately predict actual and potential ET rates over the entire peninsula.

Ground Water

Leader- Len Berry

Groundwater is a neglected and poorly understood component of the hydrology of the Everglades, especially with regard to how it will be affected by climate change. The hydraulics of the Everglades is the only real world example of a genuine sheet flow system, which makes management and restoration an arduous, learn-by-mistake task. Groundwater flow has undergone severe alteration as a result of the channelization and drainage of the Everglades. Presently, there is a need for practical modeling of sheet flow hydraulics to build a basis for future predication of SLR and climate change scenarios. We need to define critical regions throughout the Everglades and begin to integrate models, information, and people to acquire a more holistic approach of where we are and where we should be going in terms of groundwater management.

Saltwater is intruding further into the saltwater/freshwater interface. This is a critical problem as sea levels rise and will affect a number of biotic and abiotic factors in South Florida. As a result of SLR, saltwater will seep into wells, canals, aquifers, and decrease freshwater flow into Florida Bay. Raising canal levels may only be a temporary fix. Density-dependent hydrologic models of the interaction between ground and surface water may prove to be critical for future changes in sea level and climate.

One key item that should be examined as a result of groundwater alteration is the decomposition and subsidence of peat and marl throughout the Everglades, with special attention to the raising of Tamiami Trail (Highway 41) as it may serve as an example for restored water flow. Our current knowledge of the rate of peat collapse as a result of SLR and our dependence on freshwater to prevent subsidence is limited. It requires extensive investigation in terms of how much infrastructure we need to manage water in Lake Okeechobee to return it to the main hydraulic driver of the Everglades. Currently we know that peat subsidence is a result of freshwater drainage, soil loss, and exposure to wildfires.

DATA NEEDS AND RESEARCH PRIORITIES

Sheet Flow	• Understand the hydraulic dynamics of the Greater Everglades sheet flow system.
	• Examine the effects of restored sheet flow after the completion of the Tamiami Trail (US 41) project. This is vital to understanding the larger picture of restored sheet flow throughout the restored Everglades.
	• Use sulfur hexafluoride as a tracer deployed using airboats to remotely sense flow.
G	• Conduct studies that focus on the interaction between groundwater and surface flow.

	• Establish additional groundwater survey wells.
	• Continue to monitor groundwater for saltwater intrusion. This is critical for determining the impacts on the aquifer system as a result of SLR.
	• Determine the potential ecological impacts of a shifting saltwater/freshwater interface.
Evapotranspiratio	• Examine stomatal response to elevated CO_2 levels and determine how CO_2 levels affect transpiration pathways.
	• Conduct isotopic studies of water that could help to distinguish between the rates of evaporation and transpiration leading to more accurate estimates of ET.
	• Build additional towers to measure ET rates in both urban and rural areas.
	• Understand the effects of seasonal variations and the physiological differences of plant species throughout the Everglades. This is imperative for understanding ET rates.
Climate Change and Sea Level Rise	• Conduct experiments to study the effects of SLR on peat collapse in the Everglades.
	• Learn how to best manage Lake Okeechobee under drier conditions, including dike management and inflows.
	• Understand the trends in extreme precipitation events, such as tropically driven systems and droughts.
	• Examine how permanent temperature changes will affect the hydrologic cycle. This has not yet been given research priority.
	• Integrate adaptive resource management strategies to cope with the uncertainties of future climate changes.
	• Integrate SLR into natural resource and regional planning efforts.
	• Create replicable, accurate models that define the minimal scales required for the regional downscaling needs of South Florida.
	• Produce realistic and robust "what if...?" scenarios that include models with different levels of annual rainfall, e.g., 30, 50, and 70 inches.
	• Implement practical modeling of sheet flow hydraulics, which is needed to build a basis for future predictions of sea level rise and climate change scenarios.

OUTREACH RECOMMENDATIONS

• Work to improve the communication between scientists and the public to create a dialogue on how climate change may impact their lives.
• Build better media relations with the scientific community to effectively communicate climate change issues.

NEXT STEPS

As a follow up to the March hydrology workshop, the steering committee members convened in May to discuss the next steps and details for a fall 2012 workshop. This meeting generated a lively discussion and demonstrated the value of bringing multiple disciplines together.

Fact Sheet and Summary Report

Following the March workshop this summary report and fact sheet was drafted and circulated among the steering committee members for input. This report summarizes the two-day workshop and the fact sheet was created to present the more significant highlights in an 'at-a-glance' format.

Recommendations by Steering Committee for next workshop – Fall 2012:

- It was widely agreed upon that any future efforts should include ecologists. Based on steering committee recommendations, a webinar will be held August 24, 2012 to brief the ecologists on the salient issues that arose as a result of the March workshop.
- A fall workshop will be convened to cover more individualized disciplines and the ecological implications of climate change will be explored in the context of the hydrological cycle.
- There needs to be a focus on the possible changes to the landscape due to peat collapse in the mangrove zone.
- The fall workshop should include posters and presentations by scientists who are working on climate change and ecological response issues in the Greater Everglades.

Future Publication Opportunities

Ronnie Best, title, USGS, announced that a special issue series of the Southeastern Naturalist is planned entitled "Natural History and Restoration of the Greater Everglades." Topically related workshop presentations should serve as potential subjects for articles in this biannual journal.

Vasu Misra, title, organizations?, also announced an additional special issue, "Multi-Disciplinary Assessment of Southeastern Climate" Regionally-based workshop presentations should be targeted for submission to this journal. In addition, past presentations made at the March hydrology workshop and the June Sea Level Rise Summit should be considered as potential topics for these special issues.

APPENDIX 1: Abbreviations List

ACF	Apalachicola-Chattahoochee-Flint river basin
AMO	Atlantic Multi-decadal Oscillation
BCSA	Bias Correction Stochastic Analogue
BCSD	Bias Correction and Spatial Downscaling
CDF	Cumulative Distribution Functions
COAPS	Center for Ocean Atmospheric Prediction Studies
ENSO	El Niño Southern Oscillation
ET	Evapotranspiration
GCM	General Circulation Model / Global Climate Model
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
JVSD	Joint Variable Spatial Downscaling
NCEP	National Center for Environmental Prediction
NMME	US National Multi-Model Ensemble project
PDO	Pacific Decadal Oscillation
PIZA	Population Interaction Zone for Agriculture
RSMAS	Rosenstiel School of Marine and Atmospheric Science
RSM	Regional Spectral Model
SST	Sea Surface Temperature

APPENDIX 2: Steering Committee Members

- Leonard Berry, Director, Florida Center for Environmental Studies, Coordinator, Florida Climate Change Initiative, Florida Atlantic University
- G. Ronnie Best, Coordinator, Greater Everglades Priority Ecosystems Science, US Geological Survey
- Robert Fennema, Hydrologist, National Park Service, US Department of the Interior
- Karl E. Havens, Director and Professor, Florida Sea Grant, University of Florida
- Vasu Misra, Assistant Professor, Meteorology, Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University
- Jayantha Obeysekera, Hydrologic & Environmental Systems Modeling, South Florida Water Management District
- Ramesh Teegavarapu, Assistant Professor, Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University
- Russell Weeks, Chief, Hydrologic Modeling Section, US Army Corps of Engineers

APPENDIX 3: Agenda

Day 1, Thursday March 29, 2012,

10:00 – 10:30 Opening Introduction
Florida Atlantic University, US Geological Survey, Florida Sea Grant
Introduction to the Topic, Goals, and Purpose of the Workshop

10:30 – 12:30 ***Climate Change Implications for Florida: State of Knowledge and Downscaling***

- **Ben Kirtman**, Professor, Meteorology and Physical Oceanography, University of Miami
- **Vasu Misra** Assistant Professor, Meteorology, Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University
- **Aris Georgakakos**, Director, Georgia Water Resources Institute

12:30 – 1:30 Lunch

1:30 – 3:15 **Hydrology of Climate Change in Florida**

- **Aris Georgakakos,** Director, Georgia Water Resources Institute
- **Wendy Graham,** Director, University of Florida Water Institute.
- **Tirusew Asefa,** Senior Water Resources Engineer, Tampa Bay Water
- **Ramesh Teegavarapu,** Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University

3:15 – 3:30 Break

3:30 – 5:00 ***Panel Discussion with Audience Participation***

Day 2, Friday March 30:

Reviewing Components of the Hydrological Cycle – and Change

8:30 – 9:00 Introduction to the Days Agenda – Len Berry

Ronnie Best, Jayantha Obeysekera, Glen Landers, & Robert Fennema will present on behalf of their organizations on what are the hydrological aspects that they are most concerned with.

