

# **Program & Abstracts**

## ***2001 Florida Bay Science Conference***



**April 23-26, 2001  
Westin Beach Resort  
Key Largo, FL**



## **Conference Organizing Committee**

*Dr. Robert J. Brock*, Supervisory Marine Biologist, National Park Service, Everglades and Dry Tortugas National Parks, Homestead, Florida

*Ms. Laura K. Engleby*, Sea Grant Extension Agent, University of Florida Sea Grant, Tavernier, Florida

*Ms. Beth Miller-Tipton*, Director, Office of Conferences and Institutes (OCI), University of Florida, Institute of Food and Agricultural Sciences, Gainesville, Florida

## **Steering Committee**

*Florida Bay and Adjacent Marine Systems Program Management Committee*

## **Table of Contents**

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*(Abstracts are divided by Question Number and are listed in alphabetical order by presenting author's last name, which appears in bold.)*

## **Conference History and Organization**

The Florida Bay Science Conference provides an opportunity annually for scientists to exchange technical information, share that information with resource managers and other interested conference attendees, and establish collaborative partnerships. This year's conference allows investigators undertaking research and monitoring projects the opportunity to highlight their individual findings in one-hour oral synthesis and poster presentations.

As in past conferences, the sessions are organized around the five major questions that are recognized as central to understanding the problems affecting Florida Bay. Posters are organized similarly. In addition, a special synthesis session wrap-up is scheduled for Thursday afternoon when scientists and regional resource managers can discuss how information learned about Florida Bay can assist the Comprehensive Everglades Restoration Plan (CERP).

The Florida Sea Grant College Program organized the first Florida Bay Science Conference in 1995, and continues to assist the PMC in conference organization and dissemination of scientific results. Florida Sea Grant is a statewide, university-based program that not only conducts coastal research and education, but also communicates scientific information through its extension activity.

## **Conference Objectives**

**The objectives of the Florida Bay Science Conference are to:**

- *Synthesize results of research and model simulations*
- *Highlight linkages between adjacent marine systems and CERP*

## **Synthesis & Presentation Format**

Unlike the 1999 conference, there will be no oral presentations by individual scientists. Instead, members of each research team have collaborated to synthesize topical information into a one-hour oral presentation. Individual researchers will present their abstract submissions as posters, which will be displayed on a daily basis by topical question to complement the synthesis presentations.

The oral synthesis presentations for each central question will focus on the following:

- 1.) What has been learned?
- 2.) What are the unanswered questions?
- 3.) What work is currently ongoing?
- 4.) What are the expectations of future needs?

## **Relationship to Restoration Managers**

One of the most important goals of the interagency science program is to provide scientific information and models that will enable natural resource managers to make responsible decisions based on sound science. The PMC provides this information through direct briefings, PMC participation in the larger components of the South Florida Ecosystem Restoration Initiative such as the Task Force, Working Group and Science Subgroup, and by conducting the annual Florida Bay and Adjacent Marine Systems Science Conference.

## **Synthesis Wrap-up Session Format**

The conference will conclude by bringing all Florida Bay scientists together for a Synthesis Wrap-up Session that asks, “So What?” How can the scientific information we have generated thus far contribute to making responsible and knowledgeable restoration decisions in the future? Florida Bay is just one piece of the Everglades restoration puzzle and we must address how Florida Bay relates with the overall CERP and how we can contribute to the CERP Effort.

## **Central Questions**

**Question 1.** *How and at what rates do storms, changing freshwater flows, sea level rise, and local evaporation/precipitation patterns influence circulation and salinity patterns within Florida Bay and outflows from the Bay to adjacent waters?*

**Question 2.** *What is the relative importance of the advection of exogenous nutrients, internal nutrient cycling including exchange between water column and sedimentary nutrient sources, and nitrogen fixation in determining the nutrient budget for Florida Bay?*

**Question 3.** *What regulates the onset, persistence and fate of planktonic algal blooms in Florida Bay?*

**Question 4.** *What are the causes and mechanisms for the observed changes in seagrass and the hardbottom community of Florida Bay? What is the effect of changing salinity, light and nutrient regimes on these communities?*

**Question 5.** *What is the relationship between environmental change, habitat change and the recruitment, growth, and survivorship of higher trophic level species?*

## **Research Team Leaders**

The success of the Interagency Florida Bay and Adjacent Marine Systems Science Program depends largely on clear and regular communication and collaboration amongst the scientists working in the Bay. To promote this, the PMC has organized researchers and modelers into topical research teams. To date, teams have been formed in paleoecology, algal blooms, water quality/nutrient dynamics, circulation/hydrology, seagrass and benthic ecology, higher trophic levels and model integration. Teams consist of formally appointed leaders, a PMC representative, and modelers and researchers working in the Bay and adjacent marine systems.

### **QUESTION #1: Physical Sciences**

*Dr. Peter Ortner, PMC Representative*, National Oceanic and Atmospheric Administration /Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

*Dr. Thomas Lee, Co-chair*, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, Florida

### **QUESTION #2: Nutrient Dynamics**

*Dr. David Rudnick, PMC Representative*, Everglades Department, South Florida Water Management District, West Palm Beach, Florida

*Dr. Larry Brand, Co-chair*, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, Florida

*Dr. Joseph Boyer, Co-chair*, Southeast Environmental Research Center, Florida International University, Miami, Florida

### **QUESTION #3: Algal Blooms**

*Mr. John Hunt, PMC Representative*, Florida Fish & Wildlife Conservation, Marathon, Florida

*Dr. Edward J. Philips, Co-chair*, University of Florida, Institute of Food and Agricultural Sciences, Department of Fisheries and Aquatic Sciences, Gainesville, Florida

*Dr. Gary Hitchcock, Co-chair*, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, Florida

### **QUESTION #4: Seagrass Ecology**

*Dr. Michael Robblee, PMC Representative*, USGS - Biological Resources Division, Miami, Florida

*Dr. Jay Zieman, Co-chair*, University of Virginia, Department of Environmental Sciences, Charlottesville, Virginia

*Dr. Michael Durako, Co-chair*, The University of North Carolina at Wilmington, Center for Marine Science, Wilmington, North Carolina

### **QUESTION #5: Higher Trophic Levels**

*Dr. Nancy Thompson, PMC Representative*, Southeast Fisheries Science Center, National Oceanic and Atmospheric Administration and the National Marine Fisheries Service, Miami, Florida

*Dr. Joan Browder, Co-chair*, Southeast Fisheries Science Center, National Oceanic and Atmospheric Administration and the National Marine Fisheries Service, Miami, Florida

## **Poster Session Information**

Posters will be displayed on a daily basis by topical question as outlined in the Tentative Agenda. **Poster displays MUST be set up and removed by the times indicated on the program agenda.** The conference is not responsible for the loss of or damage to poster displays not taken down by the specified time.

## **Discussion Periods**

As one of the primary purposes of the Florida Bay Science Conference is to promote the free exchange of technical information by scientists, discussion periods are scheduled at the end of each topical session to allow for questions and comments. Scientists working in the Bay should be available following each session to field questions and participate in discussion.

## **Abstract Book Organization**

Abstracts are divided by Question Number and are listed in alphabetical order by presenting author's last name, which appears in bold.

This publication will also be available online after the conference at the following web site: <<http://www.aoml.noaa.gov/flbay/abstracts.html>>. Abstracts from all previous Florida Bay Science Conferences are also available through this site. For information about the Florida Bay Web Site, please contact DawnMarie Boyer at NOAA/AOML/OCD, 4301 Rickenbacker Causeway, Miami, FL 33149, PH: (305) 361-4388, FAX: (305) 361-4392, E-Mail: <[welcher@aoml.noaa.gov](mailto:welcher@aoml.noaa.gov)>.

Additional information on marine science and restoration can be obtained by contacting Florida Sea Grant, Florida Bay Education Office, 93911 Overseas Highway, Tavernier, FL 33070. PH 305-853-3592; FAX 305-853-3595.

## **Regional Context**

Florida Bay is one component of the marine and coastal ecosystems of South Florida. Waters from the Gulf of Mexico and southwestern coastal Everglades influence the Western Bay, the Northern Bay receives the drainage from much of the adjacent mainland marsh, and the Eastern Bay abuts the populated Florida Keys. Bay water, in turn, flows through the Florida Keys channels out to the reef tract and northward via Hawk Channel into Biscayne Bay. The connectivity of these waters is obvious. Collaboration among federal and state agencies that share management responsibilities for these waters is required to effectively collect data and build the tools essential for guiding restoration of the regional ecosystem.

## **Program Management Committee (PMC)**

The Program Management Committee was formed in 1994 to assure that the many individually funded scientific projects in Florida Bay were integrated into a comprehensive program addressing key issues. The PMC consists of scientific program managers from:

- **Miami-Dade County Department of Environmental Resources Management**
- **Florida Department of Environmental Protection**
- **Florida Fish and Wildlife Conservation Commission**
- **National Oceanic and Atmospheric Administration**
  - Florida Keys National Marine Sanctuary
  - National Marine Fisheries Service
  - Office of Oceanic and Atmospheric Research
- **National Park Service**
  - Biscayne National Park
  - Everglades National Park
- **South Florida Water Management District**
- **U.S. Army Corps of Engineers**
- **U.S. Environmental Protection Agency**
- **U.S. Geological Survey**
  - Biological Resources Division
  - Water Resources Division

## **Primary Functions of the PMC**

- (a) Develop and implement a research strategy designed to merge scientific understanding of the Bay with management's decision making processes;
- (b) Facilitate a consensus-based process for determining science needs and priorities;
- (c) Promote funding of critical science needs;
- (d) Develop and maintain an open and scientifically sound review process for evaluating research results and for advancing the program; and
- (e) Communicate research results and program progress to management as well as the scientific and public community.



## **Scientific Oversight Panel**

**Dr. William C. Boicourt**, University of Maryland, Horn Point Laboratory, Center for Environmental Science, Cambridge, Maryland

*- Dr. Boicourt is Professor of Physical Oceanography and specializes in physical oceanographic processes including circulation of the continental shelf and estuaries.*

**Dr. Kenneth L. Heck**, Dauphin Island Sea Laboratory, University of South Alabama Dauphin Island, Alabama

*- Dr. Heck is Professor of Marine Sciences and is a Marine Ecologist specializing in the study of seagrass ecosystems along the Atlantic and Gulf coasts of the United States.*

**Dr. John E. Hobbie (Chair)**, The Ecosystem Center, Marine Biological Laboratory, Woods Hole, Massachusetts

*- Dr. Hobbie is a Co-Director of The Ecosystems Center and is a Coastal Microbial Ecologist specializing in biogeochemical cycles of large coastal and wetlands systems.*

**Dr. Edward D. Houde**, Chesapeake Biological Laboratory, University of Maryland, Center for Environmental Science, Solomons, Maryland

*- Dr. Houde is a professor of Fisheries Science and Oceanography at the University of Maryland. He specializes in fisheries science, management, ecology, larval fish ecology and resource assessment. He has a personal interest in Trophodynamics, estuarine fisheries, ocean and estuary productivity and potential fisheries yields. Houde is also a former Director of the Biological Oceanography Program, Division of Ocean Sciences, National Science Foundation, Washington, DC.*

**Dr. Steven C. McCutcheon**, Hydrologic and Environmental Engineering, Athens, Georgia

*- A member of the 1996 Bay Circulation and Water Quality Modeling Workshops and Co-Chair of the Model Evaluation Group. Dr. McCutcheon is a specialist in water quality issues, hydronamic modeling, sediment transport and hazardous waste management.*

**Dr. Hans W. Paerl**, University of North Carolina, Institute of Marine Sciences, Morehead City, North Carolina

*- Dr. Paerl is Kenan Professor of Marine and Environmental Sciences and his research includes nutrient cycling and production dynamics of aquatic ecosystems, environmental controls of algal production, and assessing the causes and consequences of eutrophication.*

## **Program Agenda**

### **Monday, April 23, 2001**

- |               |  |
|---------------|--|
| 5:30pm-7:30pm | <b>Registration Desk Open</b>                                      |
| 5:30pm-6:30pm | <b>Poster Presenters for Questions 1 &amp; 4 to set up posters</b> |
| 6:30pm-7:00pm | <b>Welcome Address and Conference Overview</b>                     |
| 7:00pm-9:00pm | <b>Welcome Reception (Poolside)</b>                                |

### **Tuesday, April 24, 2001**

- |                |  |
|----------------|--|
| 8:00am         | <b>Morning Refreshments</b>  |
| 8:00am-11:30am | <b>Poster Session - Questions 1 &amp; 4</b><br><i>(Poster Presenters stationed at posters from 9:00am-11:00am)</i> |
| 11:30am-1:00pm | <b>Lunch on Own</b>  |
| 1:00pm-2:00pm  | <b>Synthesis Presentation of Question 1</b>  |
| 2:00pm-3:00pm  | <b>One Hour Discussion for Question 1</b>  |
| 3:00pm-3:30pm  | <b>Refreshment Break</b>   |
| 3:30pm-4:30pm  | <b>Synthesis Presentation of Question 4</b>  |
| 4:30pm-5:30pm  | <b>One Hour Discussion Period for Question 4</b>   |
| 5:30pm-6:30pm  | <b>Poster Displays Open to the General Public</b>  |
| 6:30pm-7:00pm  | <b>Poster Removal</b>  |
| 7:00pm-7:30pm  | <b>Poster Set-up for Questions 2 &amp; 3</b>   |
| 7:30pm-9:30pm  | <b>Networking Reception (Poolside)</b>   |

## Wednesday, April 25, 2001

8:00am	<b>Morning Refreshments</b>
8:00am-11:30am	<b>Poster Session - Questions 2 &amp; 3</b> <i>(Poster Presenters stationed at posters from 9:00am-11:00am)</i>
11:30am-1:00pm	<b>Lunch on Own</b>
1:00pm-2:00pm	<b>Synthesis Presentation of Question 2</b>
2:00pm-3:00pm	<b>One Hour Discussion for Question 2</b>
3:00pm-3:30pm	<b>Refreshment Break</b>
3:30pm-4:30pm	<b>Synthesis Presentation of Question 3</b>
4:30pm-5:30pm	<b>One Hour Discussion Period for Question 3</b>
5:30pm-6:30pm	<b>Poster Displays Open to the General Public</b>
6:30pm-7:00pm	<b>Poster Removal</b>
7:00pm-7:30pm	<b>Poster Set-up for Question 5</b>

## Thursday, April 26, 2001

8:00am	<b>Morning Refreshments</b>
8:00am-10:00am	<b>Poster Session - Question 5</b> <i>(Poster Presenters stationed at posters from 8:30am-9:30am)</i>
10:00am-11:00am	<b>Synthesis Presentation of Question 5</b>
11:00am-12:00pm	<b>One Hour Discussion for Question 5</b>
12:00pm-1:30pm	<b>Lunch on Own</b> <b>(Poster Displays Open to the General Public)</b>
1:30pm-3:00pm	<b>“So What?” Synthesis Wrap-up Session</b> -- How can all the information presented during the last three days contribute to making responsible restoration decisions?
3:00pm	<b>Adjourn</b>



## **Poster Directory**

(Posters are listed in alphabetical order by presenting author's last name, which appears in **Bold**.)

### **Question 1**

#### **Poster No.**

- Q1-1** **An Optical Model for Coral Community Mapping Based on Compound Remote Sensing, Biscayne National Park, Florida, USA.** **John C. Brock**, U. S. Geological Survey, Center For Coastal Geology, St. Petersburg, FL; **C. Wayne Wright**, NASA/GSFC Wallops Flight Facility, Wallops Island, VA (**pg. 3**)
- Q1-2** **Hydrologic and Biogeochemical Pulsing Events in Taylor Creek System, Southeastern Everglades, Florida (USA).** **Jaye E. Cable**, Enrique Reyes, John W. Day, Jr. Louisiana State University, Baton Rouge, LA; **Stephen E. Davis**, Florida International University, Miami, FL; **Clinton Hittle**, U. S. Geological Survey, Miami, FL; **Fred Sklar** and **Carlos Coronado-Molina**, South Florida Water Management District, West Palm Beach, FL (**pg. 5**)
- Q1-3** **Patterns and Possible Causes of Temperature and Salinity Variability in Central Florida Bay 1880-1998.** **T. M. Cronin**, U. S. Geological Survey, Reston, VA; **G. S. Dwyer**, Ocean and Atmospheric Sciences, Duke University, Durham, NC; **T. Kamiya**, Department of Geological Sciences Kanazawa University, Kanazawa, Japan; **S. Schwede**, U. S. Geological Survey, Reston, VA (**pg. 7**)
- Q1-4** **Quantity, Timing, and Distribution of Freshwater Flows into Northeastern Florida Bay.** **Clinton Hittle**, U. S. Geological Survey (**pg. 11**)
- Q1-5** **Influence of Hurricanes, Tropical Storms, and Cold Fronts on South Florida Coastal Waters.** **Elizabeth Johns**, Ryan Smith and Doug Wilson, NOAA/AOML, Miami, FL; **Thomas N. Lee** and **Elizabeth Williams**, University of Miami-RSMAS, Miami, FL (**pg. 14**)
- Q1-6** **Salinity Variability in Florida Bay from Monthly Rapid High Resolution Surveys.** **Elizabeth Johns**, Peter Ortner, Ryan Smith and Doug Wilson, NOAA/AOML, Miami, FL; **Thomas N. Lee** and **Elizabeth Williams**, University of Miami-RSMAS, Miami, FL (**pg. 16**)
- Q1-7** **Hydrogel Stabilization of Florida Bay Marl Sediments.** **J. William Louda**, Joseph W. Loitz, Anthansios Melisiotis and Earl W. Baker, Organic Geochemistry Group, Florida Atlantic University, Boca Raton, Florida; **William H. Orem**, U. S. Geological Survey, Reston, VA (**pg. 18**)
- Q1-8** **Florida Bay Salinity Transfer Function Analysis.** **Frank E. Marshall, III**, Cetacean Logic Foundation, Inc., New Smyrna Beach, FL (**pg. 20**)

Poster

No.

- Q1-9 Hydrodynamic Characteristics of Estuarine Rivers Along The Southwestern Coast of Everglades National Park.** *Victor A. Levesque* and *Eduardo Patino*, U. S. Geological Survey (pg. 23)
- Q1-10 Florida Bay Standard Data Set.** *Joseph A. Pica*, Atlantic Oceanographic & Meteorological Laboratory, Miami, FL (pg. 26)
- Q1-11 Tidal, Low-frequency and Long-term Flow through Northwest Channel.** *Patrick A. Pitts*, Harbor Branch Oceanographic Institution, Fort Pierce, FL (pg. 27)
- Q1-12 Estimating Evaporation Rates in Florida Bay.** *René M. Price* and *Peter K. Swart*, Rosenstiel School of Marine and Atmospheric Sciences, Miami, FL; *William K. Nuttle*, South Florida Water Management District, West Palm Beach, FL (pg. 29)
- Q1-13 Seawater Intrusion: A Mechanism for Groundwater Flow into Florida Bay.** *René M. Price* and *Peter K. Swart*, Rosenstiel School of Marine and Atmospheric Sciences, Miami, FL (pg. 31)
- Q1-14 Salinity Pattern in Florida Bay: A Synthesis (1900-2000).** *Michael B. Robblee* and *Gail Clement*, U. S. Geological Survey, Florida Caribbean Science Center, Florida International University, Miami, FL; *DeWitt Smith*, NPS, Everglades National Park, Homestead, FL; *Robert Halley*, U. S. Geological Survey, Center for Coastal Geology, St. Petersburg, FL (pg. 34)
- Q1-15 The Tides and Inflows in the Mangroves of the Everglades Project.** *Raymond W. Schaffranek* and *Harry L. Jenter*, U. S. Geological Survey, Reston, VA; *Christian D. Langevin* and *Eric D. Swain*, U. S. Geological Survey, Miami, FL (pg. 37)
- Q1-16 Wind-forced Interbasin Exchanges in Florida Bay.** *Ned P. Smith*, Harbor Branch Oceanographic Institution, Fort Pierce, FL (pg. 40)
- Q1-17 Moored Observations of Salinity Variability in Florida Bay and South Florida Coastal Waters on Daily to Interannual Time Scales.** *Ryan H. Smith*, *Elizabeth Johns* and *W. Douglas Wilson*, Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL; *Thomas N. Lee* and *Elizabeth Williams*, Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, FL (pg. 42)

**Poster**  
**No.**

- Q1-18** **Developing Insight into Coastal Wetland Hydrology Through Numerical Modeling.** *Eric Swain* and *Christian Langevin*, U. S. Geological Survey, Miami, FL (pg. 44)
- Q1-19** **Insights into the Origin of Salinity Variations in Florida Bay Over Short and Long Time Periods.** *Peter K. Swart* and *René M. Price*, Rosenstiel School of Marine and Atmospheric Science, Miami, FL (pg. 47)
- Q1-20** **Helium as Tracer of Groundwater Input Into Florida Bay.** *Zafer Top* and *Larry E. Brand*, RSMAS, University of Miami (pg. 49)
- Q1-21** **Simulation of the Influence of Climate Variability on Freshwater Inflow to Florida Bay during the 20<sup>th</sup> Century.** *Paul J. Trimble*, *E. Raymond Santee III*, *Randy Van Zee*, *Luis G. Cadavid*, *Jayantha T. B. Obeysekera* and *Alaa Ali*, Hydrologic Systems Modeling Department, Water Supply Division, South Florida Water Management District, West Palm Beach, FL (pg. 50)
- Q1-22** **Wetland Hydrogeologic Responses along the Taylor Creek System, Southeastern Everglades, Florida (USA).** *Brian M. Vosburg*, *Jaye E. Cable*, *James P. Braddy* and *Enrique Reyes*, Louisiana State University, Baton Rouge, LA; *Daniel L. Childers* and *Stephen E. Davis*, Florida International University, Miami, FL (pg. 52)
- Q1-23** **Paleosalinity of Florida Bay.** *Bruce R. Wardlaw*, U. S. Geological Survey, Reston, VA (pg. 54)
- Q1-24** **Development of a Variable-Density Groundwater Flow Model for the Taylor Slough Area.** *Melinda Wolfert*, *Christian Langevin* and *Eric Swain*, U. S. Geological Survey - Miami Subdistrict, Miami, FL (pg. 55)
- Q1-25** **Impact on the Sedimentary Record Derived from Micropaleontological Data.** *Carlos A. Alvarez Zarikian*, *Pat L. Blackwelder*, *Terri Hood* and *Harold R. Wanless*, University of Miami, RSMAS-MGG, Virginia Key, FL; *Terry A. Nelsen* and *Charles Featherstone*. NOAA-AOML, Virginia Key, FL (pg. 58)

**Question 2**

- Q2-1** **Dendrocronology Studies of Environmental Changes in Mangrove Ecosystems.** *Agraz-Hernandez, C. M.*, *J.W. Day Jr.*, *E. Reyes* and *C. Molina-Coronado*, Coastal Ecology Institute, Louisiana State Univ., South Stadium Road. Baton Rouge, LA; *T. Doyle*, National Biological Service Southern Science Center, Lafayette, LA; *F. J. Flores-Verdugo*, Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autonoma de Mexico, Mazatlan, Sinaloa, Mexico (pg. 63)

Poster

No.

- Q2-2 Long-Term Trends in the Water Quality of Florida Bay (1989-2000).** *Joseph N. Boyer*, Southeast Environmental Research Center, Florida International University, Miami, FL; *Ronald D. Jones*, Southeast Environmental Research Center and Department of Biological Sciences, Florida International University, Miami, FL (pg. 64)
- Q2-3 Nutrient Ratios and the Eutrophication of Florida Bay.** *Larry E. Brand* and *Maiko Suzuki Ferro*, University of Miami, RSMAS, Miami, FL (pg. 67)
- Q2-4 Trace Metals in Florida Bay.** *Frank Millero* and *Valentina G. Caccia*, RSMAS, University of Miami, FL; *Xuewu Liu*, University of South Florida, St. Petersburg, FL (pg. 69)
- Q2-5 Eutrophication Model of Florida Bay.** *Carl F. Cerco*, *Mark Dortch*, *Barry Bunch* and *Alan Teeter*, US Army Engineer Research and Development Center, Waterways Experiment Station, Vicksburg MS (pg. 72)
- Q2-6 Biogeochemical Effects of Iron Availability on Primary Producers in a Shallow Marine Carbonate Environment.** *Randolph M. Chambers*, College of William and Mary, Williamsburg, VA; *James W. Fourqurean*, Florida International University, Miami, FL (pg. 74)
- Q2-7 Nitrogen Cycling in Florida Bay Mangrove Environments: Sediment-Water Exchange and Denitrification.** *Jeffrey C. Cornwell*, *Michael S. Owens* and *W. Michael Kemp*, University of Maryland Center for Environmental Science, Horn Point Laboratory, Cambridge, MD (pg. 75)
- Q2-8 Nutrient Cycling and Litterfall Dynamics in Mangrove Forests Located at Everglades, Florida and Terminos Lagoon, Mexico.** *Coronado-Molina, C.*, *J. W. Day, Jr.*, *E. Reyes* and *B. Perez*, Department of Oceanography and Coastal Sciences, Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA; *S. Kelly*, The South Florida Water Management District, West Palm Beach, FL (pg. 77)
- Q2-9 Nutrient Dynamics in Groundwaters Surrounding a Sewage Injection Well in Key Colony Beach, Florida.** *K. Dillon*, *W. Burnett*, *G. Kim*, *J. Chanton* and *D. R. Corbett*, Department of Oceanography, The Florida State University, Tallahassee, FL (pg. 78)
- Q2-10 Florida Bay Watch: Results of Five Years of Nearshore Water Quality Monitoring in the Florida Keys.** *Brian D. Keller* and *Nicole D. Fogarty*, The Nature Conservancy, Key West, FL; *Arthur Itkin*, Islamorada, FL (pg. 81)



**Poster**  
**No.**

- Q2-11 Environmental Toxicity in Southern Biscayne Bay, Florida.** *M. Jawed Hameedi*, National Oceanic and Atmospheric Administration, Silver Spring, MD (pg. 83)
- Q2-12 Seasonal Variation of the Carbonate System in Florida Bay.** *William T. Hiscock* and *Frank J. Millero*, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, FL (pg. 85)
- Q2-13 SEAKEYS: Florida Keys Monitoring Initiative.** *J. C. Humphrey*, *Jeff Absten*, *S. L. Vargo* and *J. C. Ogden*, Florida Institute of Oceanography, St. Petersburg, FL; *J. Hendee*, *Terry Nelsen*, *Deborah Danaher* and *Clarke Jeffris*, Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL; *David Burwell*, Coastal Environmental Monitoring Stations, Coastal Ocean Monitoring and Prediction System, College of Marine Science, University of South Florida, St. Petersburg, FL (pg. 87)
- Q2-14 Flux of Inorganic Phosphate from the Sediment and Contribution to Biomass and Primary Productivity by Benthic Microalgal Communities in Western Florida Bay.** *Gabriel A. Vargo* and *Merrie Beth Neely*, University of South Florida, College of Marine Science, St. Petersburg, FL; *Gary L. Hitchcock* and *Jennifer Jurado*, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, FL (pg. 89)
- Q2-15 Nitrogen Cycling in Florida Bay Mangrove Environments: Sediment-Water Exchange and Denitrification.** *Michael S. Owens* and *Jeffrey C. Cornwell*, University of Maryland Center for Environmental Science, Horn Point Laboratory, Cambridge, MD (pg. 90)
- Q2-16 Nutrient Dynamics and Exchange within a Mangrove Creek and Adjacent Wetlands in the Southern Everglades.** *Reyes, E.* and *Day, J.W.*, Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA; *Davis, S.*, Southeast Environmental Research Program, Florida International University, Miami, FL; *Coronado-Molina C.*, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA (pg. 91)
- Q2-17 Nutrient Dynamics in the Mangrove Wetlands of the Southern Everglades — 5 Year Project Overview.** *Reyes, E.*, *Cable, J.* and *Day, J.W.*, Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA; *Rudnick, D.*, *Sklar, F.*, *Madden, C.*, *Kelly S.* and *Coronado-Molina C.*, Everglades Dept., S. FL Water Management District, West Palm Beach, FL; *Davis, S.* and *Childers, D.*, Southeast Environmental Research Center and Dept. of Biological Sciences, Florida International University, Miami, FL (pg. 93)

Poster

No.

- Q2-18 Patterns of Inorganic Nitrogen Flux from Northern Florida Bay Sediments.** *David Rudnick, Stephen Kelly and Chelsea Donovan*, Everglades Department, South Florida Water Management District, West Palm Beach, FL; *Jeffrey Cornwell and Michael Owens*, Horn Point Environmental Laboratory, University of Maryland, Cambridge, MD (pg. 96)
- Q2-19 The Role of Sediments Resuspension in Phosphorus Cycle in Florida Bay.** *Jia-Zhong Zhang*, CIMAS, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL and Ocean Chemistry Division, Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL; *Charles Fischer*, Ocean Chemistry Division, Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL (pg. 98)

**Question 3**

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- Q5-28** **Influence of Coastal Eddies and Countercurrents on the Influx of Spiny Lobster, *Panulirus argus*, Postlarvae into Florida Bay.** *Cynthia Yeung*, Cooperative Institute of Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL; *David L. Jones and Maria. M. Criales*, Division of Marine Biology and Fisheries, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL; *Thomas L. Jackson and William. J. Richards*, NOAA Fisheries, Southeast Fisheries Science Center, Miami, FL (pg. 217)



## *Question 1*



# **An Optical Model for Coral Community Mapping Based on Compound Remote Sensing, Biscayne National Park, Florida, USA**

**John C. Brock**

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Passive remote sensing has been proposed as the only means to create maps that capture regional or global reef status at a meaningful scale, and to do so on a repeat basis rapid enough to match the time scale of ongoing reef degradation. Aerial photography has been used extensively in studies of coral reefs, and given expert interpretation, this very accessible form of remote sensing is a proven method for the rapid mapping of coral communities. Attempts to use satellite and aircraft observations for the mapping and monitoring of coral reef environments began several decades ago and have yielded promising results, particularly in remote regions where these methods have been quite useful to reef managers.

Although it is clear that only remote sensing methods have the potential to meet the requirement for regional or global synoptic maps of coral communities, and to update such maps frequently enough to monitor ecological change, significant shortcomings to the approaches used thus far are apparent. The resulting maps generally portray only coarse geomorphological zones, and are not sufficiently detailed and accurate to be of high value to biologists working at the scale of the organisms that build reefs. The accuracy of benthic cover classification is typically corrupted by changes in bathymetry. Corals that exist in water deeper than about 20 meters are not detected, yet corals can exist at depths greater than 90 meters. Reliable, geographically transferable algorithms for the separation of ecologically significant coral communities zones have not been developed. Finally, the required investment in processing equipment for the characteristically large volume data sets, highly trained staff, and image data purchase is not feasible for many researchers, and given the low likelihood of a major contribution to their research, may not be justifiable. Improvements in sensor technology are usually cited as the remedy for these shortcomings. New satellite sensors such as IKONOS and aircraft sensors such as CASI have greatly improved spatial and spectral resolution compared to their predecessors. These sensor upgrades should lead to improvements in map accuracy relative to results obtained based on coarser observations from LANDSAT and SPOT satellites.

However, there is also a need to improve the methods in use for the interpretation of the remote sensing signals from coral reefs. Typically, the methods used are borrowed from terrestrial land cover classification, and generally have resulted in maps that depict reef geomorphological features more accurately than benthic cover. Applied over water, these methods are error-prone, as they do not admit the effects of light absorption or scattering in the water column, which causes alteration of the downwelling and upwelling submarine light fields.

We present a new method for the mapping of coral reef ecosystems, compound hyperspectral - lidar remote sensing, applied to a study area in Biscayne National Park about Pacific Reef. In the approach described in this poster, the merging of hyperspectral imaging with bathymetric lidar surveying permits more rigorous modelling of the radiative transfer of reflected light that carries the benthic spectral signature. The objectives of this ongoing research are to: 1) present the basic theory that underpins all efforts to use passive optical remote sensing to map coral reefs, 2) describe in detail a new method for the estimation of benthic reflectance spectra from the total spectral radiance received at an above-water sensor that is based on optical modelling coupled with compound hyperspectral - lidar remote sensing. In this description of the model used to implement this approach, "passive optical remote sensing" refers to methods that use reflected sunlight, and "lidar" refers to *light detection and ranging*, an active optical remote sensing method.

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## **Hydrologic and Biogeochemical Pulsing Events in Taylor Creek System, Southeastern Everglades, Florida (USA)**

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Florida International University, Miami, FL

Clinton Hittle  
United States Geological Survey, Miami, FL

Fred Sklar and Carlos Coronado-Molina  
South Florida Water Management District, West Palm Beach, FL

Atmospheric forcing can greatly enhance hydrologic contributions to Florida Bay and strongly influences the relationship between the Everglades and Florida Bay.. The southern Everglades influences Florida Bay through its delivery of freshwater and nutrients. Likewise, Florida Bay marine waters periodically move into the Taylor Creek system, thus altering salinity patterns and nutrient sources. We studied the Taylor Creek system under four different hydrologic regimes of varying magnitudes to evaluate ecosystem effects. In this study we compare typical hydrologic patterns for a fall/winter time period (1997) to a winter storm event (1996), Tropical Storm Harvey (1999), and Hurricane Irene (1999). These pulsed storm events represent different magnitudes and direction in winds, water and nutrient sources, and have variable event durations. We compare here discharge, stage (NAVD88), salinity, air and water temperature, wind direction and velocity, barometric pressure, and precipitation during three unique hydrologic events to surface water concentrations of total nitrogen, total phosphorus (TP), dissolved inorganic nitrogen (DIN), and soluble reactive phosphorus (SRP).

Water levels in the southeastern Everglades' Taylor Creek are primarily driven by precipitation and runoff from the northern Taylor Slough, evapotranspiration, and wind-driven tidal circulation out of Florida Bay. Water levels are typically low in the early summer but rise steadily into the fall. During the fall, winds shift and water levels will fluctuate due to changing inputs from the south out of Florida Bay. Generally, the dry season (low precipitation) occurs during the late winter and early spring. Isolated storm events can alter the typical hydrologic patterns in the southern Everglades wetlands. We evaluated hydrologic and atmospheric forcing functions during a 6-month period from May to October 1997 for comparison to episodic hydrologic events, such as winter "nortes" storms, tropical storms, and hurricanes.

Winter storms occur with some frequency during the "nortes" season between wet and dry precipitation seasons. These storms vary in duration and magnitude, but they typically have sustained winds in one direction for many days. Winter storms can drive water from Florida Bay into the freshwater marshes of Argyle Henry or push water from Taylor Slough south into Florida Bay. During a 14-day period in mid-November 1996, we observed discharge from Taylor Creek at about  $1.5 \text{ m}^3/\text{sec}$  for the first 10 days. A shift in wind then reversed flow in Taylor, and flow was measured at a maximum of about  $2 \text{ m}^3/\text{sec}$  from Florida Bay

into Taylor Creek. During this time period, precipitation was minimal (0.7 cm). Salinity was very low (< 1 ppt) in the Taylor system during the 10-day wind storm, but a marked salinity increase to about 9 ppt occurred when flow reversed in the channel. TP, DIN, and SRP generally increased as water began to move from the bay into Taylor.

Tropical Storm Harvey arrived in south Florida on September 21, 1999. It behaved like a frontal wave as it moved across the peninsula and represented a relatively brief precipitation and runoff event in the Everglades. Surface water levels of Taylor Creek and adjacent wetlands rose quickly (about 25 cm over 8 hours) in response to the rainfall and returned to a pre-storm baseline over a 20-hour period with the passing of the storm. Salinity in Taylor Creek mouth showed a slight decrease which only lasted a few hours.

One month later on October 15, 1999, Hurricane Irene (category one) passed over Florida Bay and the southwestern Everglades. In magnitude, this storm had a much more dramatic atmospheric and hydrologic effect on the Taylor Creek system than the winter storm or tropical storm. Stage rose sharply from about 0.5 m to a maximum of 7.4 m within a 12-hour period, while water levels receded over a 4-day period back to a pre-hurricane stage of 0.5 m. Barometric pressure and air and water temperature all decreased with the approach of the hurricane and returned to pre-storm conditions over 1 to 3 days. Discharge at Taylor Creek reflected the effects of the approach of the storm which drove water into the wetlands from the bay at about  $1 \text{ m}^3/\text{sec}$ , and then as the eye of the hurricane passed over the region, discharge reversed direction and water flowed back out of the creek at about  $5 \text{ m}^3/\text{sec}$ . Salinities rose from 1 ppt to 12 ppt as the storm surge moved into the Taylor Creek system.

Typical wet season hydrology can be compared to larger pulsed events, such as winter storms, tropical storms and hurricanes to evaluate the ability of the system to rebound from various magnitude events. The Taylor Creek wetland system rebounded quickly from the effects of the tropical storm. Water levels, discharge, salinity and water temperature all returned to pre-storm conditions within hours of the storm event. Likewise, TN and TP demonstrated a concentration increase of 1.5-fold and 6-fold, respectively, that corresponded to the storm's presence. These concentrations decreased with the passing of the storm to about  $40 \text{ }\mu\text{M}$  TN and  $5 \text{ }\mu\text{M}$  TP. Longer duration events do not necessarily demonstrate biogeochemical responses as large as observed for Tropical Storm Harvey but these responses generally last longer. Hurricane Irene created an abrupt increase in stage, precipitation, and salinity in Taylor Creek. TN rose slowly over the waning days of the storm's effects (1 to 7 days post-storm) but had begun to decrease within a week of the storm. TP showed little, if any, change in concentration over this same time period. Effects of the winter storm of 1996 were sustained for much longer than either cyclonic storm due to sustained winds from the northeast which drove water out of Taylor Creek. While TN showed little net change over this time period, TP increased 5-fold during the winter storm. We demonstrate here the relative influences of various magnitude and duration atmospheric and hydrologic effects on the communication between the Everglades-Taylor Creek system and Florida Bay.

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## Patterns and Possible Causes of Temperature and Salinity Variability in Central Florida Bay 1880-1998

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This project investigated patterns and causes of temperature (T) and salinity (S) variability in Florida Bay using isotopically-dated sediment cores from Russell Bank, Park Key, Bob Allen Key, and Whipray Key. The methods used include morphological (*Loxococoncha* shell length), geochemical (Mg/Ca ratios in ostracodes), and faunal (ecological) data designed to provide quantitative estimates of decadal-scale changes in T and S for the past 150 years.