9:00 – 10:30 ***Precipitation and Temperature***

- **Jayantha Obeysekera**, *South Florida Water Management District*
- **Ramesh Teegavarapu,** Dept. of Civil, Environmental and Geomatics Engineering, Florida Atlantic University
- **Tom J Smith,** United States Geological Survey
- **Glenn Landers**, Army Corps of Engineers

10:30 – 10:45 Break

10:45 – 12:00 ***Evapotranspiration***

- **Dave Sumner**, United States Geological Survey
- **Aaron Evans**, Florida Atlantic University
- **Wossenu *Abtew***, *South Florida Water Management District*
- **Jayantha Obeysekera**, *South Florida Water Management District*

12:00 – 1:00 Lunch

1:00 – 2:15	***Groundwater & Surface Water Flows***

- **Bob Johnson**, Director, South Florida Natural Resources Center
- **Robert Fennema** Hydrologist South Florida Natural Resources Center, SFEO Everglades National Park
- **Jorge Restrepo**, Dept of Geosciences, Florida Atlantic University
- **Jud Harvey**, United States Geological Survey

2:15 – 2:30	Break
2:30 – 4:00	***Breakout Groups on Rainfall (Karl Havens), Evapotranspiration (Ronnie Best), Ground Water (Len Berry)*** Discussion on Research and Monitoring Priorities
4:00 – 5:00	***Data Needs and Research Priorities – Developing a Consensus (Ronnie Best)***

APPENDIX 4: Attendee List

1. Wossenu Abtew (Speaker) South Florida Water Management District wabtew@sfwmd.gov
2. **Ricardo A. Alvarez** (Participant) Vulnerability Assessment & Mitigation ricardoalfonso@mitigat.com
3. **Tirusew Asefa** (Speaker) Senior Water Resources Engineer, Tampa Bay Water TAsefa@tampabaywater.org
4. **Omar Abdul Aziz** (Participant) Assistant Professor, Dept. of Civil & Environmental Engineering, FIU oabdulaz@fiu.edu
5. **Leonard Berry** (Speaker) Director, Florida Center for Environmental Studies, Coordinator, Florida Climate Change Initiative, FAU berry@fau.edu
6. **Ronnie Best** (Speaker) Coordinator, Greater Everglades Priority Ecosystems Science, USGS Ronnie_Best@USGS.gov
7. **Fred Bloetscher** (Invited)**,** Associate Professor, Dept.of Civil, Environmental and Geomatics Engineering, FAU fbloetsc@fau.edu
8. **Anna Cathey** (Participant) University of Florida amcathey@gmail.com
9. **Xavier Comas** (Participant) Assistant Professor, Dept. of Geosciences, FAU xcomas@fau.edu
10. **Anthony DeNardo** (Participant) FAU Graduate Student adenard1@my.fau.edu
11. **Julian Digialleonardo** (Participant) Principal Research Scientist, Battelle, DigialleonardoJ@battelle.org
12. **Vic Engel** (Participant) Hydrologist, Everglades National Park engel.vic@gmail.com
13. **Aaron Evans** (Speaker) Dept. of Geosciences Graduate Student, FAU aevans26@fau.edu
14. **Robert Fennema** (Speaker) Hydrologist South FL Natural Resources Center, SFEO Everglades National Park Robert_Fennema@nps.gov;
15. **Hilary Flower** (Participant) USF Graduate Student hflower@mail.usf.edu
16. **Dolores Forbes** (Janie), (Participant) FAU Graduate Student dforbes@my.fau.edu

17. **Hector Fuentes** (Participant) Professor of Environmental & Water Resources Engineering, FIU fuentes@fiu.edu
18. **Nancy E Gallinaro** (Participant) Director, Strategic Planning, Palm Beach County Water Utilities Department ngallinaro@pbcwater.com
19. **Aris Georgakakos** (Speaker) Director, Georgia Water Resources Institute ageorgak@ce.gatech.edu
20. **Wendy Graham** (Speaker) Director, University of Florida Water Institute wgraham@ufl.edu
21. **Yonas Habtemichael** (Participant) Water Resources Engineering Graduate Student, FIU yhabt001@fiu.edu
22. **Jud Harvey** (Speaker) US Geological Survey jwharvey@usgs.gov
23. **Karl E. Havens** (Participant) Director and Professor, Florida Sea Grant, UF khavens@ufl.edu
24. **Barry Heimlich** (Participant) Research Affiliate, CES, FAU, barryces@bellsouth.net
25. **Bob Johnson** (Speaker) Director, South Florida Natural Resources Center Robert_johnson@nps.gov
26. **Glenn Landers** (Speaker) US Army Corps of Engineers Glenn.B.Landers@usace.army.mil
27. **Caroline Lewis** (Participant)Founder and Director, The CLEO Institute carolinelewisedu@aol.com
28. **Ben Kirtman** (Speaker) Professor, Meteorology and Physical Oceanography, UM bkirtman@rsmas.miami.edu
29. **Craig Mattocks** (Participant) Rosenstiel School of Marine & Atmospheric Science, UM cmattocks@rsmas.miami.edu
30. **Vasu Misra** (Speaker) Assistant Professor, Meteorology, Center for Ocean-Atmospheric Prediction Studies (COAPS), FSU vmisra@fsu.edu
31. **Nantaporn Noosai** (Participant)Environmental Engineering Graduate Student nnoos001@fiu.edu
32. **Martha K. Nungesser** (Participant) Senior Environmental Scientist, Everglades Division SFWMD mnungesser@sfwmd.gov
33. **Jayantha Obeysekera** (Obey)(Speaker) Hydrologic & Environmental Systems Modeling, SFWMD jobey@sfwmd.gov
34. **Luis G. Perez** (Participant) Water Resources Engineering Graduate Student luchoperez@comcast.net
35. **Jorge Restrepo** (Speaker) Dept of Geosciences, FAU restrepo@fau.edu
36. **Ken Rice** (Participant) Director, USGS Southeast Ecological Science Center krice@usgs.gov
37. **Tara Root** (Invited) Assistant Professor, Dept. of Geosciences, FAU troot@fau.edu
38. **Colin J. Saunders** (Participant) Senior Scientist, Everglades Systems Assessment, Applied Science Bureau, SFWMD CSaunder@sfwmd.gov
39. **Christopher Selman** (Participant) FSU Graduate Student cms05j@fsu.edu
40. **Fred H. Sklar** (Participant) Section Admin., Everglades Systems Assessment Section, SFWMD fsklar@sfwmd.gov
41. **Tom J Smith** (Speaker) US Geological Survey tom_j_smith@usgs.gov

42. **Dave Sumner** (Speaker) US Geological Survey dmsumner@usgs.gov
43. **Patricia Strayer** (Participant) Southeast Region Coordinator, Battelle STRAYERP@battelle.org
44. **Ramesh Teegavarapu** (Speaker) Department of Civil, Environmental & Geomatics Engineering, FAU ramesh@civil.fau.edu
45. **Paul J. Trimble** (Participant) Principal Scientist, Hydrologic & Environmental Systems Modeling, SFWMD ptrimble@sfwmd.gov
46. **Maya Trotz** (Participant) Associate Professor, Department of Civil and Environmental Engineering, USF matrotz@usf.edu
47. **Kalanithy Vairavamoorthy** (Kala) (Participant) Professor, Civil and Environmental Engineering Dept., Director, School of Global Sustainability, USF vairavk@usf.edu
48. **Joel VanArman** (Participant) Environmental Scientist, SFWMD jovanarm@sfwmd.gov
49. **Viviana Villamizar** (Participant) FIU Environmental Engineering Graduate Student vvill017@fiu.edu
50. **Russ Weeks** (Participant) Chief, Hydrologic Modeling Section, US Army Corps of Engineers Russell.weeks@usace.army.mil

APPENDIX 5: Speaker Biographies

Ronnie Best

Ronnie Best is a research coordinator with the U.S. Geological Survey. He is the Coordinator of the USGS's Greater Everglades Priority Ecosystems Science. Dr. Best retired from University of Florida's College of Engineering where he was Director of UF's Center for Wetlands & Water Resources and a member of the faculty of Environmental Engineering Sciences Department. Dr. Best joined the federal service in 1995 as Branch Chief for the Wetlands Ecology Branch at USGS's National Wetlands Research Center (NWRC, Lafayette, LA). In 1997, Dr. Best moved to south Florida where he has served as Coordinator of USGS's Greater Everglades Science since 2001. Dr. Best conceived of and initiated the Greater Everglades Ecosystem Restoration (GEER) Conference(s) and the National Conference(s) on Ecosystem Restoration (NCER). Dr. Best has over three decades of research and teaching experience in the area of ecology, ecological engineering, and restoration and management of wetlands, most of which has been in Florida. He has over 70 publications including book chapters, technical reports, and journal publications; co-editor of a book on Okefenokee Swamp and is co-edited a special issue publication on Biogeochemistry of the Greater Everglades. While at UF, he taught and did research on wetlands ecology and wetlands ecological engineering, and served as major advisor to over 45 graduate students and on committees for over 120 graduate students. Dr. Best has Adjunct Professor appointments with University of Florida and Florida Atlantic University where he continues to serve on graduate student committees and occasionally lectures in classes.