Temperature and salinity reconstructions were based mainly on the ecology and the shell chemistry of the ostracode *Loxococoncha matagordensis*, a common species in modern Florida Bay and as a fossil in sediment cores. Temperature reconstructions are based on the carapace length of fossil shells of *L. matagordensis*. Carapace size in some epiphytal species of *Loxococoncha* is inversely proportional to the water temperature in which the adult carapace is secreted during final ecdysis (Kamiya 1988). Such a relationship is evident in *L. matagordensis* populations obtained from temperate to subtropical climatic zones of eastern North America, and from *Zostera* collected seasonally in Chesapeake Bay and *Thalassia* in Florida Bay (Figure 1). Because most adults grow during spring and early summer when seagrass growth is occurring, adult carapace size is an indicator of warm season water temperature.

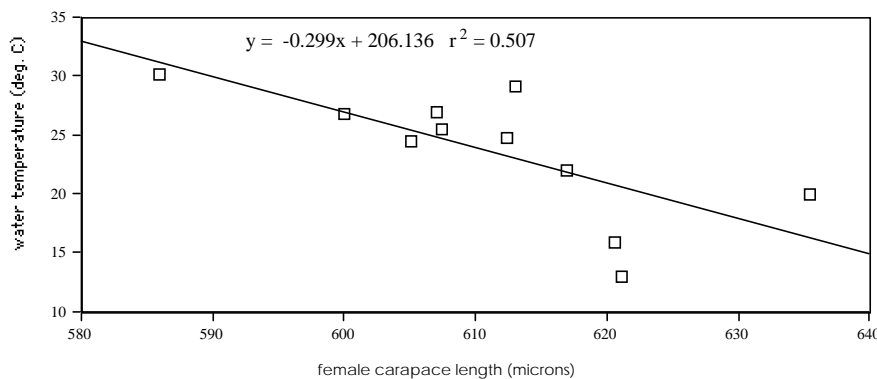


Figure 1. Relationship between adult carapace length in the ostracode *Loxococoncha matagordensis* from Chesapeake Bay and Florida Bay

Salinity was reconstructed using the Mg/Ca ratios in fossil shells of *L. matagordensis*. As discussed in Dwyer and Cronin (in press), the Mg/Ca ratios provide estimates of the Mg/Ca ratios of the Florida Bay waters over the period of record. These fossil shell ratios can then be used to estimate past Florida Bay salinity due to the strong positive correlation between

salinity and water Mg/Ca. The relationship between shell Mg/Ca and water Mg/Ca can be described as follows:

$(Mg/Ca)_{\text{ostracode calcite}} = (K_{D-Mg})(Mg/Ca_{\text{water}})$  where  $(K_{D-Mg})$  is the partition coefficient for magnesium. Using a  $K_D$  for *L. matagordensis* of 0.00743 (see Dwyer and Cronin in press), in conjunction with the water Mg/Ca-salinity relationship, we calculate estimates of past warm-season salinity of Florida Bay.  $K_{D-Mg}$  may be partially a function of water temperature, which may contribute to the observed variability in shell Mg/Ca.

Results (Figure 2) show that mean carapace length for both male and female adult *L. matagordensis* varies significantly downcore at Russell Bank in central Florida Bay for the period 1880-1998. These trends have been replicated in a second core from Russell Bank and at other sites in central Florida Bay and provide evidence for decadal variability in central Florida Bay temperatures.

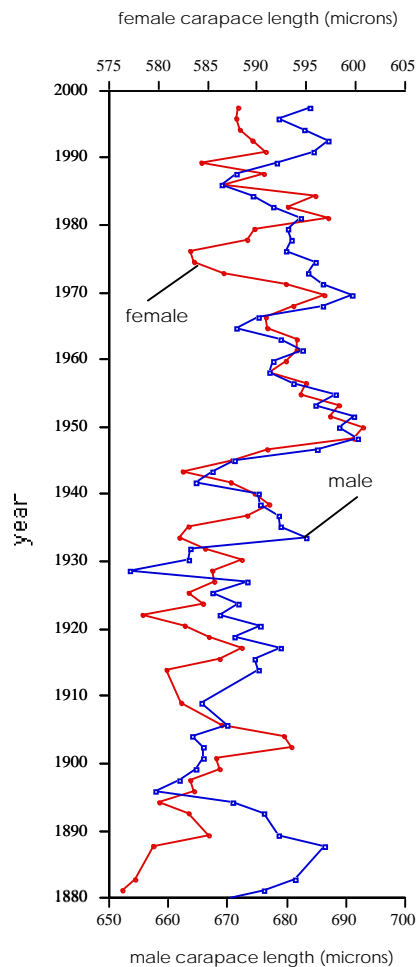


Figure 2. Changes in carapace length in adult *L. matagordensis* from sediment core from Russell Bank, central Florida Bay. Carapace size is inversely proportional to water temperature in which shell grew.

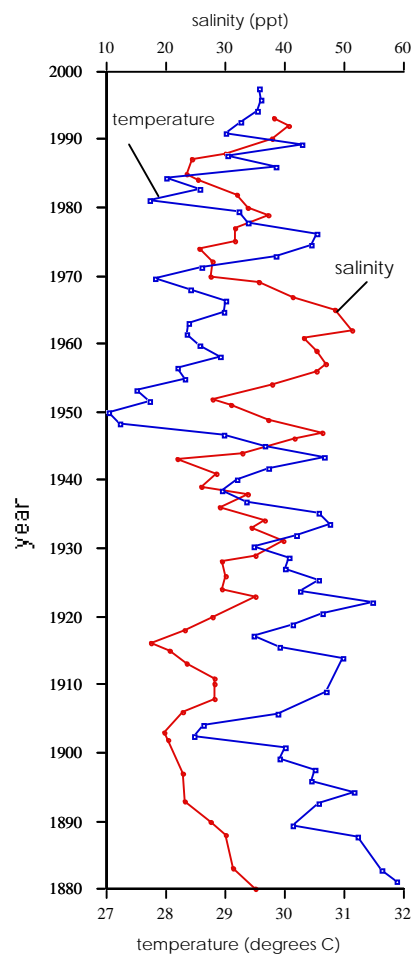


Figure 3. Salinity and temperature history of central Florida Bay for warm season based on Mg/Ca ratios and carapace length in the ostracode *L. matagordensis* from replicate sediment cores from Russell Bank. Slight offset in salinity and temperature maxima is due to coring procedure.

Using the length-temperature relationship for modern adult females shown in Figure 1, and the Mg/Ca-salinity relationship described above, we estimated temperature and salinity trends at Russell Bank from replicate cores taken in 1996 and in 2000 (Figure 3). This plot reveals several important features to the central Florida Bay T and S history. First, warm season T and S covary for the past 120 years; T and S oscillate between 27°C and 32°C and 20 and 50 ppt, respectively. This pattern would be expected because, other factors being equal, warmer temperatures should lead to greater evaporation and increased summer salinity. Second, there was a trend in both T and S from relatively high values during the late 19<sup>th</sup> century towards minima about 1940-1950. This period was followed by a steep rise in salinity and, to a lesser degree temperature, towards maxima in the 1960s and 70s. Anthropogenic diversion of fresh water of the 1950s and 60s may have caused the apparently anomalous salinity during this period.

It should be mentioned that shell size and Mg/Ca ratios vary in cores from Bob Allen, Park and Whipray Keys suggesting those observed at Russell Bay represent broad patterns characteristic of this part of Florida Bay.

The causes of decadal salinity and temperature variability can be examined in light of climatic patterns that influence the south Florida region and Florida Bay. Using the Mg-based salinity curve above, and two faunal indicators of salinity (relative abundance of *Malzella floridana* and *Loxoconcha matagordensis*), we found evidence for quasi-cyclic oscillations in the salinity of central Florida Bay that includes a 5.5 year Mg/Ca-based salinity periodicity, and three predominant modes of variability (6-7 year, 8-9 year, and 13-14 year) in all salinity proxies. Since 1950 an 8-year periodicity has been prominent in the faunal indicators.

What are the causes of these patterns? Climatological observations and modeling studies suggest that climate (especially precipitation) in the southeastern United States is strongly influenced by ‘teleconnections’ to decadal and interannual ocean/atmospheric processes originating in the Pacific Ocean, and perhaps also the Atlantic Ocean. To explore whether these processes might influence salinity in Florida Bay, we compared the Russell Bank paleosalinity curve to records of south Florida winter rainfall and to five climate indices: the Southern Oscillation Index (SOI), winter North Atlantic Oscillation (NAO), winter Pacific North American (PNA) index, and a surrogate for winter PNA, the Central North Pacific (CNP) index (Cayan and Peterson 1989). Patterns in the SOI, PNA, and CNP appear to correlate with south Florida winter precipitation. Spectral analyses of SOI and winter rainfall for the period 1910-1998 suggest ~5 year, 6-7 year, and 13-14 year cycles. The 6-7 year and the 13-14 year frequencies are similar to those observed in the faunal and geochemical time series from Russell Bank. Spectral analyses of post-1950 winter rainfall exhibits a 5 year cycle, whereas the PNA index shows an 8 year cycle for this period, similar to that observed for the paleosalinity indicators. The main periods of the CNP index are 5-6 and 13-15 years, similar to those observed in Florida Bay paleosalinity. In summary it appears that decadal salinity trends in the Florida Bay reflect regional rainfall variability associated with climate processes, except possibly during the 1950s and 60s when human factors were important. These studies give us the tools to further evaluate proposed management actions on the Everglades and adjacent coastal ecosystems.

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## **Quantity, Timing, and Distribution of Freshwater Flows into Northeastern Florida Bay**

**Clinton Hittle**

U.S. Geological Survey

A major Everglades restoration goal is to provide the wetland and Florida Bay with the right amount of water at the right time. The need for accurate information on the quantity, timing, and distribution of water flows through the Everglades into Florida Bay is necessary for successful water management as it relates to restoration efforts. Hydrologic models and biological research are dependent upon accurate outflow data to calibrate and verify boundary conditions, and establish flux parameters. With this information, water management practices can be monitored and decisions made on the distribution and amount of flow required to restore the Everglades to a more natural system.

In October 1994, the U.S. Geological Survey (USGS), as part of the South Florida Place Based Studies Program, began a study to measure freshwater discharge into northeastern Florida Bay. Water flow, stage, and salinity data were collected at five instrumented sites, and water flow data were collected at four noninstrumented sites. The five instrumented sites from east to west are West Highway Creek, Trout Creek, Mud Creek, Taylor River, and McCormick Creek. The four noninstrumented sites from east to west are East Highway Creek, Oregon Creek, Stillwater Creek and East Creek (fig. 1). Data at the instrumented sites are collected every 15 minutes and transmitted via satellite every 4 hours to the USGS Miami office. Data from the noninstrumented sites are collected on a monthly and storm event basis. The study was expanded in 1999 to determine flow distribution into Joe Bay and upstream flow characteristics for Taylor River. Four salinity probes were installed at creeks along the northern coast of Joe Bay, and additional instrumented sites were installed along upstream Taylor River and Stillwater Creek (fig. 1).

The quantity of water flowing through Taylor Slough and the C-111 Basin, including rainfall and evaporative losses, can be defined as total cumulative outflow volume in acre-feet from the creeks. The USGS water year (October through September) annual summaries for 1996-99 of outflow volume for the five instrumented and four noninstrumented sites are presented in table 1. Sheetflow over the Buttonwood embankment into northeastern Florida Bay is considered negligible due to the higher elevation of the embankment. Water levels in the area drop rapidly after storm surges (such as those associated with Hurricane Irene in 1999) and flow into the bay is mainly constrained within the creeks. Trout Creek stage, discharge, and salinity data indicate that the highest water levels correspond to negative flows during storms, and positive “freshwater” outflows return after winds subside and water levels decline.

The timing of flows is directly related to the wet/dry season variations with more than 80 percent of annual freshwater flow entering northeastern Florida Bay between June and November. Negative flows predominate the dry season and lower water levels in the wetland along with southerly winds cause saltwater to intrude upstream and into the inland subembayments, such as Joe Bay and upstream Taylor River.

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Due to the complex drainage basin of the southeastern Everglades and the flat topography, small changes in water level can cause changes in flow distribution that would not be observed without directly computing discharge at the creeks. Discharge computation and salinity observations at the creeks and sub-embayments have yielded the following: (1) Trout Creek carries approximately 50 percent of the freshwater outflow to northeastern Florida Bay including the gaged and ungaged creeks; (2) West Highway Creek rarely has net negative flow on a monthly basis; (3) McCormick Creek had net negative flow for water year 1998 following the El Nino event; (4) flow exchange between Joe Bay and Long Sound does occur, and direction of flow is dependent upon water levels in the Taylor Slough and C-111 Basins; and (5) northeastern Joe Bay shows a direct connection with outflows from S-18C.

The accurate measurement of quantity, timing, and distribution of freshwater flows to northeastern Florida Bay can be used to establish goals for restoring the Everglades. Direct field observations accompanied by model predictions will invariably facilitate a better understanding of the diverse Everglades ecosystem.

<b>Water Year</b>	<b>West Highway</b>	<b>East Highway *</b>	<b>Oregon *</b>	<b>Stillwater *</b>	<b>Trout</b>	<b>Mud</b>	<b>East *</b>	<b>Taylor</b>	<b>McCormick</b>
<b>1996</b>	33,764	12,933	12,307	13,713	143,696	18,017	22,307	16,674	12,028
<b>1997</b>	43,657	17,906	15,811	17,225	190,088	18,577	23,040	23,809	24,484
<b>1998</b>	27,909	9,694	10,258	11,761	138,853	18,748	19,308	27,959	-14,997
<b>1999</b>	28,699	10,107	10,537	14,532	110,361	19,298	23,584	28,361	22,418

Table 1. Annual outflow volumes for creeks in northeastern Florida Bay in acre-ft. \* noninstrumented creek outflows that are estimated using correlation with instrumented creeks.

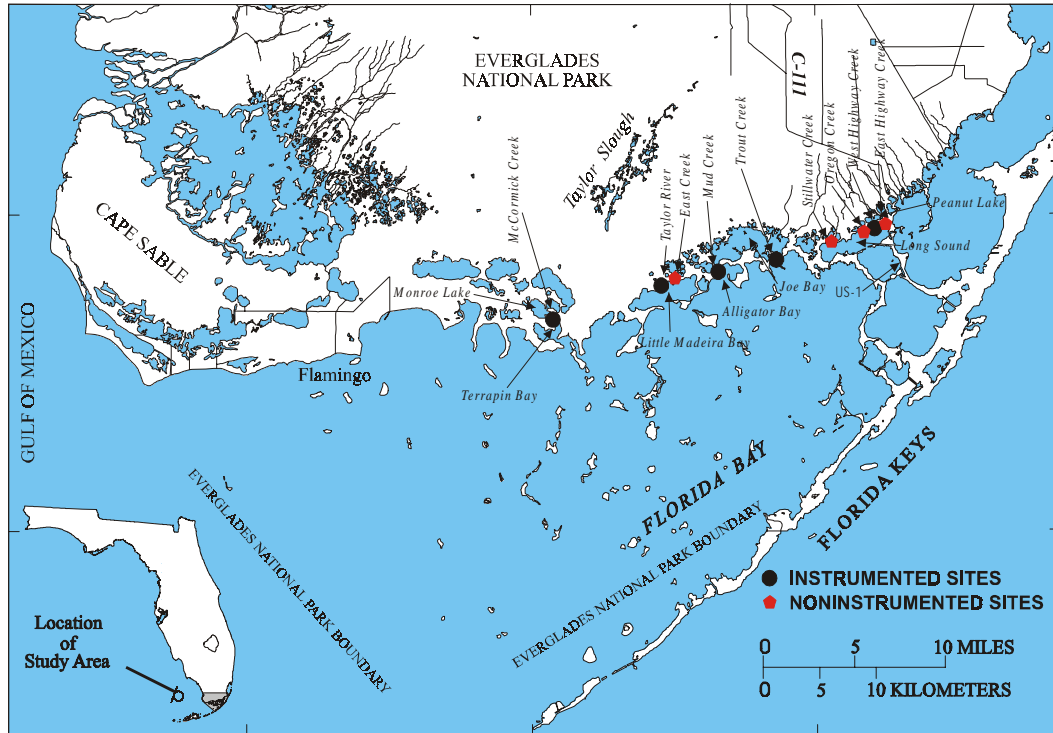


Figure 1. Location of Florida Bay Monitoring Stations

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## **Influence of Hurricanes, Tropical Storms, and Cold Fronts on South Florida Coastal Waters**

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The South Florida climate is characterized by a tropical dry season/wet season pattern, with a wet season typically beginning in June with the onset of summer rainy conditions, and much drier conditions from November to April. The regional climate is also affected in late summer by the passage of tropical cyclones, and in the winter by the passage of cold fronts. These extreme weather events are evident not only in the standard meteorological measurements such as barometric pressure, wind speed and direction, air temperature, and precipitation, but are also manifested in such oceanographic variables as sea surface temperature, sea surface height, current speed and direction, sea surface salinity, and water column turbidity.

As part of a joint University of Miami/NOAA project entitled Circulation and exchange of Florida Bay and connecting waters of the Gulf of Mexico and the Florida Keys, a variety of observations have been collected beginning in December 1995. These measurements, which were expanded in scope beginning in September 1997, now include bimonthly interdisciplinary shipboard surveys of salinity, temperature, fluorescence, and nutrients, as well as satellite-tracked surface drifters and moored arrays of currents, temperature and conductivity. The study area extends from Florida Bay north to Naples, FL, southwest to the Dry Tortugas, east to Key West and then northeast to Miami, FL. In addition to the bimonthly surveys, observations are obtained monthly within Florida Bay using a shallow draft catamaran equipped with a continuous flow-through thermosalinograph system.

Since 1995, a number of tropical cyclones have come close enough to affect South Florida environmental conditions by means of extreme wind, rain, or both. Although none of these recent tropical cyclones have come close to matching the historically most severe events of the region (e.g., the well-known Labor Day hurricane in 1935, Hurricane Donna in 1960, and Hurricane Andrew in 1992), they still influenced the regional meteorological and oceanographic climate.

For example, in the summer of 1995 four tropical storms (Allison, Erin, Jerry, and Opal) made close approaches to South Florida and delivered large amounts of rainfall to the region. As a result the summer precipitation was far above average, and nearly all of the USGS gauges in the region recorded historic high water levels and maximum discharges. This unusual amount of fresh water caused an extensive low salinity surface plume to flow out of the Everglades via the rivers of the southwest Florida coast. Evidence of this plume extended almost 100 km to the south, nearly to the Florida Keys. Later observations from 1996 to the present have shown that the spatial extent of the lower salinity water observed in December 1995 was the most extreme of the measurement program to date.



The summers of 1996 and 1997 were quiet in terms of tropical cyclones affecting South Florida, but in late September of 1998 Hurricanes Georges passed over the lower Florida Keys and into the eastern Gulf of Mexico. Passing close to the offshore array of acoustic Doppler current profilers (ADCPs), this hurricane produced the strongest ocean currents of the entire record in a short-lived peak that lasted only a day. In addition, acoustic back-scattering information obtained from the ADCPs showed a large 24-hour turbidity spike that encompassed the entire water column at each site. The sediments remained in suspension for up to a week near the bottom, indicative of the ability of strong hurricane winds to force interaction with bottom sediments. A satellite-tracked surface drifter located off the southwest Florida coast was blown rapidly north by Hurricane Georges, demonstrating that the hurricane winds were capable of transporting surface waters over relatively long distances.

The 1999 hurricane season was memorable in terms of tropical cyclone-induced rainfall. In quick succession Tropical Storms Harvey and then Hurricane Irene passed through the area (9/21-22 and 10/15-16, respectively), causing wide-spread flooding. Irene passed directly over the instrument array, leading to extrema in the moored current and conductivity measurements, affecting the surface drifter trajectories, and causing a dramatic reduction in salinity over much of Florida Bay as excess fresh water entered from Taylor Slough along the northern edge of the Bay. Due to the long residence time of water in the central and northeastern basins of Florida Bay, this low salinity event lasted for many months, through the entire winter dry season of 1999-2000, before salinities began to rise again.

Winter cold fronts have a significant influence on currents, sea level, turbidity, and water temperature in the shallow coastal waters of South Florida. Within and surrounding Florida Bay one noticeable effect of cold front passages is the exchange of water between western Florida Bay and the Gulf of Mexico.

Although extreme meteorological events such as tropical cyclones occur only occasionally, their oceanographic effects can be considerable, often leading to the strongest signals observed during the period of record of variables such as current speed, turbidity, salinity, or any of a number of other parameters. As they can have such a sudden and dramatic, yet long-lasting, impact, these extreme events need to be taken into consideration by numerical modelers and water managers as the South Florida ecosystem restoration effort proceeds, in order to gain a better understanding of the full possible range of environmental interactions.

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Question 1 - Physical Science

## **Salinity Variability in Florida Bay from Monthly Rapid High Resolution Surveys**

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As part of NOAA's South Florida Ecosystem Restoration, Prediction and Modeling (SFERPM) program, a time series of high resolution salinity maps of Florida Bay has been obtained using a shallow draft catamaran equipped with a continuous flow-through thermosalinograph system. Each survey is completed within two consecutive days. These maps, produced at an approximately monthly interval from March 1997 to the present, cover the three major subdivisions of Florida Bay, i.e. the northeast Bay, the central Bay, and the western Bay.

The three Bay regions respond differently to meteorological and other forcing mechanisms due to their differing degrees of isolation from other coastal waters. For example, the northeast Bay is relatively isolated by the geometry of its coastlines and the shallow mud banks which separate it from the central Bay. The northeast Bay is subject to time-varying inputs of fresh water from the rivers and canals of the Taylor Slough, and as a result has an extremely large salinity variability related to seasonal and interannual precipitation patterns as well as to water management practices. On the other hand, the central region of Florida Bay, although also fairly isolated in terms of its topography (except at its southern border where exchange of water with the Atlantic occurs through a few narrow tidal channels between the Florida Keys), has few direct sources of fresh water. Thus the salinity of the central Bay exhibits a different pattern of variability, responding to the changing balance between local evaporation and precipitation which regularly produces periods of hypersalinity interspersed with much lower salinity periods on a timescale of several months or longer. The persistence of these high or low salinity periods is indicative of long residence times for these basins. Western Florida Bay, on the other hand, has an open western boundary and thus is subject to open exchange of water with the eastern Gulf of Mexico and the southwest Florida shelf. The numerous rivers of the southwest Florida coast, such as the Shark, Broad, and Lostmans Rivers, contribute a time-varying source of fresh water from the Shark River Slough area of the Everglades which at times can flow around Cape Sable and interact with western Florida Bay, providing another source of salinity variability there. Due to the more open exchange with the surrounding Gulf of Mexico and southwest Florida shelf waters, the salinity of the western part of the Bay does not exhibit the long residence times of the northeast and central Bay, but instead can change rather rapidly when influenced by tropical storms, the passage of cold fronts, and other extreme forcing events.

Determination of the rates and pathways of exchange between the interior basins of Florida Bay and with the southwest Florida shelf is a critical need for predicting the effects of modifying the fresh water supply to the Everglades as part of the Everglades Restoration

effort. At present it is not understood how the proposed changes in water delivery, with increased fresh water flows to the Shark River and Taylor Slough, will affect salinity variability within Florida Bay. However, it is generally agreed that the large seasonal and longer period variations of salinity within the Bay have significant impacts on the sea grass and plankton communities within the Bay, and possibly also with adjacent marine ecosystems of the southwest Florida shelf and the Florida Keys National Marine Sanctuary (FKNMS) due to transport processes linking the regions.

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## Hydrogel Stabilization of Florida Bay Marl Sediments

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William H. Orem  
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During our studies on paleoenvironment and pigment diagenesis within the sediments of north-central Florida Bay (Louda *et al.*, 2000), we noticed an 'odd' behavior of these carbonates when they were blended prior to sieving. In essence, their nature changed from a relatively homogeneous paste to a biphasic system comprised of milky colored water and a less cohesive mixture of sediments. After observing this phenomenon, we undertook an abbreviated investigation to determine possible reasons for this physical change.

Sediment cores were taken from Pass-Eagle Bank, 2 sites in southern Whipray Basin and just off the SE edge of Jim Foot Key. Cores were retrieved in 4 inch food-grade acrylic using hydraulic-piston techniques and were sectioned at 2 or 5 cm intervals.

As usual with our studies on sediments, we routinely determine percent organic carbon (%C<sub>org</sub>, dry wt.) and percentage "wet" water (wet wt. / dry wt.) in order to relate pigment yield to both parameters (Baker and Louda, 1986). During the present study (*cf.* Louda *et al.*, 2000), we noticed that the downhole trends fractional wet weights tended to mimic those of organic carbon. This led to our cross-plotting %wet wt. and % C<sub>org</sub>. A rather well defined curve resulted and contained only 2 outliers, both highly shelly cores from near Jim Foot Key. These data, modeled as a linear function, yielded the relationship (as  $y=mx+b$ )  
**%water = (0.076807)%C<sub>org</sub> + (0.2986)** and had a Pearson  $r = 0.8974$ . This indicates that, in the absence of organic matter, these sediments would contain about 30% water, a quite reasonable value. In reality, the observed trend appears to be linear only from about 1.6 to 3% C<sub>org</sub>, above which it becomes asymptotic to about 75-80% water as C<sub>org</sub> values exceed 6%.

Given the physical behavior of these marls sediments and an observed relationship between water (dependant variable) and organic matter, we hypothesized that a weak physical hydrogel could be present in these sediments.

Pigment paleochemotaxonomy revealed that much of the OM in these sediments could certainly derive from the microphytobenthos and that those communities consisted of diatomaceous cyanobacterial mats / biofilms underlain with purple-S bacteria (Louda *et al.*, 2000).

From the above, we extended this hypothesis to include exopolymeric substances (EPS), primarily saccharide / polysaccharide based EPS, as the cross-linkers in the hydrogel. We then utilized the TPTZ (2,4,6-tripyridyl-s-triazine) method (Myklestad *et al.*, 1997) for the colorimetric determination of reducing sugars in sea water media. Free reducing sugars were determined in the water recovered by centrifugation and the polysaccharide component was

determined following hydrolysis in 1 M HCl at 150°C. Standardization was versus D-glucose and the Fe(II) TPTZ<sub>2</sub> complexes were measured at 595 nm. Analyses of several random samples from Whipray Basin revealed an average free and polysaccharide content of 28.2 and 8.6 mg/L, respectively. Apparently, the strong reducing conditions of these sediments allows for a large pool of free sugars to exist.

We conclude that a weak physical hydrogel, formed amongst a lattice of saccharides / polysaccharides and quite likely including calcium (Ca<sup>2+</sup>) complexation, exists in the fine carbonate marls of north-central Florida Bay. The existence of such an hydrogel should be remembered when considering sediment-water exchange and transport of gases, water, and nutrients, all of which should reflect departure from simple solution physicochemistry.

## ACKNOWLEDGMENTS

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## Florida Bay Salinity Transfer Function Analysis

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Linear regression models have been developed by several researchers (Tabb, 1967; Davis, 19xx; and Nuttle, 1997) for use as a salinity performance measure for Florida Bay. These linear regression equations relate hydrology in the Everglades as expressed by the water level in Shark River Slough at P33 to the salinity measured in several small bays in northern Florida Bay within the Everglades National Park. This hydrologic parameter was chosen as the best estimator of salinity levels out of all the data that were evaluated at the time.

A more in-depth analysis was performed using these data and other data as described in this abstract. This analysis has shown that the data have time series characteristics, and relationships cannot be easily ascertained through the use of linear models. This suggests that other types of time series models may be more appropriate for handling the auto-correlation and seasonality shown by the data.

A recent meeting was held (July, 2000) to discuss these findings and to assess the utility of continued use of the current salinity performance measure as management decisions regarding water management systems are made (Science Program for Florida Bay and Adjacent Marine Systems, 2000). As a primary concern, the current salinity performance measures are of no use for evaluating changes in the operational regime of the C-111 Canal system. C-111 flows are thought by many researchers to be affecting salinity levels in some of the coastal bays of north Florida Bay, and particularly more of an effect than the water level in the Everglades more than 30 miles away (P33). Therefore, an improvement in salinity performance measures is desired.

The data used for this statistically-based study and the previous analyses were collected in the Everglades National Park and the adjacent Dade County area drained by the C-111 Canal system operated by the South Florida Water Management District (SFWMD). The coastal bays that are the subject of this and the previous studies are Joe Bay, Little Madeira Bay, Terrapin Bay, and Garfield Bight. Raw data were obtained from the Southeast Environmental Research Center, SFWMD, Nuttle (1999). Three periods of data were examined, first to verify the previously developed linear regression models, then to evaluate further the continued use of linear regression models.

After the data were assembled and the existing salinity performance measure verified, a comprehensive residuals analysis using the existing models was completed to determine if the existing models adhered to the basic assumptions of linear regression modeling (linear parameters, normally distributed errors with a 0 mean, and a constant variance). From this initial analysis, data outlier presence, auto-correlation, cross-correlation, and seasonality were identified as factors in the data that may be affecting the applicability of the simple (single independent variable) linear regression relationships.

To evaluate the affect of water management operations on the salinity in the subject bays, a double mass curve analysis was performed using cumulative flow values. A consistent, periodic high / low slope pattern was seen in double mass plots of C-111 structure flows and P33, so linear regression models for salinity using P33 were developed using only high slope and only low slope values separately. For Joe Bay, a statistically significant difference was found (95% confidence level) between the two groups of data, indicating that the water management operations were affecting the salinity in Joe Bay. For Little Madeira Bay, there are also less significant indications that water management operations may be affecting the salinity regime. For Terrapin Bay and Garfield Bight, both geographically further removed from the C-111 Canal system, there is little or no indication of an affect on salinity regimes.

A preliminary analysis using lagged values of all variables showed that there are statistically significant relationships between salinity in the bays and C-111 system flow parameters, Taylor Slough flows, and rainfall. These lagged value relationships were not considered important in the original analysis used to develop the P33 relationships. For some of these independent variables, the strongest correlation values were developed for two- and three-month time step lags. In the context of the numerous evaluations that were performed, this indicates a time factor in the relationship that may not be able to be accounted for with linear regression models.

Evaluating all of the statistical evidence, it appears that there are problems with seasonality of the data and the remaining error after fitting models that may not be correctable by commonly used statistical techniques such as transformations. One problem inherent in this data set is that all of the independent variable values are averages of many measurements, and the dependent variables are not, being instead a single snap-shot of the salinity conditions at one point in time during the month. There is ample evidence that lagged values of some of the independent variables are related to salinity variation in the subject water bodies. For example, the salinity response in the bays to operational measures appears to be delayed. The response of salinity to lagged rainfall is also delayed, and salinity may be affected by rainfall for several months. Sometimes a multi-variable linear regression model may provide improved model performance by including the effect of operational activities and rainfall.

Nuttle (1997) improved model performance using multi-variable linear regression and data transforms at the expense of the predictive function. However, the seasonality, autocorrelation, and cross-correlation of the available data appears to also impair the ability of a multi-variable linear regression model to accurately predict the response to changes in operations. Linear regression models including multi-variable forms are known to be poor in handling the effects of time variable factors, particularly when they are present in the error term (Neter, Wasserman, and Kutner, 1990). Other time series transfer function models such as seasonal autoregressive integrated moving-average (SARIMA) models are available that are usually more robust to the deviations from the basic model assumptions that have been seen in this analysis (Marshall, 1997).

When the results from all of the various analyses are weighed, it is clear that Joe Bay is affected by water management operations in the C-111 Canal system. Little Madeira Bay

may also be affected. Even though the inclusion of lagged data values in the transfer function for Joe Bay and possibly Little Madeira Bay would explain additional model variability and take into account the effects of operational activities, the effects of seasonal and climate induced effects that may lead to spurious conclusions. The characteristics of the available data may not be able to be handled by linear regression relationships, even multi-variable models. Time series models that are more robust to the characteristics of this data set may provide a more reliable salinity performance measure and take into account the effect of revised water management operations in the C-111 Canal system, and should be considered for improving the existing salinity performance measures.

Cetacean Logic Foundation, Inc. would like to thank Dr. William K. Nuttle of the Florida Bay Science Program and Dr. David T. Rudnick of SFWMD for their assistance in this effort and review of the analysis.

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Question 1 – Physical Science



## **Hydrodynamic Characteristics of Estuarine Rivers Along The Southwestern Coast of Everglades National Park**

Victor A. Levesque and **Eduardo Patino**  
U.S. Geological Survey

As a part of the U.S. Geological Survey South Florida Ecosystems Initiative and Placed Based Systems programs, a study was initiated to describe the hydrodynamic characteristics of selected estuarine streams receiving water from the Shark River Slough drainage basin. The analysis of 1999 discharge data provides information on annual discharge characteristics and the effects of weather systems on discharges for the Broad, Harney, and Shark Rivers. These three estuarine-river sites were selected using the criterion that a large amount of the water that flows through Shark River Slough, sometimes referred to as the "Heart of the Everglades," must pass by these sites. Each station was equipped with instruments for recording water level, velocity, specific conductance, and temperature. More recently, the network of monitoring stations has been expanded to cover a larger area, from Whitewater Bay to Everglades City, and includes the North River in White Water Bay, Lostmans and Chatham Rivers to the northwest, and additional sites equipped only with water-level, specific conductance, and temperature sensors. All data generated through this study will be used to describe the salinity patterns in relation to freshwater inflow and weather events along the southwestern coast of Everglades National Park (ENP) and for the development and calibration of the Tides and Inflows in the Mangrove Ecotone (TIME) hydrologic model currently in development by the USGS.

Discharges from the Broad, Harney, and Shark Rivers are influenced by semi-diurnal tides, wind events, and freshwater inflow. All three rivers are well mixed, with a difference in specific conductance from top to bottom usually no greater than 500 microsiemens per centimeter during flood and ebb tides. Discharge is one-dimensional except for brief (less than 20 minutes) periods during slack water (between flood and ebb tide) when flow is vertically bidirectional (moving upstream and downstream). The flood discharges (water moving upstream denoted as negative values) are usually of greater magnitude and shorter duration than the ebb discharges (water moving downstream denoted as positive values).

Instantaneous and residual discharges for the three stations were calculated for the 1999 calendar year. During 1999, the Broad River instantaneous discharges ranged from -2,400 to +3,500 cubic feet per second, whereas the Harney and Shark River instantaneous discharges ranged from -15,600 to +12,900 cubic feet per second and -10,100 to +10,500 cubic feet per second, respectively. The instantaneous discharges values were processed using a ninth-order Butterworth low-pass filter to remove semidiurnal tidal frequencies that eliminates bias associated with lunar cycles when computing daily, weekly, monthly, or yearly mean or median residual (filtered) discharge values. The residual discharges for the Broad, Harney, and Shark River stations ranged from -900 to +2,500 cubic feet per second, -3,600 to +5,700 cubic feet per second, and -2300 to +4,400 cubic feet per second, respectively. The Broad River station is the farthest upstream from the Gulf of Mexico (9.3 river miles) and exhibits less magnitudes of instantaneous and residual discharges than the other two stations and

longer duration positive discharges than the Harney (4.4 river miles upstream) or Shark (6.2 river miles upstream) River stations.

Mean annual residual discharges were computed for the Broad and Shark River stations and estimated for the Harney River station. Discharge data were missing for the Harney River from April 4 to June 11, 1999, due to erroneous index-velocity data. This period coincided with prolonged minimum residual discharges recorded at the Broad and Shark River stations. The mean annual residual discharge for the Broad and Shark River stations, using the complete 1999 record were computed as +400 and +440 cubic feet per second, respectively. Excluding the period of missing discharge data for the Harney River station, the mean annual residual discharges for the Broad, Harney, and Shark River stations were +520, +580, and +550 cubic feet per second, respectively. Applying the same difference of about 100 cubic feet per second between mean annual residual discharges for the Broad and Shark River stations, the Harney River station mean annual residual discharge for 1999 was estimated to be about +470 cubic feet per second. The mean annual residual discharges reflect the net downstream flows with minimal errors associated with water storage.

Wind events such as cold fronts, tropical storms, and hurricanes can amplify, attenuate, or completely overwhelm the tidal forces that normally dominate flow patterns in the estuaries along the southwestern coast of ENP. Four strong cold fronts occurred between January and March 1999 that significantly affected short-term discharges (less than a few days) for the Broad, Harney, and Shark Rivers. The lowest water levels for the Broad, Harney, and Shark Rivers occurred during the passage of strong cold fronts in February and March 1999, when mean water levels were lower than in the late summer and early fall. The most significant effects on maximum water level and discharge occurred during the passages of Tropical Storm Harvey and Hurricane Irene in September and October 1999, respectively. The two storms had different effects on the water levels and discharges during their movement toward and away from the southwestern coast.

Tropical Storm Harvey approached the Broad, Harney, and Shark Rivers from the northwest and moved to the east with maximum sustained winds of 60 miles per hour. The winds associated with Harvey forced water into the mangrove forests of the southwestern coast to water levels of about 1.81 feet above sea level at the Broad River station, 3.30 feet above sea level at the Harney River station, and 2.96 feet above sea level at the Shark River station. Some pulsations in water level and discharge, not attributable to semidiurnal tidal forcing, preceded the storm by 2 to 3 days. The center storm surge caused a prolonged flood flow that lasted almost 24 hours; then as the winds shifted and abated, the stored water flowed back to the Gulf of Mexico for about 24 hours with no tidal flow reversal. The maximum positive and negative instantaneous and residual discharges for the Harney and Shark River stations were recorded on September 21, 1999, as Tropical Storm Harvey made landfall. The Broad River discharges exhibited similar patterns, but to a magnitude less than the Harney and Shark River stations due to the location of the station and the storm track.

Hurricane Irene caused a different response at the three river stations because of the storm path and wind strength. Hurricane Irene approached from the southwest and moved to the northeast on October 15, 1999, with maximum sustained winds of 85 miles per hour. The

winds associated with Irene forced water from the mangrove forests, and the return seiche was less in magnitude than during Tropical Storm Harvey. Water levels during Hurricane Irene decreased and caused a rapid increase in ebb flow (toward the Gulf of Mexico) that lasted about 24 hours with no flow reversals during the 24-hour period. The Broad River instantaneous and residual discharges reached maximum values of +3,500 and +2,500 cubic feet per second, respectively, during the passage of Hurricane Irene.

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## Florida Bay Standard Data Set

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Out of the past evaluation of hydrodynamic and water quality models of Florida Bay, the necessity arose for being able to judge model quality based on how each performs over a standard time frame with common input and target data. In addition, this data must capture the variations and characteristics of Florida Bay. In March, 2000, this necessity for a Standard Data Set was discussed at a Florida Bay workshop in Homestead, Florida. The results of that workshop were to establish the functions of the standard data set, to designate a period of record, and to determine the types of data to be obtained.

### Functions of the Standard Data Set

1. Validate hydrodynamic and water quality models.
2. Define “normal”, “wet”, and “dry” water years.
3. Assemble data on water quality and hydrology needed to investigate linkages between Everglades hydrology and the surrounding coastal area.

### Time Frame

10/94-9/00, 5 years

### Data Types

1. Oceanographic – Hydrography, Tides, Currents
2. Climate – Precipitation, Air Temperature, Dewpoint, Wind Direction and Speed, Solar Radiation, Pan Evaporation
3. Water Quality – Salinity, Water Temperature

Data is being assembled from the various cooperating agencies that collect data in Florida Bay and Adjacent Marine Systems. The primary focus is to assemble oceanographic, climate, and selected water quality data from point sources in and around Florida Bay. This Standard Data Set, including metadata, is being made available to users via the World Wide Web.

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Question 1 – Physical Science

## Tidal, Low-frequency and Long-term Flow through Northwest Channel

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A 353-day current meter time series is used to describe tidal, low-frequency and long-term flow through Northwest Channel, the main channel connecting the Gulf of Mexico with the Atlantic Ocean just west of Key West. The study period was August 24, 1999 to August 11, 2000. Meteorological data, recorded at NOAA's C-MAN station on Sand Key 16 km south of the study site over the same time period, are combined with current data to investigate wind forcing through the channel.

Current data were recorded hourly using an acoustic doppler current meter that provided an average current speed and direction through a 4.8 m section of the water column. The instrument was moored on the bottom in 7 m of water. Data were extrapolated from the top of the instrument's transducers down to the bottom (0.5 m) and from the top of the uppermost cell sampled by the instrument to the surface (~2 m) to provide an average top-to-bottom current at the study site. Extrapolations assumed a logarithmic current profile and pressure data were incorporated to provide water level fluctuations.

Results indicate a long-term inflow to the Gulf of Mexico through Northwest Channel that averaged  $4.5 \text{ cm s}^{-1}$  through the nearly one year study period. There was some indication of a seasonal signal as nontidal inflow to the Gulf was remarkably steady from the beginning of the study period to late February and again from early June to the end of the study period. However, from early March to the end of May flow through the channel was dominated by low-frequency reversals that generally lasted about 2 weeks, and there was a resultant net outflow from the Gulf that averaged  $2.4 \text{ cm s}^{-1}$  during that time.

Tidal ebbs and floods dominate the instantaneous current through Northwest Channel. Harmonic analysis indicates that the amplitude of the  $M_2$  tidal constituent, the dominant semi-diurnal constituent, is  $65 \text{ cm s}^{-1}$ . Amplitudes of the other principal diurnal and semi-diurnal tidal constituents range between 3 and  $17 \text{ cm s}^{-1}$ . Based on the  $M_2$  amplitude, the tidal excursion, the horizontal distance a parcel of water would move during a half tidal cycle, is 9.2 km. Northwest Channel is approximately 14 km long.

The total along-channel component of the current was passed through a numerical filter to remove high-frequency variability, including the tides. The resulting low-frequency currents generally ranged between  $\pm 15 \text{ cm s}^{-1}$  and currents typically fluctuated  $2\text{-}20 \text{ cm s}^{-1}$  over time scales of just a few days. A maximum nontidal inflow to the Gulf of just over  $60 \text{ cm s}^{-1}$  occurred in mid October, which was followed immediately by a maximum nontidal outflow from the Gulf of  $-30 \text{ cm s}^{-1}$ . Both were in response to the passage of Hurricane Irene through the Lower Florida Keys.

To investigate wind forcing, wind speed and direction pairs recorded at the C-MAN station on Sand Key were converted to wind stress vectors. Hourly measurements of air pressure

and air temperature recorded at the station were incorporated to calculate air density, which was then used to refine wind stress calculations. A plot of the east-west and north-south components revealed a seasonal pattern that is typical for this region. Relatively weak winds from the east and southeast are most common during spring, summer and early fall. Stronger northeast winds dominate the late fall and winter months. Hurricane Irene produced winds from the east-northeast that reached  $22.7 \text{ m s}^{-1}$  at Sand Key as the storm approached the study area from the south, which were followed within a few hours by winds from the west-northwest that reached  $19.7 \text{ m s}^{-1}$  as the storm moved northeast into Florida Bay. Passages of winter cold fronts are also visible in the record.

Spectral analysis was used to investigate the relationship between wind stress and along-channel flow. To determine the wind stress components and periodicities for which along-channel flow was most responsive, coherence spectra were calculated at wind stress intervals of  $30^\circ$ . Results indicate statistically significant coherence between currents and winds from the east and east-southeast over all time scales greater than 30 hours. Highest coherence of 0.905 was observed for the  $090\text{-}270^\circ$  wind stress component at the 91-hr periodicity, indicating that this component of wind stress accounts for over 90% of the variance in the along-channel flow through Northwest Channel over the 91-hr periodicity. The magnitude of the transfer function ( $16.1 \text{ cm s}^{-1}$  per  $\text{dyne cm}^{-2}$ ) indicates that a wind stress toward the west reaching  $1 \text{ dyne cm}^{-2}$  should force an inflow into the Gulf that reaches  $16.1 \text{ cm s}^{-1}$  at the 91-hr periodicity.

The long-term Atlantic-to-gulf flow observed through Northwest Channel is significant in two respects. First, the finding is inconsistent with the long-term gulf-to-Atlantic flow through all major tidal channels in the Middle and Lower Keys reported from earlier studies. Secondly, both published and unpublished data indicate a long-term east-to-west flow in Hawk Channel on the Atlantic Ocean side of the lower Florida Keys and a persistent north-to-south flow near the Content Keys on the gulf side of the Lower Keys. Combining those results with the earlier tidal channel work and the long-term Atlantic-to-gulf flow observed through Northwest Channel suggests the presence of a clockwise re-circulation feature in this region of the Florida Keys. This feature may play an important role as a larval retention mechanism in the lower Florida Keys and southern Florida Bay.

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Question 1- Physical Science

## **Estimating Evaporation Rates in Florida Bay**

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Evaporation is an important component of the water budget in Florida Bay and its variability with time and space in Florida Bay must be known if hydrodynamic models are to be used to estimate the effects of management practices on the Bay. The aim of this investigation is to provide mean rates of evaporation and its variation both spatially and temporally in Florida Bay. Mean rates of evaporation in Florida Bay are being estimated using four different methods. These are the energy budget-Priestly-Taylor method, the vapor flux-Dalton Law formula, a box model of salinity, and a method utilizing the stable isotopes of oxygen and hydrogen. The energy balance method uses net radiation to quantify estimates of evaporation. The Dalton Law formula relates evaporation to dispersive water vapor flux, which scales with wind speed. The box model will utilize 10 years of salinity data from Florida Bay. The stable isotope method uses the Craig-Gordon model of fractionation of the oxygen and hydrogen isotopes of water molecules during evaporation to estimate the flux of water vapor away from an evaporation surface.

The spatial and temporal variation of evaporation is addressed through the placement of two stations in Florida Bay, one in the northeast, near Butternut Key and one in the one in the western area of the bay where mudbanks dominate, near the Rabbit Keys. At each of these stations, net radiation, water temperature, air temperature, relative humidity, rainfall amount, and wind speed and direction, are being monitored for two years. In addition, once during the summer wet season and once during the winter dry season of each year, the spatial variation of net radiation along an east-west transect spanning the Bay is being monitored using a Kipp and Zonen net radiometer mounted on a motor boat.

For the method utilizing stable isotopes of oxygen and hydrogen, two land-based stations are established in the Florida Keys: one at the Everglades Ranger Stations and the other at the Keys Marine Laboratory on Long Key. The isotopic enrichment of an evaporation water body is being monitored at each of these stations using evaporation pans. The pans are filled with freshwater and the change in water level in the pans due to inputs of rainfall or loss due to evaporation is monitored daily. The oxygen and hydrogen isotopic composition of the water in the pans, as well as the rainfall falling into the pans, is monitored on a monthly basis. Air temperature, relative humidity, rainfall amount, and wind speed and direction are monitored continuously adjacent to the pans. Twice each year, once during the summer and once during the winter, intensive isotope investigations are to be conducted in Florida Bay. These include the collection of hourly surface water samples over a 24-hour period for stable isotope analysis. The samples are to be collected adjacent to each of the stations located in Florida Bay.

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Long-term estimates of evaporation are being made utilizing existing time series of oxygen and hydrogen, and salinity data of Florida Bay. Stable isotopes of oxygen and hydrogen of Florida Bay water has been monitored on a monthly basis since 1983. Evaporation estimates made in this project via the stable isotope method may be combined with the stable isotope record of water samples from Florida Bay since 1983 to provide an estimate of the long-term variation in evaporation across the bay. In addition, there is a potential for the application of the data from this project to be applied to the over 100-year isotope record of a coral from Florida Bay. Monthly salinity data monitored at 28 sites in Florida Bay is available for the 10-year period 1990 to 2000. This salinity data is being applied to a regional box model for each of the four major regions of Florida Bay, i.e. West, Central, East and South. The result of the salinity-box-model is to estimate long-term average evaporation for each of these areas.

A final aspect of this project is a refinement of the stable isotopic method of estimating evaporation using stable isotopes of oxygen and hydrogen. In an effort to identify the effects of isotopic evaporation in a more controlled setting, an evaporation station is established at the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS). The evaporation station consists of four evaporation pans: two with freshwater and two with seawater. Two of the pans, one with freshwater and one with seawater are spiked with deuterium and  $^{18}\text{O}$  depleted water. Furthermore, air temperature, relative humidity, rainfall, and wind speed and direction are monitored at RSMAS. The results of this experiment will be applied to the Craig-Gordon model of evaporation, and compared to the results obtained from the Florida Keys evaporation stations.

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## Seawater Intrusion: A Mechanism for Groundwater Flow into Florida Bay

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Estimates of groundwater discharge into Florida Bay have been the subject of recent debate. Published estimates of groundwater discharge into Florida Bay range from 1 to 16 cm/d (Corbett et al., 1999; Top et al., 2001). These estimates seem large when compared to the 0.2 cm/d estimated for rainfall into Florida Bay (Nuttle et al., 2000). Furthermore, a significant landward extend of seawater intrusion into the coastal aquifer along the northern boundary of Florida Bay prevents the direct discharge of fresh groundwater into Florida Bay (Fitterman et al., 1999). Although seawater intrusion prevents the discharge of fresh water into Florida Bay, it does provide a mechanism for Florida Bay water to be recycled into the Bay as groundwater discharge.

The work presented here was part of a detailed geochemical investigation of groundwater flow in Everglades National Park. Groundwater was collected from 46 groundwater wells screened at various depths (2 to 60 m) within the Surficial Aquifer System (SAS) at Everglades National Park (ENP), and from one deep well within the underlying Hawthorn Group. The wells were located in both the fresh groundwater lens and the seawater mixing zone of the SAS. The wells were sampled once a year for three years for helium isotopes, tritium, neon, and CFCs. In addition, the wells were sampled on a monthly basis for 2.75 years for major cations and anions and the stable isotopes of oxygen and hydrogen. Surface water (if present) was collected adjacent to each well and analyzed for major cations and anions and stable isotopes of oxygen and hydrogen. Groundwater levels were measured at the time of sampling and compared to surface water levels.

In the fresh groundwater wells,  $^4\text{He}$  excess increased linearly with depth from slightly above atmospheric levels (5 - 25%) near the aquifer surface to a range of 150 to 550% in the Hawthorn Group. Low  $^4\text{He}$  excess values (0 and 10%) are indicative of young (recently recharged) groundwater that has not been in contact with the aquifer matrix for a long period of time. As groundwater flows through an aquifer it may acquire  $^4\text{He}$  from the aquifer matrix or by mixing with  $^4\text{He}$  enriched groundwaters from a deeper aquifer. Radioactive decay of one  $^{238}\text{U}$  atom produces eight  $^4\text{He}$  atoms. The upper units of the Hawthorn Group, located beneath the SAS, are reported to contain up to 40 percent phosphate grains which in turn contain uranium. The high concentrations of  $^4\text{He}$  in the Hawthorn Group is anticipated to be a result of radioactive decay of uranium contained in the phosphate grains. The linear distribution of the  $^4\text{He}$  within the freshwater portion of the SAS was modeled with an advection-dispersion groundwater flow model. The model results suggested that the transport of  $^4\text{He}$  from the bottom to the top of the SAS in the freshwater portion was dispersion dominated with an upward velocity estimated between  $2.7 \times 10^{-5}$  and  $8.2 \times 10^{-5}$  cm/d.

In every instance, wells screened within the seawater mixing zone had higher values of  $^4\text{He}$  excess as compared to wells screened at similar depths in the fresh groundwater zone. For

instance,  $^4\text{He}$  excess of greater than 100% were observed in two shallow wells screened at depths of 1.8 m and 3.3 m within the seawater mixing zone. These results indicate that the vertical transport of  $^4\text{He}$  in the seawater mixing zone is faster and by a different mechanism than observed in the freshwater lens. The dynamics of groundwater flow associated with seawater intrusion can be used to explain the high concentrations of  $^4\text{He}$  in the seawater mixing zone. Due to density differences between freshwater and seawater, seawater from Florida Bay intrudes into the SAS along the bottom of the aquifer and entrains high concentrations of  $^4\text{He}$ . The intruding seawater mixes with the freshwater to form a mixing zone of variable salinity and density. The less dense brackish water flows upward, carrying the high concentrations of  $^4\text{He}$  to the top of the aquifer. The brackish groundwater then discharges to the overlying surface water along the coastline, and surface water flow into Florida Bay completes the cyclic flow of seawater back into Florida Bay.

A comparison between surface water and groundwater levels within the seawater mixing zone indicate the potential for groundwater to discharge to the overlying surface water. Further evidence of brackish groundwater discharge to the overlying surface water was provided by the major ion chemistry of Everglades surface waters. The sodium and chloride concentrations in surface waters overlying brackish groundwater increased when both surface water and groundwater levels were low. During times of high water levels, the quantity of fresh surface water probably dilutes the inputs of the brackish groundwater.

The extent of seawater intrusion in the SAS increases from east to west, from approximately 6 km inland in the C-111 Basin to about 28 km in Shark Slough. The landward extent of seawater intrusion, combined with observed high concentrations of  $^4\text{He}$  in surface waters along the coastline of Florida Bay (Top et al., 2001) indicate that brackish groundwater discharges to the overlying surface waters of the Everglades within a 6 to 28 km wide strip that parallels the coastline. The salinity of the discharging groundwater would be low along the inland side of the strip and become more saline toward the coast. The portion of the strip that underlies Florida Bay discharges high salinity groundwater. The quantity of brackish groundwater discharge along this strip can be estimated by:

$$Q = \frac{2xk}{G}$$

where  $Q$  is the groundwater discharge in  $\text{m}^3/\text{d}/\text{m}$  of coastline,  $x$  is the width of the groundwater discharge zone,  $k$  is the aquifer hydraulic conductivity and  $G$  is a measure of the density difference between fresh water and seawater.  $G$  is typically 40 and equals  $\Delta w/(\Delta s - \Delta w)$  where  $\Delta w$  is the density of freshwater and  $\Delta s$  is the density of seawater. In solving the above equation,  $k$  was varied from 0.045 m/d to 38.6 m/d. The groundwater discharge width,  $x$ , was varied from 6 to 28 km. The resultant groundwater discharge ranged from 13.5 to 63  $\text{m}^3/\text{d}/\text{m}$  for a  $k$  of 0.045 m/d and from 11,580 to 54,040  $\text{m}^3/\text{d}/\text{m}$  for a  $k$  of 38.6 m/d. Assuming that this groundwater discharged along the northern coastline of Florida Bay, a distance of 65,500 m, then the resultant groundwater discharge would range from  $8.8 \times 10^5 \text{ m}^3/\text{d}$  to  $3.5 \times 10^9 \text{ m}^3/\text{d}$ . Dividing these estimates by the 2000  $\text{km}^2$  area of Florida Bay results in a groundwater discharge rate of 0.04 to 175 cm/d. The published estimates of groundwater flux into Florida Bay (1 to 16 cm/d) fall within this range (Top et al., 2001; Corbett et al, 1999). To further clarify, most of the groundwater discharge associated with

seawater intrusion is brackish and discharges to the surface waters of the Everglades mainland. Any direct discharge of groundwater as a result of this mechanism into Florida Bay would be of high salinity. Although groundwater discharge associated with seawater intrusion is insignificant for the freshwater budget of Florida Bay, it is an important mechanism in the transport of constituents such as  $^4\text{He}$ , and may be important in the transport of other constituents such as nutrients.

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Question 1-Physical Science

## Salinity Pattern in Florida Bay: A Synthesis (1900 – 2000)

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Existing salinity observations and salinity information for Florida Bay are being compiled in a relational database accessible via the Internet for the purpose of characterizing salinity conditions in Florida Bay over the last century. To compile this comprehensive salinity database, extensive searches for salinity data have been conducted across a diverse body of published and unpublished literature and collections spanning more than 150 years. A salinity observation was included in the database if the following criteria were met: 1) the observation had been made within Florida Bay waters or in waters adjacent to the bay; 2) the measurement was a discrete observation (not an average value); 3) the date and time that the observation had been made was known; 4) the location at which the salinity observation had been made was available or could be estimated; and 5) the depth at which the observation had been made was known or could be determined. At this time the domain of the database is being expanded to include the southwest mangrove coast of Everglades National Park and temperature data is being included when available.

The quantitative record of salinity in Florida Bay begins in 1908 (Moore, 1908). To date salinity observations have been gathered from seventy-two published and unpublished studies. Some data is available from the 1930's and 40's but effectively, a usable database exists from about 1955. Even at this data after 1955 are scattered in space and time. In 1981, long-term monitoring of salinity was initiated by Everglades National Park in northeastern Florida Bay. This monitoring network was expanded to include bay-wide coverage inside Park boundaries by 1988. More recently spatially synoptic salinity surveys are being conducted in the bay related to restoration of the Everglades. A significant database issue has been the integration of data sets differing greatly in temporal and spatial intensity.

Since 1955, Florida Bay has behaved generally as a marine lagoon that is often hypersaline. Salinities within the bay can be described along a southwest/west to northeast gradient. The Gulf of Mexico/Atlantic Ocean and Taylor Slough/C-111 canal, the latter being the bay's primary direct freshwater sources, serve as endpoints on this gradient, respectively. Along this gradient the marine influence of the Gulf and Atlantic decreases from the west while evaporation in the increasingly shallow and confined waters of central and eastern Florida Bay becomes dominant particularly in dry years. Estuarine conditions in Florida Bay are largely confined to the bay's northeastern margin near the freshwater source.

Salinity conditions along this gradient can be summarized for the period-of-record. In western Florida Bay relatively constant marine salinities predominate. Mean monthly ( $\pm 1$  sd) salinity has averaged about 36 psu  $\pm$  2.0 psu in the vicinity of Long Key. This region of the bay is in close contact with the Gulf and Atlantic. In a region centered on Johnson Key Basin mean monthly salinities average about 36 psu  $\pm$  5.5 psu. Johnson Key Basin is located south of Flamingo sheltered by extensive shallow water banks. The range of monthly

average salinities observed in these areas over the period-of-record was 28.7 psu to 40.2 psu and 20.0 psu to 53.2 psu, respectively. In the vicinity of Long Sound, Joe Bay and Little Madeira Bay in northeastern Florida Bay, immediately downstream of Taylor Slough and the C-111 Canal, mean monthly salinities averaged about 20 psu  $\pm$  11.7 psu. The range of observed monthly average salinities was 0 psu to 57.6 psu over the period-of-record. Extreme salinity changes occur in these fringing waters. In contrast mean monthly salinities in the vicinity of Duck Key, immediately downstream of Joe Bay in Florida Bay proper, averaged about 33 psu  $\pm$  9.4 psu with a period-of-record range of 13.3 psu to 51.3 psu. In Florida Bay salinity variability is greatest in the northeast declining to the west.

Generally, annual variation in salinity exceeds seasonal variation in Florida Bay with the exception of the upper estuaries, Long Sound, Joe Bay and Little Madeira Bay. This result is due to size and complex geometry of the bay, the relative dominance of marine influence over freshwater inflow, patterns of rainfall, and the importance of the wet/dry cycle in south Florida.

Over the period-of-record, Florida Bay has often been hypersaline. Hypersaline conditions in the bay occur in years of average or slightly below average rainfall; extreme hypersalinity occurs with cyclic drought conditions in south Florida (Thomas, 1974). The highest reported salinity for open waters in Florida Bay was 70 psu (Finucane and Dragovitch, 1959). This salinity has been observed twice near Buoy Key, east of Flamingo, at the end of the dry season, once in 1956 and again in 1991. During severe drought salinities exceed 40 psu occur over most of Florida Bay including Long Sound, Joe Bay and Little Madeira Bay. Characteristically hypersaline conditions in Florida Bay appear first and are most persistent in central Florida Bay in the vicinity of Whipray Basin where mean monthly salinities for the period-of-record have averaged about 42 psu  $\pm$  8.9 psu (range = 21.2 psu to 57.3 psu). During this period salinities in Whipray Basin have reached or exceeded 40 psu for almost 60% of the months when data is available. In contrast, estuarine conditions across Florida Bay are rare and usually associated with high rainfall episodic events such as tropical waves, depressions, and hurricanes or with periods of above average rainfall like the 1994 to 1995 high period. Water management has influenced these processes as well. Increased flows through the C-111 Canal due to upstream operational requirements lowered salinities across the bay during a period of below average rainfall in south Florida, 1983-1985. However, variation in salinity due to water management in Florida Bay is probably small when compared to the natural variation in salinity.

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## **The Tides and Inflows in the Mangroves of the Everglades Project**

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The coastal land-margin interface of the freshwater Everglades with Florida Bay and the Gulf of Mexico provides nesting habitat, and is a primary productivity area for the food web of numerous endangered species. Land-margin ecosystems, composed mainly of mangrove thickets, brackish marshes, tidal creeks, and coastal embayments, constitute roughly 40 percent of Everglades National Park (ENP). The need to preserve hydrological and ecological conditions that are consistent with habitat requirements in these sensitive ecosystems is particularly problematic for water management agencies implementing the Comprehensive Everglades Restoration Plan (CERP) due to the delicate balance that exists among freshwater inflows, tidal fluxes, meteorological forces, and salt concentrations.

A coupled hydrodynamic/transport surface-/ground-water model is under development in the Tides and Inflows in the Mangroves of the Everglades (TIME) project of the U.S. Geological Survey (USGS) South Florida Ecosystem Program. The TIME model is needed to provide insight into saltwater and freshwater mixing in the wetland/coastal transition zone of ENP that presently is not considered by existing management models of the south Florida ecosystem. Use of the TIME model will complement ongoing CERP efforts by addressing questions critical to preserving these land-margin ecosystems. How do the Everglades wetlands and coastal marine ecosystems respond concurrently to freshwater inflow regulation? What concurrent changes in wetland hydroperiods and coastal salinities are likely to occur in response to various restoration plans and management actions? What dynamic forcing factors, e.g., sea-level rise, meteorological effects, etc., could adversely affect regulatory plans? What factors affect salt concentrations in the coastal mixing zone and how do they interrelate? What effects will upland restoration and management actions have on endangered species in the land-margin ecosystems?

The TIME project (<http://sofia.usgs.gov/projects/time/>) is building on and using hydrologic process-study findings (Schaffranek, 1999) and results of modeling and monitoring efforts derived from the USGS Southern Inland and Coastal System (SICS) project (Schaffranek and others, 1999). The SICS project was conducted within the Taylor Slough and C-111 drainage basins of the southern Everglades interface with Florida Bay. Sensitivity testing with the precursor surface-water SICS model has demonstrated the importance of external forcing factors on land-margin ecosystems, including the dynamic effects of winds on flow patterns in the wetlands and discharges through tidal creeks dissecting the Buttonwood embankment along the Florida Bay boundary (Swain, 1999). For the TIME project, the same two-dimensional, vertically integrated, hydrodynamic Surface Water Integrated Flow and Transport (SWIFT2D) model (Leendertse, 1987) used in the SICS project is being explicitly coupled with the three-dimensional, variable-density ground-water flow model SEAWAT.

SEAWAT is a coupled version of the Modular Ground-water Flow (MODFLOW) model (McDonald and Harbaugh, 1988) and the modular solute transport model MT3D (Zheng, 1990). The TIME model domain encompasses the entire saltwater-freshwater interface zone along the southwest Gulf coast and Florida Bay boundaries of ENP. The model boundaries extend from Tamiami Trail south to Florida Bay and from L-31N, L-31W, and C-111 canals west to the Gulf coast and Everglades City. Additional flow-monitoring stations are being installed in ENP to provide boundary-value data as well as wider synoptic measurements of surface-water flows and ground-water levels for model calibration and verification. The coupled TIME model will be able to simulate flow exchanges and dissolved salt fluxes between the surface- and ground-water systems comprising the entire land-margin interface of the Everglades with Florida Bay and the Gulf of Mexico.

The TIME model-development effort involves collaborations among numerous projects within the USGS South Florida Ecosystem Program. Hydrological needs for critical estuarine species studies have been used to assign resolution scales and to develop information linkages between the TIME and Across Trophic Level System Simulation (ATLSS) (<http://atlss.org/>) models (Gross and DeAngelis, 1999). Initial progress has been made on a number of efforts within the TIME project including development of the model-coupling algorithm, computational surface-water and ground-water grids, vegetation classifications, hydrologic-process formulations, model data bases, and the field-monitoring network. A numerical algorithm, designed to synchronize SWIFT2D tidal-compatible time steps with SEAWAT stress periods, has been developed and is undergoing initial testing. A preliminary and partial land-surface elevation grid of 500-meter square cells covering the Dade County portion of the model domain has been generated from 400-meter-spaced helicopter Aerial Height Finder (AHF) survey data, collected by the USGS National Mapping Division. The model grid has been supplemented with land-surface elevations interpolated from the 2-mile square grid cells of the South Florida Water Management Model where AHF data are not yet available. A companion 500-meter-square aquifer grid for the SEAWAT ground-water model is under development. Ground-truthing of vegetation classifications determined from remote-sensing imagery has begun in support of hydrologic-process representations in the model. In preparation for design and setup of numerical simulations, a project Web site (<http://time.er.usgs.gov>) with a data-base repository for compilation of input data and sharing of model results has been developed and populated with data from more than 100 stations for 1995 to present. Flow data for approximately 70 culvert and structure openings along a 100-kilometer extent of Tamiami Trail have been compiled for water years 1987-99. The data have been entered into a spreadsheet for use in the TIME model and distribution to the south Florida scientific community via the South Florida Information Access (SOFIA) website (<http://sofia.usgs.gov>). An acoustic Doppler flow-monitoring station has been established in Shark River Slough to determine the feasibility of continuous in situ velocity measurements in the heavily vegetated marsh environment for use in model calibration and verification. Progress in development of the model and ancillary project findings routinely are posted on the TIME Web site.



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## Wind-forced Interbasin Exchanges in Florida Bay

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Data from a series of circulation studies conducted around the perimeter of Florida Bay and in the interior are combined with wind data from the Molasses Reef and Long Key C-MAN weather stations. Results describe low-frequency wind-forced exchanges (1) between Florida Bay and inner shelf waters of the eastern Gulf of Mexico, (2) between Florida Bay and Hawk Channel on the Atlantic side of the Florida Keys, and (3) between sub-basins within Florida Bay. Field studies were conducted separately for the most part, starting in 1992, and results do not provide a synoptic picture of the response to specific wind events. Results can be combined, however, by integrating results for specific wind stress conditions.

Study sites include Tavernier Creek, Indian Key Channel, Long Key Channel and Moser Channel, all connecting Florida Bay with Hawk Channel; a channel near the Gopher Keys and another through Nine Mile Bank, both in the interior of the bay; Jewfish Creek, connecting Blackwater Sound with Barnes Sound; Northwest Channel, connecting Hawk Channel south of Key West with inner shelf waters of the Gulf of Mexico north of the Lower Keys; and six open-water study sites along the  $81^{\circ} 05'W$  meridian, which is taken here to represent the western boundary of Florida Bay.

The objective of the analysis is to determine which wind directions are most effective in forcing water into or out of Florida Bay, or between sub-basins within the bay. In all cases, along-channel flow is low-pass filtered before it is compared with low-pass filtered components of the wind stress vector.

Regional-scale patterns are difficult to detect, because the driving forces at opposite ends of any channel can be quite different. For tidal channels connecting Gulf and Atlantic sides of the Keys, for example, Ekman dynamics are more important in the relatively deep water on the Atlantic side of the Keys, while topographic steering is undoubtedly important in the shallow waters of Florida Bay. Flow into and out of sub-basins in Florida Bay are determined to a large extent by where the channel lies relative to the upwind or downwind directions. Along the western boundary of the bay, topographic constraints are significant at the northern end, yet they are minimal at the southern end.

Results suggest that for any given wind conditions, the response will be greater at some locations, and relatively small at others. For example, winds blowing toward  $280-300^{\circ}$  (oceanographic convention) are most effective in forcing water into Florida Bay through Long Key Channel, the Seven Mile Bridge Channels and Indian Key Channel--three of the major tidal channels in the Middle Keys. Wind stress within this range of headings is common in summer months. The same winds are effective for forcing water westward through the channel south of the Gopher Keys. But these west-northwestward winds are inefficient for transporting water into Blackwater Sound through Jewfish Creek. Generally speaking, flow into Florida Bay from Hawk Channel is greatest when the channel lies  $35-55^{\circ}$  to the right of the wind stress heading. This suggests an Ekman-like response. In the Upper Keys, however, flow through Tavernier

Creek is most responsive to wind stress with a heading of  $306^{\circ}$ . This is a nearly directly onshore heading, suggesting that the lowering of water levels on the Florida Bay side of the channel is more important in forcing the exchange, and Ekman dynamics, raising water levels on the Atlantic side of the keys, assumes a lesser importance. A one-year study of flow through Jewfish Creek, connecting Blackwater Sound with Barnes Sound, indicates that exchanges are most responsive to the  $210-030^{\circ}$  wind stress component. In this case, transport is an indirect response to the movement of water within the Biscayne Bay System.

Within Florida Bay, exchanges among the many sub-basins are strongly influenced by where channel mouths are positioned relative to the direction of the wind. For example, exchanges through Iron Pipe Channel, on the west side of Rabbit Key Basin, are most responsive to the east-west component of the wind stress. Similarly, exchanges through Man of War Channel, on the southwest side of Johnson Key Basin, are most responsive to the northeast-southwest component of the wind stress.

The exchange of water between Florida Bay and the inner shelf of the Gulf of Mexico varies significantly along the north-south  $81^{\circ} 05'W$  meridian, taken here to define the open western boundary of Florida Bay. Results from two studies suggest that at the northern end of the boundary the northwest-southeast component of the wind stress is most efficient for moving water between the Bay and the Gulf. At the southern end of the boundary, the southwest-northeast component of the wind stress is most efficient in moving water into or out of the bay.

Long-term monthly resultant wind directions are out of the easterly quadrant (wind stress headings vary from southwestward to northwestward) for most of the year. Summertime wind directions are commonly out of the southeast; wind directions are more frequently out of the north and northeast during late fall and winter months. However, multi-annual monthly resultant winds are a poor indicator of Gulf-Bay-Ocean exchanges. Monthly resultant wind stress for a given year can vary substantially from the long-term average. More important, the low-frequency variation of wind stress during any given month can deviate significantly from the resultant. For example, a one-year study using weather observations from the Molasses Reef C-MAN station indicated that the resultant wind stress during September 1997 was northwestward, but the low-frequency variability about the resultant was primarily in the northeast-southwest component of the wind stress.

Results of the study suggest that exchanges within Florida Bay, and exchanges between the Bay and either the Atlantic Ocean or Gulf of Mexico are a complex response to low-frequency fluctuations in wind forcing. As wind directions slowly change, transport will increase in some channels even as it decreases in others. The result can be a slow simultaneous filling and draining of sub-basins within Florida Bay. As a result of the coupling of sub-basins, and because of the large size of Florida Bay, the response to wind forcing can begin with any given wind event, but the effects may persist over several days.

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Question 1 - Physical Science

## **Moored Observations of Salinity Variability in Florida Bay and South Florida Coastal Waters on Daily to Interannual Time Scales**

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In support of the South Florida Ecosystem Restoration, Prediction, and Modeling Program (SFERPM), a three year, physical oceanographic study of the connectivity between Florida Bay and the surrounding waters of the Gulf of Mexico, the southwest Florida shelf, and the Atlantic Ocean was conducted. The field survey included a moored array equipped with current meters, bottom pressure sensors and conductivity/temperature sensors, satellite-tracked surface drifters, and bimonthly interdisciplinary shipboard surveys with continuous underway thermosalinograph observations of surface salinity, temperature, and fluorescence.

The moored conductivity/temperature array consists of 21 sensors positioned from the Florida Keys reef tract, through western Florida Bay and around Cape Sable, extending northward off the mouths of the Shark, Broad, and Lostmans Rivers, to Indian Key just south of Marco Island, Florida.

Salinity time series collected from this array are affected by the local precipitation/evaporation balance, riverine discharge from the Everglades which is in turn influenced by precipitation as well as anthropogenic factors, fluctuations in the Gulf of Mexico Loop Current, meteorological forcing events such as hurricanes and tropical storms in the summer and cold fronts in the winter, and interannual meteorological events such as El Niño.

Though the bulk of the array was deployed in late 1997, the effects of the 97/98 El Niño on the climate patterns of South Florida can be seen throughout the salinity time series. A wet season / dry season reversal is evident in 1998 with salinity minima occurring at our moorings in April (traditionally the most saline period of the year due to dryer, winter weather) and maxima prevalent in late summer (contradictory to typical wet season conditions).

Larger scale oceanographic transport mechanisms have also been seen to affect the moored salinity records. Low salinities from June 1998 through September 1998 at our Florida Keys moorings, including sites at Tennessee Reef, Hawk Channel, and Looe Key, suggest the presence of Mississippi River Water. During this time period the Gulf of Mexico Loop Current was in a prolonged state of partial development. This “young” Loop Current may be responsible for driving eastward flow towards the Tortugas and southward flow onto the Southwest Florida Shelf, pulling Mississippi River Water from the northern Gulf, around the

Tortugas, and into the Florida Keys.

By the spring of 1999 salinities throughout the region had returned to normal dry season conditions. As a result, the moorings exhibited higher springtime salinities, followed by lower salinities through the summer months due to the onset of more abundant precipitation.

The most dramatic influence of a tropical cyclone on the time series appeared in October 1999, when Hurricane Irene dumped massive amounts of freshwater over South Florida. A significant quantity of this precipitation was eventually discharged through the rivers of the Everglades, north of Cape Sable. This flushing caused extreme salinity minima in the days following Irene at our Lostmans River, Broad Creek, and Shark River mooring locations. This low salinity water mass migrated southeastward into Florida Bay, which had already seen an influx of freshwater through the Taylor Sough. As a result, salinities in Florida Bay remained low for four to five months, indicative of a relatively long residence time following such extreme events.

In addition to the conductivity/temperature moorings, four moored upward-looking ADCPs were positioned west of Lostmans River and Cape Sable, with the offshore pair located 30 nm west of the southwest Florida coast. The ADCPs provided a continuous measure of currents, and will be paired with data from the other moored instrumentation, allowing a quantitative analysis of the freshwater discharge. Bottom pressure sensors are included on the moorings 30 nm offshore of Cape Sable, adjacent to Cape Sable, in western Florida Bay, and in the Atlantic, offshore of Long Key, Florida. From these instruments a continuous record of sea level height and the slope of the sea surface was obtained and will be described.

The locations of many of the moorings in the array were modified in October 2000 in support of a new moored array, which will include real-time monitoring capabilities at several mooring sites. The shipboard surveys will continue as part of this real-time monitoring effort. As a result of these modifications, data quality will improve. Additionally, real-time data made available over the Internet will benefit researchers and program managers by providing early warning of oceanographic events and contributing to the tools needed to more accurately describe the unique marine environments of South Florida.

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## **Developing Insight into Coastal Wetland Hydrology Through Numerical Modeling**

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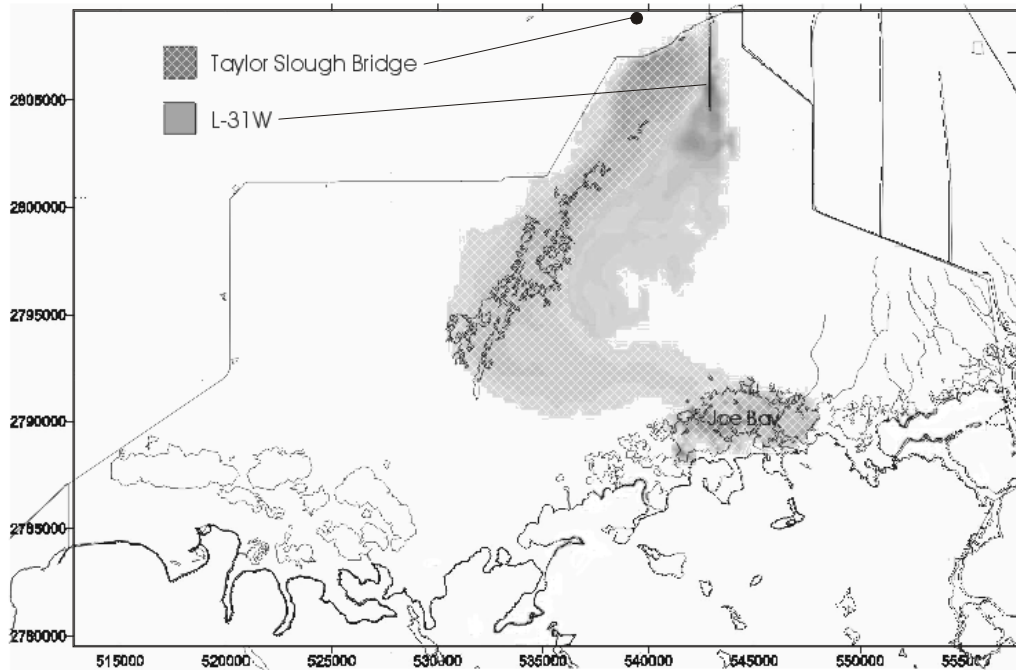
The need for tools to scientifically examine the hydrology of the coastal wetlands in southeastern Everglades National Park has led the U. S. Geological Survey (USGS) to develop the Southern Inland and Coastal Systems (SICS) numerical model. SICS is an application of the SWIFT2D two-dimensional hydrodynamic model, with necessary modifications for the study area.