Aris Georgakakos

Dr. Aris P. Georgakakos holds a civil engineering Diploma from the National Technical University of Athens, Greece, and Masters and Ph. D. degrees in water resources from the Massachusetts Institute of Technology. Dr. Georgakakos is currently a Professor at the School of Civil and Environmental Engineering at Georgia Tech, Head of the Environmental Fluid Mechanics and Water Resources Program, and Director of the Georgia Water Resources Institute. Dr. Georgakakos' research and technology transfer activities aim to develop and implement prototypical information and decision support systems for integrated water resources assessment, development, and management. These systems combine data from conventional and remote sources, GIS, and models from various scientific and engineering disciplines (including climate, hydrology, agricultural science, water resources, wetland and river ecology, hydro-thermal power systems, economics, statistics, and operations research). Dr. Georgakakos has been involved in several world regions and his decision support systems are currently used for river basin planning and management in Georgia and the southeast US, California, East Africa, Brazil, Jordan, Greece, and China. His research and technology transfer activities have been sponsored by

U.S. and foreign organizations including the US Geological Survey, US Army Corps of Engineers, National Oceanic and Atmospheric Administration, National Science Foundation, Environmental Protection Agency, Food and Agriculture Organization of the United Nations, World Bank, US and European International Development Agencies, and several domestic and foreign electrical utilities. Dr. Georgakakos publishes extensively, is an Associate Editor for the Advances in Water Resources Journal and the Journal of Hydrology, and currently serves as a Convening Lead Author for the water sector chapter of the US National Climate Assessment.

Wendy Graham

Wendy D. Graham is the Carl S. Swisher Eminent Scholar in Water Resources in the Department of Agricultural and Biological Engineering at the University of Florida and Director of the University of Florida Water Institute. She graduated from the University of Florida with a Bachelor's degree in Environmental Engineering. Her PhD is in Civil Engineering from the Massachusetts Institute of Technology. She conducts research in the areas of coupled hydrologic-water quality-ecosystem modeling; water resources evaluation and remediation; evaluation of impacts of agricultural production on surface and groundwater quality; and development of hydrologic indicators of ecosystem status. She has served as PI or co-PI on over $11 million in grants and contracts, has supervised 30 doctoral and master's thesis committees and has served on an additional 45 graduate student committee.

Jud Harvey

Dr. Judson W. Harvey investigates hydrologic transport processes and how they affect aquatic ecosystem processes in rivers and wetlands. The research is conducted in varied environments, from steep forested watersheds in Colorado and California to alluvial rivers in Arizona and Louisiana to headwater streams and wetlands of Midwestern agricultural areas, urban areas of the Atlantic coastal plain, and the vast Everglades floodplain in south Florida. Jud has served on editorial boards for *Water Resources Research* and *Wetlands*, and on committees of the *American Geophysical Union*, the *National Research Council*, and the *American Society of Limnology and Oceanography*. He has taught "Groundwater-Surface Water Relationships: Chemical and Hydroecological Interactions" at USGS' National Training Center in Denver for nearly twenty years, and he is co-author of the immensely popular USGS circular "Groundwater and Surface Water: A Single Resource" with 44,000 copies in print. In 2010 Jud was elected as a Fellow of the *Geological Society of America*

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Bob Johnson

Robert Johnson has served as Director since October 1995, seeing the Center through the settlement of the Water Quality Lawsuit, through much of the planning and implementation of the Modified Water Deliveries Project, and through the development of the Comprehensive Everglades Restoration Plan.

Bob holds a B.S. in Geology from James Madison University and an M.S. in Environmental Sciences/Water Resources from the University of Virginia with additional graduate coursework completed at Florida International University. He started working for the Center in 1983 as a Staff Hydrologist, later serving as Supervisory Hydrologist, and then as Branch Chief both for Physical Resources and for the former Ecosystem Analysis and Modeling branch. He has represented the NPS on more than 20 advisory and technical committees charged with protecting and restoring the south Florida environment. These committees have spanned a broad range of topics from water quality protection and water supply planning, to watershed management, land use planning, and inter-disciplinary science coordination. Bob has been called to serve as a technical expert on more than 25 litigation cases in federal and state courts and has represented NPS positions before Florida's Governor and Cabinet as well as other state and federal legislative bodies. Bob has received numerous NPS awards including the Southeast Region Director's Award for Science in 1990 and in 1992, an NPS Honor Award for Superior Service in 1995, and two awards for Natural Resource Management in 2001: the Southeast Region Director's Award and the NPS Director's Award. Also, in 1997 he received the George Barley Award for sustained public service at the annual Everglades Coalition Conference.

Greg Kiker

Greg Kiker teaches and conducts research in the integration of ecological, hydrological and decision models. He has diverse research experience from both federal agencies and academic institutions in environmental decision analysis, development of decision support systems and object-oriented design/programming. His current research projects include the following: savanna and rangeland ecosystem dynamics, mercury dynamics in restored wetland areas, invasive species modeling for risk assessment and management, food/ecology/marine system integration for decision support/scenario analysis in the Caribbean, and practical linkages of risk analysis, adaptive management and multi-criteria decision analysis. His current modeling products include the development and application of the Acru2k agro-hydrological model and the QnD scenario/game modeling system. Dr Kiker was a Fulbright Scholar to South Africa in 1992 and received his PhD from Cornell University in Agricultural and Biological Engineering in 1998. He has consulted internationally in the use of ecological and environmental models for ecosystem management, crop yield prediction, nutrient-transport, and climate change.

Ben Kirtman

Professor Benjamin Kirtman received his BS in Applied Mathematics from the University of California-San Diego in 1987, and his MS and PhD in 1992 from the University of Maryland-College Park. From 1993-2002 Dr. Kirtman was a research scientist with the Center for Ocean-Land-Atmosphere Studies and in 2002 joined the faculty of George Mason University as a tenured Associate Professor. In 2007, Dr. Kirtman moved to the University of Miami – Rosenstiel School for Marine and Atmospheric Science as a full professor and also serves as the Program Director of Physical Sciences and Engineering at the Center for Computational Science. In 2011, he was appointed Associate Dean for Research for the Rosenstiel School.

In 2008, Professor Kirtman received the Distinguished Alumnus Award from the Department of Atmospheric and Oceanic Science at the University of Maryland. Dr. Kirtman continues to be active in scientific leadership both internationally and nationally. Currently, Dr. Kirtman is co-Chair of the US Clivar Prediction, Predictability and Applications Interface (PPAI) panel and a co-Chair of the NOAA Climate Test Bed – Climate Science Team. Internationally, Dr. Kirtman has enjoyed a leadership role in the World Climate Research Program (WCRP) seasonal-to-interannual prediction activities. In particular, he co-chairs the International Clivar Working Group on Seasonal to Interannual Prediction (WGSIP), and chairs the WCRP Task Force for Seasonal Prediction (TFSP). Professor Kirtman is also an Executive Editor of Climate Dynamics one the most prestigious peer reviewed journals in the field. Professor Kirtman is the author and/or co-author of over 90 peer reviewed papers focused on understanding and predicting climate variability on time scales from intra-seasonal to decadal. Recently, Dr. Kirtman has also published on understanding how climate variability might change in a warmer climate. Dr. Kirtman has advised and continues to work with several Ph. D. students.

Vasu Misra

My research interests are in climate variability and predictability. I like to work with a variety of numerical models to understand climate variations from diurnal, intra-seasonal to interannual time scales. These numerical tools include regional atmospheric models, atmospheric general circulation models and coupled ocean-atmosphere models. While I am keen on understanding the predictability of a model, the challenges of real-time climate prediction have also been part of my research vocation. Phenomenologically I have worked on ENSO, the South American Monsoons, Tropical Atlantic Variability, US hydroclimate and some aspects of equatorial African climate. Diagnosing the role of air-sea and land-atmosphere interactions in climate and weather variations is another pet project of mine. I believe the paradigm of using coupled ocean-land-atmosphere systems for predictability or prediction studies of climate and even weather at the expense of weaning away from "reduced" component model systems is a worthy cause of scientific pursuit.

Jayantha Obeysekera

Jayantha Obeysekera is the Director of the Hydrologic & Environmental Systems Modeling Department at the South Florida Water Management District (SFWMD), a regional governmental agency in South Florida, United States. Dr. Obeysekera holds a bachelor's degree in Civil Engineering from University of Sri Lanka, M. Eng. from University of Roorkee, India, and a Ph.D. in Civil Engineering from Colorado State University with specialization in water resources. Prior to joining SFWMD in 1987, he worked as an Assistant Professor in the Department of Civil Engineering at Colorado State University. He also has taught courses in the water resources area at George Washington University, Washington, D.C. and at Florida Atlantic University, Boca Raton. He has also held the position of Courtesy Associate Professor, Department of Civil and Environmental Engineering, University of South Florida in Tampa. During his career, Dr. Obeysekera has published nearly 40 research articles in refereed journals and over 50 others in the field of water resources. Dr. Obeysekera has over 25 years of experience practicing water resources engineering with an emphasis on computer modeling with emphasis on implications of climate variability on planning and operations of complex water resources systems. He has taught short courses on modeling in the countries of Dominican Republic, Colombia, Spain, Sri Lanka, and U.S. Recently he was appointed as a member of National Research Council committees to review hydrologic studies of the Klamath River Basin in Oregon and California, and the Sustainability of California Bay-Delta, and as an external advisory member to review the computer modeling of the New Orleans area in the aftermath of the hurricane Katrina. He was a co-principal investigator for a US NSF funded project on the investigation of the tsunami impacts on coastal water resources in Sri Lanka. His group has been instrumental in the application of climate outlook on such indices as ENSO and AMO in planning and operations of the south Florida water resources system and has recently published chapter on this experience in a book published by the American Society of Civil Engineers. Presently, he is the technical lead for climate change and climate variability investigations at SFWMD.