The development of SICS began with the realization that the only way to generate an adequate model input data set was to have well-defined empirical data. For this purpose, and to better define study area hydrology, a series of process studies were implemented to examine important parameters. The model was developed while these studies were in progress and updated whenever new data were obtained.

During the preliminary model development, topography data were based on sparse ground-based surveys. Subsequent helicopter-assisted mapping of the SICS area provided a higher resolution grid of elevation data that is based on a more accurate vertical datum. The addition of these data improved the model's representation of ponding and flows. Representation of evapotranspiration (ET) was improved using data from field energy-budget stations. Research projects also have yielded additional data for wind-friction effects on flow, salinity boundaries, coastal creek outflows, and wetland flow velocities.

The basic modeling approach was to create an input data set consisting almost entirely of field data, using fewer assumptions, and to assess the model's response. The direct use of the process study results included simple spatial interpolation of land elevation data within the model grid, application of regional ET equations derived from the field study, and assignment of frictional resistance terms for defined vegetation types in the study area. These uncalibrated data produced a model that reproduced the model-area hydrology well.

The model has various uses, including estimating flows at the coast, delineating ponding areas, and tracking flow paths of input waters. This last use is illustrated in figure 1 which shows water entering the SICS area from Taylor Slough Bridge and L-31W canals, and flowing through the wetlands. On October 14, 1996, Taylor Slough Bridge waters have reached Joe Bay, but L-31W waters have not.



**Figure 1.** - Location of waters from Taylor Slough Bridge and L-31W on October 14, 1996

After the development of the first model version, several unknown parameters existed that required estimation. Although the wetland frictional resistance had been defined by the field studies, the friction coefficients for the coastal creeks were not researched. These values were adjusted to obtain modeled flows at the creeks that matched those measured as part of a process study. Another parameter with high uncertainty is the quantity and spatial distribution of the ground-water leakage. Estimates were made based on seepage measurements and the total mass balance of the model.

To increase the amount of empirical data in these two areas, further studies are being undertaken. At one of the coastal locations where discharge is measured (Taylor River) an additional upstream site has been added to obtain a water level slope. These slope data, along with measured discharge, can be used to derive a frictional resistance term. A more extensive study involves the coupling of the SWIFT2D model with a variant of the ground-water flow model MODFLOW. This variant, SEAWAT, allows for density-dependent flow, a requirement with the Florida Bay saltwater interface. The coupling is accomplished using the main routine FTLOADDS (Flow and Transport in a Linked Overland-Aquifer Density Dependent System). For a given timestep, SWIFT2D computes surface-water flow, stage, and ground-water leakage based on the previous timestep's ground-water heads. SEAWAT then computes the ground-water heads while accounting for this leakage rate.

In the coupled model, recharge and ET for the ground water, as well as the surface water, are computed by SWIFT2D. If the surface-water condition is wet for a particular cell, the computed recharge and ET is applied to the surface water, and the computed leakage is applied to the ground water. If the surface-water condition is dry for the cell, the recharge

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and a computed ET rate, rather than leakage, are applied to the ground water. This method provides a continuity of recharge and ET between the SWIFT2D and SEAWAT models as surface wetting and drying occurs. The unique ability of the coupled model to hydrodynamically represent flows as well as water levels makes it a valuable tool for understanding the Everglades/Florida Bay interface.

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## Insights into the Origin of Salinity Variations in Florida Bay Over Short and Long Time Periods

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Salinity in Florida Bay varies markedly in both time and space. Hypersaline conditions (>40) in one part of the bay frequently coexist with more estuarine conditions (<30) in another. These variations in salinity the result of changes in freshwater inputs to Florida Bay, combined with the effects of evaporation. Freshwater inputs to Florida Bay include 1) runoff from the Everglades watershed to the north and 2) direct inputs from rainfall. Currently, the freshwater inputs to Florida Bay from Everglades runoff are estimated to be one-tenth that of rainfall, suggesting that Florida Bay is highly sensitive to climatic conditions. Furthermore, an exact estimate of freshwater runoff is difficult due to the dominantly unchannelized, diffuse flow through the Everglades. In light of the current Everglades Restoration efforts, in which varying water flow deliveries is being investigated, a monitoring method is needed to distinguish between the influences of water management practices and natural climatic conditions on salinity in Florida Bay. The stable isotopes of oxygen and hydrogen can be used as a natural tracer of water flow to identify the dominant sources of freshwater inputs into Florida Bay. Through long-term monitoring of the oxygen and hydrogen isotopic composition of water from the Everglades, Florida Bay and rainfall, we have been able to ascertain the temporal and spatial variability of the dominant sources of freshwater into Florida Bay.

The hydrogen and oxygen isotopic composition of rainfall from Miami was monitored between 1986 and 1987, and more recently from the Everglades and Miami from 1997 to 1999. Hydrogen and oxygen isotopic composition of surface waters from the Everglades has been monitored on a monthly basis since 1995. In addition, monthly water samples collected from 28 sites in Florida Bay since 1993 by the Southeast Environmental Research Center (SERC) at Florida International University (FIU) were analyzed at RSMAS for stable isotopes of hydrogen and oxygen. Salinity data from the 28 sites in Florida Bay was obtained from the South Florida Water Management District.

Freshwater derived from the Everglades had a more positive oxygen and hydrogen isotopic composition than rainwater. The mean oxygen and hydrogen isotopic composition of Everglades surface water was 0.55 ‰ and 6.75 ‰, respectively. Although the ultimate source of freshwater in the Everglades is rainfall, this water become highly evaporated, and therefore isotopically enriched in  $^{18}\text{O}$  and D, as it flowed through the Everglades. In contrast, rainfall was relatively depleted in  $^{18}\text{O}$  and D with mean values of -2.9 ‰ and 9.95 ‰, respectively. Surface waters in Florida Bay exhibit a wide range in  $\delta^{18}\text{O}$  (1.62 ‰ +/- 1.0) and  $\delta\text{D}$  (mean = 11.35 ‰ +/- 6.66) values related to evaporation, precipitation, and mixing with water derived from the Everglades, the Gulf of Mexico, and the Florida Reef Tract.

For each of the 28 sites in Florida Bay, a linear relationship between  $\delta^{18}\text{O}$  and salinity was established. The intercept of the linear regression reflected the  $\delta^{18}\text{O}$  at zero salinity, and was

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used to describe the source of freshwater for that site. Sites with an intercept between -2 and -3 ‰ indicate a mixing of seawater with rainfall, while sites with an intercept +0.5 ‰ and above indicate a mixing of seawater with Everglades runoff. Sites with an intercept between +0.5 ‰ and -2 ‰ represent varying mixtures of seawater, rainfall, and Everglades runoff.

Using the calculated intercepts for each of the 28 sites in Florida Bay a two component mixing model was developed using the mean oxygen isotopic compositions of Everglades runoff and rainfall as the two end-members. Based upon this mixing model, the percentage of freshwater derived from rainfall for each of the Florida Bay sites was estimated. The results of this isotopic mixing model indicated that runoff from the Everglades was the dominant source of freshwater input to the northeastern regions of Florida Bay, while direct inputs of rainfall was the dominant source of freshwater to the western areas of Florida Bay. The central areas of Florida Bay received mixtures of Everglades runoff and rainfall.

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## Helium as Tracer of Groundwater Input Into Florida Bay

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Dissolved helium anomalies are used to quantify groundwater input to Florida Bay waters. The method relies on the fact that groundwater dissolves large quantities of  $^4\text{He}$ , produced in the radioactive-decays of the uranium-chain elements, that accumulate over geological time periods. Seasonal surveys in Florida Bay show average helium concentration anomalies of 13.6% and 16.5% in the summer and winter, respectively. As a comparison, excess  $^{222}\text{Rn}$ , in excess of that in equilibrium with  $^{226}\text{Ra}$ , was found to vary from 3 dpm.L<sup>-1</sup> in the summer to 2 dpm.L<sup>-1</sup> in the winter. The fact that such anomalies are present in the 1.5 m deep unstratified waters is a strong indication of groundwater input to the Bay. A simple box model based on helium data yields a groundwater flux of 2.5 - 4.0 cm.d<sup>-1</sup> in the summer and 10-16 cm.d<sup>-1</sup> in the winter while the same model results in a flux of 0.8-1.7 cm.d<sup>-1</sup> using radon data.

In addition to  $^4\text{He}$ , the less abundant isotope  $^3\text{He}$  ( $^3\text{He}/^4\text{He}=1.384*10^{-6}$ ) and tritium,  $^3\text{H}$ , are used to develop a hypothesis regarding the origin of excess helium in the water column.  $^3\text{He}$ , in addition to the atmospheric component, is also produced in the radioactive decay of tritium, the legacy of the atmospheric nuclear tests of the late 1950s and early 1960s. The presence of  $^3\text{He}$  excess in water above saturation indicates an age of formation within the last 40-45 years. Simultaneous measurements of  $^3\text{H}$  and radiogenic  $^3\text{He}$  allow the calculation of the time period elapsed, i.e., the  $^3\text{H}$ - $^3\text{He}$  age, to produce the observed  $^3\text{He}$  anomaly,  $\Delta^3\text{He}$ .  $^3\text{He}$  measurements suggest two populations: those with  $\Delta^3\text{He}$  greater than 10% and those with less than 10%. The first population has tritium levels decreasing as  $\Delta^3\text{He}$  increases that is typical of a reasonably isolated system with an apparent isolation age between 10 and 35 years. The second population has little  $\Delta^3\text{He}$ , but tritium levels have about the same range as the first population. The present day rainfall varies between 1.5 and 3 TU with the lower value representing winter. Our observations, on the other hand, include values as low as 0.8-1.0 TU in the summer, and only a few as high as 3 TU, a strong signature of mixing of very low-tritium groundwater with the bay waters. Therefore, the combined tritium and He isotope data point to one viable scenario for the groundwater input: The deep aquifer (Floridan) waters, under mainly artesian pressure, continually rise through fissures, cracks, and solution holes in the confining layers and mix with the waters of shallow aquifer(s) before entering Florida Bay. The two-layer structure of the aquifer system underlying Florida Bay can also explain the difference between the flux figures obtained from helium and radon.

According to the present estimates, groundwater appears to be a significant fraction of the circulating volume of the Florida Bay. The proposed scenario, combined with the fact that the site of the phosphorus maximum in the northwest corner of the Bay is coincident with both the location of phosphorite deposits and high groundwater input, suggests that groundwater may be an important pathway for the source of persistent phosphorus in Florida Bay. The mechanism also suggests that leakage from deep injection wells in South Florida can not be ruled out and should be re-evaluated in light of the present findings.

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Question 1- Physical Science

## **Simulation of the Influence of Climate Variability on Freshwater Inflow to Florida Bay during the 20<sup>th</sup> Century**

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During the latter portion of the 20<sup>th</sup> century great strides were made in the diagnostics and predictions of regional climate variability. A large segment of the success in climate prediction was made by recognizing the existence of low frequency global oscillatory modes that occur within the earth's coupled ocean-atmospheric system. Persistent shifts in regional hydrologic and meteorologic variables, collected throughout south Florida during the 20<sup>th</sup> century, appear to be associated with the phase changes of a number of these low frequency global oscillatory modes. The dynamic forces that drive many of these global oscillations are still under investigation and the topic of much debate in the scientific community. However, recognition of the existence of the transitions between phases of these oscillatory modes is crucial for understanding the natural variability of freshwater flows into Florida Bay. Identifying the amplitude of this natural variability will allow for a more comprehensive understanding of the adaptability of ecosystems of Florida Bay. In addition, it will give insight to how natural ecosystems may adapt to anthropogenic climate change that may occur in the future. This understanding is essential for a successful restoration of the Florida Bay ecosystem.

The most publicized mechanism for driving climate variability during recent decades has been the El Nino-Southern Oscillation (ENSO). This phenomenon is recognized by sea surface temperatures anomalies (SSTAs) in the eastern equatorial Pacific Ocean. During periods when the SSTAs are warmer than normal, south Florida tends to be wetter and cooler than normal during the dry season months (November-April). During periods when SSTAs are cooler than normal, south Florida tends to be warmer and drier than normal during the same dry season period. The Pacific Decadal Oscillation (PDO), which is centered in the Pacific Ocean poleward of 20 degrees north latitude (Zhang et al, 1997) has similar direct effects on the Florida climate as ENSO. Therefore the negative anomalies are associated with less rainfall and warmer temperatures while positive anomalies are associated with greater rainfall and cooler temperatures in south Florida. Indirectly, the positive phase of the PDO is identified with an increase in the number and strength of warm ENSO events, while the negative phase of the PDO is identified with a decrease in the number and strength of warm El Nino Events. During the wet season months (May through October), the Atlantic Ocean has the more significant effect on Florida's climate. Gray et al (1997) discuss the effects that the Atlantic multi-decadal variability has on the frequency of intense hurricanes in the Atlantic Basin. Trimble et al (1998) report on the strong association between the Atlantic multi-decadal variability as defined by Gray et al and the south Florida rainfall.

The Hydrologic Systems Modeling department (HSM) of the South Florida Water Management District (SFWMD) applies regional hydrologic models for operational and water resources planning purposes. The South Florida Water Management Model (SFWMM) has been applied extensively to simulate water levels and flows across southern Florida, for

evaluating refined operational rules, simulating the benefits of infrastructure improvements and projecting the effect of population growth on regional water supply and the environment. These scenarios are normally considered for the climatic period beginning in 1965 and extending through 1995. This period has the highest quality and quantity of meteorological and hydrologic data that is currently available<sup>1</sup>. In this analysis, a more extended period of record is simulated beginning in 1912 and extending into the year 2000. The more extensive period of simulation is required to evaluate the effects that the PDO and the Atlantic multi-decadal oscillation had on the variability of freshwater inflow into Florida Bay during the 20<sup>th</sup> century.

In this analysis, two parallel regional hydrologic models will be applied to discern what effect climate variability has on freshwater inflows to Florida Bay. The first model, the SFWMM, will be applied to determine the effects that climate variability would have if the sequence of climate regimes that existed during the 20<sup>th</sup> century were to repeat itself assuming that the current infra-structure, population and operational rules were in place during the entire simulation period. The second model, the Natural Systems Model, will likewise be applied with the purpose of estimating the pre-drainage and development response to the same climatic sequence.

This effort was completed with climate data obtained from the National Climatic Data Center, along with rainfall data available from the SFWMD data archives. This analysis does not consider changes to the spatial and temporal distribution of rainfall that have occurred due to drainage and development in the south Florida region during the 20<sup>th</sup> century. A future goal should be to run the hydrologic and meteorologic models in a coupled mode for both the existing and pre-development cases. This will allow a more thorough understanding of the feedback mechanisms that exists between the atmospheric and hydrologic systems. Accomplishing the last task will aid in determining what additional ways drainage and development in south Florida has contributed to alter the natural freshwater flows to Florida Bay.

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<sup>1</sup> The hydro-climatological input for the SFWMM is currently in the process of being updated through the year 2000.

## **Wetland Hydrogeologic Responses along the Taylor Creek System, Southeastern Everglades, Florida (USA)**

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Water levels and sediment stratigraphy were evaluated in this study to elucidate the hydrogeologic responses of different wetland sediments in the southeastern Florida Everglades. Hydrology can enhance biogeochemical fluxes across the sediment-water interface by flushing sediment pore spaces. The hydrology of the southern Everglades could greatly enhance biogeochemical contributions to Florida Bay waters through its delivery of freshwater and nutrients. This system may also act as a sink for surface waters from the north. In the southeastern Everglades wetlands, sediments are subject to a range of physical forcing functions from both northern freshwater sources and southern marine sources, including tides, winds, and precipitation/runoff events. Another important control on the sediment flushing time is sediment permeability. We evaluate here the net movement of water at the sediment-water interface in the mangrove salinity transition zone of the Taylor Creek system.

Two main study sites were established in the mangrove fringe north of Buttonwood Ridge along Taylor Creek in the southeastern Everglades. These two stations were positioned at 1.7 km (southern site) and 3.2 km (northern site) north from the Taylor Creek mouth at Florida Bay. Each study site along Taylor Creek was characterized by dwarf mangroves. At each study location, two boardwalks were built in an east-west direction perpendicular to Taylor Creek and extended about 50 m into the mangroves. Along these boardwalks, we established a variety of experiments to evaluate subsurface to surface water communication. A transect of five 1-m deep wells were installed in the sediments adjacent to the boardwalk, and each well was screened for the bottom 30 cm. In addition, a transect of ten 50-cm deep multi-level porewater samplers were placed along the boardwalk, and were used to obtain porewaters for nutrients (TN,TP) and salinity. One autosampler was placed at the wetland end of the boardwalk for collection of surface waters for nutrients and salinity. Finally, two ultrasonic water level recorders (*Infinities USA, Inc.*) were installed about 30 m into the dwarf mangrove wetlands at each boardwalk. A surface water level recorder was mounted to a platform adjacent to each boardwalk in the mangroves. The groundwater level recorder was installed atop an additional screened well nearby each surface recorder platform.

In June 2000, an elevation survey was performed at each site in conjunction with a sedimentary stratigraphic cross-section transect through the wetlands. Transects were oriented perpendicular to the creek channel. The topographic survey indicates that the northern site is generally more uniformly flat than the southern site where greater local relief between wetland ponds and mangrove peat mounds was observed. The topographic effect on water movement through the wetlands likely creates sheet flow water movement in the northern site, and more channelized-like flow among peat mounds in the south. The

stratigraphic cross-sections at each wetland site show a consistent difference in sediment type from north to south. In the north, the sediments are typically lower permeability clays and chalky carbonate marl. In the south, sediments are generally peat with minor and discontinuous clay streaks present. Both sites are characterized by a sediment layer that is about 1 m thick above the chalky, re-crystallized limestone bedrock of the Everglades.

Wetland water levels were evaluated over one and a half years beginning in June 1999 in both surface and ground waters at two sites along the Taylor Creek system. Surface water levels at each boardwalk site demonstrate a rapid response to variations in external water sources (e.g., direct precipitation, runoff, tidal surges, and wind-driven flow). Ground water level response times vary from the northern site to the southern site and do not occur as rapidly as surface water levels. Variations in the response time are likely due to different sediment types in the northern and southern sites. Sediment transmissivity and ground water response times to surface water heads will be calculated from bail and slug tests in screened wells in the wetland sediments.

Our findings generally indicate a consistent negative hydraulic head through time at each site. The clay-rich environment of the north demonstrates more constant negative head (about 5 cm) that does not respond to surface water level fluctuations except perhaps during dramatic weather events. The water levels were generally out of phase in the north between surface and ground waters. The southern peat substrate is characterized by a negative head as well (3 to 17 cm), but this ground water is in phase with surface waters and tends to respond more rapidly to changes in both salinity and water level than the north. Thus, sediments in the mangrove salinity transition zone of the lower Everglades appear to be a sink for water. Local, event-driven flushing of sediment pore spaces may provide brief biogeochemical sources, but the overall effect is a net hydrologic sink.

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## Paleosalinity of Florida Bay

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Biotic and chemical proxies for salinity in Florida Bay provide a wealth of information for understanding the historic interplay of rainfall and runoff in influencing the salinity of the Bay.

Biotic proxies, the distribution and abundance of ostracodes, mollusks, foraminifers, and diatoms, provide reasonable trends in salinity variation on decadal and slightly finer scales. The trends show agreement with a strong negative correlation with rainfall amount and strong positive correlation with frequency. An overall trend for a slight increase in the salinity of the Bay is indicated as well as a subtle change in the response to rainfall frequency patterns over the last 30 years.

Chemical proxies derived from the analysis of the tests of the biotic proxies appear very promising in providing finer and finer resolution of salinity variability in the Bay. An understanding of the life cycle, specifically, the growth history of some biotic proxies allows for very accurate salinity determinations.

The ostracode *Loxoconcha matagordensis* grows its adult shell in the late Spring-early Summer (May through July). The Ca/Mg ratio of the test reflects the salinity and temperature of the day that test was secreted during this time interval. Analysis of many tests from a single horizon, then, gives an insight into the salinity and temperature through the growth season. Detailed analysis of the *Loxoconcha matagordensis* from two cores compared to the average January through May rainfall from NOAA data compiled over the last 100 years yields predictive, site specific, linear equations for salinity values.

The clam, *Chione cancellata*, has a relatively robust shell in comparison to other Florida Bay inhabitants. Initial growth studies indicate that this species lives for about 1.5 years and secretes calcite to its prismatic shell layer on a daily basis. We are actively conducting growth experiments to quantify the growth rate of this species and to use as standards for chemical analysis including elemental mapping and carbon and oxygen isotope analysis on a SHRIMP mass spectrometer, where resolution should be down to 2-3 prisms or 2-3 days. Specimens of *Chione cancellata* have been collected live from or near monitoring stations from the Bay, so that we can calibrate the carbon and oxygen isotopes from those shells with the known salinity and temperature record. Oxygen isotopic ratios are sensitive to the salinity and temperature of the water and carbon isotopic ratios are sensitive to the amount of rainfall and runoff that contributed to the particular water mass at time of secretion. We plan to due our first analyses in December and January and hope to present the initial results at the conference.

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## **Development of a Variable-Density Groundwater Flow Model for the Taylor Slough Area**

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The U.S. Geological Survey recently completed the development and calibration of the Southern Inland and Coastal Systems (SICS) model, which simulates overland flow within the Taylor Slough area and uses a flow term as a rough approximation of groundwater leakage. The SICS model domain is bounded to the north and west by Old Ingraham Highway, to the east by the C-111 canal, and to the south by Florida Bay. The SICS model was calibrated to measured water levels, coastal flows, and surface-water salinities for a 7-month period between July 15, 1996 and February 28, 1997. The simulation period for the SICS model was recently increased to 2 years, beginning July 16, 1996 and ending June 9, 1998.

To better quantify leakage between surface water and groundwater within the SICS area, a preliminary groundwater flow and solute-transport model was developed for the SICS model domain using the same grid. The groundwater model simulates variable-density groundwater flow for the same 2-year period as the SICS surface-water model. The SEAWAT code, which is a combined version of MODFLOW and MT3D, was used for the simulations. The groundwater model contains 10 layers, each 2.8-meters thick. General-head boundaries were assigned to the perimeter of each layer in the model. Salinities for the general-head boundaries were estimated from an airborne electrical resistivity survey of the area. General-head boundaries also were applied to the top of the groundwater model to represent surface water. Results from the SICS model were used to assign spatially and temporally varying stages and salinities to the overlying general-head boundaries. When cells in the SICS model were dry, recharge and evapotranspiration were applied to the groundwater model cells. Conductance values for the general-head boundaries were calculated using maps of peat thickness and estimates of vertical hydraulic conductivity. Values for other aquifer parameters, such as horizontal hydraulic conductivity, anisotropy ratio, storativity, porosity, and dispersivity were obtained from the literature or estimated through calibration.

Preliminary results from the model show good correlation with measured water levels at three monitoring wells (Figure 1). Simulation results for 2 months, one in the wet season and one in the dry season, show two apparent differences in aquifer leakage. During the wet season (e.g. June 1997) (Figure 2), leakage is downward, from the surface water into the aquifer. During the dry season (e.g. November 1996) (Figure 3), most of the leakage is upward, from the aquifer into the wetlands. Some variation from these trends has been observed along the Buttonwood Embankment and near Taylor Slough Bridge, where aquifer recharge and discharge respectively occur during most of the year.

Future plans for SICS modeling include (1) developing a fully integrated surface-water and groundwater model using an explicit link between SWIFT2D and SEAWAT to simulate leakage and the transfer of associated salt concentrations, and (2) driving the integrated model with predictive results from the South Florida Water Management District model.

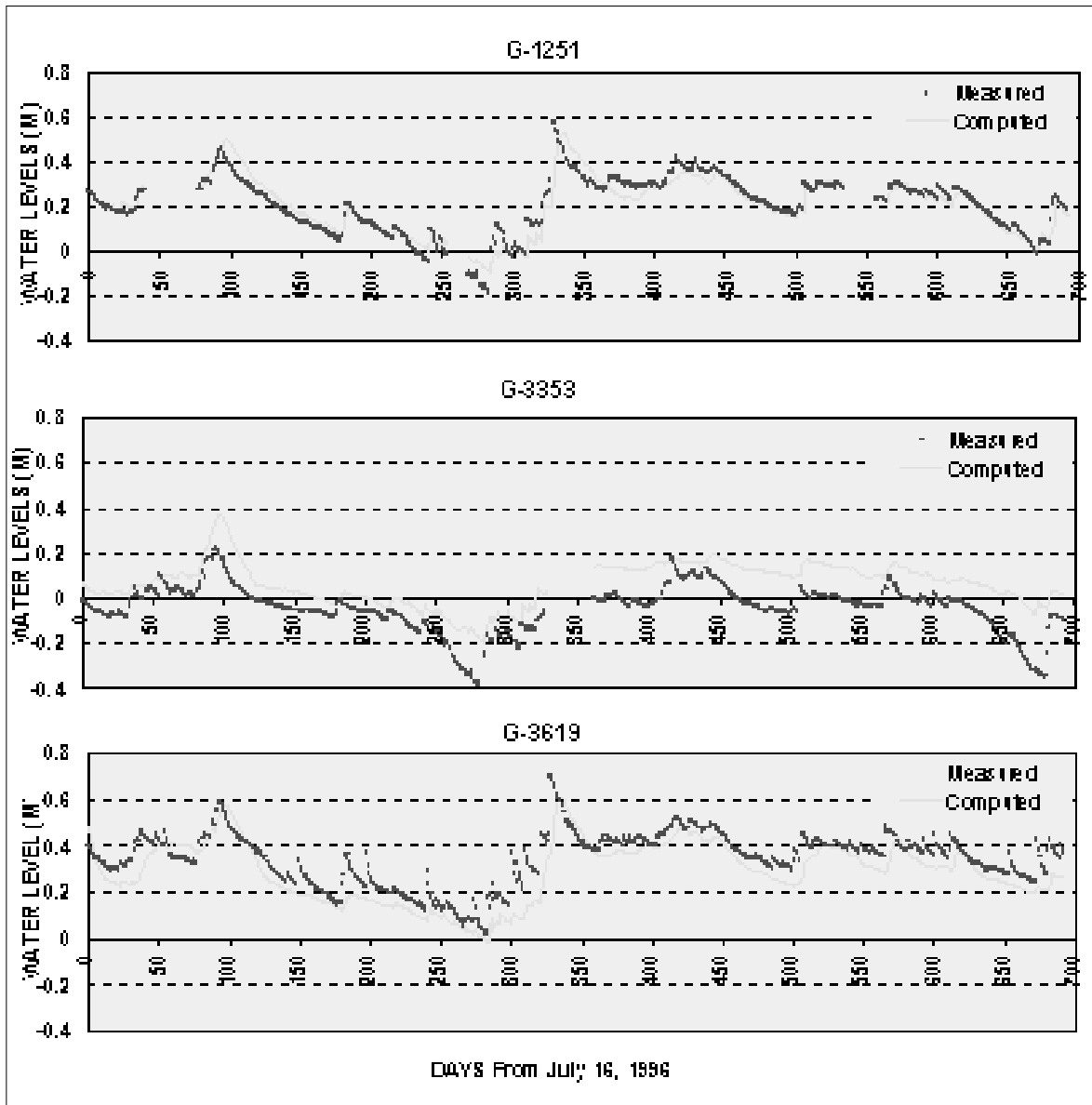


FIGURE 1: Water levels measured at three monitoring wells compared with water levels computed by the numerical groundwater model.

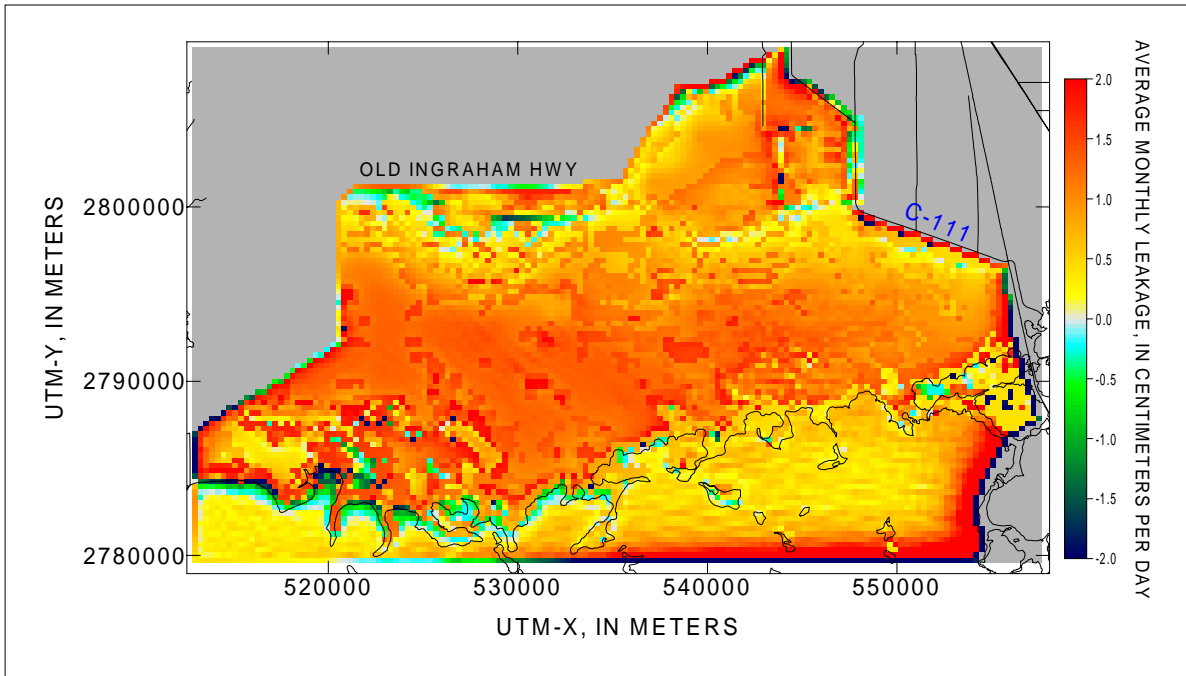


FIGURE 2: Wet season leakage values for June 1997. Positive values indicate downward flow.

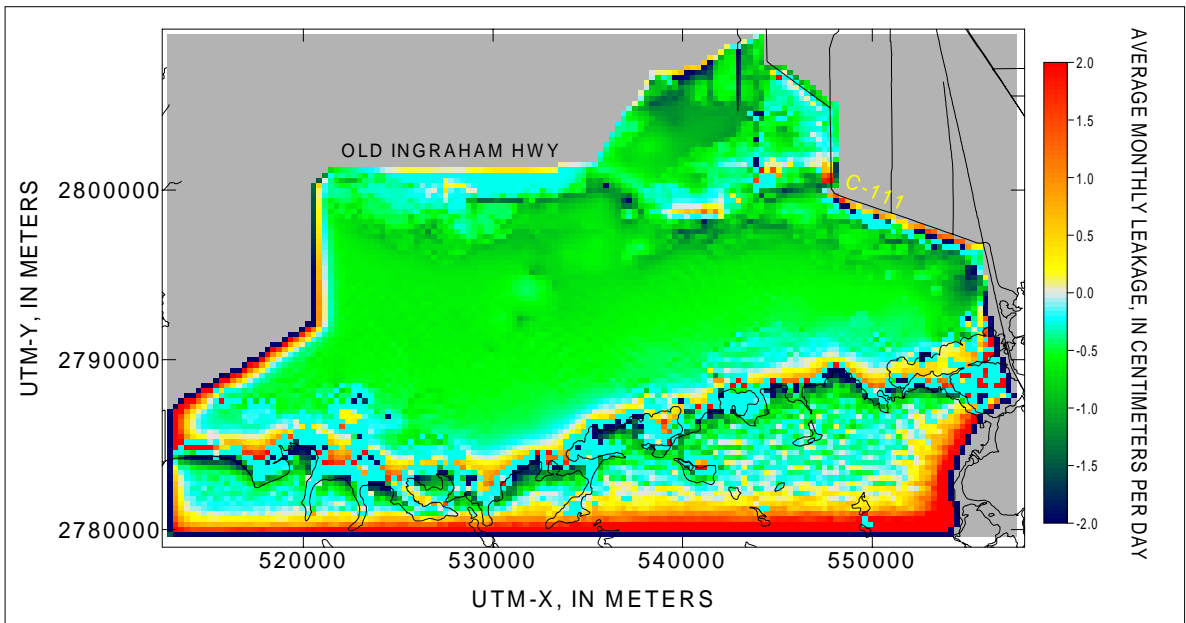


FIGURE 3: Dry season leakage values for November 1996. Positive values indicate downward flow.

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## Impact on the Sedimentary Record Derived from Micropaleontological Data

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Hurricanes are the strongest force causing immediate and long-term environmental changes to coastal areas in the lower Everglades and Florida Bay, and their sedimentary record. Hurricane-induced sediment erosion and deposition, and bi-directional sediment transport can disrupt the sediment record blending the signature of other ecological factors (i.e. salinity fluctuations) leaving behind a complex overprint of natural and anthropogenic influences. Their frequency is also a potential mechanism for carbon storage and removal. Paleohurricane impact in the stratigraphic record is marked by abrupt changes in microfaunal abundance and community structure, as well as in quantitative and qualitative organic carbon content and sediment texture.

Hurricane signatures, verifiable by offsets in  $^{210}\text{Pb}$ -geochronology data, are found in sediment cores recovered from Florida and Oyster bays. Sediment core location controls the magnitude of variations in the sediment record. Semi-protected areas, such as Oyster Bay, exhibit the least amount of sediment disruption during and following the Labor Day Hurricane of 1935 and Hurricane Donna in 1960, where as, unprotected or less-protected areas such as the First National Bank and Jimmy Key in western and central Florida Bay, respectively, experience the greatest effects.

At the Oyster Bay core location, onshore sediment transport corresponding to Hurricane Donna was demonstrated by a distinct layer of continental shelf derived species of ostracods and benthic foraminifera. These species averaged ~13% of the microfauna throughout the core except at the time of the hurricane when they account for ~39% of the total microfaunal assemblage. Hurricane impact at the First National Bank core location was comparatively more extensive. There, a 15-cm thick layer of transported carbonate material was deposited during Hurricane Donna in 1960. This layer exhibits a very high concentration of *Bairdia gerda*, *B. laevicula* (>80%), and calcareous coralline algae fragments. Both, the ostracod species and the red algae are characteristic of hard bottom communities in the southeastern region of Florida Bay, and are not common in mudbank environments.

Major hurricanes can also impact diversity and general microfaunal abundance over relatively longer time scales. At Oyster Bay, subsequent to the Labor Day Hurricane of 1935, a decade-long reduction in ostracod diversity was observed. The low diversity interval corresponds to elevated organic carbon in the sediment core, which indicates that resulting changes in ostracod microhabitats may have adversely affected these communities. In comparison, the less-protected core location near Jimmy Key in central Florida Bay shows a more dramatic scenario as a result of the Labor Day Hurricane. At this time, characterization of the ostracod community structure was not possible because of a decade-long ostracod

barren zone. This time interval is distinguished by deposition of very fine mud. Likewise, in central Florida Bay, decade long trends of alternating buildup and reduction of sediment organic C content coincides respectively with periods of infrequent and more frequent hurricane activity. This supports the idea of storm activity frequency as a potential mechanism for carbon storage and removal from Florida Bay sediments.

These results allowed the following conclusions: (1) Hurricanes are a powerful mechanism of sediment erosion and deposition and their effects can easily blend the signature of other natural and anthropogenically induced changes in the lower Everglades and Florida Bay. (2) Ostracod and benthic foraminifer assemblages can be used to identify and assess hurricane impact on the sedimentary record; and (3) our results demonstrate that recognition of hurricane-induced changes in sedimentary sequences in Florida Bay is essential for accurate paleoecological interpretations.

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## *Question 2*





## Dendrocronology Studies of Environmental Changes in Mangrove Ecosystems

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Climate events are registered through rings in the wood of the trees, recording ecological and environmental processes with annual resolution. Ring studies can evaluate the economic and ecological importance of the forest through their dating. These studies provide the necessary information for conservation and restoration of forest mangroves. It is assumed that the mangroves located in arid and a semiarid region of the world form rings in response to rainfall and tides specifically recording wet season/dry season alterations in root zone hydrology. Natural and human activities that change the hydrology can be also evaluated through these studies. Tree-ring analysis of black mangrove *Avicennia germinans* trees on the southeastern coast of Florida were used to characterize the growth, age, and trends of possible historical stressors occurring in the environment. Events such as floods, droughts, hurricanes, hydrological changes, ENSO episodes and other environmental characteristics were considered as possible stressors. In this analysis, we observed the presence of lenticular structures that seemingly are correlated with environmental fluctuations. Two rings were observed per year. One ring is related to wet/dry seasonality and the other, to flooding period (tides). The distances between rings define growth rate fluctuations during previous years and are related to natural or anthropogenic events.

We studied black mangroves *Avicennia germinans*, from the buttonwood ridge at the mouth of Taylor Slough, Florida. Our preliminary results showed five age groups (i.e., 11 +/- 1.5, 16 +/- 1.4, 18 +/- 1.4, 19 +/- 1.5, and 24.5 +/- 1.4 years old). Growth rates changed in 1991 - 1992, and 1994 - 1998 for all trees examined. Growth rate changes were evident in 1990 and 1986 to 1988 for 83% and 58% of trees, respectively. We identified three wood structures diagnostic for changes in mangroves growth: lenticular structures, false rings and scars. Many lenticular structures, indicating rapid growth rate changes, were observed in 1990, 1991, and 1995 with frequencies of 82% in each year. In 1996 and 1997 observed frequencies were 94% and 100%, respectively. Similarly, in 1993 and 1996, 70% of all false rings were detected. In 1992 and 1994 scar formations were observed with a frequency of 29.4% and 17.6%, respectively. As a preliminary discussion, we suggest that mangrove forests in southeast Florida responded to several controls, such as ENSO in 1996-1997; 1986-1987 (El Niño) and 1997-1998; 1987-1988 (La Niña), Hurricane Andrew in 1992, tropical storms, such as Albert (1994), Allison (1996), changes in the pattern of Florida average monthly precipitation in 1998, major precipitation during the rainy season of 1994 and 1995, changes in the precipitation pattern from 1975 to 1999, and drought conditions in 1981, 1990 and 1999 during the dry season.

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## Long-Term Trends in the Water Quality of Florida Bay (1989-2000)

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One of the primary purposes for conducting long-term monitoring projects is to be able to detect trends in the measured variables over time. These programs are usually initiated as a response to public perception (and possibly some scientific data) that 'the river-bay-prairie-forest-etc. is dying'. In the case of Florida Bay during 1987, the impetus was the combination of a seagrass die-off, increased phytoplankton abundance, sponge mortality, and a perceived decline in fisheries. In response to these phenomena, a network of water quality monitoring stations was established in 1989 to explicate both spatial patterns and temporal trends in water quality in an effort to elucidate mechanisms behind the recent ecological change.