APPENDIX 6: Selected Abstracts and References on Everglades Hydrology

Compiled by Anthony Denardo III

Precipitation

Optimal Functional Forms for Estimation of Missing Precipitation Data

Ramesh S.V. Teegavarapu, Mohammad Tufai, Lindell Ormsbee

ABSTRACT A fixed functional set genetic algorithm method (FFSGAM) is proposed and is investigated in the current study to obtain optimal functional forms for estimating missing precipitation data. The FFSGAM provides functional forms with optimal combination of parameters of surrogate and actual measures of strength of correlation among observations for estimating missing data. The method uses genetic algorithms and a nonlinear optimization formulation to obtain optimal functional forms and coefficients, respectively. Historical daily precipitation data available from 15 rain gaging stations from the state of Kentucky, USA, are used to test the functional forms and derive conclusions about the efficacy of the proposed method for estimating missing precipitation data. The tests of FFSGAM at two rainfall gauging stations in Kentucky, using multiple error and performance indices, indicate that better estimates of precipitation can be obtained compared to those from a traditional inverse distance weighting technique. Also, results from the use of the method confirm its robustness when only six rain gauging stations out of 14 were used for estimating missing data

High-Resolution Subtropical Summer Precipitation Derived from Dynamical Downscaling of the NCEP/DOE Reanalysis: How Much Small-Scale Information is Added by a Regional Model?

Young-Kwon Lim , Lydia B. Stefanova, Steven C. Chan, Siegfried D. Schubert, James J. O'Brien

ABSTRACT This study assesses the regional-scale summer precipitation produced by the dynamical downscaling of analyzed large-scale fields. The main goal of this study is to investigate how much the regional model adds smaller scale precipitation information that the large-scale fields do not resolve. The modeling region for this study covers the southeastern United States (Florida, Georgia, Alabama, South Carolina, and North Carolina) where the summer climate is subtropical in nature, with a heavy influence of regional-scale convection. The coarse resolution (2.5_ latitude/longitude) large-scale atmospheric variables from the National Center for Environmental Prediction (NCEP)/DOE reanalysis (R2) are downscaled using the NCEP/Environmental Climate Prediction Center regional spectral model (RSM) to produce precipitation at 20 km resolution for 16 summer seasons (1990–2005). The RSM produces realistic details in the regional summer precipitation at 20 km resolution. Compared to R2, the RSM-produced monthly precipitation shows better agreement with observations. There is a reduced wet bias and a more realistic spatial pattern of the precipitation climatology compared with the interpolated R2 values. The root mean square errors of the monthly R2 precipitation are reduced over 93% (1,697) of all the grid points in the five states (1,821). The temporal correlation also improves over 92% (1,675) of all grid points such that the domain-averaged correlation increases from 0.38 (R2) to 0.55 (RSM). The RSM accurately reproduces the first

two observed eigenmodes, compared with the R2 product for which the second mode is not properly reproduced. The spatial patterns for wet versus dry summer years are also successfully simulated in RSM. For shorter time scales, the RSM resolves heavy rainfall events and their frequency better than R2. Correlation and categorical classification (above/near/below average) for the monthly frequency of heavy precipitation days is also significantly improved by the RSM.

Simulation of Daily Rainfall Scenarios with Interannual and Multidecadal Climate Cycles for South Florida

Hyun-Han Kwon, Upmanu Lall, Jayantha Obeysekera

ABSTRACT Concerns about the potential effects of anthropogenic climate change have led to a closer examination of how climate varies in the long run, and how such variations may impact rainfall variations at daily to seasonal time scales. For South Florida in particular, the influences of the low-frequency climate phenomena, such as the El Niño Southern Oscillation (ENSO) and the Atlantic Multi-decadal Oscillation (AMO), have been identified with aggregate annual or seasonal rainfall variations. Since the combined effect of these variations is manifest as persistent multi-year variations in rainfall, the question of modeling these variations at the time and space scales relevant for use with the daily time step-driven hydrologic models in use by the South Florida Water Management District (SFWMD) has arisen. To address this problem, a general methodology for the hierarchical modeling of low- and high-frequency phenomenon at multiple rain gauge locations is developed and illustrated. The essential strategy is to use long-term proxies for regional climate to first develop stochastic scenarios for regional climate that include the low-frequency variations driving the regional rainfall process, and then to use these indicators to condition the concurrent simulation of daily rainfall at all rain gauges under consideration. A newly developed methodology, called Wavelet Autoregressive Modeling (WARM), is used in the first step after suitable climate proxies for regional rainfall are identified. These proxies typically have data available for a century to four centuries so that long-term quasi-periodic climate modes of interest can be identified more reliably. Correlation analyses with seasonal rainfall in the region are used to identify the specific proxies considered as candidates for subsequent conditioning of daily rainfall attributes using a Non-homogeneous hidden Markov model (NHMM). The combined strategy is illustrated for the May–June–July (MJJ) season. The details of the modeling methods and results for the MJJ season are presented in this study.

Accurate Quantification of Seasonal Rainfall and Associated Climate-Wildfire Relationships

Matthew G. Slocum, William J. Platt, Brian Beckage, Steve L. Orzell, Wayne Taylor

ABSTRACT Wildfires are often governed by rapid changes in seasonal rainfall. Therefore, measuring seasonal rainfall on a temporally fine scale should facilitate the prediction of wildfire regimes. To explore this hypothesis, daily rainfall data over a 58-yr period (1950--2007) in south-central Florida were transformed into cumulative rainfall anomalies (CRAs). This transformation allowed precise estimation of onset dates and durations of the dry and wet seasons, as well as a number of other variables characterizing seasonal rainfall. These variables were compared with parameters that describe ENSO and a wildfire regime in the region (at the Avon Park Air Force Range). Onset dates and durations were found to be highly variable among years, with standard deviations ranging from 27 to 41 days. Rainfall during the two seasons was distinctive, with the dry season having half as much as the wet season despite being nearly 2 times as long. The precise quantification of seasonal rainfall led to strong statistical models describing linkages between climate and wildfires: a multiple-regression technique relating the area burned with the seasonal rainfall characteristics had an of 0.61, and a similar analysis examining the number of wildfires had an of 0.56. Moreover, the CRA approach was effective in outlining how seasonal rainfall was associated with ENSO, particularly during the strongest and most unusual events (e.g., El Niño of 1997/98). Overall, the results presented here show that using CRAs helped to define the linkages among seasonality, ENSO, and wildfires in south-central Florida, and they suggest that this approach can be used in other fire-prone ecosystems.

Stochastic Multi-Site Generation of Daily Rainfall Occurrence in South Florida

Tae-woong Kim, Hosung Ahn, Gunhui Chung, Chulsang Yoo

ABSTRACT This paper presents a stochastic model to generate daily rainfall occurrences at multiple gauging stations in south Florida. The model developed in this study is a space–time model that takes into account the spatial as well as temporal dependences of daily rainfall occurrence based on a chain-dependent process. In the model, a Markovian method was used to represent the temporal dependence of daily rainfall occurrence and a direct acyclic graph (DAG) method was introduced to encode the spatial dependence of daily rainfall occurrences among gauging stations. The DAG method provides an optimal sequence of generation by maximizing the spatial dependence index of daily rainfall occurrences over the region. The proposed space–time model shows more promising performance in generating rainfall occurrences in time and space than the conventional Markov type model. The space–time model well represents the temporal as well as the spatial dependence of daily rainfall occurrences, which can reduce the complexity in the generation of daily rainfall amounts.

Comparison of NEXRAD and Rain Gauge Precipitation Measurements in South Florida

Courtney Skinner, Frederick Bloetscher, and Chandra S. Pathak,

ABSTRACT The South Florida Water Management District _SFWMD_ relies on a network of nearly 300 rain gauges in order to provide rainfall data for use in operations, modeling, water supply planning, and environmental projects. However, the prevalence of convective and tropical disturbances in South Florida during the wet season presents a challenge in that the current rain gauge network may not fully capture rain events that demonstrate high spatial variability. Next Generation Radar _NEXRAD_ technology offers the advantage of providing a spatial account of rainfall, although the quality of radar-rainfall measurements remains largely unknown. The comparison of rainfall estimates from a gauge-adjusted, NEXRAD-based product developed by the OneRain Company with precipitation measurements from SFWMD rain gauges was performed for the Upper and Lower Kissimmee River Basins over a four-year period from 2002 to 2005. Overall, NEXRAD was found to underestimate rainfall with respect to the rain gauges for the study period, demonstrating a radar to gauge ratio of 0.95. Further investigation of bias revealed the tendency for NEXRAD to overestimate small rainfall amounts and underestimate large rainfall amounts relative to the gauge network. The nature of bias present in the data led to the development of a radar-rain gauge relationship to predict radar precipitation estimates as a function of rain gauge measurements. The intent of this paper is to demonstrate the importance of identifying systematic offsets which may be present in radar-rainfall data before application in hydrologic analysis.

Evapotranspiration

Pan Evaporation and Potential Evapotranspiration Trends in South Florida

Wossenu Abtew, Jayantha Obeysekera and Nenad Iricanin

ABSTRACT Declining trends in pan and lake evaporation have been reported. It is important to study this trend in every region to evaluate the validity of the trend and water management implications. Data from nine pan evaporation sites in South Florida were evaluated to see if there is a trend and if the quality of the data is sufficient for such analysis. The conclusion is that pan evaporation measurements are prone to too many sources of errors to be used for trend analysis. This condition is demonstrated in South Florida and in other regions by differences in magnitude and direction between spatially related pan stations and unexplainable observations. Also, potential evapotranspiration (ETp) was estimated with the Simple (Abtew equation) and the Penman–Monteith method. Both cases indicated no decline in evapotranspiration for the period of analysis. Based on the decline in humidity and the increasing trend in vapor pressure deficit for the short period of analysis, 1992–2009, it appears that South Florida is experiencing increase in evaporation and evapotranspiration at this time assuming no systematic error in the weather stations' observations. Copyright 2010 John Wiley & Sons, Ltd.

Regional Evaluation of Evapotranspiration in the Everglades

Edward R. German

ABSTRACT One of the most important components of the Everglades (south Florida) water budget is evapotranspiration (ET). In this area, most rainfall is likely returned to the atmosphere by ET. A study to quantify and model ET in the Everglades was begun in 1995. A network of nine ET-evaluation sites was established that represents the varied hydrologic conditions and vegetative characteristics of the Everglades. Data from continuous measurements of parameters for evaluation of ET at the sites for the period January 1996 through December 1997 were used to develop regional models that can be used to simulate ET at other times and places throughout the Everglades. The Bowen-ratio energy budget method was selected for the ET evaluation. After careful screening to eliminate erroneous data, site and regional models of ET were calibrated for the nine sites. A modified Priestley-Taylor model of ET was calibrated for each site. In these models the Priestley-Taylor coefficient (α) was expressed as a function of incoming solar energy and water level. The individual site models were then combined into two regional models: one is applicable to vegetated wet-prairie and sawgrass-marsh sites in the natural Everglades system, and the other is applicable to freshwater sloughs and other open areas with little or no emergent vegetation. Computed ET totals for all nine sites ranged from 42.78 inches per year at a sometimes-dry sparse-sawgrass site to 55.54 inches per year at an open-water site. Differences in annual ET relate to water availability and perhaps to density of vegetation. The annual total ET values simulated by the regional models generally are in relatively close agreement with the computed values. The difference between computed and simulated ET generally was less than 3 inches per year. The median difference was about 1.4 inches per year.

Evaporation Estimation for Lake Okeechobee in South Florida

Wossenu Abtew

ABSTRACT Lake Okeechobee, located in subtropical South Florida, is the second largest completely contained freshwater lake in the United States. The average, annual evaporation is 132 cm, reported following five years of meteorology data analysis (1993–1997). Simple models, developed from an open-water lysimeter evaporation study, are recommended to estimate daily lake evaporation from solar radiation or solar radiation and maximum air temperature. Seven evaporation estimation methods were evaluated to compare their applicability in providing daily, lake evaporation estimation for water management purposes. The analysis used five-year meteorology data, measured inside the lake. Monthly pan coefficients and annual average pan coefficients were produced for seven pan evaporation stations in the vicinity of Lake Okeechobee. Using the recommended simple models and the remote meteorology data collection, Lake Okeechobee daily evaporation can be reported at the end of each day for water management decision-making.

Estimating Reference Evapotranspiration with Minimum Data in Florida

Christopher J. Martinez, and Mayank Thepadia

ABSTRACT Reference evapotranspiration estimation methods that require minimal data are necessary when climatic data sets are incomplete, inaccurate, or unavailable. This study was conducted to evaluate temperature-based reference evapotranspiration methods in Florida. Using reference evapotranspiration estimates using satellite-derived radiation as the standard for comparison, the “reduced-set” Penman-Monteith, Hargreaves, and Turc equations were evaluated using monthly temperature data from 72 weather stations in Florida. The reduced-set Penman-Monteith equation requires maximum and minimum temperature only and uses recommended methods to estimate radiation, humidity, and wind speed. The reduced-set Penman-Monteith and Hargreaves equations were found to overestimate reference evapotranspiration while the Turc equation neither overestimated nor underestimated. The reduced-set Penman-Monteith equation showed greatest error in coastal stations while the Hargreaves equation showed greatest error at inland and island locations. In the absence of regionally calibrated methods the Turc equation is recommended for estimating reference evapotranspiration using measured maximum and minimum temperature and estimated radiation in Florida.

Evapotranspiration from Areas of Native Vegetation in West-Central Florida

W.R. Bidlake, W.M. Woodham, and M.A. Lopez

ABSTRACT A study was conducted to evaluate the suitability of three micrometeorological methods for estimating evapotranspiration from selected areas of native vegetation in west-central Florida and to estimate annual evapotranspiration from areas having a specific vegetation type. Evapotranspiration was estimated using the methods of energy-balance Bowen ratio (EBBR) and eddy correlation. Potential evapotranspiration was computed using the Penman equation. Field measurements were made intermittently from February 1988 through September 1990.

The EBBR method was used to estimate evapotranspiration from unforested and forested sites. A mean-gradient Bowen ratio system was used to measure and average vertical air temperature and vapor-pressure gradients, and the Bowen ratio was computed using the mean air temperature and vapor-pressure gradients. The Bowen ratio estimated in this manner was then used to compute evapotranspiration by the EBBR method. Computations based on objective review criteria indicated that the Bowen ratio, computed using measurements made using the mean-gradient Bowen ratio system, was not always realistic. During a period of extended operation at a dry prairie site, 9 percent of measured available energy during the daytime occurred when the Bowen ratio obtained using the mean-gradient Bowen ratio system was unrealistic. During 5 out of 14 days of continuous operation at a marsh site, more than 30 percent of measured available energy during the daytime occurred when the Bowen ratio obtained using the mean-gradient Bowen ratio system was unrealistic. One of the primary causes of unrealistic Bowen ratios at the unforested sites was condensation of moisture within the tubing of the mean-gradient Bowen ratio system. Measurements made using the mean-gradient Bowen ratio system at a forested pine flatwood site indicated that vapor-pressure gradients were too weak to be resolved by the system. As a result, the Bowen ratio computed for the forested sites was unreliable when it was obtained using the mean-gradient Bowen ratio system.

Direct estimates of sensible and latent heat flux that were computed from eddy correlation measurements were generally insufficient to account for measured available energy at all sites. Analysis of eddy correlation and energy-balance data indicated that the sum of sensible and latent heat fluxes accounted for 68 percent of available energy at dry prairie and marsh sites, 74 percent of available energy at a pine flatwood site, and 45 percent of available energy at a cypress swamp site. Because specific causes of the energy-balance discrepancies could not be quantified, corrections to the direct eddy correlation flux estimates could not be made, and eddy correlation data were combined with other energy-balance data to yield two alternative evapotranspiration estimates. The first alternative evapotranspiration estimate was computed by combining sensible heat flux obtained from eddy correlation with measurements of available energy to compute latent heat flux as the residual of the equation for the surface energy balance. The second alternative evapotranspiration estimate was computed by using direct sensible and latent heat flux estimates that were obtained from eddy correlation measurements to compute the Bowen ratio. The Bowen ratio obtained from eddy correlation measurements was then combined with measurements of available energy to compute evapotranspiration by the EBBR method. Of the three alternative evapotranspiration estimates obtained from eddy correlation measurements, the estimate computed using the EBBR method, with the Bowen ratio computed from eddy correlation measurements, agreed most strongly with the corresponding evapotranspiration estimate computed using the EBBR method with the Bowen ratio obtained from the mean gradient Bowen ratio system. It is probable that actual evapotranspiration was within a range defined by the standard eddy correlation computation, which consistently indicated the smallest evapotranspiration, and the energy-balance residual computation, which consistently indicated the largest evapotranspiration.

Daily potential evapotranspiration, as computed by the Penman method, and daily evapotranspiration, as computed by the EBBR method, did not seem to correlate with each other at a dry prairie site during late spring and summer; however, the two were correlated with each other at a marsh site during late spring and summer. Evapotranspiration was approximately 57 percent of potential evapotranspiration at the marsh site. The correlation between evapotranspiration and potential evapotranspiration at the marsh site, and the fact that evapotranspiration approached potential evapotranspiration, indicated that the Penman method can be useful for estimating evapotranspiration from marshes in west-central Florida.

Annual evapotranspiration estimates were developed for each vegetation type by pooling EBBR and eddy correlation measurements among sites and among the 3 years during which field measurements were made. Three different estimates, which correspond to the three eddy correlation computation methods, were made for each vegetation type. The centric estimates, which were calculated by using the EBBR method with the Bowen ratio obtained from either a mean gradient system or from eddy correlation measurements, were 1,010 millimeters per year for the dry prairie type, 990 millimeters per year for the marsh vegetation type, 1,060 millimeters per year for the pine flatwood type, and 970 millimeters per year for the cypress swamp type.

Groundwater

Simulation of Water Levels and Water Diversions in a Subtropical Coastal Wetland

J.I. Restrepo, D. Garces, A. Montoya, N. Restrepo, and J. Giddings

ABSRTACT A ground-water model was developed for Miami–Dade County Florida, which lies within the Southeast Atlantic Coastal Zone, as a predictive tool that will be used to analyze different water-management scenarios, including regional water-supply plans and the Comprehensive Everglades Restoration Plan (CERP). The model is being developed by the South Florida Water Management District (SFWMD) based on a modified version of the US Geological Survey modular three-dimensional, finite-difference, ground-water-flow model (MODFLOW). This version includes the Wetland and Diversion packages, which are MODFLOW modules that enable the top layer of the grid system to include overland flow through dense vegetation, channel flow through a slough network, and interaction with levees, and thus can closely simulate the natural system.