### Overall Period of Record

A spatial analysis of data from our monitoring program resulted in the delineation of 3 groups of stations which have robust similarities in water quality (Fig. 1). We have argued that these spatially contiguous groups of stations are the result of similar loading and processing of materials, hence we call them 'zones of similar influence'. The Eastern Bay zone acts most like a 'conventional' estuary in that it has a quasi-longitudinal salinity gradient caused by the mixing of freshwater runoff with seawater. In contrast, the Central Bay is a hydrographically isolated area with low and infrequent terrestrial freshwater input, a long water residence time, and high evaporative potential. The Western Bay zone is the most influenced by the Gulf of Mexico tides and is also isolated from direct overland freshwater sources.

Climactic changes occurring over the data collection period of record had major effects on the health of the bay. Precipitation rebounded from the drought during the late 80's being greater than the long term average ( $9.2 \text{ cm mo}^{-1}$ ) for the last 7 of 10 years. Over this period, salinity and total phosphorus (TP) concentrations declined baywide while turbidity (cloudiness of the water) increased dramatically. The salinity decline in Eastern, Central and Western Florida Bay was 13.6, 11.6, and 5.6 psu, respectively. Some of this decrease in Eastern Bay could be accounted for by increased freshwater flows from the Everglades but declines in other areas point to the climactic effect of increased rainfall during this period. The Central Bay continues to experience hypersaline conditions ( $>35 \text{ psu}$ ) during the summer but the extent and duration of the events is much smaller.

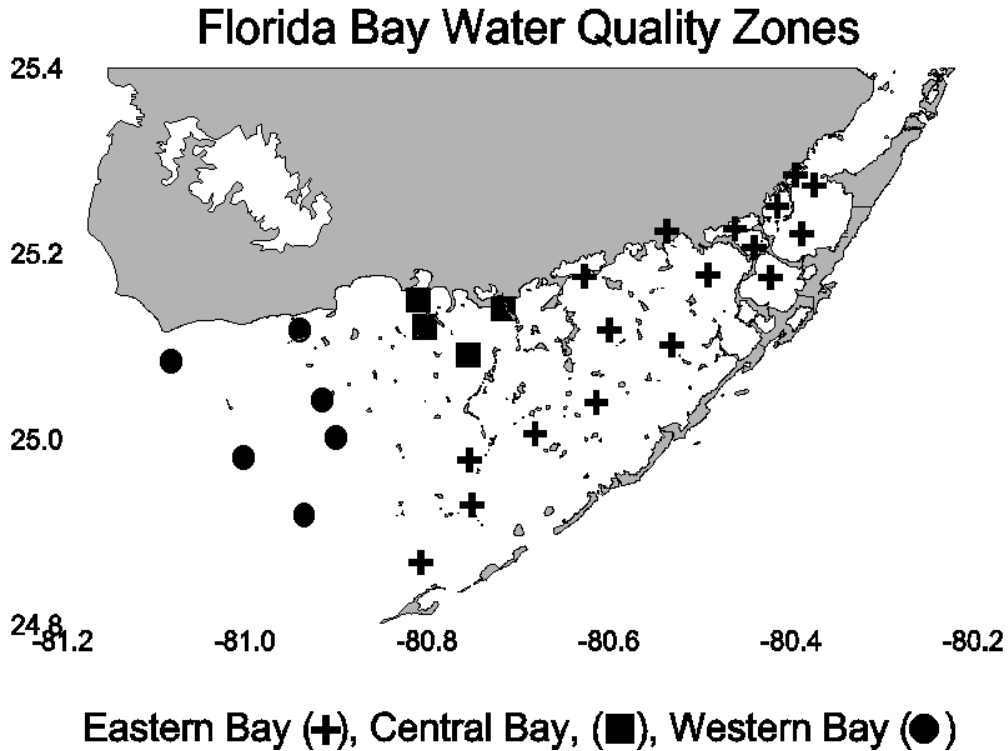


Figure 1. Zones of similar water quality in Florida Bay.

As mentioned previously, TP concentrations have declined baywide over the 10 year period. The Eastern Bay has the lowest concentrations while the Central Bay is highest. Unlike most other estuaries, increased terrestrial runoff may have been partially responsible for the decrease in TP concentrations in the Eastern Bay. This is because the TP concentrations of the runoff are at or below ambient levels in the bay. The elevated TP in the Central Bay is mostly due to concentration effect of high evaporation. It is important to understand that almost all the phosphorus measured as TP is in the form of organic matter which is much less accessible to plants and algae than inorganic phosphate (fertilizer).

Turbidity in Eastern Bay increased 2-fold from 1991-98, while Central and Western Bays increased by factors of 20 and 4, respectively. Generally, the Eastern Bay has the clearest water which is due to a combination of factors such as high seagrass cover, more protected basins, low tidal energy, and shallow sediment coverage. Turbidity in the Central and Western Bays have increased tremendously since 1991. We are unsure as to the cause but the loss of seagrass coverage may have destabilized the bottom so that it is more easily disturbed by wind events.

Chlorophyll *a* concentrations (Chl *a*), a proxy for phytoplankton biomass, were particularly dynamic and spatially heterogeneous. In the Eastern Bay, which makes up roughly half of the surface area of Florida Bay, Chl *a* declined by  $0.9 \mu\text{g l}^{-1}$  or 63%. The isolated Central Bay zone underwent a 5-fold increase in Chl *a* from 1989-94, then rapidly declined to previous levels by 1996. In Western Florida Bay, there was a significant increase in chlorophyll *a*, yet median concentrations of chlorophyll *a* in the water column remained

modest ( $\sim 2 \mu\text{g l}^{-1}$ ) by most estuarine standards. There were significant blooms in Central and Western Bays immediately following Hurricanes Georges (Nov. 1998) and Irene (Oct. 1999). It is important to note that these changes in turbidity and chlorophyll *a* happened after the poorly-understood seagrass die-off in 1987. It is likely that the death and decomposition of large amounts of seagrass biomass can at least partially explain some of the changes in water quality of Florida Bay but the connections are temporally disjoint and the processes indirect and not well understood.

Ammonium ( $\text{NH}_4^+$ ) levels displayed large variability over the period of record and was much higher in the Central Bay than anywhere else. Only in Central Bay did the  $\text{NH}_4^+$  pool increase substantially over time (3-6 fold). Trends in nitrate ( $\text{NO}_3^-$ ) concentrations mirrored those of  $\text{NH}_4^+$  and were mostly due to the biological conversion of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  (nitrification) under aerobic conditions. Total organic carbon concentrations (TOC) vary widely among the different zones and show significant intra-annual cycles. Highest TOC levels generally occur in the Central Bay during summer as a result of evaporative concentration and restricted mixing with the rest of the Bay.

#### 2000 Alone

Most water quality variables during 2000 generally followed typical annual trends but there were a couple exceptions. Both Central and Western Bays experienced hypersalinity during the summer months. Salinity in the Western Bay was  $\sim 45$  psu during Sept.; the Central Bay got up to 48 psu and remained hypersaline during June – Sept. In addition, a moderate phytoplankton bloom ( $4-12 \mu\text{g l}^{-1}$ ) occurred in Central Bay during March and April.

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Question 2 and 3

## Nutrient Ratios and the Eutrophication of Florida Bay

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### N:P ratios

Although much of the ocean is nitrogen (N) limited, shallow tropical waters tend to be phosphate (P) limited because calcium carbonate chemically scavenges P from the water. Throughout Florida Bay, ratios of total N:total P and inorganic N:inorganic P are well above the Redfield ratio, leading many researchers to assume that P is the primary limiting nutrient and that inputs of N are not a significant cause of the eutrophication observed. It is well known however that many organic N molecules are not readily available to phytoplankton while many organic P molecules are available, due to the activity of phosphatase enzymes. This reflects the fact that organic N is bound by direct carbon bonds while organic P is bound by ester bonds. Therefore, inorganic N:total P ratios may more closely reflect the nutrient ratio available to phytoplankton.

An examination of the ratio of inorganic N:total P in Florida Bay indicates ratios greater than the Redfield ratio in eastern Florida Bay and less than the Redfield ratio in western Florida Bay. This suggests the potential for P limitation in the east and N limitation in the west. Nutrient bioassays indeed show mostly N limitation in the west and P limitation in the east, with a spatial distribution similar to the inorganic N:total P ratios. The largest algal blooms are in central Florida Bay where high P from the west meets high N from the east, and the inorganic N:total P ratio is close to the Redfield ratio. The divergent distribution of nutrients, with high P in the west and high N in the east, suggests different sources for N and P.

### Sources of P

Because calcium carbonate chemically scavenges P, much of the P derived from Lake Okeechobee and the Everglades Agricultural Area never makes it to Florida Bay. It is hypothesized that natural phosphorite deposits along the western side of Florida are the major source of the persistent high concentrations of P found in west Florida Bay. P from erosion of surface phosphorite deposits in central Florida, enhanced by phosphate mining, is transported down the Peace River and may account for a significant fraction of the P along the southwest coast of Florida. Underground Miocene-Pliocene phosphorite deposits mixed with quartz sand eroded from the Appalachian Mountains along the west side of the Florida platform may have groundwater moving up through them, transporting P up into the southwest coastal waters, particularly in western Florida Bay where the phosphorite deposits are thickest. The distribution of water column P correlates with phosphorite deposit thickness, and <sup>4</sup>He tracer data indicate significant amounts of groundwater entering Florida Bay. It is possible that these phosphorite deposits are spread throughout large areas of the west Florida shelf and may account for the relatively high P concentrations (compared to N) over much of the southwest Florida shelf. It is hypothesized that these natural phosphorite deposits have shifted western Florida Bay from a P limited carbonate system to a N limited ecosystem.

### Sources of N

N is not chemically scavenged by calcium carbonate like P and can easily flow from inland agricultural and sewage sources to coastal waters. This can be easily seen in the canals that lead from Lake Okeechobee and agricultural fields to Florida Bay. While most of the P is scavenged out quickly by the limestone and vegetation in the Everglades, approximately 60  $\mu\text{M}$  N remains in the water at the southern end of the Everglades. This explains the high concentrations of N and low concentrations of P in the northeast corner of Florida Bay. The flow of this N-rich water into Florida Bay increased in the early 1980's for two reasons. As a result of the eutrophication of Lake Okeechobee, backpumping of water from the Everglades Agricultural Area into the lake was greatly reduced and the flow of water to the south was greatly increased. At the same time, more land was drained for expanded agricultural operations and for development of suburban areas west of the Miami-Ft. Lauderdale metropolis. As a result, more N-rich water was pumped through an expanded South Dade Conveyance System into Florida Bay. This increased flow coincides with the observations by frequent boaters in Florida Bay of increased algal blooms in Florida Bay starting around 1981. More increases in the early 1990's in water flow through Taylor Slough further to the west and closer to the high P area in the west led to huge algal blooms in north central Florida Bay. The algal blooms in central Florida Bay where natural P from the west meets anthropogenic N from the east respond seasonally to freshwater runoff of N-rich water from the Everglades-agricultural watershed, with large blooms during high runoff periods and small blooms during low runoff periods.

### Implications

It is hypothesized that the increase in freshwater flow into Florida Bay proposed by the Central and Southern Florida Project Comprehensive Review Study will increase the flux of N into eastern Florida Bay, which will then mix with the P from the west and further increase the algal blooms observed in central Florida Bay. Furthermore, it is hypothesized that the proposed opening of more passes between the Florida Keys to enhance water exchange between Florida Bay and the coral reef tract will lead to a decline in water quality over the coral reefs.

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2 Nutrients/Water quality and 3 Algal Blooms

## Trace Metals in Florida Bay

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The principal sources of trace metals to estuaries are rivers, wastewater discharges, agricultural runoff, atmospheric deposition, marinas and boat traffic. As heavy metals enter estuaries, they tend to become associated with fine-grained sediments and other particulate matter. Estuarine sediments act as major repositories of heavy metals, and serve as a source of contaminants for biota and overlying waters. The northern side of the Florida Bay receives riverine input with higher trace metals, as well as high nutrient loading. The sediments are characterized mostly by very fine grain calcium carbonate with high organic content that acts as a heavy metal trap (Segar and Pellenburg, 1973). The water is very shallow and localized anoxic conditions develop in the sediments to make the sediment the possible source of trace metals to the overlying water. Input of heavy metals to estuarine and marine waters is a potentially serious problem because these contaminants are toxic to organisms above a threshold availability, and at elevated concentrations can adversely affect the structure and function of biotic communities (Kennish, 2000).

Previous research on heavy metals in Florida Bay is very limited. The heavy metal data in the Florida Bay waters are not available at present. There are only two sites from the National Status and Trends (NS&T) Program in the Florida Bay area that are directed towards trace metal studies, one near to Flamingo Center and other in Joe Bay. This program monitors contaminant levels through the mussel watch projects, which determines concentrations of trace metals in sediments and mollusk samples. For almost all trace metals, the concentration in both sediments and oysters were higher in Flamingo than Joe Bay. The problem of trace metal contamination is more serious when looking at trends from data gathered during the past decade or so. Even though there is generally a decrease in chlorinated hydrocarbons and other types of contaminants, Florida Bay has the only increasing trend in trace metals among the South Florida monitoring sites, despite the fact that the area is the least populated (Cantillo et al., 1999).

Our trace metal study plans to characterize the distribution and to identify the sources and fates of these contaminants in Florida Bay waters.

Our field trace metal sampling is conducted in cooperating with NOAA group (Dr. J.Z. Zhang) on board a catamaran equipped with a continuous thermosalinograph. Acid-cleaned polyethylene bottles (250 ml) were submerged off the bow to collect surface water samples. We have been sampling 40 stations across the bay in January, May, Jun, August and September, November 2000 and January, February and March 2001. Also, sediment samples were collected at same stations as the surface samples in June, November 2000 and February 2001. Sample processing were carried out under laminar flowing bench upon returning the samples to lab. The seasonal sampling allows us to evaluate the role of freshwater input that

varies due to the highly seasonal rainfall in South Florida, high in the summer and low in the winter.

The concentrations of trace metals: Al, Sc, V, Cd, Cr, Co, Cu, Pb, Mn, Ni and Zn, have been measured by Inductively Coupled Plasma (ICP) Mass Spectroscopy. In seawater, the high salt content exerts significant spectroscopic and nonspectroscopic interferences on trace metal analysis by ICP-MS. To eliminate matrix interferences we have developed a coprecipitation method, which efficiently removes the trace metals by co-precipitating them on 1 mg of iron hydroxide. After adding 1mg of Iron (III) to 30 ml of seawater in a centrifuge tube, the pH of the solution is adjusted to about 8 with small amount of high purity ammonia solution. The precipitate is separated from seawater by centrifuging at 12000 rpm for 10 minutes. After brief washing with MilliQ water, the precipitate is dissolved in 10 ml of 3% HNO<sub>3</sub> and analyzed by ICP-MS. This method has recoveries between 87% to 100% for all metals mentioned above. The sediment samples were first digested with small amount of concentrated HNO<sub>3</sub>, and then subjected to the coprecipitation procedures discussed above.

Total iron in seawater and sediments have been measured using the chemiluminescence technique. The FI chemiluminescence system was custom made in our lab (King et al., 1995). The pH of the seawater is adjusted to about 5 using acetate buffer to maintain it. After that, Na<sub>2</sub>SO<sub>3</sub> is then mixed with the buffered seawater to reduce Fe (III) to Fe (II). The reduced Fe (II) is injected into the detector housing where it mixes with the reagent luminol and gives out photons.

Preliminary results show that the highest Mn concentration in surface water for all months is at station 7, which is close to Rankin Bight. At station 7 the concentrations varied from 59 nM to 135nM. The lower concentrations across the bay were found to the South, near the Keys, with concentrations from 10 nM to 17 nM. For all sampling months, the lowest concentration was found at station 18. In General, manganese distribution in Florida Bay decreases from North to the South.

The highest concentrations of Fe in seawater were found between station 8 to 15. The highest values between June to September varied from 85 nM to 297 nM during this year. The sources of iron seems to come from freshwater input. Previous results made in the same month of 1999, also showed higher concentrations in these area, with values between 50 nM to 300 nM, similar our recent measurements. The lowest concentrations for Fe were found in the Southeast near to the Keys.

Cu showed higher concentrations at stations in the eastern part of the bay, which receives the discharge of Taylor Slough at NE, and has higher boat traffic at SE near to the Key's marinas. The highest concentrations varied from 3 nM to 30 nM and the lowest from 0.3 nM to 2.4 nM. The lower concentrations were found in the west side of the bay.

Vanadium concentrations shown a general increasing trend from East to West for all the months studied. We attribute the higher concentration to be the influence of seawater which has higher concentration compared to freshwater. The principal discharge of Taylor Slough is Trout Creek at East of Florida Bay. The highest concentrations were found at the



highest salinities in the center of the Bay, and the lowest concentrations were found at the lowest salinities. The highest concentrations varied from 34 nM to 62 nM and the lowest from 12 nM to 21 nM. In general the concentrations increase from January to September which is corresponding to the salinity increase.

In summary, trace metal concentrations are controlled by many factors such as the riverine input, interactions with sediments, abundance of suspended organic matter, water flows, tides, currents, residence time, winds, salinity, chemical sorption, organisms, among some others.

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## Eutrophication Model of Florida Bay

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This report describes the development and application of a two-dimensional, depth-integrated water quality model to Florida Bay. The model includes dynamically-linked components for water column transport and eutrophication processes, sediment resuspension and effects on light attenuation, benthic sediment processes and interaction with the water column, and seagrass biomass and interactions with water column and sediments. The report describes linkage to a finite-element hydrodynamic model, estimation of freshwater inflows and nutrient loadings to the system, model formulations, and application. Application consists of calibrating the model to the two-year period 1996-1997, testing model sensitivity for the two-year period, and simulating the ten-year period 1988-1997 to evaluate model long-term performance. This is the first application of a detailed water quality simulation model to Florida Bay. The application provides improved understanding of nutrient transport, fate, and effects. Although significant progress was achieved through this initial effort, there were also many improvements identified that must be undertaken before the model can be advanced further.

The study successfully linked a finite-element hydrodynamic model with a conventional eutrophication model based on local conservation of volume. To our knowledge, this study represents the first time such a linkage has been accomplished. Although the linkage methodology is not perfected, the major hurdles have been cleared.

The water quality model linked modules including water-column eutrophication, seagrass dynamics, sediment diagenesis, solids and nutrient resuspension, and benthic algal production. To our knowledge, this is a first for Florida Bay. In fact, we know of few systems that presently have a model application to rival the current effort in Florida Bay. The model does require substantial upgrading, however, to fully represent processes in the Bay.

Nutrient loads to the bay and surrounding waters from various sources were calculated for this study. Estimates indicate the atmosphere is the largest of the loading sources to the bay. Runoff from the mainland is the least source of phosphorus and second least source of nitrogen.

No in-situ measures of nitrogen fixation were available to us. Rates associated with seagrass beds, measured in other systems, were adapted for the model. Estimated nitrogen fixation associated with seagrass leaves equals the estimated atmospheric nitrogen load. The sum of nitrogen fixed in the leaves and roots makes nitrogen fixation the largest single source to the system. To our knowledge, measures of nitrogen fixation are currently being conducted. These measures should be swiftly incorporated into the model and into system nutrient budgets.

Neither were measures of denitrification within benthic sediments available. Rates of denitrification were calculated by the sediment diagenesis model with parameters adapted from Chesapeake Bay. Calculated denitrification roughly equals total nitrogen fixation. Denitrification rates should be measured and used to verify the computations provided by the model.

The model underestimates the amount of nitrogen in both the sediments and water column. Sensitivity analysis indicates the shortfall is unlikely to originate in loading estimates. Either a source of nitrogen has been omitted or the estimated loads are greatly in error. Potential sources of omission or error include groundwater, nitrogen fixation, and denitrification.

Successful simulation of a ten-year sequence of water quality was virtually impossible without corresponding hydrodynamics. The highest priority should be given to application of a detailed, volume-conservative hydrodynamic model to the bay and adjoining waters. The model should simulate a ten-year period, at least, and provide good agreement to salinities observed within that period.

The major uncertainty in the system nutrient budget is transport across the western boundary and through the Keys passes. This transport cannot be observed on a long-term basis. Computation via a model is the only alternative for long-term budget estimates. High priority should be given to estimating flow across system boundaries once a verified hydrodynamic model is available.

Sensitivity analysis indicates model computations are very sensitive to the biological activity at the sediment-water interface. In the present model, this activity is represented by the benthic algal component. The model, as formulated, cannot represent all observed fluxes, especially of dissolved organic matter. Attention should be devoted to quantifying sediment-water fluxes, to investigating the nature of the benthic community, and to process-based modeling of this community.

A great deal of observations have been collected in the bay since this study commenced and a good deal more is known about the bay than was known a few years ago. Once suitable hydrodynamics are available, the water quality model should be re-applied, on a ten-year time scale, and validated with the latest observations of conditions and processes in the bay. Concurrent with the re-application, first-order improvements (e.g. division of dissolved organic matter into labile and refractory components) can be incorporated into the water quality model.

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Question 2 – Nutrients/Water Quality

## Biogeochemical Effects of Iron Availability on Primary Producers in a Shallow Marine Carbonate Environment

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We completed a synoptic survey of iron, phosphorus and sulfur concentrations in shallow marine carbonate sediments from south Florida. Extracted iron concentrations typically were less than  $50 \mu\text{mol gDW}^{-1}$  and tended to decrease away from the Florida mainland. Extracted phosphorus concentrations mostly were less than  $10 \mu\text{mol gDW}^{-1}$  and tended to decrease along a gradient of decreasing seagrass production. Concentrations of sulfur minerals, up to  $40 \mu\text{mol gDW}^{-1}$ , tended to co-vary with sediment iron availability, suggesting that sulfide mineral formation was iron-limited. An index of iron availability derived from sediment data was negatively correlated with chlorophyll-a concentrations in surface waters, demonstrating the close coupling of sediment-water column processes in this shallow system.

Biogeochemical effects of increasing iron availability in the sediments were measured by examining sediment and plant responses to iron additions. Eight months after applying a surface layer of reactive iron granules to experimental plots, sediment iron, phosphorus and sulfur were elevated to a depth of 10 cm relative to control plots. Biomass of the seagrass *Thalassia testudinum* was not different between control and iron addition plots, but individual shoot growth rates were significantly higher in experimental plots. The iron content of leaf tissues was significantly higher from iron addition plots. Although no differences in phosphorus content of leaves were observed, the reduction of sulfide stress in plants from iron addition plots was documented by a significant change in  $^{34}\delta\text{S}$  of leaf tissue. The dual nature of iron as both a buffer to toxic sulfides and contributor to phosphorus limitation has important implications to the structure and function of shallow marine ecosystems.

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## Nitrogen Cycling in Florida Bay Mangrove Environments: Sediment-Water Exchange and Denitrification

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In August 1999 and March 2000, we sampled a diverse subset of Florida Bay ecosystems, including a site with thriving *Thalassia* beds, sites with substantial seagrass losses, and a more eutrophic site in Sunset Cove. Measurements of sediment-water exchange, pore water chemistry and  $^{210}\text{Pb}$ -based N burial were made at 6 sites. Cores from both vegetated (*Thalassia testudinum*) and unvegetated (where available) sites were collected for exchange studies.

The sediment-water exchange of oxygen is strongly affected by the presence of microphytobenthos, with high rates of primary production at most sites. Sediment respiration rates in August were generally around  $2 \text{ mmol m}^{-2} \text{ h}^{-1}$ , while daytime rates of  $\text{O}_2$  efflux can exceed  $4 \text{ mmol m}^{-2} \text{ h}^{-1}$ . In general, vegetated and unvegetated sediments had similar biomass and oxygen flux. Apparent primary production (light minus dark oxygen flux; assume  $1 \text{ O}_2 = 1 \text{ CO}_2$ ) ranged from  $\sim 1$  to  $10 \text{ mmol m}^{-2} \text{ d}^{-1}$ , or for 12 hours of light,  $\sim 12$  to  $120 \text{ mg C m}^{-2} \text{ d}^{-1}$ . Although this productivity is considerably lower than that of *Thalassia testudinum*, the combination of seagrass and microphytes nutrient uptake may present an effective nutrient buffering mechanism at the sediment-water interface. In March 2000, sediment chlorophyll concentrations and the rate of respiration and photosynthesis were approximately half that of the August data.

The sediment-water exchange of ammonium was highest at Rankin Bay, Terrapin Bay and under dark conditions at Johnson Key. While rates of dark ammonium release that exceed  $100 \mu\text{mol m}^{-2} \text{ h}^{-1}$  were unexpected, other ammonium flux data (Yarbro and Carlson) for combined light and dark incubation were also quite high. At Johnson Key (vegetated), the dark flux of ammonium was higher than the light flux. At Sunset Cove and Little Madeira, all fluxes were directed into the sediment.

The dark fluxes of  $\text{N}_2\text{-N}$  were all directed out of the sediment, indicating net denitrification (i.e. denitrification  $>$  N fixation). Under illuminated conditions, Sunset Cove, Little Madeira unvegetated and Rabbit unvegetated all exhibited a net  $\text{N}_2\text{-N}$  uptake, suggesting net N fixation. If the Redfield ratio applies to these benthic algae, primary production rates at Sunset Cove ( $\sim 6 \text{ mmol m}^{-2} \text{ h}^{-1}$ ) require N at a rate of  $\sim 0.9 \text{ mmol m}^{-2} \text{ h}^{-1}$ ; about 1/3 of the N needed for primary production can be supplied by N fixation + ammonium flux. Clearly, these N fixation rates are not in excess of those needed to supply the needed N to the algae.

Under dark conditions, denitrification appears to be a major flux path for remineralized N. Given the demand for N by microalgae and macrophytes, this “leakage” of N from the system represents a flux that must be balanced by new supplies of N into the system. While remineralization of phytoplankton may play a role, there appears to be an imbalance that suggests that N fixation (or other new external supplies) must be important. We are currently

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examining both DON and DOC fluxes in these sediments, as well as evaluating independent measures of N fixation.

This USEPA study that has supported the current data collection has provided a good first level understanding of the rates of N cycling in Florida Bay sediments; there is the need for considerably more effort to better define the temporal and spatial differences in benthic nutrient cycles and to provide greater understanding of nutrient cycles associated with the die back phenomena.

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Question 2 – Nutrients/Water Quality

## **Nutrient Cycling and Litterfall Dynamics in Mangrove Forests Located at Everglades, Florida and Terminos Lagoon, Mexico**

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Litterfall, standing litter, green and senescent leaves were collected in two mangrove forests located at Terminos Lagoon, Mexico and four forests located at the Everglades National Park, Florida. The objective was to assess the differences in nutrient use efficiency and evaluate the relative importance of nutrient retranslocation as a nutrient conservation mechanism among the mangrove communities located at two contrasting regions: Florida and Terminos Lagoon. Annual litterfall rates were 254, 830, 650, and 580 g m<sup>-2</sup> yr<sup>-1</sup> at each of the four sites of Florida. Litterfall rates were higher in Terminos Lagoon that ranged from 1125 to 768 g m<sup>-2</sup> yr<sup>-1</sup>.

Leaf fall nitrogen and phosphorus concentrations ranged from 10 to 14 and from 0.11 to 0.65 mg g<sup>-1</sup>, respectively. However, values were higher for mangrove forests located in Terminos Lagoon relative to the sites located in Florida. Differences in nutrient concentrations were related to soil fertility that characterize each study site. Nitrogen and phosphorus returns to the forest floor were higher in the sites located in Mexico which led to lower both nitrogen and phosphorus use efficiency. In contrast, low nutrient concentration in the canopy of sites located in Florida led to higher nutrient use efficiency. Phosphorus use efficiency was particularly high in Florida. Carbonate systems such as the Everglades are phosphorus limited, this limitation suggests that high phosphorus retranslocation is an important process contributing to high nutrient use efficiency observed in the Florida.

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## Nutrient Dynamics in Groundwaters Surrounding a Sewage Injection Well in Key Colony Beach, Florida

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Key Colony Beach's waste water (WW) treatment and disposal system is one of the largest and most advanced WW treatment facilities in the Florida Keys. The facility disposes of tertiary treated WW by means of an array of injection wells that gravity feeds the WW into the subsurface to a depth of 18 to 27 m. During September 1999, the average daily injection volume was 2.3 million liters of WW per day. Groundwater tracer experiments indicate that the WW plume rises rapidly in the subsurface after injection due to the large density difference between the WW (salinity ~0 ppt) and the ambient groundwaters (salinity ~35 ppt). Typical vertical transport rates (VTRs) ranged from 0.15 m/day to 3 m/day at wells located 15 m from the injection well while VTRs were as high as 98 m/day at wells located immediately adjacent to the injection well. Typical horizontal transport rates (HTRs) were 0.27 to 7.94 m/day 15 m from the injection point while rates at the closer wells were as high as 27 m/day. After rising to the mud layer (which extends to a depth of approximately 5m) the majority of the plume is transported in a southeastern direction due to the hydraulic gradient that exists at this depth, a result of the sea level difference between the Atlantic Ocean and Florida Bay. The fate of the nutrients (nitrate and phosphate) in this plume is of great concern as they could drastically affect the environmental health of local surface waters, which have historically been oligotrophic.

During October 1999, we characterized the nutrient plume by monitoring a well field that has been installed around the injection wells. The concentrations of nitrate ( $\text{NO}_3$ ) and phosphate ( $\text{PO}_4$ ) being injected were 382  $\mu\text{M}$  and 26  $\mu\text{M}$ , respectively. Comparable concentrations were found at 5 wells located 2.5 to 15 m from the primary injection well. The plume was found to extend beneath the entire well field, which extended as far as 160 m away from the array of injection wells. Phosphate levels decreased along the waste water plume's path to a minimum concentration of 7.9  $\mu\text{M}$  at the well cluster located 160m east of the primary injection well. Concentrations of nitrate also decreased at wells located 40 and 80 m from the injection well, however concentrations at the eastern most well (160 m away) were considerable higher than the WW being injected at the time of this sampling campaign. This is most likely due to a pulse of WW with higher nitrate concentration shortly before our sampling effort.

We also conducted a dual tracer experiment to examine the fate of  $\text{PO}_4$  that is injected into the subsurface during October 1999. Sulfur hexafluoride ( $\text{SF}_6$ ) served as our conservative groundwater tracer and allowed us to account for groundwater mixing processes such as dilution, diffusion, and advection. Radiolabeled phosphate ( $^{32}\text{PO}_4$ ) served as our reactive tracer and allowed us to monitor the behavior of phosphate after injection. The use of  $^{32}\text{PO}_4$  allowed us to disseminate between the known quantity of phosphate that we injected and the elevated ambient concentrations that have developed after 5 years of continuous WW injection.

Our results indicate that radiolabeled  $\text{PO}_4$  was quickly removed from solution, presumably due to adsorption to the Key Largo Limestone (KLL) that underlies the Keys (Figure 1). Evidence also suggests that the  $\text{PO}_4$  becomes remobilized after initial adsorption



but at a slower rate. The KLL appears to be functioning as a phosphate buffer, maintaining groundwater  $\text{PO}_4$  concentrations of approximately  $25 \mu\text{M}$  at wells located within 15 m of the primary injection well. Column experiments conducted by Elliot (1999) showed that when a solution with elevated  $\text{PO}_4$  concentration (over  $50 \mu\text{M}$ ) was recirculated over KLL, the  $\text{PO}_4$  levels decreased rapidly at first then began to slowly approach an equilibrium concentration of approximately  $25 \mu\text{M}$ . Several different solutions with elevated  $\text{PO}_4$  were added to the column and they all showed rapid removal followed by a slower removal until a concentration of  $25 \mu\text{M}$  was reached. The column was then allowed to drain and the experiment was repeated using seawater with an undetectable  $\text{PO}_4$  concentration.  $\text{PO}_4$  elevations began to climb rapidly then eventually leveled off at a concentration of  $25 \mu\text{M}$ . In conjunction, these results suggest that phosphate is rapidly adsorbed to the KLL then slowly released over time due some surface chemistry that is poorly understood. Mineralization of the  $\text{PO}_4$  (apatite formation) seems unlikely due to the rapid times scales of the adsorption / desorption processes that were observed in this study.

Denitrification is the most likely explanation for nitrate removal in the WW plume as the carbon rich, anoxic water surrounding the injection well is an ideal habitat for denitrifying bacteria. *In situ* rates of denitrification were calculated using 2 independent methods. We measured excess nitrogen gas (elevated  $\text{N}_2/\text{Ar}$  ratios) at several of the wells, indicating denitrification rates of 11 to  $57 \mu\text{moles NO}_3 \text{ m}^{-3} \text{ d}^{-1}$ . Other calculations based on measured  $\text{NO}_3$  concentrations and salinity suggest denitrification rates of 14 to  $305 \mu\text{moles NO}_3 \text{ m}^{-3} \text{ d}^{-1}$ . Acetylene-block assays were also conducted using core material collected when some of the wells were installed in May 1999. These experiments showed higher potential rates of denitrification of 400 – 3000  $\mu\text{moles NO}_3 \text{ m}^{-3} \text{ d}^{-1}$ , comparable to estimated rates from a similar study conducted on Long Key at the Keys Marine Lab (Corbett et al. 1999).

Seagrass and macroalgae from around KCB were collected and their tissues were analyzed for  $^{15}\text{N}$ . Samples from canals showed significant enrichment (del  $^{15}\text{N}$  values were +6.48 and +13.55 per mil for the west and east canals, respectively) over samples collected from the Atlantic side of the island (+2.73 to +4.64 per mil). These results suggest that sewage-derived nitrate is contributing to a significant portion of these primary producers nitrogenous requirements. The canal with the highest del  $^{15}\text{N}$  value was also the canal that had the lowest species diversity and the highest turbidity, suggesting that the WW nitrate loading to this canal is contributing to an ecosystem shift from benthic primary production to water column photosynthesis by microalgae.

More work needs to be conducted to determine the long term effect of nutrient loading to the subsurface of the Keys. Additional sampling campaigns at KCB should indicate whether the WW plume is expanding and contracting seasonally (due to change in tourist densities) or if it is continuously increasing in size. Additional column experiments also need to be conducted to determine how KLL from pristine areas affects phosphate concentrations. These column experiments should recirculate WW and seawater with increasing concentrations of  $\text{PO}_4$  starting at concentrations much lower than the equilibrated concentration of  $25 \mu\text{M}$ . We believe this will provide us with more information to evaluate how the plume may evolve with continuous loading of phosphate.

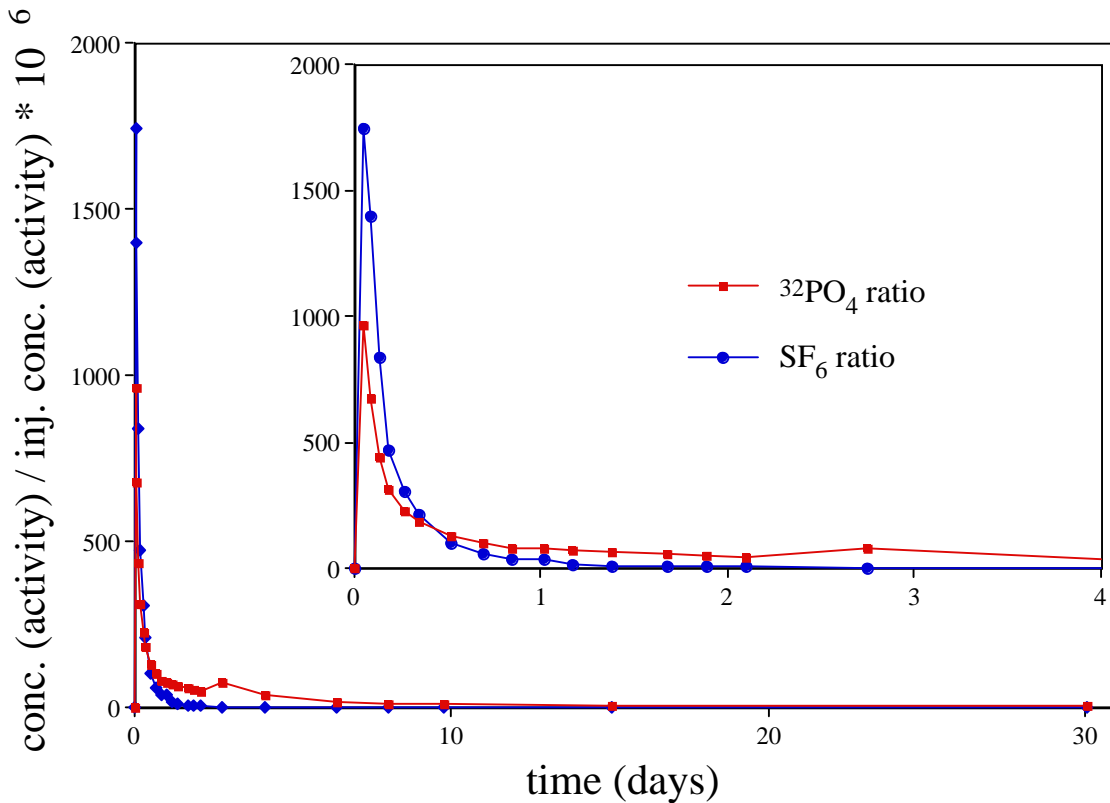


Figure 1. Tracer results from well cluster I, 18.3 m depth. The data has been normalized to the injection slug's concentration (for SF<sub>6</sub>) or activity (for <sup>32</sup>PO<sub>4</sub>) then multiplied by 10<sup>6</sup> to get the numbers on a convenient scale. If both tracers (SF<sub>6</sub> and <sup>32</sup>PO<sub>4</sub>) were acting conservatively in the subsurface then their breakthrough curves would look identical. This data shows that <sup>32</sup>PO<sub>4</sub> is rapidly removed from solution initially (when the <sup>32</sup>PO<sub>4</sub> curve is below that of SF<sub>6</sub>) then is remobilized (as shown when the phosphate curve is above the SF<sub>6</sub> curve) after less than one day.

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 Question/Team #2 – Nutrients/Water Quality

## **Florida Bay Watch: Results of Five Years of Nearshore Water Quality Monitoring in the Florida Keys**

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Arthur Itkin  
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Florida Bay Watch is a volunteer-based program of The Nature Conservancy in which trained volunteers collect seawater samples and environmental data using standard scientific methods. It is designed to augment and assist scientific studies conducted by universities, agencies, and other institutions. This poster presents results of monitoring total phosphorus, total nitrogen, and chlorophyll-*a* in nearshore waters at stations along Florida Bay shores in the upper Keys and elsewhere in the Keys. This is an ongoing program; data are presented for the five-year period November 1994 - October 1999. These nearshore data complement offshore data collected in Florida Bay and along the Keys by Florida International University (FIU); analyses for this project were performed by the water quality laboratory at FIU's Southeast Environmental Research Center (SERC).