The model domain is discretized into 430 rows by 367 columns with a uniform cell size of 500 ft 3 500 ft (152.4m). Four horizontal layers are used to represent lithologic zones within the surficial aquifer, one of the most transmissive aquifers in the world, with transmissivity values as high as 300,000 ft2/d (27,870.9 m2/d). Boundary conditions were established by water levels in canals on the northern and southern edges of the modeled region and by water level measurements in wetlands along the western edge. The eastern boundary with the Atlantic Ocean was determined by using mean tidal fluctuations to calculate the equivalent fresh-water head.

The main advantage of this model, besides the high degree of detail and the number of variables, is that it can simulate hydroperiods within wetland areas using the Wetland and Diversion packages. These packages allow the model to represent the full hydrologic cycle within the wetland areas, including sources and sinks on a daily basis, starting with total precipitation as a driving force.

During calibration (1988–90), a very low sensitivity to conductivity and canal conductances was observed. Therefore, the fit between the model-computed water levels and the observed historical ground-water levels was achieved mainly by adjusting general head boundary conditions and wetland parameters within the active domain. The model is highly sensitive to the operational rules, especially the stages at which the canals are maintained, and is therefore responsive to the way that the system is managed.

A Wetland Simulation Module for the MODFLOW Ground water Model

Jorge I. Restrepo, Angela M. Montoya, and Jayantha Obeysekera

ABSTRACT The alteration of wetland habitat by natural and anthropogenic processes is an issue of worldwide concern. Understanding the changes that occur in wetlands often requires knowledge of how surface water relates to adjacent aquifer systems. The ability to simulate surface water movement and its interaction with ground water and wetland slough channels is a desirable step in the design of many projects constructed in or near wetlands. Currently, most ground water flow models incorporate wetland systems as general head boundary nodes. The purpose of this research was to develop a computer package for the widely used MODFLOW

code that would simulate three-dimensional wetland flow hydroperiods and wetland interactions with aquifer and slough channels. The ground water flow model was used to reproduce the surface water flow process through wetlands, and then to estimate new flow rates and values using a Manning-type equation. This package represents flow routing, export and import of water and evapotranspiration from wetlands for different hydroperiods. A basic verification procedure for the numerical solution of the diffusion equation was applied, based on a test case that was solved using two-dimensional surface water model. This example is a transient solution to the diffusion equation, in which the initial conditions were depicted by a sinusoidal water surface profile and a flat bottom.

Groundwater's Significance to Changing Hydrology, Water Chemistry and Biological Communities of a Floodplain Ecosystem, Everglades, South Florida, USA

Judson W. Harvey & Paul V. McCormick

ABSTRACT The Everglades (Florida, USA) is one of the world's larger subtropical peatlands with biological communities adapted to waters low in total dissolved solids and nutrients. Detecting how the pre-drainage hydrological system has been altered is crucial to preserving its functional attributes. However, reliable tools for hindcasting historic conditions in the Everglades are limited. A recent synthesis demonstrates that the proportion of surface-water inflows has increased relative to precipitation, accounting for 33% of total inputs compared with 18% historically. The largest new source of water is canal drainage from areas of former wetlands converted to agriculture. Interactions between groundwater and surface water have also increased, due to increasing vertical hydraulic gradients resulting from topographic and water-level alterations on the otherwise extremely flat landscape. Environmental solute tracer data were used to determine groundwater's changing role, from a freshwater storage reservoir that sustained the Everglades ecosystem during dry periods to a reservoir of increasingly degraded water quality. Although some of this degradation is attributable to increased discharge of deep saline groundwater, other mineral sources such as fertilizer additives and peat oxidation have made a greater contribution to water-quality changes that are altering mineral sensitive biological communities.

Coastal Groundwater Discharge – An Additional Source of Phosphorus for the Oligotrophic Wetlands of the Everglades

Rene´ M. Price1, Peter K. Swart & James W. Fourqurean

ABSTRACT In this manuscript we define a new term we call coastal groundwater discharge (CGD), which is related to submarine groundwater discharge (SGD), but occurs when seawater intrudes inland to force brackish groundwater to discharge to the coastal wetlands. A hydrologic and geochemical investigation of both the groundwater and surface water in the southern Everglades was conducted to investigate the occurrence of CGD associated with seawater intrusion. During the wet season, the surface water chemistry remained fresh. Enhanced chloride, sodium, and calcium concentrations, indicative of brackish groundwater discharge, were observed in the surface water during the dry season. Brackish groundwaters of the southern Everglades contain 1–2.3 lM concentrations of total phosphorus (TP). These concentrations exceed the expected values predicted by conservative mixing of local fresh groundwater and

intruding seawater, which both have TP<1 lM. The additional source of TP may be from seawater sediments or from the aquifer matrix as a result of water–rock interactions (such as carbonate mineral dissolution and ion exchange reactions) induced by mixing fresh groundwater with intruding seawater. We hypothesize that CGD maybe an additional source of phosphorus (a limiting nutrient) to the coastal wetlands of the southern Everglades.

Untangling Complex Shallow Groundwater Dynamics in the Floodplain Wetlands of a Southeastern U.S. Coastal River

D. Kaplan, R. Muñoz-Carpena, and A. Ritter

ABSTRACT Understanding the hydrological functioning of tidally influenced floodplain forests is essential for advancing ecosystem protection and restoration goals in impacted systems.
However, finding direct relationships between basic hydrological inputs and floodplain hydrology is hindered by complex interactions between surface water, groundwater, and atmospheric fluxes in a variably saturated matrix with heterogeneous soils, vegetation, and topography. Thus, an explanatory method for identifying common trends and causal factors is required. Dynamic factor analysis (DFA), a time series dimension reduction technique, models temporal variation in observed data as linear combinations of common trends, which represent unidentified common factors, and explanatory variables. In this work, DFA was applied to model water table elevation (WTE) in the floodplain of the Loxahatchee River (Florida, USA), where altered watershed hydrology has led to changing hydroperiod and salinity regimes and undesired vegetative changes in the floodplain forest. The technique proved to be a powerful tool for the study of interactions among 29 long-term, nonstationary hydrological time series (12 WTE series and 17 candidate explanatory variables). Regional groundwater circulation, surface water elevations, and spatially variable net local recharge (cumulative rainfall – cumulative evapotranspiration) were found to be the main factors explaining groundwater profiles. The relative importance of these factors was spatially related to floodplain elevation, distance from the river channel, and distance upstream from the river mouth. The resulting dynamic factor model (DFM) simulated the WTE time series well (overall coefficient of efficiency, Ceff = 0.91) and is useful for assessing management scenarios for ecosystem restoration and predicted sea level rise.

<u>General</u>

Chapter 5: Hydrology of the Everglades Protection Area

Wossenu Abtew, R. Scott Huebner and Violeta Ciuca

SUMMARY Hydrology of the Everglades Protection Area (EPA) is a new chapter in the *2004 Everglades Consolidated Report*. In this chapter, the contemporary hydrology of the Everglades Protection Area is presented, with the main objective of depicting Water Year 2003 (May 1, 2002 to April 30, 2003). In cases where historical hydrologic analysis or compiled data are available, comparisons with hydrology from the last few decades are presented. This chapter does not include comparisons of current hydrology with predevelopment hydrology. For the current reporting year, rainfall in Water Conservation Areas 1 and 2 was 14 percent below historical average. Rainfall in Water Conservation Area 3 was close to the average. Everglades National Park rainfall was slightly higher than historical average. Evapotranspiration was close

to expected values. Water levels were generally higher than historical averages except in Water Conservation Area 2A. Major flows occurred during the wet season. In most cases, the highest flows were during the month of July. No major hydrologic events occurred during Water Year 2003. The recent drought (2000-2001) is over, and this year a minor El Niño was observed,with no significant direct effect on the EPA.

Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in Southern Everglades, Florida (U.S.A.)

M. Sutula, J.W. Day, J. Cable & D. Rudnick

ABSTRACT Hydrological restoration of the Southern Everglades will result in increased freshwater flow to the freshwater and estuarine wetlands bordering Florida Bay. We evaluated the contribution of surface freshwater runoff versus atmospheric deposition and ground water on the water and nutrient budgets of these wetlands. These estimates were used to assess the importance of hydrologic inputs and losses relative to sediment burial, denitrification, and nitrogen fixation. We calculated seasonal inputs and outputs of water, total phosphorus (TP) and total nitrogen (TN) from surface water, precipitation, and evapotranspiration in the Taylor Slough/C-111 basin wetlands for 1.5 years. Atmospheric deposition was the dominant source of water and TP for these oligotrophic, phosphorus-limited wetlands. Surface water was the major TN source of during the wet season, but on an annual basis was equal to the atmospheric TN deposition. We calculated a net annual import of 31.4 mg m−2 yr−1 P and 694 mg m−2 yr−1 N into the wetland from hydrologic sources. Hydrologic import of P was within range of estimates of sediment P burial (33–70 mg m−2 yr−1 P), while sediment burial of N (1890–4027 mg m−2 yr−1 N) greatly exceeded estimated hydrologic N import. High nitrogen fixation rates or an underestimation of groundwater N flux may explain the discrepancy between estimates of hydrologic N import and sediment N burial rates.