Nearshore stations were located at the homes and workplaces of Florida Bay Watch volunteers. Stations were distributed from Key Largo to Key West and included sites both bayside and oceanside of the Keys. Addition of new stations and the termination of others occurred over the five years; three stations were active for the entire period. Sampling occurred at both developed (residential canals and boat basins) and natural/unobstructed shorelines.

Florida Bay Watch volunteers were trained in basic water quality sampling methods, which included instruction on filling out data forms, techniques for calibrating field equipment, and emphasis on careful handling of water samples to ensure the integrity of the data. Periodic evaluations were conducted to ensure consistency, and all data went through a quality-control check to identify possible sampling errors. Volunteers were instructed to sample each week during a low tide; data sets for most stations followed this routine, with some exceptions. The following information was recorded on a standardized data form: date, time, tide, Beaufort number for wind and sea state, wind direction, current strength, current direction, Secchi depth, time of Secchi reading, sea-surface temperature, specific gravity, and rainfall in the previous 24 hours. In addition, volunteers collected and froze a water sample for analysis of total nitrogen (TN) and total phosphorus (TP). For determination of chlorophyll-*a* (Chl-*a*) concentrations, two 60 mL aliquots of seawater were drawn into a syringe and then squirted through a filter unit containing a Whatman glass microfiber filter, GF/S, 25 mm diameter. The filter paper was placed in a vial, closed within an opaque bottle, and frozen.

Water samples and data forms were collected from the volunteers monthly and the samples were sent to the water quality laboratory at SERC. Total nitrogen, total phosphorus, and chlorophyll-*a* concentrations were determined using standard methods.

To examine possible patterns through time in concentrations of these three water-quality parameters, three stations with five-year data sets were employed. Two of the stations were in the Upper Keys and one was in the Middle Keys. Two stations were at developed shorelines and one was at a natural/unobstructed shoreline; all were bayside of the Keys. Monthly station means were used in analyses of variance to compare nutrient and chlorophyll-*a* levels among the five years.

To examine water quality parameters for possible patterns across space, stations were categorized by the three criteria noted above: region of the Keys, developed vs. natural shorelines, and oceanside vs. bayside of the Keys. Developed shorelines included various kinds of canals (dead-end, open-ended, aerated, non-aerated) and boat basins. Natural shorelines often included a dock from which samples were collected. One-year periods between November 1994 and October 1999 were used in one-way analyses of variance to compare the levels of the water-quality parameters within each of the three categories of stations.

Small-scale variations in nearshore water quality parameters were a striking feature of this data set, as reported in Florida Bay Watch Quarterly and Annual Reports. Values often fluctuated considerably both at a particular station from week to week and among nearby stations; these fluctuations sometimes were on a scale of one or two orders of magnitude.

Conducting a long-term data analysis is often difficult due to the nature of volunteer programs; some stations dropped out and others joined at various times. Since only three stations collected samples throughout the first five years of this program, stations with at least six consecutive seasons, regardless of their start date, were also included in this preliminary analysis.

Preliminary results of this long-term analysis indicated the following trends. Concentrations of TP rose steadily from 0.41  $\mu\text{M}$  in the first year to 0.51  $\mu\text{M}$  five years later. This paralleled a similar trend in the Florida Keys National Marine Sanctuary measured by the SERC lab; though, Florida Bay Watch's nearshore TP concentrations were three times greater. Over the five years TN appeared to have a downward trend (36.8  $\mu\text{M}$  to 34.8  $\mu\text{M}$ ), while chlorophyll-*a* concentrations fluctuated with means ranging from 0.55-0.85  $\mu\text{g/L}$ .

TN (38.2  $\mu\text{M}$ ), TP (0.45  $\mu\text{M}$ ), and Chl-*a* (0.74  $\mu\text{g/L}$ ) means were slightly higher during the wet season compared to the dry season (33.7  $\mu\text{M}$ , 0.42  $\mu\text{M}$ , 0.64  $\mu\text{g/L}$ ); however, a statistically significant difference was not found. The only spatial trend that appeared was a higher concentration of TN in the Upper Keys (43.6  $\mu\text{M}$ ) compared to the Middle Keys (27.4  $\mu\text{M}$ ). Lower Keys stations did not have a sufficient amount of data to include in this analysis.

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## **Environmental Toxicity in Southern Biscayne Bay, Florida**

### **M. Jawed Hameedi**

National Oceanic and Atmospheric Administration, Silver Spring, Maryland

The “Biological Effects” component of the National Oceanic and Atmospheric Administration’s National Status and Trends (NS&T) Program for Marine Environmental Quality conducts intensive regional surveys to describe the incidence, severity, and the spatial extent of adverse biological effects associated with chemical contamination. These studies are conducted in specific coastal areas. Their selection is based on a number of considerations, including: high levels of contamination found in mussels and oyster tissues samples under the “Mussel Watch” component of NS&T program; likelihood or documentation of adverse biological effects of contamination according to state and local environmental data; and possible collaboration with other Federal, state and local agencies. Typically, the studies are designed to obtain data simultaneously on the levels of chemical contaminants in sediment, results of multiple toxicity tests, analysis of biomarker responses, and changes in benthic biological community structure. By combining and synthesizing data from field observations, chemical analyses, toxicity tests, and measures of benthic community structure, NOAA’s biological effects studies provide a holistic understanding of regional environmental quality and the spatial extent of contamination-related adverse biological effects. To date, NOAA has performed such studies in over 25 different estuaries and other coastal waters throughout the United States, often in close cooperation with coastal states. In Florida, such studies have been conducted in Tampa Bay, four bays of the Florida Panhandle (Pensacola, Choctawhatchee, St. Andrew and Apalachicola), and Biscayne Bay. Presently, a study of environmental toxicity is underway in St. Lucie Estuary under a Joint Project Agreement between NOAA and State of Florida.

In Biscayne Bay, comprehensive bay-wide sampling was conducted over two years (1995 and 1996) to determine the incidence, severity and spatial extent of sediment toxicity. It was based on a stratified-random sampling design that comprised a total of 226 stations covering an area of 484 sq. km. As in previous NOAA studies, toxicity tests were selected to ensure different modes of contaminant exposure (i.e., bulk sediment, porewater, and chemical extracts of sediments) to a variety of test organisms (invertebrates, bacteria, and vertebrate cells) and to measure different assessment end-points (i.e., mortality, impaired reproduction, physiological stress, and enzyme induction). As expected, the study results showed high levels of sediment contamination and severity of toxicity in several peripheral canals and tributaries, notably the lower Miami River. In terms of the areal extent, sediment toxicity as inferred from the amphipod mortality test was 13 percent of the total area, that inferred from the sea urchin fertilization test was ca 47 percent, and that inferred from the Microtox test was 51 percent. In comparison, a compilation of results of NOAA’s sediment toxicity from 23 different coastal areas in 1998 showed that 7 percent of total studied area was classified as toxic based on the amphipod mortality tests, 39 percent based on sea urchin fertilization test, and 66 percent based on the Microtox test.

The data also showed unexpectedly wide, but apparently sporadic, occurrence of sediment toxicity in southern Biscayne Bay. Although sediment toxicity was expected at stations located in or just outside Black Creek-Gould’s Canal, Military Canal, and Mowry Canal, it

was not expected in the open waters of the bay extending eastward to Featherbed Banks and Elliott Key. Also, unlike other parts of the bay, the observed toxicity in this area was not associated with high levels of contaminants; to the contrary, contaminant levels at those sites were generally very low, in some instances at or below the method detection limits.

In 1999, NOAA initiated a follow-up study to determine patterns of toxicity in southern Biscayne Bay and to define certain measures of environmental quality before major environmental restoration and mitigation activities are implemented. Its initial objectives were to define the existence of toxicity associated with effluents from freshwater discharge canals in coastal waters of south Florida (including the C-111 canal), and to determine whether the pattern of sediment toxicity observed in southern Biscayne Bay was persistent. The study included a wider array of potential toxicants than before and a broader suite of toxicity tests, including tests for genotoxic effects. Samples were collected in November-December 1999 from 30 sites, most of which coincided with sites in the previous study. Data analyses and interpretation of results are presently underway. Preliminary results suggest that: (1) the pattern of sediment toxicity in the area is remarkably similar to that found before; (2) even though the levels of contaminants in the canals are generally higher, contaminant plumes and associated toxicity do not extend seaward in an appreciable manner; (3) concentrations of contaminants in the sediments of the bay are generally low; and (4) water concentrations of contemporary pesticides in the dissolved phase were unremarkable during the sampling period. Fiscal and logistical constraints prevented intensive event-based sampling of pesticides, which might have identified more pesticides at greater frequency and at higher concentrations than those measured in this study. There were two sites with moderate levels of alkylphenol ethoxylates: Florida Canal (mouth) and Princeton Canal (mouth).

In view of the results to date, NOAA scientists are considering other plausible explanations to describe sediment toxicity in the bay, including groundwater discharges to the bay, localized patterns of water circulation and contaminant transport, and other potential toxicants. These discussions and those anticipated at the Florida Bay Science Conference will help formulate hypotheses for the future course of our studies in the region.

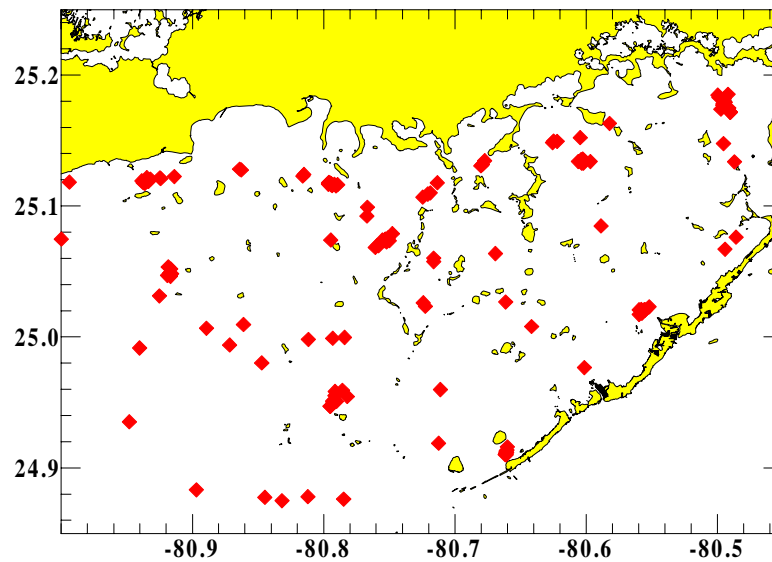
Hameedi, Jawed, National Oceanic and Atmospheric Administration, N/SC11, 1305 East-West Highway, Silver Spring, MD 20910, Phone: (301) 713-3034x170; Fax: (301) 713-4388; [Jawed.Hameedi@noaa.gov](mailto:Jawed.Hameedi@noaa.gov), Question 2 – Nutrients / Water Quality

## Seasonal Variation of the Carbonate System in Florida Bay

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The carbonate system has been studied in the Florida Bay from 1997 to 2000. Measurements of pH, total alkalinity (TA) and total inorganic carbon dioxide ( $\text{TCO}_2$ ) were made from twenty stations (Figure 1) in the bay and used to calculate the partial pressure of carbon dioxide ( $\text{pCO}_2$ ) and the saturation states of aragonite ( $\Omega_{\text{Arg}}$ ) and calcite ( $\Omega_{\text{Cal}}$ ). The results were found to correlate with the salinity. The pH was low and the  $\text{pCO}_2$  was high for the freshwater input from the mangrove fringe due to the photochemical and biological oxidation of organic material. The TA and  $\text{pCO}_2$  for the freshwater input are higher than seawater due to the low values of pH and  $\Omega$  (Figure 2). The pH was high and the  $\text{pCO}_2$  was low in November in regions where the chlorophyll is high due to biological production. During the summer when the salinity is the highest, the normalized values of TA and  $\text{TCO}_2$  were lower than average seawater, due to the inorganic precipitation of  $\text{CaCO}_3$  caused by the resuspension of sediments or the biological loss by macroalgae. A transect across the mangrove fringe (Figure 3) near the outflow of Taylor Slough shows that  $\text{PO}_4$  and TA increases as the freshwater enters the Bay. This is thought to be due to the dissolution of  $\text{CaCO}_3$  in the low pH waters from the bacterial and photo oxidation of plant material.



**Figure 1.** Typical stations sampled in Florida Bay.

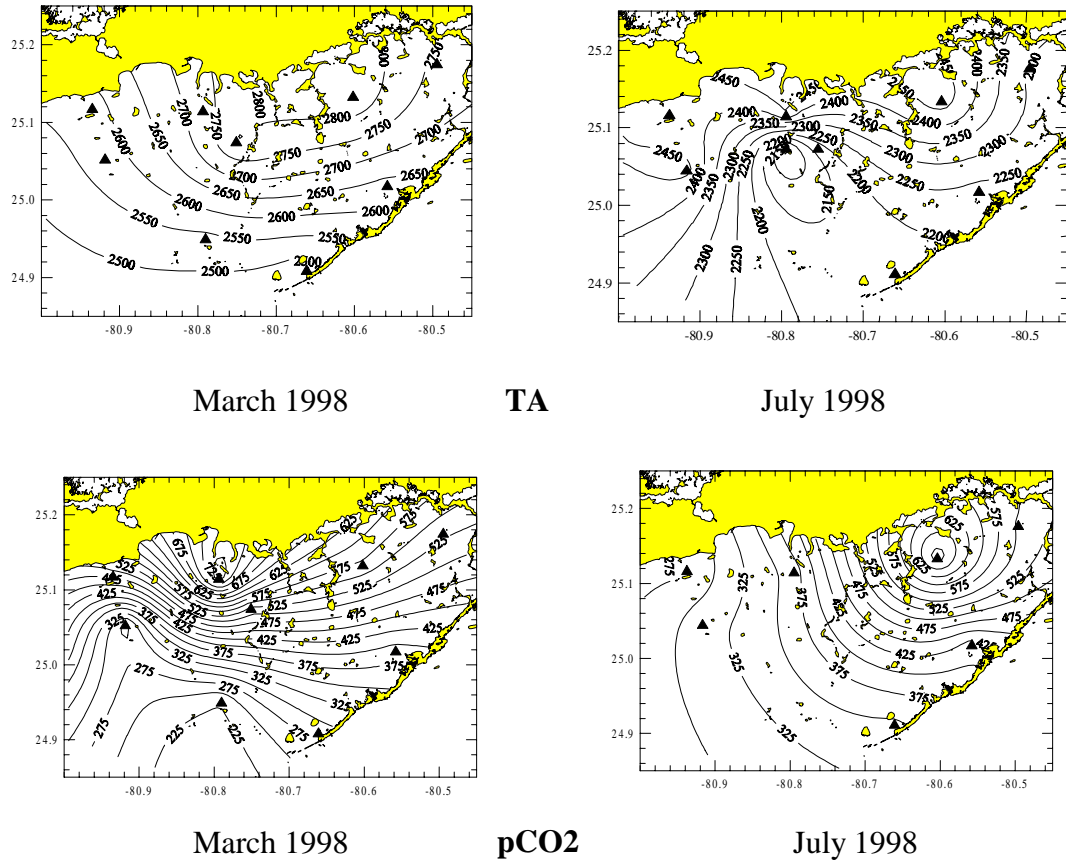


Figure 2. Total Alkalinity ( $\mu\text{mol kg}^{-1}$ ) and pCO<sub>2</sub> ( $\mu\text{atm}$ ) contours in Florida Bay.

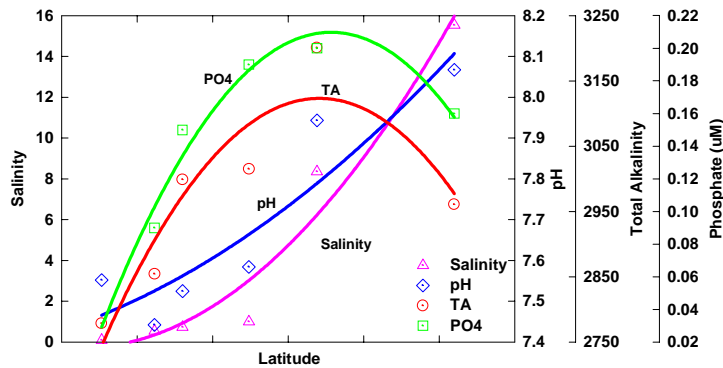


Figure 3. Measurement along transect across mangrove fringe.

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## **SEAKEYS: Florida Keys Monitoring Initiative**

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David Burwell  
Coastal Environmental Monitoring Stations, Coastal Ocean Monitoring and Prediction System, College of Marine Science, University of South Florida, St. Petersburg, FL

The Sustained Ecological Research Related to the Management of the Florida Keys Seascape (SEAKEYS) program was organized in 1991 by the Florida Institute of Oceanography with initial funding from the John D. and Catherine T. MacArthur Foundation, and has been maintained through continuing support provided by the South Florida Ecosystem Restoration, Prediction and Monitoring program, administered by the National Oceanic and Atmospheric Administration (NOAA). The SEAKEYS environmental monitoring program was designed to provide data for a long-term database of meteorological and oceanographic data from the Florida Straits and Florida Bay. The SEAKEYS network provides wind speed, wind gust, air temperature, barometric pressure, sea temperature and salinity for all stations; and tide level, precipitation, photosynthetically active radiation, fluorometry, and transmissometry for selected stations. These data are transmitted hourly to a GOES satellite, and from there are downloaded for data and information management purposes.

SEAKEYS data have been used to characterize the dynamics of several hurricanes since 1992, and have been of great benefit to hurricane forecasters at the National Weather Service, and at AOML's Hurricane Research Division in Miami, Florida. Daily data are posted to NOAA's Coral Health and Monitoring Program Web site at <http://www.coral.noaa.gov>, while historical data are available at <http://www.neptune.noaa.gov>. These data have also allowed researchers to correlate meteorological and hydrographic dynamics, for example El Niño\ La Niña conditions, with environmental changes in Florida Bay and the Florida Keys National Marine Sanctuary.

As a value-added enhancement to the SEAKEYS data, the Environmental Information Synthesizer for Expert Systems (EISES) software was developed to provide information synthesis from raw data so that speciality applications could be developed for the reporting of instances in which environment clues are conducive to certain biological events. For instance, the Coral Reef Early Warning System (CREWS) has been constructed, using EISES information products, to warn sanctuary management and researchers as to when conditions are conducive to coral bleaching. Similarly, applications have been prototyped for the alerting of conditions theoretically conducive to the onset of harmful algal blooms, and for conch survival. These environmental models are easily configurable through interaction with

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researchers who have expertise in these areas, and are being further developed, using their feedback, for decision support systems for environmental managers and researchers.

The SEAKEYS effort continues in FY 2001, through indirect complementary funding for coral research, with the addition of speciality sensors (e.g., for pCO<sub>2</sub> and ultraviolet light) and a significant upgrade in computing architecture, to include a Beowulf-cluster data server (to provide for enhanced expert system and neural network parallel processing), and new commercial database software (Oracle). The SEAKEYS *in situ* data will also provide near real-time ground-truthing of NOAA's and USF's satellite monitoring programs, and thus continue to provide significant research data and information products for Florida Keys National Marine Sanctuary and Florida Bay researchers and management.

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Question 2—Nutrients/water quality

## **Flux of Inorganic Phosphate from the Sediment and Contribution to Biomass and Primary Productivity by Benthic Microalgal Communities in Western Florida Bay**

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Gary L. Hitchcock and Jennifer Jurado

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The objective of this study is to address the relationship between benthic microalgal communities and the phosphate nutrient dynamics of Florida Bay sediments and how they relate to benthic and water column primary production. Inorganic phosphate (P) flux from the sediment was measured in two types of chambers inserted into the sediment devoid of seagrasses under both light and dark conditions. Sampling sites were East Cape Sable and Sandy Key and studies were conducted bimonthly from May, 2000 to the present. Runs were a minimum of 3 hours and a maximum of 9 hours in duration. Following each run, chlorophyll measurements were taken from 5 replicate cores within each chamber and extracted in 90% acetone with hexane fractionation.

Chlorophyll values were variable, but were an order of magnitude higher than the water column values and consistent with measurements from the West Florida Shelf. Chlorophyll analysis seems to indicate a spring in the benthic microalgae, however less than a year of data has been collected.

Inorganic P flux measurements have been variable, but some trends have been noted. There is generally an increase in P concentration within the dark chambers throughout the incubation, especially during the afternoon hours when primary productivity is highest. Light chambers generally exhibited no P flux or removed P from the water column. Some runs in both treatments show no accumulation of inorganic P relative to duration of incubation. Tidal influences may explain some of these results. P flux in May and early June was up to 7 times greater than P flux in later months, perhaps owing to a coincident peak in benthic microalgal biomass. Seasonal trends in P flux may be more evident upon analysis of an entire year of data.

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## **Nitrogen Cycling in Florida Bay Mangrove Environments: Sediment-Water Exchange and Denitrification**

**Michael S. Owens** and Jeffrey C. Cornwell

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Sediment-water exchange experiments were used with  $^{210}\text{Pb}$  geochronology and pore water chemistry to provide a first order understanding of the processes which control nitrogen and phosphorus cycling in Everglades mangrove environments. Cores were collected in July and November 1999 from two dwarf mangrove (*Rhizophora mangle*) environments, as well as an adjacent pond. Dissolved oxygen time courses of dark and light incubations were used to estimate the productivity of the microphytobentic community. Although these systems generally were net heterotrophic, modest rates of primary production were observed at the sediment-water interface. The rates of  $\text{N}_2$  flux were measured directly using mass spectrometry and in general showed relatively low rates of nitrogen loss. During July, two sites had measurable  $\text{N}_2$  flux into the sediment, an indication of N fixation. The sediment cycling of N has minimal influence on the composition of overlying water, with little efflux of ammonium or  $\text{N}_2$ . Burial rates of N in this system are similar to the net loss of nitrogen (denitrification minus N fixation). Overall, the sediment-water interface and surficial sediments in this mangrove ecosystem are very retentive of nitrogen, with the unassessed uptake of ammonium by mangrove roots an important pathway for N retention.

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## **Nutrient Dynamics and Exchange within a Mangrove Creek and Adjacent Wetlands in the Southern Everglades**

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Coronado-Molina C.

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Restoration of the Everglades and Florida Bay, as mandated in the Everglades Forever Act and associated Florida Bay Restoration legislation, is a fundamental objective of the South Florida Water Management District's Everglades Program. Current hydrologic restoration efforts for the wetlands of Everglades National Park (ENP) and Florida Bay include the C-111 Project, Modified Water Deliveries to ENP, and the Experimental Water Deliveries to ENP program. These efforts are changing both the structural and operational basis of managing freshwater flow into ENP, through its wetlands, and to Florida Bay.

A primary goal of these efforts is to understand the role of changing hydrological, chemical, and biological patterns and the influence of water management on ecological dynamics. With such predictive understanding, restoration efforts can be guided and monitoring can then document the success, shortcomings, and cost-effectiveness of restoration actions. Given the apparent nutrient enrichment of Florida Bay, as evidenced by algal blooms and the documented importance of both P and N in sustaining these blooms, nutrient exports from, or imports to, the transition zone could affect the ecology and water quality of the Bay.

The wetlands bordering Florida Bay are characterized by alternating flooding and prolonged draining. This variability results in sequential anaerobic and aerobic conditions of the sediment surface that affects chemical transformations of the soil elements. Nutrient dynamics are thus affected by the presence or absence of flooded sediments. Nitrogen transformations such as fixation, denitrification and uptake are mediated by the presence of an oxidized zone over anaerobic sediments. Denitrification is especially important as a removal mechanism of inorganic N. Another loss of N is through burial of organic material.

Our project entitled "Nutrient Exchange Between Florida Bay and the Everglades' Salinity Transition Zone" is a cooperative agreement between the District and Louisiana State University and Florida International University started in September 1995. The principal objective was to determine how water management and climate affect the exchange of water and nutrients between Florida Bay and the transitional mangrove dominated wetlands at the southern boundary of the Everglades. This transition zone is important because it may strongly affect the water quality of Florida Bay, which in turn can affect seagrass and algal dynamics in the Bay. The transition zone is also important because it is a nursery for many of the Bay's fish populations and provides habitat for wading birds. It is likely that the ecology

of the transition zone is highly sensitive to the quantity and quality of water in the southern Everglades watershed and thus sensitive to water management practices.

To date, our results demonstrate that the quantity of freshwater flow from the Everglades into Florida Bay is a primary determinant of the amount of phosphorus (P), nitrogen (N), and carbon (C) that enters the Bay from the transition zone; Most nutrient export to the Bay is in the form of dissolved organic matter; Within the creeks of the transition zone, N and C concentrations are higher in the wet season than in the dry season, while P concentrations are higher in the dry season than in the wet season; A spatially-articulated computer model simulates the hydrology and water column nutrient cycling for the Taylor River wetland system. Simulation results indicate that the TN and TP concentration in surface waters is largely controlled by flux of the organic forms of these constituents from upland and bay sources. The model shows that bay and upland inputs also constrain the concentrations of the dissolved inorganic constituents, however, there nutrient cycling within the mangrove wetland plays a greater role in the controlling the concentration of dissolved inorganic than organic nutrients.

Based on these results, N exports appear large enough to be of some concern. However, the source of this N has not been identified. In contrast, the transition zone appears to be an effective filter for P, and in some years, P may even be removed from the Bay by the transition zone. However, we do not know the circumstances under which the large store of P that exists in transition zone plants and soils could be released into the Bay. The finding of high P concentrations in transition zone surface water during the dry season implies that P may be more readily released following a drought year. A better understanding of residence time of water in the system to adjust the ratio of surface water inputs to wetland surface area are needed. This project, to date, has collected information on nutrient mobility mostly during the relatively wet years of 1996 and 1997.

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## **Nutrient Dynamics in the Mangrove Wetlands of the Southern Everglades – 5 Year Project Overview**

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Material exchanges at the land-sea interface have long been of interest not only for their importance as a source of energy to offshore ecosystems, but also for their function in the transformation of imported material. This material exchange is dependent on the “energy signature” of the corresponding coastal environment. The energy signature of the Florida Bay-Everglades system is unique among North American estuaries because of its carbonate sedimentary environment, restricted tidal regime, and sub-tropical climate. Preliminary analysis of climate data for southern Florida and review of flux studies in micro-tidal estuaries emphasize the importance of capturing temporal variation during non-local forcing events such as cold fronts and extra-tropical storms and during different seasons rather than variation during tidal cycles.

Efforts to restore the Everglades and Florida Bay largely entail changing the supply of fresh water and reducing the nutrient loads to these ecosystems. Changing fresh water inflow to the Bay may affect its ecological structure and function via several mechanisms. Our research is focused on quantifying how changing fresh water inflow affects the net transport and cycling of nutrients within the mangrove dominated ecotone between Florida Bay and the Everglades. Specific objectives were to determine the mechanistic link between freshwater flow and material exchanges, and the relationship between these ecological processes and environmental forcing. Also as part of this project, the structure and litterfall dynamics, and nitrogen use efficiency in dwarf and ridge mangrove forests were quantified to complement our understanding of the nutrient utilization cycle in this area. Understanding nutrient dynamics in this ecotone is important because this region could contain a large pool of nutrients and its role as a source or sink of nutrients may change with increased fresh water flow. Furthermore, salinity in this ecotone has a wide range and high variability. Effects of changing salinity on nutrient biogeochemical cycles should be evident in this region.

During the past five years, we have measured the net exchange of water and nutrients between Florida Bay and a major creek flowing from Taylor Slough. Concurrently, we seasonally measured some nutrient fluxes within this region of the mangrove ecotone. These nutrient fluxes include benthic-pelagic exchange in coastal ponds, mangrove island-pelagic exchange in the scrub mangrove zone, creek bank - creek exchange in the mangrove fringe zone, and mangrove prop root - creek exchange. This project was designed to examine nutrient and organic exchanges at different temporal and spatial scales. Different monitoring

efforts and experiments were implemented to investigate the temporal variation in material concentration and flux over several time scales (daily, weekly, seasonally, and annually). These exchanges were quantified at a lower scale using a flume and enclosures monitoring program. For the intermediate scale, intensive monitoring at different locations was used. Long-term analysis derives from daily synoptic sampling and water level monitoring. As a complement to the water column sampling efforts, research of the mangrove forest structure and nutrient utilization by the trees was also initiated expanding through the intermediate and long-term scales. Additionally, we measured mangrove tree growth, litter production, litter decomposition, soil respiration (carbon dioxide production, sulfate reduction, and methanogenesis), and net soil accretion in the fringe forest and scrub mangrove wetland. To synthesize this wealth of information, an ecological model was prepared to integrate the different rates and scales at which the nutrient dynamics occur.

Net movement of water across the sediment-water interface was evaluated using surface and subsurface water levels, marsh elevation, and sediment stratigraphic cross-sections. We performed bail and slug tests on wells to estimate sediment hydraulic conductivity. Sediments tend to be much lower in hydraulic conductivity in the northern portion of our study area (Argyle Henry) where it is typically clays and carbonate marl. In the south, the sediment is peat and transmits water much more rapidly. Nonetheless, we found a net negative head at both locations, indicating the mangrove wetland sediments represent a small hydrologic sink.

The mangrove creek and pond system of southern Taylor Slough is a region that processes nutrients derived both from the Everglades and Florida Bay. Concentrations of TOC, DOC, TN, and TP tend to be higher during the wet season (in the dwarf wetland) or when water flows from the south (in the fringe wetland). Inorganic nutrients are generally higher when water flows north. Nitrate + nitrite is exported and total nitrogen and ammonium is imported by the dwarf wetland. Statistical analysis of flux results indicate an effect of temperature, salinity, and concentration on the exchange of materials between the mangrove and water column. Higher concentrations generally result in increased uptake, especially for inorganic nitrogen species in the dwarf wetland.

Phosphorus concentrations in the waters of this ecotone tend to be higher than in either the fresh water slough or the bay, but net exchanges of P between the waters of this creek and pond system and its mangrove islands and sediments were of a small magnitude ( $< 1 \mu\text{mol m}^{-2} \text{h}^{-1}$ ). Net N exchanges had a higher magnitude, with DIN release from islands as high as  $30 \mu\text{mol m}^{-2} \text{h}^{-1}$  and uptake by sediments as high as  $60 \mu\text{mol m}^{-2} \text{h}^{-1}$ . The fate of nutrients in the Everglades-Florida Bay landscape may be strongly influenced by the accumulation of P and the loss of N via nitrification and denitrification within the mangrove ecotone.

Atmospheric forcing strongly influences the relationship between Florida Bay and the southern Everglades. We evaluated ecosystem effects in the Taylor Creek mangrove wetlands during four different hydrologic regimes of varying magnitudes. We observed the typical pattern of largest daily water fluxes from the mangrove zone to Florida Bay early and late in the wet season, from early 1996 through October 1997. We compared this typical wet season hydrologic pattern to a winter storm event (1996), the atypical conditions attributed to the 1997 El Niño event, Tropical Storm Harvey (1999), and Hurricane Irene (1999). Each



forcing event is marked by its difference in magnitude and duration. The winter storm of November 1996 was driven by sustained northeastern winds which forced water into Florida Bay and kept salinity down in the wetlands for 10 consecutive days. Tropical storm Harvey arrived in south Florida in September 1999 as a frontal wave and deposited about 25 cm of precipitation on the wetlands over an 8-hour period, but it did little else to affect the system. Hurricane Irene offered a much larger magnitude storm surge and higher velocity winds when it passed over the southern Everglades one month later. However, the duration of its hydrologic effects lasted only about a week. Hydrologic communication at the Florida Bay-Southern Everglades interface is critical to flushing the wetlands, delivering sediments, and biogeochemical transformations.

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Topical Question: 2 – Nutrients/Water Quality

## Patterns of Inorganic Nitrogen Flux from Northern Florida Bay Sediments

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The availability of nitrogen in Florida Bay for the production of algal blooms may be dependent upon rates of decomposition of organic matter in Bay sediments and the resultant release of inorganic nitrogen from these sediments. As part of an program to understand the ecosystem-level effects of the hydrological restoration of Florida Bay and the Everglades, we measured benthic fluxes of dissolved oxygen and nutrients near the northern coast of Florida Bay, including ponds within the mangrove ecotone. Five sites along north-south transects through Little Madeira Bay and Terrapin Bay were measured seasonally using in situ chambers from May 1996 through September 1998 and measured less frequently since then. Both dark chambers and clear chambers were used to estimate fluxes during day and night.

Nitrate plus nitrite ( $\text{NO}_x$ ) was not released by sediments at any site. Rather, the sediments consistently removed from these nutrients from the water column under both dark and light conditions. Time-weighted mean  $\text{NO}_x$  uptake by sediments (integrated day and night over a two year period) ranged from  $22 \mu\text{moles m}^{-2} \text{d}^{-1}$  to  $77 \mu\text{moles m}^{-2} \text{d}^{-1}$  at four bay sites. Higher  $\text{NO}_x$  uptake rates ( $240 \mu\text{moles m}^{-2} \text{d}^{-1}$  time weighted mean) were found at a mangrove zone pond site.

Sediments were a net source of ammonium to the water column at all bay sites, but rates were higher at central bay sites than eastern bay sites (time weighted mean release from sediments:  $290$  to  $430 \mu\text{moles m}^{-2} \text{d}^{-1}$  near Little Madeira Bay and  $790$  to  $1400 \mu\text{moles m}^{-2} \text{d}^{-1}$  near Terrapin Bay). In contrast, sediments were a net sink of ammonium in the mangrove pond site (time weighted mean uptake by sediments:  $240 \mu\text{moles m}^{-2} \text{d}^{-1}$ ). Ammonium release was much greater under dark conditions than light conditions, indicating the importance of uptake by benthic phototrophs (seagrass and algae). However, relative to rates of oxygen uptake by sediments in the dark, ammonium release was very low. Median O:N molar ratios in dark chambers ranged from 63 to 124 (O uptake:N release as ammonium) at the eastern bay sites and from 51 to 57 at the central bay sites. This ratio was negative at the mangrove pond site (because of ammonium uptake by sediments) with a median of  $-49$ . These ratios deviate greatly from the ratios expected from the mineralization of algal or seagrass detritus (between 7 and 20).

For all sites other than the pond sites, ammonium release from sediments in the dark was strongly correlated with temperature. Between temperatures of  $20^\circ\text{C}$  and  $25^\circ\text{C}$ , fluxes were very low (relative to oxygen) and net ammonium uptake frequently occurred. At

temperatures above 30°C, these fluxes were five fold to ten fold higher. This extreme temperature sensitivity and the occurrence of high O:N flux ratios may indicate the importance of coupled nitrification and denitrification as a mechanism that removes N from Florida Bay . We hypothesize that when temperatures are high (near 30°C), nitrification and thus denitrification is inhibited by low O<sub>2</sub> availability that occurs because of low O<sub>2</sub> saturation and high aerobic respiratory demand for O<sub>2</sub>. This results in large ammonium fluxes from the sediments only during the summer and early fall and these fluxes may influence the seasonality of algal blooms in Florida Bay.

In order to assess the importance of denitrification, field experiments were conducted at three sites, such that waters within dark chambers were allowed to become anoxic. At all sites, ammonium fluxes increased more than five fold immediately after anoxia occurred. Furthermore, we directly measured N<sub>2</sub> fluxes in the benthic chambers, thus quantifying the balance between denitrification and nitrogen fixation. In October 1999, median N<sub>2</sub> fluxes from the sediments in dark chambers at bay sites ranged from 102 to 320 μmoles m<sup>-2</sup> h<sup>-1</sup> (showing denitrification rates > fixation rates). These rates were three to five times higher than measured ammonium flux rates in the same chambers. Denitrification appeared to be even more important in mangrove pond sediments, with N<sub>2</sub> flux rates exceeding ammonium flux rates by eight times. These results indicate that nitrogen availability in Florida Bay is strongly influenced by O<sub>2</sub> availability at the sediment water interface and the processes of coupled nitrification and denitrification.

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## The Role of Sediments Resuspension in Phosphorus Cycle in Florida Bay

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The mass mortality of sea grass and frequent algal blooms in Florida Bay are a result of eutrophication. Existing data indicate that phosphorus is the limiting nutrient while nitrogen is abundant. Therefore the supply of phosphorus is critical to the onset and persistence of phytoplankton blooms in Florida bay. Biogenic calcium carbonates are major components of the sediments (>90%) in the Florida Bay. Our studies have shown that phosphorus is strongly adsorbed on the surface of calcium carbonate sediment. Sediments in Florida Bay can easily be suspended by storms and tidal mixing due to shallow water depth (~3 m). Phosphorus cycling processes such as release from, adsorption to and coprecipitation with suspended sediment may play an important role in the supply phosphorus to phytoplankton bloom. Our project has been focused on following three aspects:

(1). The time scales of phosphate availability through sediment resuspension in Florida Bay water and kinetic of interaction of sedimentary phosphorus with seawater. Our results indicate that the exchange of phosphate between particle and seawater is a rapid process. When sediment is suspended in seawater, phosphate weakly bounded on the particle surface release to seawater within a few minutes and maintained in seawater in absent of phytoplankton uptake. However, phosphate in seawater was found to decrease dramatically after sediments have suspended in seawater for about 20 hours. Since the surface seawater is usually super-saturated with respect to calcite and aragonite it is thermodynamically unstable and tends to form calcium carbonate precipitation. The lack of particle seeds is often the kinetic hindrance for such precipitation. Suspended sediments, therefore, provides essential seeds (solid surface) for initiating precipitation. Coprecipitation of calcium phosphate with  $\text{CaCO}_3$  scavenges the dissolved phosphate out of seawater, resulting a rapid decrease in available phosphate in seawater. Time scales of phosphate availability by sediment resuspension are crucial for onset and persistent of phytoplankton bloom.