Linking Water Use and Nutrient Accumulation in Tree Island Upland Hammock Plant Communities in the Everglades National Park, USA

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ABSTRACT The tree island hammock communities in the Florida Everglades provide one of many examples of self-organized wetland landscape. However, little is understood about why these elevated tree island communities have higher nutrient concentration than the surrounding freshwater marshes. Here we used stable isotopes and elemental analysis to compare dry season water limitation and soil and foliar nutrient status in upland hammock communities of 18 different tree islands located in the Shark River Slough and adjacent prairie landscapes. We observed that prairie tree islands, having a shorter hydroperiod, suffer greater water deficits during the dry season than slough tree islands by examining shifts in foliar d13C values. We also found that prairie tree islands have lower soil total phosphorus concentration and higher foliar N/P ratio than slough tree islands. Foliar d15N values, which often increase with greater P availability, was also found to be lower in prairie tree islands than in slough tree islands. Both the elemental N and P and foliar d15N results indicate that the upland hammock plant communities in slough tree islands have higher amount of P available than those in prairie tree islands. Our findings are consistent with the transpiration driven nutrient harvesting chemohydrodynamic model. The water limited prairie tree islands hypothetically transpire less

and harvest less P from the surrounding marshes than slough tree islands during the dry season. These findings suggest that hydroperiod is important to nutrient accumulation of tree island habitats.

Three-Hundred-Year Hydrological Changes in a Subtropical Estuary, Rookery Bay (Florida): Human Impact Versus Natural Variability

Timme H. Donders, P. Martijn Gorissen, Francesca Sangiorgi, Holger Cremer, Friederike Wagner-Cremer, Vicky McGee

ABSTRACT The coastal wetland ecosystems in Florida are highly sensitive to changes in freshwater budget, which is driven by regional sea surface temperature, tropical storm activity, and the El Niño–Southern Oscillation (ENSO). Although studying Florida wetlands is pivotal to the understanding of these interacting climate systems, wetland dynamics have been severely altered by recent land use and drainage activities. To gather insights into the natural variability of the coastal ecosystems in Florida versus the effects of anthropogenic impact in the area, we present a 300-year record of changes in the hydrological cycle from a shallow subtropical estuary (Rookery Bay) on the western shelf of Florida, Gulf of Mexico. Palynological (pollen and organic-walled dinoflagellate cysts), diatom, and sedimentological analyses of a sediment core reveal significant changes in past runoff and wetland development. The onset and development of human impact in Florida are evident from high influx of Ambrosia pollen at about A.D. 1900, indicative of land clearance and disturbed conditions. To date, this is the southernmost record of Ambrosia increase related to human impact in the United States. Wetland drainage and deforestation since A.D. 1900 are evident from the reduced freshwater wetland and pine vegetation, and lower abundances of phytoplankton species indicative of lagoonal and brackish conditions. High runoff after A.D. 1900 relates to increased erosion and may correspondingly reflect higher impact from hurricane landfalls in SW Florida. Several phases with high siliciclastic input and greater wetland pollen abundance occur that predate the human impact period. These phases are interpreted as periods with higher runoff and are likely related to regional longer-term climate variability.

Sea Level Rise and South Florida Coastal Forests

Amartya K. Saha, Sonali Saha, Jimi Sadle, Jiang Jiang, Michael S. Ross, René M. Price, Leonel S. L. O. Sternberg, Kristie S. Wendelberger

ABSTRACT Coastal ecosystems lie at the forefront of sea level rise. We posit that before the onset of actual inundation, sea level rise will influence the species composition of coastal hardwood hammocks and buttonwood (*Conocarpus erectus* L.) forests of the Everglades National Park based on tolerance to drought and salinity. Precipitation is the major water source in coastal hammocks and is stored in the soil vadose zone, but vadose water will diminish with the rising water table as a consequence of sea level rise, thereby subjecting plants to salt water stress. A model is used to demonstrate that the constraining effect of salinity on transpiration limits the distribution of freshwater-dependent communities. Field data collected in hardwood hammocks and coastal buttonwood forests over 11 years show that halophytes have replaced glycophytes. We establish that sea level rise threatens 21 rare coastal species in Everglades National Park and estimate the relative risk to each species using basic life history and population traits. We review salinity conditions in the estuarine region over 1999–2009 and associate wide variability in the extent of the annual seawater intrusion to variation in freshwater

inflows and precipitation. We also examine species composition in coastal and inland hammocks in connection with distance from the coast, depth to water table, and groundwater salinity. Though this study focuses on coastal forests and rare species of South Florida, it has implications for coastal forests threatened by saltwater intrusion across the globe.

Climate Change and its Implications for Water Resources Management in South Florida

Jayantha Obeysekera, Michelle Irizarry, Joseph Park, Jenifer Barnes, Tibebe Dessalegne

ABSTRACT Recent climate change projections suggest that negative impacts on flood control and water supply functions and on existing and future ecosystem restoration projects in south Florida are possible. An analysis of historical rainfall and temperature data of the Florida peninsula indicates that there were no discernible trends in both the long-term record and during the more recent period (1950–2007). A comparison of General Circulation Model (GCM) results for the 20th century with the historical data shows that many of the GCMs do not capture the statistical characteristics of regional rainfall and temperature regimes in south Florida. Investigation of historical sea level data at Key West finds evidence for an increase in the occurrence and variance of maximum sea level events for the period 1961–2008 in relation to 1913–1960, along with a shift of energy from shorter to longer timescales. In order to understand the vulnerability of the water management system in south Florida in response to changing precipitation and evapotranspiration forcing, a sensitivity analysis using a regional-scale hydrologic and water management model is conducted. Model results suggest that projected climate change has potential to reduce the effectiveness of water supply and flood control operations for all water sectors. These findings emphasize that questions on the potential impacts of climate change need to be investigated with particular attention paid to the uncertainties of such projections.

Tropical Wetlands: Seasonal Hydrologic Pulsing, Carbon Sequestration, and Methane Emissions

William J. Mitsch, Amanda Nahlik, Piotr Wolski, Blanca Bernal, Li Zhang, Lars Ramberg

ABSTRACT This paper summarizes the importance of climate on tropical wetlands. Regional hydrology and carbon dynamics in many of these wetlands could shift with dramatic changes in these major carbon storages if the inter-tropical convergence zone (ITCZ) were to change in its annual patterns. The importance of seasonal pulsing hydrology on many tropical wetlands, which can be caused by watershed activities, orographic features, or monsoonal pulses from the ITCZ, is illustrated by both annual and 30-year patterns of hydrology in the Okavango Delta in southern Africa. Current studies on carbon biogeochemistry in Central America are attempting to determine the rates of carbon sequestration in tropical wetlands compared to temperate wetlands and the effects of hydrologic conditions on methane generation in these wetlands. Using the same field and lab techniques, we estimated that a humid tropical wetland in Costa Rica accumulated 255 g C m-2 year-1 in the past 42 years, 80% more than a similar temperate wetland in Ohio that accumulated 142 g C m-2 year-1 over the same period. Methane emissions averaged 1,080 mg-C m-2 day-1 in a seasonally pulsed wetland in western Costa Rica, a rate higher than methane emission rates measured over the same period from humid tropic wetlands

in eastern Costa Rica (120–278 mg-C m-2 day-1). Tropical wetlands are often tuned to seasonal pulses of water caused by the seasonal movement of the ITCZ and are the most likely to be have higher fire frequency and changed methane emissions and carbon oxidation if the ITCZ were to change even slightly.

Perceptible Changes in Regional Precipitation in a Future Climate

Irina Mahlstein, Robert W. Portmann, John S. Daniel, Susan Solomon,
and Reto Knutti

ABSTRACT Evidence is strong that the changes observed in the Earth's globally averaged temperature over the past half century are caused to a large degree by human activities. Efforts to document accompanying precipitation changes in observations have met with limited success, and have been primarily focused on large-scale regions in order to reduce the relative impact of the natural variability of precipitation as compared to any potential forced change. Studies have not been able to identify statistically significant changes in observed precipitation on small spatial scales. General circulation climate models offer the possibility to extend the analysis of precipitation changes into the future, to determine when simulated changes may emerge from the simulated variability locally as well as regionally. Here we estimate the global temperature increase needed for the precipitation "signal" to emerge from the "noise" of interannual variability within various climatic regions during their wet season. The climatic regions are defined based on cluster analysis. The dry season is not included due to poor model performance as compared to measurements during the observational period. We find that at least a 1.4°C warmer climate compared with the early 20th century is needed for precipitation changes to become statistically significant in any of the analyzed climate regions. By the end of this century, it is likely that many land regions will experience statistically significant mean precipitation changes during wet season relative to the early 20th century based on an A1B scenario.

Modeling Climate Change Uncertainties in Water Resources Management Models

Ramesh S.V. Teegavarapu

ABSTRACT The impact of climate change on hydrologic design and management of hydrosystems could be one of the important challenges faced by future practicing hydrologists and water resources managers. Many water resources managers currently rely on the historical hydrological data and adaptive real-time operations without consideration of the impact of climate change on major inputs influencing the behavior of hydrologic systems and the operating rules. Issues such as risk, reliability and robustness of water resources systems under different climate change scenarios were addressed in the past. However, water resources management with the decision maker's preferences attached to climate change has never been dealt with. This short paper discusses issues related to impacts of climate change on water resources management and application of a soft-computing approach, fuzzy set theory, for climate sensitive management of hydrosystems. A real-life case study example is presented to illustrate the applicability of a soft-computing approach for handling the decision maker's preferences in accepting or rejecting the magnitude and direction of climate change.

SELECTED REFERENCES

Abtew, W., & Member, P. E. (2001). Evaporation estimation for lake Okeechobee in south Florida. *Journal of Irrigation and Drainage Engineering*, 140-147.

Abtew, W., Huebner, R. S., & Ciuca, V. (2005). *2004 Everglades consolidated report: Chapter 5: Hydrology of the Everglades Protection Area* (Rep.). West Palm Beach, FL: South Florida Water Management.

Abtew, W., Obeysekera, J., & Iricanin, N. (2011). Pan evaporation and potential evapotranspiration trends in South Florida. *Hydrological Processes*, *25*(6), 958-969. doi: 10.1002/hyp.7887

Bidlake, W. R., Woodham, W. M., & Lopez, M. A. (1996). *Evapotranspiration from areas of native vegetation in west-central Florida* (Working paper No. U.S. Geological Survey water-supply paper 2430). FL.

Castanede, E. (2010). *Landscape patterns of community structure, biomass, and net primary productivity of magrove forests in the Florida coastal everglades as a function of resources, regulators, hydroperiod, and hurricane disturbances* (Unpublished doctoral dissertation). Lousiana State University.

Donders, T. H., Gorissen, P. M., Sangiorgi, F., Cremer, H., Wagner-Cremer, F., & McGee, V. (2008). Three-hundred-year hydrological changes in a subtropical estuary, Rookery Bay (Florida): Human impact versus natural variability. *Geochemistry Geophysics Geosystems*, *9*(7). doi: 10.1029/2008GC001980

Favero, L., Mattiuzzo, E., & Franco, D. (2007). Practical Results Of A Water Budget Estimation For A Constructed Wetland. *Wetlands*, *27*(2), 230-239. doi: 10.1672/0277-5212(2007)27[230:PROAWB]2.0.CO;2

Harvey, J. W., & McCormick, P. V. (2009). Groundwater's significance to changing hydrology, water chemistry, and biological communties of a floodplain ecosystem, Everglades, South Florida, USA. *Hydrogeology Journal*, *17*, 185-201.

Huebner, R. S. (33406). *Water Budget Analysis for Stormwater Treatment Area 2 (Water Year 2007; May 1, 2006-April 30, 2007)* (pp. 1-43, Tech. No. SFWMD-103). West Palm Beach, FL: South Florida Water Management District.

Kaplan, D. (2010). Untangling complex shallow groundwater dynamics in the floodplain wetlands of a southeastern U.S. coastal river. *Water Resources Research*, *46*(8), 1-18.

Kim, T., Ahn, H., Chung, G., & Yoo, C. (2008). Stochastic multi-site generation of daily rainfall occurrence in south Florida. *Stochastic Environmental Research and Risk Assessment*, *22*(6), 705-717. doi: 10.1007/s00477-007-0180-8

Kwon, H., Lall, U., & Obeysekera, J. (2009). Simulation of daily rainfall scenarios with interannual and multidecadal climate cycles for South Florida. *Stochastic Environmental Research and Risk Assessment*, *23*(7), 879-896.

Lim, Y., Stefanova, L. B., Chan, S. C., Schubert, S. D., & O'Brien, J. J. (2011). High-resolution subtropical summer precipitation derived from dynamical downscaling of the NCEP/DOE reanalysis: How much small-scale information is added by a regional model? *Climate Dynamics*, *37*(5-6), 1061-1080. doi: 10.1007/s00382-010-0891-2

Mahlstein, I., Portman, R. W., Daniel, J. S., Solomon, S., & Knutti, R. (2012). Perceptible changes in regional precipitation in a future climate. *Geophysical Research Letters*, *39*, 1-5. doi: 10.1029/2011GL050738

Martinez, C. J., & Thepadia, M. (2010). Estimating Reference Evapotranspiration with Minimum Data in Florida, USA. *Journal of Irrigation and Drainage Engineering*, *136*(7), 494. doi: 10.1061/(ASCE)IR.1943-4774.0000214

Mitsch, W. J., Nahlik, A., Wolski, P., Bernal, B., Zhang, L., & Ramberg, L. (2010). Tropical wetlands: Seasonal hydrologic pulsing, carbon sequestration, and methane emissions. *Wetlands Ecology and Management*, *18*(5), 573-586. doi: 10.1007/s11273-009-9164-4

Obeysekera, J., Irizarry, M., Park, J., Barnes, J., & Dessalegne, T. (2011). Climate change and its implications for water resources management in south Florida. *Stoch Environ Res Risk Assess*, *25*, 495-516.

Obeysekera, J. Park, M. Irizarry-Ortiz, P. Trimble, J. Barnes, J. VanArman, W. Said, and E. Gadzinski. Past and Projected Trends in Climate and Sea Level for South Florida. South Florida Water Management District, Hydrologic and Environmental Systems Modeling Technical Report, July 5, 2011, 148 pp. http://my.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/ccireport_publicationversion_14jul11.pdf

Price, R. M., Swart, P. K., & Fourqurean, J. W. (2006). Coastal groundwater discharge – an additional source of phosphorus for the oligotrophic wetlands of the Everglades. *Hydrobiologia*, *569*(1), 23-36. doi: 10.1007/s10750-006-0120-5

Redfield, G., VanArman, J., Rizzardi, K., & Chimney, M. (2004). *Everglades Interim Report: Chapter One* (pp. 1-1-1-26, Rep.). West Palm Beach, FL: SFWMD.

Restrepo, J. I., Garces, D., Montoya, A., Restrepo, N., & Giddings, J. (2006). Simulation of Water Levels and Water Diversions in a Subtropical Coastal Wetland. *Journal of Coastal Research*, *222*, 339-349. doi: 10.2112/04-0262.1

Restrepo, J. I., Montoya, A. M., & Obeysekera, J. (1998). A wetland simulation module for the MODFLOW ground water model. *Ground Water*, *36*(5), 764-770. doi: 10.1111/j.1745-6584.1998.tb02193.x

Riscassi, A. L., & Schaffrenek, R. W. (n.d.). *Flow velocity, water temperature, and conductivity in Shark River Slough, Everglades National Park, Florida:June 2002- July 2003* (pp. 1-56, Rep. No. Open File Report 04-1233). U.S. Department of the Interior.

Saha, A. K., Saha, S., Sadle, J., Jiang, J., Ross, M. S., Price, R., ... Wendelberger, K. S. (2011). Sea level rise and south Florida coastal forests. *Climatic Change*, *107*, 81-108.

Shoemaker, W. B., & Sumner, D. M. (2006). Alternate Corrections For Estimating Actual Wetland Evapotranspiration From Potential Evapotranspiration. *Wetlands*, *26*(2), 528-543. doi: 10.1672/0277-5212(2006)26[528:ACFEAW]2.0.CO;2

Skinner, C., Bloetscher, F., & Pathak, C. S. (2009). Comparison of NEXRAD and Rain Gauge Precipitation Measurements in South Florida. *Journal of Hydrologic Engineering*, *14*(3), 248. doi: 10.1061/(ASCE)1084-0699(2009)14:3(248)

Slocum, M. G., Platt, W. J., Beckage, B., Orzell, S. L., & Taylor, W. (2010). Accurate Quantification of Seasonal Rainfall and Associated Climate-Wildfire Relationships. *Journal of Applied Meterology & Climatology*, *49*(12), 2559-2573.

Smith III, T. J., Hudson, J. H., Robblee, M. B., Powell, G. V., & Isdale, P. J. (1989). Freshwater flow from the everglades to Florida Bay: A historical reconstruction based on fluorescent banding in coral Solenastrea Bournoni. *Bulletin of Marine Science*, *44*(1), 274-282.

Sutula, M., Day, J. W., Cable, J., & Rudnick, D. (2001). Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in southern Everglades, Florida (U.S.A.). *Biogeochemistry*, *56*, 287-301.

Teegavarapu, R. S. (2010). Modeling climate change uncertainties in water resources management models. *Environmental Modelling & Software*, *25*(10), 1261-1265. doi: 10.1016/j.envsoft.2010.03.025

Teegavarapu, R. S., Tufail, M., & Ormsbee, L. (2009). Optimal functional forms for estimation of missing precipitation data. *Journal of Hydrology*, *374*(1-2), 106-115. doi: 10.1016/j.jhydrol.2009.06.014

Willard, D. A., & Bernhardt, C. E. (2011). Impacts of past climate and sea level change on Everglades wetlands: Placing a century of anthropogenic change in a late-Holocene context. *Climate Change*, *107*, 59-80. doi: DOI 10.1007/s10584-011-0078-9