(2). The distribution coefficients for phosphorus partitioning between sediment/seawater in Florida Bay. The partitioning of any elements between water and sediment is usually quantified by the distribution coefficient  $K_d$ . Distribution coefficient  $K_d$  of phosphorus is defined as  $K_d = C_s/C_w$ , where  $C_s$  is the concentration of phosphorus on particle surface and  $C_w$  is the concentration of phosphorus in seawater.  $K_d$  is a key parameter that governs phosphorus partitioning between seawater and particle surface. Preliminary estimated  $K_d$  is in an order of 0.1 L/g. Since Florida Bay is subdivided by mud banks into partially isolated basins, spatial variation in sediment characteristics is expected due to differences in environmental condition. Further study is underway to verify any spatial variation of  $K_d$  in

Florida Bay and the effect of salinity and temperature on the  $K_d$ . With such a systematic study, a quantitative relationship between  $K_d$  and environmental conditions can be used in a water quality model to predict the fate of input phosphorus in Florida Bay.

(3). The reactivity and partitioning of various pools of sedimentary phosphorus in Florida Bay surface sediments. We have modified the current sequential extraction method and developed procedures to overcome the alkalinity interference by monitoring the pH and using appropriate buffer solutions. With our improved method we can selectively and accurately determine the various pools of phosphorus in Florida Bay sediments. Our preliminary results showed significant spatial variation of sedimentary phosphorus in Florida Bay. The highest total sedimentary phosphorus was found in western bay area (8-9  $\mu\text{mole/g}$ ) where diatoms dominate blooms possibly as influence of Gulf of Mexico. The lowest was found in eastern bay (2-3  $\mu\text{mole/g}$ ) where low phytoplankton biomass is usually found. A sharp transition in sedimentary phosphorus concentration was found in central bay. Exchangeable phosphorus, iron-bound phosphorus and apatite and  $\text{CaCO}_3$  bound phosphorus show similar patterns of distribution as total sedimentary phosphorus. Sediment samples from Rankin Bight showed the highest detrital apatite phosphorus. Central bay shows a maximum in organic phosphorus and minimum in sedimentary iron, possibly due to the bloom production of organic matter and the reduction of ferric oxide in the anoxic sediment. Organic phosphorus accounts for about 50% of sedimentary phosphorus in center bay and decreases to about 20% in eastern and western bay. Phosphorus associated with biogenic apatite and  $\text{CaCO}_3$  accounts for 25% of total sedimentary phosphorus in Florida bay. Detrital apatite phosphorus of igneous or metamorphic origin account about 30-40% in eastern and western bay. As organic phosphorus dominates in central bay, detrital apatite phosphorus of igneous or metamorphic origin accounts only 5% in central bay. A significant fraction of sedimentary phosphorus is tied up with Fe(III) in Florida bay sediments, a linear correlation between phosphorus and Fe content in the sediment samples was found with exception of eastern bay where low phosphorus and high iron coexist. Results of this study will provide the spatial distribution of various pools of sedimentary phosphorus and iron in Florida Bay and improve current understanding of dynamic of phosphorus cycling in Florida Bay.

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## *Question 3*





## Growth, Grazing, Distribution and Carbon Demand in the Plankton of Florida Bay

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The zooplankton community of Florida Bay was examined over 4-years from September 1994 through November 1998 to determine zooplankton distribution and abundance and to allow calculation of community metabolic demands. Net-zooplankton were collected at 10 sites within the bay on a bimonthly basis using a 64 $\mu$ m net, and copepod nauplii were collected from the surface at each site using a 10L bucket and 20 $\mu$ m mesh. The net-zooplankton were split into 4 functional groups—copepods, copepod nauplii, meroplanktonic larvae, and “others”. The microplankton community was also investigated using the dilution technique of Landry and Hassett (1982). Microphytoplankton growth and microzooplankton grazing rates were determined fluorometrically at 4 sites, one in each region, from May 1997 through September 1998. Community structure within the microphytoplankton was determined using HPLC analysis. All data were used to determine if the 4 regions of Phlips *et al.* (1995), which were established based on primarily physical characteristics of the waters within each region, were applicable to the zooplankton community of Florida Bay.

The copepod community was typically dominated by 3 genera—*Acartia*, *Oithona*, and *Paracalanus*, though other genera occasionally constituted >20% of the copepod stock. The “others” category was typically composed of chaetognaths, larvaceans, medusae, isopods, flatworms, and polychaetes, with distributions and abundances varying with no obvious seasonality.

Copepods and their nauplii dominated the net-zooplankton numerically and in terms of biomass and metabolic demands. Seasonal trends were apparent for most parameters within each group, with maxima occurring most frequently during the summer or fall and minima in the winter

Daily metabolic C demand of the net zooplankton community ranged from <2% to >100% of the phytoplankton C stock. Expanding that metabolic demand by a factor of 3 to approximate net-zooplankton demands for C ingestion indicates the net-zooplankton are typically capable of consuming a significant fraction of the phytoplankton community daily, and thus exerting important controls on the biomass and composition of the phytoplankton community. Some of the parameters measured during our net-zooplankton collections sorted into the 4 regions previously identified by Phlips *et al.* (1995). Most, however, did not. None of the data from the microplankton community analysis support the 4 regions.

Microphytoplankton growth rates ranged from 0.08 to 2.33 d<sup>-1</sup> at 50% available light. Diatoms, dinoflagellates, and the cyanobacterium *Synechococcus* typically dominated the microphytoplankton community, though chlorophytes and prasinophytes were occasionally

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major constituents. Microzooplankton grazing rates ranged from 0.00 to 5.28 d<sup>-1</sup>, and their average ingestion rates ranged from 0.67 to 3.42 mg C m<sup>-3</sup> d<sup>-1</sup>. Those ingestion rates correspond to a daily ingestion demand ranging from < 1 % to >300 % of the initially available C, indicating that microzooplankton are capable of exerting a controlling influence on the phytoplankton community.

From our studies, it is clear that the zooplankton community is capable of significantly impacting the phytoplankton community in Florida Bay. The increased frequency of phytoplankton blooms suggests that zooplankton grazing rates and phytoplankton growth rates undergo periods of imbalance, the difference of which is significant enough to allow blooms to form. The cause(s) of that imbalance will likely require further research to allow their elucidation.

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## **An EOF Analysis of Water Quality Data For Florida Bay**

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The object of this analysis was to examine the underlying processes affecting nutrient cycling and the formation of algal blooms in Florida Bay. We have used Empirical Orthogonal Functions (EOFs) to find the dominant spatial patterns of variation in water quality parameters. The analysis also produces temporal variation of these pattern and shows that both local and bay-wide processes affect the concentrations of nutrients, and hence of phytoplankton, in the bay and need to be represented in models of the system.

The occurrence of phytoplankton blooms in the central region of the bay has led to concern that human activities have changed the local ecosystem. To understand these changes requires an understanding of both local and bay-wide processes. Empirical Orthogonal Function analysis is a mathematical technique for analyzing large data sets. It allows spatial and temporal distributions of variance to be ascertained. Connections can then be made between water quality parameters and external factors such as rainfall.

We used the database of water quality parameters collected by researchers at Florida International University (F.I.U.), courtesy of J. Boyer. The database covers a suite of 20 water quality variables collected at 28 stations within Florida Bay. Data at the stations were collected semi-monthly between July 1989 and December 1990, and then monthly from March 1991 to the present date.

We used a subset of the database in our analysis. We did not use data prior to 1992 since the western-most stations were not included before then. We chose a subset of water quality variables; temperature, salinity, nitrate, nitrite, ammonia, APA, Chla-*a*, total nitrogen and total phosphorus. This choice was based on the relevance of the parameters to understanding phytoplankton blooms and the completeness of the time series. Gaps in the time series that we used were filled using a one-dimensional, linear interpolation. Each resulting time series was smoothed using a 3-point Hanning filter to reduce noise and the subsequent time series were then interpolated to a regularly spaced (1/12th of a year) sequence of dates.

Two separate EOF analyses were performed. One used the covariance matrix of the data between stations to generate the EOFs, and produced spatial patterns that were very similar to the spatial distribution of standard deviations. Using the covariance matrix to generate the EOFs can skew the results because locations with large mean concentrations and associated large variances dominate the variance to be explained, even if there is a signal that is common to all locations. The other analysis used the correlation matrix of the data (*i.e.*, the data were normalized by their standard deviation before calculating the EOFs). This made the fractional change of concentration the parameter being explained in the analysis and thus decreased the importance of stations with large fluctuations in concentrations and revealed the presence of any bay-wide signal.

Our results show that the bay can be subdivided into three basic regions, confirming the results of Fourqurean et. al (1995). We also show the presence of a background, bay-wide fluctuation. This is particularly evident with nitrate and Chl-*a*. The spatial distribution of these variables using the correlation matrix show uniform variation across the bay, whereas the EOFs using the covariance matrix reveal more intense, localized patterns. The temporal variations of these spatial patterns also differs between the two analyses.

The EOFs calculated from the correlation matrix show a significant, bay-wide shift between 1994 and 1995. This is most evident in nitrite, ammonia, APA and Chl-*a*, but is not seen in nitrate. These changes correspond to increased rainfall and runoff occurring during this time. Curiously though, the system appears not to have returned to its prior state.

These results indicate that Florida Bay is responding to a series of processes affecting the area as a whole. Two examples of such processes are rainfall and wind; the former can affect salinities across the bay, and the latter changes the amount of resuspension within the bay. The response however is not uniform. Fourqurean et al. (1995) have suggested that the bay can be subdivided into three regions. These correspond the broad spatial distribution of bottom types in the bay (Prager and Halley, 1997) which range from hard, sandy bottom to thick mud layers. These materials have different resuspension properties as well as different concentrations of benthic organisms and algal mats. One hypothesis is that regional variations in water quality parameters may result from the interaction of bay-wide processes (*e.g.*, wind) and local distributions of bottom type.

The use of Empirical Orthogonal Functions clearly demonstrates the presence of both local and bay-wide processes affecting nutrient and Chl-*a* distributions in the bay.

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Question 3 – Algal Blooms.

## Development of a Silicate Budget for Northwestern Florida Bay

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Exogenous silicate input and silicate regeneration are hypothesized as important factors contributing to the development, maintenance and termination of annual diatom blooms in northwestern basins of Florida Bay and the southwest Florida inner-shelf. The Shark River is a major source of silicate to the southwest Florida inner-shelf. The reliance of diatom bloom development on the Shark River silicate flux is apparent in the timing of the diatom bloom and the inverse relationship between diatom abundance and silicate concentration. Increased freshwater flow in June, with the onset of the wet-season, provides an exogenous silicate source to the inner-shelf and stimulates diatom bloom development. Maximum diatom abundance is observed in October, when flow from the Shark River is greatest. The inverse relationship between diatom abundance and silicate concentration was most pronounced in October and December 1999. Silicate concentrations were greatest near the mouth of the Shark River and followed a decreasing gradient as water was advected southeast along the southwest Florida inner-shelf. Where diatom abundance was maximum, in northwestern Florida Bay, silicate concentrations were depleted to undetectable levels. This inverse relationship did not exist in spring, prior to diatom bloom development. In February and April 1999 netplankton chlorophyll *a* (>5  $\mu\text{m}$  size fraction) accounted for 49 and 12% of total chlorophyll *a* (chl *a*) concentrations, respectively. However, in February and April 2000, while not as pronounced, the inverse relationship between diatom abundance and silicate concentration did persist following termination of the fall-winter diatom bloom. During these months diatoms continued to represent 84 and 70% of total chl *a*, respectively.

The predominance of diatoms in near-shore waters off Cape Sable in spring contributed to silicate-limited growth conditions. Silicate enrichments made to undiluted seawater yielded netplankton growth rates of  $1.2 \text{ day}^{-1}$ , compared to growth rates of  $<1 \text{ day}^{-1}$  obtained with separate nitrogen and phosphorus enrichments. Silicate enrichment of samples in December 1999 stimulated biogenic silica production, even when silicate was not limiting to diatom growth. An increase in biogenic silica concentration, not accompanied by a similar increase in netplankton chl *a*, suggests biogenic silica production due to thickening of the silica frustule, which would provide additional material for silica dissolution.

Netplankton chlorophyll *a* concentrations off Cape Sable were greater in April 2000 than in any other month since December 1998, and may be indicative of early diatom bloom development in northwestern Florida Bay. Elevated netplankton chl *a* concentrations in April may have resulted in an exceptionally high silicate demand in spring, thus silicate-limited diatom growth. The silicate demand, which is a function of diatom standing stock, growth rate and ratio of biogenic silica:netplankton chl *a*, was greatest in October and December 1998, when diatom standing stock was greatest. Pelagic and benthic dissolution of biogenic silica provide an important mechanism by which silicate is regenerated and the silicate demand can be satisfied. Since silica dissolution is a temperature-dependent process, the warm waters of northwestern Florida Bay increase dissolution rates and reduce silicate-limited growth conditions.

The next phase of research will focus on quantification of the benthic silicate flux. Clear and opaque benthic chambers are used to measure the rates of benthic silicate regeneration and reductions in the benthic silicate flux due to removal by benthic microalgae. Preliminary investigations yielded maximum regeneration rates in dark chambers of 71.66 and 24.53  $\mu\text{mol}/\text{m}^2/\text{hr}$ , in early summer. In clear chambers, benthic microalgae reduced the respective silicate flux by 52 and 63%. Average rates of benthic silicate production of 1.27 and 0.40  $\mu\text{mol}/\text{L}/\text{day}$  were compared to the silicate demand determined for comparable months of the previous year. The benthic silicate flux measured in summer 2000 would satisfy a maximum of 94%, and a minimum of 20% of the daily diatom silicate demand measured in 1999. Pelagic dissolution of biogenic silica in northwestern Florida Bay was shown to satisfy 100% of the silicate demand in summer and approximately 40% of the demand in winter.

In the future, silicate turnover rates will be determined based on the daily diatom silicate demand, exogenous silicate supply, and silicate regeneration rates. The final objective is the development of a silicate budget for northwestern Florida Bay.

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## **Pigment-Based Chemotaxonomic Assessment of Florida Bay Phytoplankton and Periphyton**

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This report covers an extension of similar studies on the photosynthetic pigments, the chlorophylls and carotenoids, in the phytoplankton and periphyton of north-central Florida Bay ( see Louda *et al.* 1999, 2000).

Pigment-based chemotaxonomy relies upon the separation and identification of the photosynthetic pigments, chlorophylls and carotenoids, using reversed phase high-performance liquid-chromatography (HPLC) coupled to full spectra photodiode array detection (PDA). This 2D analysis (HPLC-PDA) affords excellent precision and more than adequate accuracy in the identification of dozens of these pigments in a single determination (*aka* “run”). Data obtained from the HPLC-PDA methodology is also being compared to conventional estimates made using fluorimetric and polychromatic spectrophotometry. This is especially valuable when comparing the estimates of “chlorophyll” and “pheopigments”.

Pigment ratios, specifically taxonomically specific carotenoids to chlorophyll-*a*, are being reevaluated in order to refine 1<sup>st</sup> order regression formulae generated for Florida Bay as well as to compare such data to highly reiterative programs such as “CHEMTAX”, developed for the phytoplankton of the Southern Ocean ( see Mackey *et al.*, 1996).

Cyanobacterial blooms sampled September 28 (8.5 µg-CHL*a*/L) and November 30, 2000 (11.8 – 15.4µg-CHL*a*/L) allowed calculation of the Chlorophyll-*a* to zeaxanthin (CHL/ZEA) ratio in natural populations, as very little diatom signal was present and could be quantitatively backed out. The CHL/ZEA value found was 1:1 not the 5:1 which we observed for laboratory grown cyanobacteria such as *Synechococcus elongatus* from the FMRI lab. Zeaxanthin is an extremely important marker in these waters and is a ‘non-photosynthetic photoprotectorant pigment’ (NPPP), as opposed to the ‘photosynthetic accessory pigments’ (PAP) such as chlorophyll-*b* (Chlorophyta), fucoxanthin (Chromophytes incl. Diatoms) and peridinin (Pyrrophyta) which are found in relatively well defined stoichiometric relationships with chlorophyll-*a*. Thus, knowledge of light induced alteration of CHL/ZEA is paramount to obtaining valid chemotaxonomic estimates of the phytoplanktonic and epiphytic microalgal communities in the bay.

A survey of the north-central and western portion of the bay on February 1-2, 2001 revealed several discrete zones by total chlorophyll-*a* and Chemotaxonomic evaluation. Sites in Snake Bight, between Camp and Rankin Keys (‘Rankin Key Basin’), and 4 in Whipray Basin (= ‘WRB’: Derelict Key, Dump Keys, central and southern WRB) all had total CHL*a* levels of 0.28 – 0.42 µg/L and were 100% ± diatom, except for a site in SW WRB which had a mix of diatoms and dinoflagellates (~ 70:30).

Sites extending west from the area Joe Kemp Key / Dave Foy Bank to Sandy Key Basin and northwest to middle Cape Sable had elevated CHL<sub>a</sub> levels and more diverse phytoplankton community, based on the pigments present. Chlorophytes (chlorophyll-*b*), diatoms (fucoxanthin) and cryptophytes (alloxanthin) were found in these waters and gave total CHL<sub>a</sub> values between 1.0 – 2.8 µg/L. Diatoms dominated (50-76%) in sites closest to shore between Flamingo and East Cape Sable. Chlorophytes dominated (53-65%) in a line from Sandy Basin to Middle Cape Sable. Cryptophytes were found to overlap these 2 fields in a triangle (formed by sampling spacing) at levels of 3-16% from a point half way between Middle (0%) and East Cape Sable to Sandy Key Basin to Flamingo. The highest cryptophyte populations (13-16%) were found in the trough from the middle ground to markers 9/10 off Flamingo.

Selecting 2 areas for comparison, we can reveal the applicability of pigment-based chemotaxonomy to spatial and temporal assessment of microalgal communities.

**TABLE 1:** Chemotaxonomic estimates of phytoplankton at markers 9/10 off Flamingo and in Whipray Basin, September 2000 – February 2001.

SITE DATE	PERCENTAGE					µg/L	
	CYANOS	GREENS	DIATS	DINOS	CRYPTO	SUM CHL <sub>a</sub>	CHL <sub>a</sub> -% HPLC/EST*
FLAMINGO							
09/29/00	0	0	100	0	0	4.6	132.0
11/30/00	0	0	100	0	0	1.5	98.9
02/01/01	0	10	76	0	14	2.6	87.0
WHIPRAY BASIN							
09/29/00	0	0	75	25	0	1.8	129.2
11/30/01	88/91**	0	12/9	0	0	12-15	99.5 / 104.6
02/01/01	0	0	100	0	0	0.4	96.3

\*CHL<sub>a</sub>% represents CHL<sub>a</sub> directly measured by HPLC over that estimated by back-calculation using the accessory pigment based regression formula. \*\* Represents 2 separate sites in Whipray Basin proper. Regression formula used herein follows;

$$\text{CHL}_a = (1 \times \text{ZEA}) + (2.4 \times \text{CHL}_b) + (1.2 \times \text{FUCO}) + (1.5 \times \text{PERI}) + (3.8 \times \text{ALLO}) + (3.6 \times \text{PRASIN}) \\ = \text{CYANO} + \text{GREENS} + \text{DIATS} + \text{DINOS} + \text{CRYPTO} + \text{PRASINO}$$

Studies on the macrophytes, macroalgae and their epiphytes have also begun. Host species analyzed to date include *Thalassia testudinum*, *Halodule wrightii*, *Sargassum platycarpus*, *Laurencia sp.*, *Penicillus capitatus* and *Caulerpa lanuginosa*. The host plants have been analyzed in order to establish their pigment complements and thus be able to discern host pigment contamination of epiphyte isolates. Epiphytes have been found to be vastly dominated by diatoms with lesser amounts of dinoflagellates and only traces of cyanobacteria. Sporadic occurrences of macro red algae can indeed be the biomass dominant epiphytes, when present.

Golf-ball sized cyanobacterial mounds were found in the extreme NE portion of Whipray Basin near Derelict Key. These very dark green-black mounds were comprised of about 86% cyanobacteria and 14% diatoms and formed an approximately 1mm layer over mounded homogeneous marls sediments. The sediments within this mound were a bit less hydrated than the surficial sediments in the area and were apparently deposited in growth related layers. The main interest in these ‘mounds’ comes from their possessing a highly unusual



chlorophyll (~ 15% of sum chlorophylls). This pigment is less polar than chlorophyll-*a* and is still under investigation.

These studies are aimed at assessing planktonic, benthic and epiphytic microalgal community succession as may occur during recurrent annual phytoplankton blooms and as a result of alterations to water quality, quantity and timing in conjunction with the Everglades restoration process.

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## Florida Bay Microalgal Blooms: Competitive Advantages of Dominant Species

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Florida Bay is a unique tropical shallow water habitat in southeastern United States. The bay has been historically characterized by large regions of lush seagrass meadows and a clear water column supporting a low phytoplankton biomass. Significant changes in the ecosystem have been documented since 1987 that include widespread seagrass, mangrove and sponge mortalities as well as hypersaline events, and increased water column turbidity resulting from sediment resuspension and microalgal blooms. The microalgal blooms consist of mixed microalgal populations of diatoms, dinoflagellates, flagellates and cyanobacteria. The abundance and persistence of the blooms often dominated by the cyanophyte *Synechococcus elongatus* has raised concerns about the ecological health and stability of the bay. A central question regarding these blooms would address the factors that convey a competitive advantage to the microalgal species dominating these blooms. In addition to environmental factors, it has been suggested that the differences in phytoplankton species' ability to acquire and utilize nutrients may be an important factor in the determination of phytoplankton community composition.

To begin to answer this question, the light, salinity and nutrient requirements of the following numerically dominant microalgal taxa of Florida Bay were examined; the blue green algae *Synechococcus elongatus*, an unidentified spherical blue green picoplankter, and the diatoms *Chaetoceros cf. salsugineus*, and *Cyclotella choctawhatcheeana*. The effect of salinity on the growth rates of fully acclimated populations of these species was measured over a range of 0-50 ppt, at 25 °C, 72  $\mu\text{Em}^{-2}\text{sec}^{-1}$ , under a 12:12 light:dark cycle using continuous batch culture. Distinct optima for growth were observed for *C. choctawhatcheeana* (20-45 ppt) and *C. cf. salsugineus* (10-40 ppt). While *S. elongatus* and the picoplankter did show optima (10-20 ppt), their growth rates were largely unaffected by salinity.

The acclimated growth rate in response to irradiance was determined for each of the four species at a salinity of 25 ppt, 25 °C, in a 12:12 light:dark cycle using semi-continuous batch culture. The saturation irradiance of both diatom species was approximately twice that of the two blue green species.

The kinetics of phosphorus ( $\text{PO}_4\text{-P}$ ) dependent growth was determined for each species using batch cultures at 25 ppt, 25 °C, in a 12:12 light:dark cycle at salinities (S) of 15, 25 and 50 ppt. The results were fit to the Monod model and the maximal growth rate ( $U_{\text{max}}$ ) and the half-saturation constant for growth ( $K_u$ ) were determined. At S=25 the maximal growth rates for *S. elongatus*, the picoplankter, *C. cf. salsugineus* and *C. choctawhatcheeana* were 1.38, 1.37, 2.48 and 3.37 divisions  $\text{day}^{-1}$ , respectively. The half-saturation constant was 0.004  $\mu\text{moles liter}^{-1}$  for the picoplankter, 0.044  $\mu\text{moles liter}^{-1}$  for *C. cf. salsugineus* and 0.052  $\mu\text{moles liter}^{-1}$  for *C. choctawhatcheeana*. The  $K_u$  for *S. elongatus* could not be determined as the growth rate was still maximal at the lowest concentration of phosphate measured (0.03

uM). The  $K_u$  value for *S. elongatus* was lower than all the other species at each of the three salinities. The results at  $S=15$ ,  $S=25$  and  $S=50$  showed that each species  $U_{max}$  value was found to differ with salinity as predicted from the salinity growth curve data while each species  $K_u$  value although having wide confidence intervals, did not differ significantly with salinity.

A direct experimental test of phytoplankton resource-based competition using Tilman's equilibrium theory of competition was carried out using the same four microalgal species. Equilibrium Resource Competition (ERC-theory) predicts that under P-limitation a species that is a P-specialist by having the lowest equilibrium requirement ( $R^*$ ) for P, will have a competitive advantage and will in time competitively exclude all other species with higher minimal P requirements. Each species nutrient kinetic parameters,  $U_{max}$  and  $K_u$ , was used to calculate a species competitive power ( $R^*$ ) under phosphorus limitation at  $S=15$ , 25, and 50 ppt. The ERC model calculated  $R^*$  values for each species. *S. elongatus* was ranked as the superior competitor under P-limitation at salinities of 15, 25 and 50 ppt. The superior competitive ranking of *S. elongatus* can be attributed largely to the fact that the  $K_u$  values for *S. elongatus* were so low that they could not be determined at any salinity because it maintained maximal growth rates at the lowest phosphate concentrations used (0.03 - 0.04 uM). The model ranked the picoplankter second as a phosphate competitor at all three salinities, while *C. cf. salsugineus* was ranked higher than *C. choctawhatcheeana* for two of the three salinities.

Competition experiments were carried out at  $S=15$ ,  $S=25$  and  $S=50$  under P-limitation and under N-limitation. Under each of the above two nutrient regimes (P-limitation and N-limitation) were three treatments consisting of (1) a 'steady' supply of the limiting nutrient, (2) a periodic pulse (every 5<sup>th</sup> day) of the limiting nutrient and (3) a 'steady' supply of the limiting nutrient coupled with a repeating oscillating salinity fluctuation (2.5 ppt decrease followed by a 2.5 ppt increase, cycle period of 10 days). All experimental flasks were maintained at  $D=0.2$  using semi-continuous dilution which consisted of manually removing a portion of the culture and replacing it with an equal volume of medium. In competition experiments under P-limitation, approximating steady state conditions ('steady' nutrient supply) *S. elongatus* dominated in terms of biovolume at the end of the experiment at  $S=15$ , 25 and 50, verifying the model's predictions. Because ERC-theory applies only to systems that approximate steady state conditions, and many natural phytoplankton communities are not usually characterized by steady state conditions for long periods of time, the potential role of a temporal disturbance on resource competition, through nutrient pulsing and a salinity fluctuation was also examined. Under each of these non-steady state conditions under P-limitation, at all salinities, *S. elongatus* dominated in terms of biovolume at the end of the experiment and the trends implied that given enough time *S. elongatus* would competitively displace all the other species. In summary, under both steady state and non-steady state conditions at all salinities *S. elongatus* was the superior competitor for orthophosphate. Competition experiments revealed that under N-limitation at  $S=15$  and  $S=50$ , the two blue-green algae usually codominated in terms of biovolume under steady and non-steady state conditions. Under N-limitation at  $S=25$  for all treatments, *C. choctawhatcheeana* was dominant in terms of biovolume at the end of the experiment.

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Cellular quotas are being determined for both N and P for all species and will be used to determine estimates of luxury consumption for each species, which will be helpful in understanding resource competition under non steady-state conditions. Minimum cell quotas of phosphorus normalized to cell volume were comparable between all 4 species at S=25, suggesting that the increased competitive ability of *S. elongatus* was not the result of a more efficient use of phosphorus.

Bill, Richardson, Florida Fish and Wildlife Conservation Commission Florida Marine Research Institute, 100 8<sup>th</sup> Ave S.E., St Petersburg , FL, 33701, Phone: (727) 896-8626, Fax: (727) 823-0166, [Bill.Richardson@dep.state.fl.us](mailto:Bill.Richardson@dep.state.fl.us), Question 3 – Algal Blooms

## **Inverse Analysis of Carbon Flows through the Planktonic Food Webs of Florida Bay**

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Florida Bay is a shallow coastal ecosystem that provides habitat and nursery areas for many commercially important fish and invertebrates. We used an inverse analysis approach to examine carbon flows and trophic interactions during summer and winter for two contrasting regions of Florida Bay, the eastern and north-central regions. The eastern region has variable salinity and relatively low phytoplankton concentrations, while the north-central region exhibits sporadic blooms of the picoplanktonic cyanobacterium *Synechococcus*. The objective of this research was to describe quantitatively the fate of algal production within these planktonic food webs using data from field investigations. The shallow depth of Florida Bay (< 2 m) means that links with the benthos are important, so we were particularly interested in quantifying carbon export from (or import to) the planktonic system. Our overall goal is to combine this information with on-going seagrass modeling and studies of inter-basin exchange to develop a comprehensive forward model of Florida Bay food webs.

In general, marine food webs are complicated systems with the potential for a variety of interactions that are not easily sampled or understood. Typical ecological (field) studies are able to measure only a few of the many interactions known or suspected to be occurring within an ecosystem. Solving the problem of estimating the nature of a system in the presence of insufficient data has long been an important research area. A set of techniques has evolved for inferring properties of a system when insufficient data are available to unambiguously define them, this is known as inverse analysis. Vézina and Platt (1988) first applied inverse analysis to marine ecosystems when they used the technique to estimate multiple food web interactions from a limited set of measurements. The technique incorporates available data on carbon flows through the system (e.g. rates of primary productivity, grazing or bacterial production). We reduce the number of possible solutions to the unknown flows is by applying biological constraints that include known assimilation and production efficiencies and allometric relationships from the literature.

Our Florida Bay inverse models include compartments for small phytoplankton (0.2 to ~5  $\mu\text{m}$ ; e.g. *Synechococcus*), large phytoplankton (5-200  $\mu\text{m}$ ), bacteria, protozoa (heterotrophic flagellates, dinoflagellates, and ciliates <63  $\mu\text{m}$  in size), microzooplankton (larger ciliates, flagellates, and/or small copepods 63-200  $\mu\text{m}$ ), and mesozooplankton (>200  $\mu\text{m}$ ). All living compartments add to a dissolved organic carbon (DOC) pool through excretion and can contribute to the pool of detritus. An external compartment is included for flows to and from the benthos, advective flows, and/or losses to higher trophic levels. Gross primary production (GPP) of the large and small phytoplankton was the primary carbon input, while outflows occurred due to respiration by all living compartments.

The size structure of the producers and consumers was a major determinant of the trophic dynamics of the system. Protozoa were allowed to consume bacteria, small phytoplankton and detritus. Mesozooplankton consumed large phytoplankton, protozoa, microzooplankton

and detritus. Since we had scant information about the diet of the microzooplankton, two different model formulations were used. One formulation allowed the microzooplankton to consume small phytoplankton, bacteria, large phytoplankton, detritus, and protozoa while the second allowed them to consume only large phytoplankton, protozoa, and detritus. We used field data to formulate "known" flows in the model. Biomass concentrations and phytoplankton growth rates from dilution experiments of Brenner et al. (2001) and Brenner & Dagg (unpublished) were used to calculate rates of net primary production (NPP) of phytoplankton. The community was divided into large and small phytoplankton based on data on the relative abundance of *Synechococcus* vs. other phytoplankton in Florida Bay (Phlips et al. 1999). Temperature data, rates of ingestion by microzooplankton and mesozooplankton and values for net bacterial production and abundance were also taken from the literature (Brenner et al. 2001, Cotner et al. 2000). Constraints on flows predicted by the model included assimilation efficiencies, net production efficiency of bacteria, gross production efficiencies, and upper and lower bounds on respiration, excretion, and ingestion that are based on allometric equations taken from the literature. Equations for mass balance, known flows, and constraints used in the inverse analysis were solved using programs written in Matlab.

The inverse calculations returned rates of GPP, respiration for all living compartments, grazing for all zooplankton compartments, DOC excretion, gross bacterial production (GBP), detritus dissolution rates, and export rates from the planktonic food web. In general, calculated rates differed greatly between regions but not between seasons or formulations of the model. Estimated rates of GPP varied between 15 - 180 mg C m<sup>-3</sup> d<sup>-1</sup> and were within range of those reported for similar ecosystems. Rates were highest in the north-central region in summer. Our study showed that the microbial loop (DOC-Bacteria-Protozoa) plays an important role in the cycling of carbon through the planktonic food web of Florida Bay. In the eastern region, for example, the majority of the GPP was due to large phytoplankton and carbon flowed initially to the microzooplankton and mesozooplankton. Instead of being exported from the food web, however, the majority of the carbon went to the production of DOC, either directly (through excretion by zooplankton) or through dissolution of detritus. This production of DOC was necessary to fuel bacterial production. Calculated rates of DOC excretion by protozoa, microzooplankton, and mesozooplankton agreed well with grazer-associated DOC rates published in the literature. Rates of GBP ranged from 15.6 - 62.6 mg C m<sup>-3</sup> d<sup>-1</sup> with the highest rates in the north-central region in summer. Bacterial respiration rates were estimated to be between 48-53% of GBP. Carbon export rates were highest from the north-central region in summer (82-128 mg C m<sup>-3</sup> d<sup>-1</sup>); export from the eastern region was lower by a factor of 12-14. The role of picoplanktonic cyanobacteria in the export of carbon from this system is somewhat unconventional. In the open ocean, picoplankton are usually involved in food webs based on regenerated production through the microbial loop, with larger phytoplankton playing the key role in export. However, the shallow depths and relatively high production in the north-central region of Florida Bay resulted in high export of picoplankton-derived carbon in the form of detritus, despite the active microbial loop. Variations in the dietary composition of the microzooplankton resulted in different paths of carbon within the food web but had relatively little effect on carbon export. Carbon export values calculated for the north-central region of Florida Bay are higher than those estimated for other pelagic ecosystems.

While this inverse analysis estimate flows that were consistent with observations in other systems, the technique depends on the reliability of the data used in the known equations and the equations used to constrain the calculated values. There are many possible sources of uncertainty, including difficulty in interpretation of dilution experiment results and use of non-contemporaneous data sets. Our biggest limitation while constructing these models was the lack of data for many of the interactions and flows. The advantage of the analysis, however, is that it has allowed us to identify gaps in our knowledge of the trophic functioning of Florida Bay. Characterization of the interactions within the microbial loop, particularly protozoan bacterivory and the extent of microzooplankton grazing on picoplanktonic cyanobacteria versus heterotrophic bacteria are key areas for future research.

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Question 3- Algal Blooms

## Florida Bay Microalgal Blooms

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Persistent microalgal blooms in Florida Bay have consisted of blue-green algae (cyanobacteria), diatoms, dinoflagellates, and flagellates, many of which are in the pico- to ultraplankton size ranges. These nuisance blooms can make the water turbid and potentially alter community structure and physical aspects of a subsystem's habitat. Between May 1994 and May 1997, the Florida Marine Research Institute (now a part of the Florida Wildlife Conservation Commission) maintained six permanent sampling stations in Florida Bay and also sampled additional stations (not-fixed) with the help of the Nature Conservancy's Florida Baywatch volunteers. These stations/sites were sampled monthly until May 1996; then bimonthly until May 1997. The program had field and laboratory components to evaluate environmental variables in relation to species or group composition, biomass, production, and dominant species adaptations. The central question addressed was "what regulates the onset, persistence, and fate of planktonic algal blooms in Florida Bay?"

Environmental data (including chlorophyll *a* and cyanobacterial counts/biomass) support the geographic division of Florida Bay into four zones or regions: the western region, influenced by the Gulf of Mexico waters; the north-central and south-central regions, influenced by resident microalgal populations and runoff; and the eastern region, which is less variable and does not typify the bloom area. The four regions of Florida Bay were discernable by similarity indices of biomass at the taxonomic group level, as well as the species level, using fixed station samples.

Correlation analyses show that certain environmental variables are highly correlated. Pairwise relationships between chlorophyll *a* and organic particulate load, total particulate load and inorganic particulate load, salinity and temperature, and secchi depth and water depth all were apparent. These results are based on 163 samples (data sets with missing data were removed). Ordination of these environmental data via non-metric multidimensional scaling (MDS) revealed that the north-central region is high in total particulate load, chlorophyll *a*, and organic particulate load, followed by the south-central region, then the western region, and finally the eastern region. Inorganic particulate loads are the highest in the western region.

The epicenter for the blue-green colored blooms appears to be the north-central region, which contains Rankin Basin (Sta. 4), where high chlorophyll *a* and high cellular biomass can reach  $40.58 \mu\text{g L}^{-1}$  and  $2.13 \times 10^7 \mu^3$  of blue-greens, respectively. Meteorological events such as storms and high winds can influence the spread of microalgal blooms from the north-central region to the south (Sta. 6, Twin Keys Basin) and to the west or from the west (Sta. 1,



Sprigger; Sta 2, Sandy Key; and Sta. 3, Johnson Key) to the central regions. Typically in spring, the microalgal blooms recede to the north-central basins.

Blooms of  $>20\mu\text{g L}^{-1}$  chlorophyll *a* primarily represent blue-greens in the western and south-central regions and blue-greens and large armored dinoflagellates in the north-central region. At other times in the north-central region, high biomass can be dominated by *Cyclotella choctawatcheeana*, *Synechococcus elongatus*, and *Chaetoceros* cf. *salsugineus*, with dominance shifting seasonally. Other high biomass blooms are Rhizosoleniaceae in the western region. More than 50% of the microalgae have benthic representation, either as a resting stage or directly as benthic species. It is important to recognize that our study showed co-dominance of blue-green species with other species or groups and that blue-greens dominated ( $>50\%$  of the biomass) in 16 -37.5% of samples over a 3 year period.

Analyses of 256 samples from non-fixed stations to determine group co-dominance are also being performed. These samples will be added at the group level to the other 187 samples from the fixed stations as another means of determining co-dominance by group rather than species. At the same time, we will compare the value of species, versus generic, versus group identifications in order to evaluate the level at which key factors in microalgal community structure become evident.

Presently, the cell counts for all species and the cell volume measurements for the forty most common species found among the samples have been completed and are being analyzed using the PRIMER multivariate analysis package for the entire three year dataset. Analyses, including multi-dimensional scaling (MDS) and principal component analysis (PCA) will be conducted in an effort to link environmental variables like particulate loading, salinity, temperature, chlorophyll, secchi depth and water depth with biomass, species assemblages, season, and zone using all three years of data. Patterns with the station location and dry/wet season are apparent despite inter-annual variability.

More than 205 taxa provided the dataset used in the PRIMER analyses. During this study, *Skeletonema*, which typically dominates the planktonic microalgae of estuaries was not found in Florida Bay. This absence needs to be defined in relation to species adaptations, competition, and system dynamics.

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Question 3

## **A Summary of Results from Drifter and Fixed Location House Boat Based Studies: Growth Rates, Production, Proximate Composition and Nutrient Requirements of Phytoplankton Populations during Blooms in Northwestern and South-Central Florida Bay**

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The main objective of this research program was to quantify the role of advection and circulation in the nutrient requirements of Florida Bay phytoplankton blooms. A series of four studies was initiated to achieve this goal and included drifter studies, bimonthly cruises, multi-disciplinary experiments during blooms, and diel sample collections coupled with ADCP measurements across the two major passes along the southern boundary of Florida Bay. Here we report on two of these studies: the drifter and multi-disciplinary studies.

Interpretation of the data, based on a preliminary analysis, suggests that phytoplankton populations in western Florida Bay grow at intermediate rates and may be seasonally nitrogen or phosphorus limited. Potential sources of nutrients in support of the observed growth and production remain to be evaluated.

Drifter studies were carried out during June, 1998 and July, 1999. CODE type drifters were deployed and tracked for several days. Samples were collected for growth rate determinations once a day in the morning and twice a day, at 12 hr. intervals for particulate and dissolved nutrients and proximate composition. Day to day changes in the growth rates, community particulate composition and dissolved nutrients were used to estimate production and subsequent nutrient requirements.

Multi-investigator studies (termed Houseboat experiments because we used a Everglades National Park houseboat modified as a floating laboratory by NOAA/AOML (Dr. Peter Ortner) as a base during the experiments) were carried out during phytoplankton blooms that occurred in January, 1999 in north-western Florida Bay and October, 1999 in the south-central portion of the bay. Phytoplankton community growth and production rates were done daily with twice daily particulate carbon, nitrogen, and phosphorus measurements, and twice daily total dissolved nitrogen and phosphorus concentrations.

During the June, 1998 drifter study, growth, in dialysis and cage cultures and in dilution cultures used to determine microzooplankton grazing rate, required nutrient additions. Average growth rates based on all methods were approximately 0.75 doublings per day. Results of the dilution culture experiments indicated that microzooplankton grazing was

minimal which suggests that the lack of growth in unamended bottles was due to overall nutrient limitation. Sufficient total dissolved nitrogen (TDN) was available to meet the phytoplankton nitrogen requirements but the utilizable fraction of TDN is currently unknown. Compositional ratios of the phytoplankton community were found to be approximately in Redfield proportions suggesting that the community was growing at maximal rates for the environmental conditions and that they were not nutrient limited. The flux of N and P from the Shark River or from other sources was sufficient to maintain growth but the overnight losses from advection or grazing by mesozooplankton and/or benthic filter/suspension feeders maintained the phytoplankton community at essentially steady state biomass levels.

Growth rates measured using the same techniques during the July, 1999 drifter study were negligible. This study took place within a “Whiting” event along the western margin of Florida Bay and contained a diatom dominated community consisting primarily of *Chaetoceros* species. Chlorophyll levels were highly spatially variable with values outside the “whiting” area of 0.2 to 0.5 ug/l and 4.0 to >5.0 ug/l within the “whiting”. Molar ratios of C:N ranged from 8.2 to 12; which is greater than expected from typical Redfield values (~6.0). Additional information will be added in the updated version of the abstract.

Growth rates based on cage/dialysis cultures in January, 1999 and, in October, 1999, based on *in situ* changes in phytoplankton biomass were of a similar magnitude. Growth rates calculated from changes in chlorophyll-a concentration in January, 1999 ranged from 0.1 to 0.55 doublings/day while the range obtained in October was 0.07 to 0.42 doublings/day. Carbon based growth rates estimated from *in situ* changes during the October, 1999 study were typically higher with a range over the course of the experiment (4 days) of 0.3 to 1.44 doublings/day.

During the January experiment the molar C:P and C:N ratios significantly exceeded Redfield values while the N:P molar ratio was comparable to Redfield values (~16:1). This result suggests that there was an excess of detritus in the water column yielding the elevated ratios with carbon while the N:P ratios indicate a nutrient sufficient community. Conversely the October C:P and N:P ratios were much higher than Redfield values while the C:N ratios were equivalent to Redfield. This suggests that the phytoplankton community was phosphorus limited during this bloom in south central Florida Bay.

Calculations of production and nutritional requirements are incomplete at this time. They will be included in the revised version of this abstract.

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## **Spatial and Temporal Changes in Phytoplankton Biomass, Proximate Composition, and Total Dissolved Nitrogen and Phosphorus Based on Bimonthly Cruises throughout Western Florida Bay**

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Bimonthly cruises were done in January, April, June, July, October and December of 1998, in February, April, June, August, October, and December of 1999, and February, April, and June, 2000. Samples for particulate carbon, nitrogen, and phosphorus and total dissolved nitrogen and phosphorus were collected from surface waters at approximately 35 to 43 stations (varied over the course of the study) for duplicate analyses of each parameter. The sampling regime was designed to provide information for flux calculations for a series of transects along the Florida Keys, the mouths of the major rivers entering western Florida Bay, and between the Dry Tortugas and Cape Romano (i.e. the western boundary between Florida Bay and the Gulf of Mexico). Calculation of net fluxes across the western boundary of the bay will be done in conjunction with the current meter measurements being made at fixed locations and continuously while underway with an ADCP (acoustic doppler current profiler) by Dr. Tom Lee; Univ. of Miami.

Although all samples for the 1998 cruises, except the DON samples, have been analyzed and all particulate and total dissolved phosphates for 1999 have been analyzed we must still complete analysis of samples for particulate carbon and nitrogen and the DON samples collected during the last three cruises before data interpretation can be finalized. Preliminary analysis indicates that particulate and dissolved nitrogen and phosphorus concentrations along the western boundary are typically low but vary seasonally with higher values during the summer and fall. Particulate carbon and nitrogen concentrations and the C:N ratio increase dramatically in near shore waters across the salinity gradient at the mouths of the rivers indicating elevated input of detrital carbon into coastal waters. TDN and TDP concentrations are also elevated at river mouths indicating these location are a source for the N and P required to support phytoplankton blooms in western Florida Bay. However, based on analyses done to date, the TDN is primarily DON which suggests little anthropogenic input. TDP concentrations varied spatially and seasonally with lower values during winter and spring and higher concentrations during the fall and off river mouths. The concentration of TDP during the summer/fall season more than doubled (~1 uM average for the entire area) relative to winter/spring.

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## *Question 4*



## A Comparison of Seagrass Die-off in Barnes Key and Sunset Cove, Florida Bay

**B.A. Blakesley et al.**

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In the summer of 1987 an acute die-off in dense, apparently “healthy,” seagrass beds in the central and western basins of Florida Bay resulted in the loss of more than 4,000 ha of *Thalassia testudinum* Banks ex König (turtle grass) and it also affected an additional 23,000 ha (Robblee et al., 1991). *Thalassia* appeared to be the only seagrass affected by the die-off and during this event large mats of *Thalassia* were reported floating on the water surface (M. Durako, pers. comm.). Blade lesions were reported in *Thalassia* in the area by Porter and Muehlstein (1989). No definitive cause(s) was determined, but many possible etiological factors were proposed, including high temperatures and salinities, overdeveloped seagrass beds, elevated sediment sulfide levels, hypoxia, and disease (Robblee et al., 1991; Durako and Kuss, 1994; Carlson et al., 1994).

Chronic seagrass mortality in Florida Bay continued into the 1990's. In the spring of 1995 a study was initiated to investigate this mortality and develop health criteria for seagrass in Florida Bay. Information on diseases in seagrass is minimal, with the exception of documentation of wasting disease, caused by the slime mold *Labyrinthula*. Virtually no work has been done on viruses or many of the other possible pathogens which probably affect the health of seagrass. Because of the omnipresence of lesions with *Labyrinthula* in our *Thalassia* samples from areas in Florida Bay experiencing seagrass losses, our studies soon focused on the distribution of blade lesions in *Thalassia* and the associated distribution of the slime mold *Labyrinthula* (Blakesley et al., 1996; Landsberg et al., 1996). During this study (spring of 1995 to spring 1999), no acute seagrass die-offs were observed in Florida Bay. However, there were continuing losses of *Thalassia* especially in the basins where the initial acute die-off was reported in 1987-89 (Blakesley et al., 1996, 1999a; Hall et al., 1999). The data collected both during this field study and from associated laboratory studies (Blakesley et al., 1998) resulted in the formulation of a hypothetical model describing the effects of the seagrass parasite *Labyrinthula* on *Thalassia* in Florida Bay (Blakesley et al., Florida Bay Conference, 1999b). At this same conference a recurrence of acute die-off of *Thalassia* was reported in western Florida Bay near Barnes Key (Mike Robblee, Paul Carlson, pers. comm.). As in the acute event of 1987-89, *Thalassia* appeared to be the only seagrass affected and the die-offs were occurring in dense, apparently “healthy” seagrass beds. Carlson reported that seagrass affected by the new acute die-off exhibited symptoms like that of the 1987 event i.e. the lateral meristem tissue appeared to be the tissue most immediately affected. Meristem tissue seemed mushy and smelled like “mustard” while the rest of the blade looked green and healthy. At that meeting, an effort was made to coordinate research in the affected area and develop methods for monitoring and studying the event to determine the cause(s) of the die-off. Beginning in early winter, 1999 an investigation of the new acute seagrass die-off in Barnes Key was initiated to try to readdress the question first asked and unresolved 12 years before; why did the *Thalassia* suddenly start dying in Florida Bay?

The theoretical model had suggested 3 different roles that *Labyrinthula* might play in Florida Bay under different environmental conditions. These included: (1) a nonpathogenic parasite; (2) an opportunistic secondary pathogen; and (3) a primary pathogen. Five different factors were discussed as critical elements in determining the role(s) of *Labyrinthula* in seagrass health at a particular site in Florida Bay (Blakesley et al., 1999b). **Salinity** controls infection (infection does not occur at < 15 ppt). **Seagrass density** determines the extent to which *Labyrinthula* infection spreads because the slime mold transmission is thought to depend on blade-to-blade contact (Muehlstein, 1992). **Pathogenicity** of a particular strain of *Labyrinthula* will determine severity of infection. **Environmental stressors** (abiotic factors) such as low light or high temperatures may weaken *Thalassia* and, in combination with the infection by pathogenic *Labyrinthula*, cause seagrass die-off. **Resistance to disease** due to genetic factors or production of phenolic compounds may be important in determining the health of *Thalassia* in Florida Bay. The model predicted that in areas with high seagrass density, high salinity, “suboptimal seagrass conditions (environmental stress)”, and presence of pathogenic *Labyrinthula*, the slime mold could contribute to either chronic or acute die-off acting as an **opportunistic secondary pathogen**. With the same conditions, but without environmental stress, it was suggested that *Labyrinthula* could still cause “thinning” or patchy die-off acting as a **primary pathogen** (Blakesley et al., 1999b).

The recurrence of an acute die-off in Barnes Key presented an opportunity to test a portion of the theoretical model by comparing the symptoms and progression of an acute event in the Barnes Key mudbank area with the symptoms and progression of what we believed to be chronic die-off in Sunset Cove. We hypothesized that in Sunset Cove *Labyrinthula* acted as a primary pathogen in an environmentally unstressed site whereas in Barnes Key *Labyrinthula* more likely played the role of a secondary pathogen in an environmentally stressed site.

At each of the two study sites three, 150 m transects were laid out and boundaries of vegetative change (dense and sparse *Thalassia*, stubble, and bare as well as presence of *Halodule* and drift algae) were marked with surveyor flags and positional data collected at each visit (every 2-6 weeks). In addition, sediment sulfide levels were measured in the different vegetative zones and estimates of both lesion presence and severity as well as Braun-Blanquet abundance were made at each vegetative boundary. Periodically, estimates were verified by shoot counts and videotaping. In addition, a total of 9 die-off patches were marked at the Barnes Key site. At five of these sites extensive measurements were made of sediment sulfide levels, seagrass productivity, and sediment depth. Seagrass abundance was estimated along with lesion presence and severity in bare, margin, 1 m dense, and 2 meter dense zones. In addition, samples of “healthy” and “diseased” *Thalassia* blade, meristem, and rhizome tissue were collected and fixed for histological and TEM analyses to look for possible unknown disease organisms. As previously mentioned, very little is known about seagrass disease and the processing and analyses of these tissues is ongoing.

Comparisons of results for the Sunset Cove and Barnes Key sites revealed that although active die-off was occurring in both places, the sites were very different. At both sites the pattern of die-off was patchy, suggesting disease processes rather than a physical process as the primary cause. Both sites had high salinities (> 15 ppt) and dense *Thalassia* beds -



necessary elements for *Labyrinthula* infection and transmission. However the data from the two sites revealed important differences summarized below:

Barnes Key	Sunset Cove
Seagrass loss is rapid Meristem “rots” Lesions occur <i>after</i> die-off Water temps are high in summer “High” sediment sulfide levels (up to 7,000 µM) Levels vary in different zones with highest values found in active die-off zones.	Seagrass loss is slower Meristem “healthy” Lesions occur <i>before</i> die-off Water temps are “normal” “Low” sediment sulfide levels (≤ 1600 µM) in bare, sparse, and dense seagrass zones.

These differences strongly suggest that the mechanisms for the die-offs in Barnes Key and Sunset Cove are not the same. We propose that the acute die-off in Barnes Key results from a series of events beginning with heat stress and an initial infection/disease (not *Labyrinthula*-induced) which rapidly kills the infected seagrass. The resultant large amount of decaying below-ground biomass from the rapidly dying *Thalassia* roots and rhizomes promotes microbial activity that in turn elevates the sediment sulfide levels selectively in those vegetative zones where the die-off is occurring or has recently occurred. We believe that the high sediment sulfide levels do not kill seagrass outright, but instead further stress the other seagrass in the immediate area. Finally, *Labyrinthula*, acting as an opportunistic secondary pathogen, infects the already weakened remaining seagrass. We propose that the chronic die-off in Sunset Cove is directly related to the presence of the slime mold *Labyrinthula* acting as a primary pathogen. Sediment sulfide levels may remain relatively low in all the vegetative zones tested simply because the slowly dying *Thalassia* roots and rhizomes result in a smaller decaying below-ground biomass so that the sediment sulfide levels may remain relatively low in contrast to the Barnes Key scenario. Such chronic seagrass die-off is still ongoing in many parts of Florida Bay where the *Thalassia* beds are dense enough for transmission of the disease and the salinity is high enough for infection to occur.

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## **Seagrass Dieoff in Florida Bay: Meristematic Anoxia, a Mechanism for the Initiation of Primary Seagrass Dieoff**

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Seagrasses were first observed to dieoff in Florida Bay in the fall of 1987. The dieoffs occurred only in the continentally influenced *Thalassia testudinum* beds, and then only in exceedingly dense beds. Sparse and medium density beds were not affected by the primary seagrass dieoff, although many succumbed during the secondary, eutrophic driven phase.

While the specific areas experiencing dieoff were subjected to a varying mix of environmental stresses, including high salinities, high temperatures in the late summer and throughout the fall, high BOD due to excessive blade loss from banks and subsequent decomposition, and chronically high sulfides in the sediments. A conceptual model formulated to organize these phenomena (Zieman, Fourqurean, and Robblee) noted that primary dieoff occurred largely in the fall and winter and not in the summer. This is a time when water temperatures and therefore respiration are held high by high water temperatures, while light intensity and day length are decreasing. Studies in Denmark linked *Zostera marina* dieoff to meristematic anoxia and a series of experiments were conducted to determine if this occurred in Florida Bay seagrasses.

Diel measurements were made in November *in situ* in stable *Thalassia* beds near Porjoe Key and in Rabbit Key Basin, and in a very dense beds experiencing primary dieoff in southern Twin Key Basin north of Barnes Key. Additionally detailed profiles from the water column to the sediments were made for oxygen, pH, and sulfide.

In at all stations meristematic oxygen pressure showed typical diel patterns. At this latitude and time of the year, oxygen pressure declined with decreasing light in the late afternoon, and reached a minimum near 06:00. After that values rose sharply as the light increased and reached atmospheric oxygen pressure between 09:00 and 11:00. At Barnes Key and Porjoe Key, all meristematic values remained positive and oxygen was present at all times. At Barnes Key two of the samples were taken at the periphery of a dieoff site and one at the center of the site. The Barnes Key sites showed much more rapid declined of oxygen in the evening than the other stations and all reached anoxia. The peripheral sites were near anoxic for five hours and anoxic for at least one hour. The sample in the middle of the dieoff zone was near anoxic for over 1.5 hours and anoxic for five hours. In the morning these stations on

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average were much slower to show positive oxygen production, and by 14:00, two of the samples did not reach equilibrium oxygen pressure of 0.21 atm. At no time did the water column oxygen pressure decline lower than 50% atmospheric pressure.

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## **A Preliminary Investigation of Below Ground Productivity in *Thalassia Testudinum* within Florida Bay**

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Viable estimates of below ground productivity in *Thalassia testudinum* are logistically difficult to obtain, but are necessary for the accurate modeling of total plant elemental budgets. While below-ground biomass exceeds above-ground biomass by many times in south Florida, below ground production in seagrass beds is generally thought to be close to or possibly greater than above ground production. This study is a preliminary investigation of the relationship between quantifiable above-ground plant parameters and below ground production and biomass.

Morphology and growth dynamics of *Thalassia testudinum* were measured from June to September 2000 in a monospecific seagrass bed in Florida Bay. Individual short shoots in 10 x 10 cm quadrats were tagged and individual leaves were marked and measured to determine leaf width and elongation rate. Measurements were repeated throughout the summer at time intervals ranging from 3 to 12 days. New leaves were marked with a unique identifier allowing for an estimate of individual short shoot leaf plastochrone interval. At the conclusion of the measurement period a .25 x .25 meter sod was removed to extract the tagged short shoots. The following structural components were quantified for each of the tagged short shoots: rhizome diameter, internodal distance and other structural components of the rhizome and below ground portion of the short shoot. Short shoot age was estimated by counting leaf scars and this data was used to estimate the short shoot PI. These measurements were taken to test the hypothesis that quantifiable above ground characteristics can be related to below ground productivity in *Thalassia testudinum*. Skewness and kurtosis confirm that the (preliminary) age frequency distribution is skewed in this study population. Short shoot scar measurement ranged from a minimum of 2 and a maximum of 108 scars, with an average of 21.72 scars. Another preliminary result shows high variability in the number of scale leaves between successive short shoots. While 51.2 % of samples did have rhizome scale leaves that numbered 9, 11, or 13, the remaining percentage are made up of counts as high as 23, and as low as 5 scales. If viable this study will yield a method that will make estimation of below ground production more feasible and easily accessible.

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## **Coastal and Estuarine Data/Document Archeology and Rescue for South Florida**

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The Coastal and Estuarine Data/Document Archeology and Rescue (CEDAR) locates unpublished documents and data related to the South Florida by contacting academia, Federal, state and municipal governments, industry, and non-profit organizations and individuals. A database of found materials has been created containing the following data: full bibliographic information (author, title, year, funding agency, pagination, key words, etc.); physical location of original material; physical state of original materials (mimeograph, photocopy, etc.); and summary. Priorities for data or document restoration of the found material will be establish based on topic (chemical measurements, physical measurements, assessment studies, contamination evaluation, anthropogenic damage, monitoring, restoration efforts and results, and dredging) and geographical coverage (Biscayne Bay, Florida Bay, Florida Keys and coral reefs offshore, St. Lucie Estuary, Ten Thousand Islands, Dry Tortugas, Tampa Bay, and Apalachicola Bay). Primary coastal environments of interest include estuaries, bays, mangrove forests, seagrasses, and coral reefs. Conversion of priority data and documents into electronic form and publication in printed form and on the Internet will co-occur with data and document search.

Documents rescued are available online as full text pdf files at the CEDAR site resident at the NOAA Miami Regional Library Internet site:

<<http://www.aoml.noaa.gov/general/lib/CEDAR.html>>.

The search for unpublished material continues. Please contact one of the authors if you know of unpublished data or documents related to the coastal environment of South Florida, specially material dated before the 1970s.

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## **Recovery Potential of Seagrasses in Florida Bay: The Contribution of Phytoplankton Blooms, Sediment Resuspension, and Epiphytes to Light Attenuation**

**P. R. Carlson, Jr.**, L. A. Yarbrow, B. J. Peterson, J. Davis and B. Davis.

To assess the potential for seagrass recovery in Florida Bay, we have continuously measured subsurface and bottom PAR at seven stations in Florida Bay since fall 1998. In addition to continuous light data, we collect discrete water samples monthly for analysis of turbidity, color, chlorophyll and total suspended solids and plant samples for epiphyte light attenuation measurement. Diffuse attenuation coefficients vary seasonally and among basins within Florida Bay: attenuation is higher in winter than in summer and generally higher in the basins which lost large amounts of seagrass in die-off episodes between 1987 and 1991. Persistent phytoplankton blooms in the north-central region of the Bay are associated with high ( $>3$ )  $K_d$  values, but water clarity at most sites was higher in 2000 than in 1999. Epiphyte attenuation is higher in winter and spring (30-50%) than in summer and fall (15-30%), and values are higher in the eastern region of the Bay ( $>40\%$ ) than in the west (ca. 20%). Calcium carbonate derived from calcareous algae and resuspended sediment comprise more than half of the epiphyte load.

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## Photosynthetic Characteristics of *Thalassia testudinum* Measured *in situ* in Florida Bay: A Tale of Leaves, Lesions, and Locations

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A recurrence of rapid mortality of the seagrass *Thalassia testudinum* Banks ex König (turtle grass) has been observed recently at several locations in Florida Bay. The recent die-offs resemble those first observed during the period from 1987 to 1989, which subsequently resulted in more than 4,000 ha of seagrass beds being lost, and an additional 23,000 ha having been affected (Robblee et al., 1991). The current die-off also appears to be most severe in areas that previously supported very dense *Thalassia*-dominated populations. Low-density areas and the sparse, *Thalassia*-dominated, populations of the lower salinity basins in northeast Florida Bay continue to be unaffected by this phenomenon. Die-off patches in the Barnes Key area and Sunset Cove have been spreading, resulting in a contagious distribution pattern which seems to be dependent on short-shoot density and, possibly, shoot-to-shoot contact.

An endemic species of *Labyrinthula* has been suggested as the possible cause of the Florida Bay *Thalassia* die-off (Porter and Muehlstein, 1989; Durako and Kuss, 1994). *Labyrinthula* is the most common eucaryotic micro-organism isolated from affected *Thalassia* during, or shortly following, die-off episodes (Porter and Muehlstein, 1989; Barbara Blakesley, personal communication). This marine slime mold is related to the pathogenic species *L. zosterae* Porter and Muehlstein, which is the causative agent of the catastrophic wasting disease of the temperate eelgrass, *Zostera marina* L. (Muehlstein et al., 1988). The *Labyrinthula* sp. from Florida Bay also produces blackened, necrotic lesions similar to those symptomatic of wasting disease (Porter and Muehlstein, 1989). Durako and Kuss (1994) investigated the effect of *Labyrinthula* infection and the resulting lesions on the photosynthesis versus irradiance (P/I) responses leaf segments obtained from field-collected *Thalassia* short-shoots. They found that infection by *Labyrinthula*, as evidenced by necrotic leaf lesions, decreased the photosynthetic capacity of *Thalassia* leaves, thereby reducing the amount of oxygen available for transport to belowground tissues. Maximum photosynthetic rate,  $P_{max}$ , decreased to below zero when lesions covered 25% or more of the leaf tissue. In addition, respiration rates in infected leaves were up to three times greater than in adjacent, uninfected tissue. Reduced oxygen transport to roots and rhizomes resulting from infection by *Labyrinthula* may increase their susceptibility to hypoxic stress and sulfide toxicity, both of which have been hypothesized to play important roles in the die-off process (Carlson et al., 1994). High sulfide levels in sediments have been observed during, and after, die-off episodes (Carlson et al., 1994). However, photosynthetic rates in *Thalassia* increase as a function of increasing sulfide up to 6 mM, and sulfide levels up to 10 mM have failed to produce visual signs of acute sulfide toxicity in lab bioassays (Erskine and Koch, 2000). High sulfide levels have been shown to result in reduced leaf elongation rates (Erskine and Koch, 2000).



In this study, a submersible pulse amplitude modulated fluorometer (Diving-PAM) was used to investigate photosynthetic characteristics of *Thalassia testudinum* leaf material *in situ* at several locations in Florida Bay, including short-shoots adjacent to, and within, recent die-off patches. Chlorophyll *a* fluorescence, quantum yield, and electron transport rate estimates were obtained from varying positions along leaves, from leaves of differing ages (ranks), from leaves with and without visible lesions, and from leaves on shoots within, and adjacent to, die-off patches.

Maximum chlorophyll *a* fluorescence ( $F_m'$ ) in response to short pulses of saturating light and quantum yield ( $(F_m' - F)/F_m'$ ) were significantly lower near the tips of leaves compared to the middle and basal regions. Mean quantum yield did not significantly differ as a function of leaf rank, although the variability of the quantum yield data did increase with leaf age. Electron transport rates (ETR) were not significantly different among leaf positions ( $184 \pm 69$ ,  $214 \pm 66$ , and  $212 \pm 64$  for top, middle, and bottom, respectively) or leaf ranks ( $150 \pm 104$ ,  $193 \pm 75$ , and  $196 \pm 50$ , for ranks 1, 2, and 3, respectively), but were consistently lowest for leaf tops and youngest (rank 1) leaves. Measured leaf absorption factor (AF) values were lower than the AF of 0.84 used as the instrument default value to calculate ETR. Although measured AF values were significantly lower for the youngest (rank 1  $AF = 0.67 \pm 0.03$  sd) leaves compared to rank 2 ( $AF = 0.78 \pm 0.04$  sd) & rank 3 ( $AF = 0.77 \pm 0.04$  sd) leaves, this did not result in significant differences in corrected ETR values among leaf ranks. Based on these data, subsequent PAM fluorescence measurements were standardized to be taken from the middle portion of the rank 2 (2<sup>nd</sup> youngest) leaf of a short shoot.

Chlorophyll *a* fluorescence and photosynthetic characteristics of *Thalassia* from Sunset Cove and Cross Bank were significantly lower for regions of the leaf that had visible lesions. This pattern agrees with that previously reported by Durako and Kuss (1994). However, close interval PAM fluorescence measurements along an individual leaf with several visible lesions indicated that the reductions in photosynthesis were restricted to the immediate area of the lesion. Quantum yield and ETR values of lesion-free leaf regions of short-shoots declined along a transect from a dense, apparently-healthy bed to a recent die-off patch. The photosynthetic characteristics of solitary short shoots within the die-off patch were significantly lower than those of shoots along the ecotone and shoots 1 m inside the bed. It is unknown whether the patch was continuing to decline or was in a recovery phase. These results, in combination with the recent findings of tolerance to high sulfide exposure by *Thalassia* (Erskine and Koch, 2000), provide additional support for the hypothesis of Durako and Kuss (1994) that reduced photosynthetic capacity, caused by *Labyrinthula*-induced lesions, make *Thalassia* susceptible to sulfide toxicity and hypoxia, possibly by imposing a negative carbon drain on belowground tissues. The PAM data reveal that the severity of stress imposed by the leaf lesions will be a function of the proportion of total leaf surface that is necrotic and it remains to be determined what is the lethal threshold for lesion coverage.

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## Recent Seagrass Dynamics in Florida Bay

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Seagrasses are the dominant biological community within Florida Bay. Recent losses of seagrasses in Florida Bay have undergone at least two phases: the first phase being the initial die-off which occurred during the relatively dry and clear period of 1987 to early 1991. Several years after the initiation of the seagrass die-off, Florida Bay began exhibiting widespread and chronic turbidity. The increase in turbidity, which began during the fall of 1991, was principally due to cyanobacteria-dominated phytoplankton blooms and resuspended sediments associated with the loss of seagrasses in the central and western basins and banks. The turbid conditions have complicated measurements and interpretations of seagrass losses and changes in species' distributions between changes due to die-off versus changes attributable to light limitation. Because of increasing concerns regarding the extent and magnitude of seagrass changes within Florida Bay, and the need to assess the effects of water management alterations associated with the South Florida Ecosystem Restoration Program on this dominant biological community within the Bay, we initiated the Fisheries Habitat Assessment Program (FHAP) during spring 1995.

Sampling for FHAP is conducted twice per year, during spring and fall. Each of ten basins, representing a range of conditions and gradients in Florida Bay, were partitioned into approximately 30-35 tessellated hexagonal grid cells. Sampling-station locations are randomly chosen from within each cell, for a total of about 330 stations per sample period. This type of sampling design results in systematic random sampling, it scales the sampling effort to the size of the basin, and it is well-suited for interpolation (i.e., kriging) and mapping of the data. At each station, seagrass cover is visually quantified within four, haphazardly-located 0.25m<sup>2</sup> quadrats using a modified Braun-Blanquet frequency/abundance scale (Mueller Dombois and Ellenberg, 1974). Seagrass distribution and abundance and changes in abundance are estimated using a contouring and 3D mapping program. The geostatistical gridding method of kriging has been used to express the spatial trends in the Braun-Blanquet data. To assess changes in total species abundance, planar areas for each cover class were calculated and a dimension-less estimate of the total abundance of a species within a basin is then obtained by multiplying the planar area for each cover class by the cover-class midpoint and adding the resulting values together.

Despite seagrass die-off and the presence of widespread, chronic turbidity since 1991, *Thalassia testudinum* has remained the most widespread and abundant seagrass species in Florida Bay. However, the relative total abundance of *Thalassia* in the ten basins sampled by FHAP dropped from being over 5 times that of *Halodule wrightii* Ascherson in spring 1995 to being less than 3 times more abundant in spring 2000. Most of this change in relative abundance has been due to dramatic increases in *Halodule* distribution and abundance over

this time period. Bay-scale *Thalassia* abundance exhibited very little change ( $\pm 8\%$  of the mean) from spring 1995 to spring 2000, although there were some substantial changes in *Thalassia* abundance within individual basins ( $\pm 30\%$  of the mean, range 12 to 101%). This is in dramatic contrast to the more than doubling in total *Halodule* abundance over this same time period, with the greatest increases occurring in the western basins and in Blackwater Sound in northeast Florida Bay. Total abundance of *Halodule* has increased over 450% in Johnson Key (JKB) and Rabbit Key Basins (RKB); since spring 1997, *Halodule* has become the most abundant seagrass within JKB.

During fall 1996, the small-bodied, low-light adapted species, *Halophila engelmannii* Ascherson (star grass), was observed at one station in Johnson Key Basin; by spring 1998 this species was present at 15 of the 32 stations. The fall 1998 sampling was initiated nine days following the passage of hurricane Georges over the Florida Keys. Many uprooted fragments of *Halophila* were observed floating in the wrack and drifting along the bottom in JKB and it was present at only 5 stations. The other seagrasses in Florida Bay seemed relatively unaffected by this storm, although loss of senescent leaves, reduction in epiphytes, and less leaf litter on the bottom were observed. During spring 1999 and 2000, patches of *Halophila* were observed in Rankin Lake, Whipray Bay and Twin Key Basin, in addition to JKB. This rapid increase in spatial distribution suggests that the hurricane may have played a role in distributing propagules. In the spring 1999 core samples, reproductive short-shoots of *Thalassia* were present at 19 sites in 7 basins, spanning most of the Bay. Reproductive short-shoots of *Halodule* were also observed at 24 sites in 4 of basins, but for this species the reproductive shoots were all in the western part of the Bay.

Declines in abundance of *Thalassia* along the western margin of the Bay have been offset by increases in central and eastern basins. *Halodule* has exhibited consistent increases in abundance and is now present in all ten basins sampled by FHAP. The dramatic increases in *Halodule* in the Bay may reflect its lower light requirements and ability to rapidly spread into areas where the *Thalassia* canopy has been removed. In addition, the first-time observation of fruits of *Halodule* in Spring 1999 core samples from several basins, indicates that conditions in the Bay have become favorable for sexual reproduction in this species. Recruitment and spread of another low-light adapted and small-bodied seagrass, *Halophila engelmannii*, in the western basins indicates that the major seagrass community response in Florida Bay following die-off and chronic turbidity is a change to a more shade-adapted seagrass community.

The initial seagrass die-off is generally thought to have been initiated in the interior basins of the Bay (Robbee et al., 1991), however, the spatial patterns of change from 1995-2000 suggest that the most dynamic environment, is along the western Bay margin, bordering the open waters of the Gulf of Mexico. Management and restoration efforts need to be responsive to the fact that the greatest changes in the dominant biological community within Florida Bay are presently occurring far from the Everglades/Florida Bay land/sea interface.

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## **The Statistical Relationship between Benthic Habitats and Water Quality in Florida Bay**

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Extensive modifications to the natural flow of freshwater through the Everglades ecosystem have been made over the past 70 years. These modifications have drained water from historic freshwater marshes and sloughs and diverted water that once flowed through the Shark and Taylor Sloughs to Florida Bay. The ecological consequences of this diversion have never been fully explored, but it is clear that the diversion has changed the flux of organic matter to Florida Bay as well as the amount and variability of freshwater runoff and salinity of the bay. Paleoecological evidence is mounting that the flora and fauna of the bay may have changed as a result of engineering of the Everglades watershed. It has also been suggested that reduction in the variability and amount of freshwater runoff has caused a “marinization” of Florida Bay, leading to changes in the species composition and biomass of the seagrass beds of Florida Bay. Human alteration of freshwater flow has also been implicated as a potential cause of the recent dieoff of seagrasses in western Florida Bay; but this contention remains an untested hypothesis.

Because of the sensitivity of Florida Bay to freshwater inflows, it is widely held that changes in water management may cause further changes in the biota of Florida Bay. Unfortunately, there are a few tools available to predict changes in Florida Bay that may occur under various management scenarios. This project provides a method for predicting the changes in benthic habitats in Florida Bay that would likely result from Restudy scenarios.

Present-day Florida Bay supports one of the most extensive seagrass beds in the world, with over 2000 km<sup>2</sup> of seagrass. Species composition and density of seagrasses in the bay are controlled by salinity, sediment accumulation and phosphorus availability. Seagrasses are sensitive to changes in water quality; in fact major losses of seagrasses have been attributed worldwide to declining water quality. Because of this sensitivity and their ecological importance, seagrasses can be used as sentinel organisms to assess water quality. Recovery of seagrass habitat in degraded areas is also a goal of many restoration efforts, since seagrasses are known to contribute significantly to the high productivity of many estuaries (e.g. Chesapeake Bay). In Chesapeake Bay, statistical relationships between water quality variables and seagrass survival have been used to establish “habitat criteria” for the survival of seagrasses (Dennison et al. 1993); these criteria have in turn been used to set goal for restoration efforts. We expand on the habitat criteria approach to develop a tool for predicting the response of Florida Bay to changes in water management practices: we

develop a series of relationships that will predict the probability of a given type of benthic habitat will occur under a water quality regime.

There is a spatial pattern to water quality in Florida Bay. In general, the mangrove-lined upper estuaries experience greater variability and lower mean salinity; while the western margin of Florida Bay within Everglades National Park has a much more constant salinity. Average depth also increases from east to west; water depth along with water clarity control the amount of light reaching the benthos. The amount of light reaching the bottom is a primary determinant of seagrass biomass. Phosphorus availability increases from east to west in Florida Bay, and phosphorus controls biomass of both seagrasses and phytoplankton in the bay. Currently-funded monitoring programs collect data on the temporal and spatial variability of water quality, and allow for a spatially-explicit description of the water quality regime. We use data from the SFWMD-ENP funded water quality monitoring program at FIU, as well as more frequent data from Everglades National Park's marine monitoring program, to describe means and variances of water quality variables. We apply modern multivariate data-reduction techniques to determine which water quality parameters describe independent modes of variation in the water quality data set. Statistically-independent water quality parameters are used in conjunction with spatially-explicit maps of benthic habitat type to develop a discriminant function that will allow for the prediction of the probability of occurrence of distinct habitat types under a given water quality regime.

Distinct benthic habitat types will be determined using the species distribution data that is being collected in four separate, but coordinated, monitoring programs. Data from three of these programs has recently been compiled to generate the first detailed maps of the spatial distribution of seagrasses in south Florida (Fourqurean et al. in press). Cover and abundance data from these monitoring programs are used to define naturally-occurring assemblages on benthic plants that define distinct benthic habitat types. We used a clustering algorithm to define subsets of stations with similar plant communities. Our knowledge of the data suggests that these habitat types will be distributed in spatially distinct areas of the bay; indeed habitat types have been used to describe the zonation of Florida Bay. The habitat types will be the groups used to create the discriminant function describing the most probable habitat type to occur.

The statistical models developed in this project will be used in conjunction with output from other models to predict the effects of Restudy scenarios on the benthic habitats of Florida Bay. It must be noted that this project will not address the mechanisms or degree of change in water quality that results from Restudy scenarios; other models (like the NSM, FATHOM, and the Florida Bay salinity transfer function models currently employed by the Restudy) must simulate water quality change across Florida Bay that will provide the input to the new models developed in this project. As a consequence, we anticipate that the benthic habitat change predictions of our models will be the most reliable in the regions most closely coupled with water management practices, i.e. in the enclosed, mangrove-lined estuaries on the fringe of Florida Bay. As the fidelity of the physical water quality models to the behavior of the system declines, the benthic changes predicted by our model will also decline. But, since the statistical relationships will be based on data from more marine areas as well as upper

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estuaries, the basic relationships between actual water quality (not modeled) and benthic habitats will be robust.

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## **Epiphytic Light Attenuation on *Thalassia testudinum* in Florida Bay**

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Seagrass growth models indicate that ambient light and those factors affecting light levels at the leaf surface are principal factors determining the distribution of seagrasses. Seagrass ecosystem modelers have expressed a critical need for quantitative relationships between epiphyte loading and light transmission to the leaf surface. Presently, the accurate determination of epiphytic light attenuation suffers from the lack of standard methodologies for the various plant types. Investigators attempting to measure epiphytic light attenuation on seagrasses have measured light transmission through glass microscope slides, suspended epiphyte slurries, Mylar strips, and intact seagrass leaves.

This investigation has measured epiphytic light attenuation using Mylar strips and a light attenuation measurement apparatus that has been successfully employed by investigators in Australia and Chesapeake Bay. The Mylar strips have been set out within various seagrass meadows across the bay for a sufficient time period to allow for the accumulation of epiphytic organisms. Distinct epiphytic communities consisting of benthic diatoms, coralline red algae (*Melobesia membranacea*, *Hydrolithon farinosum*), and filamentous red and brown algae occur seasonally in various regions across Florida Bay. These various epiphyte functional forms, and combinations thereof, result in differing levels of light attenuation at the leaf surface relative to the amount of epiphyte loading. These light attenuation characteristics of the various epiphyte communities will be discussed in relation to the regional and temporal distribution of the community types and those factors affecting epiphyte accumulation (e.g., seagrass leaf productivity, elevated nutrient availability, grazer abundance).

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## Morphometric Variability in *Thalassia testudinum*

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The importance of seagrass habitats and the key role they play in coastal ecosystems has led to increased efforts to quantify their annual productivity and growth dynamics to gain insight into the health of coastal ecosystems. Allometric relationships may provide a basis for prediction of species succession patterns and seagrass productivity from simple morphometric characteristics. In *Thalassia* many of these characteristics are subject to environmental conditions and are possibly suitable for evaluating the ecological condition of *Thalassia* beds and the coastal habitat (ecoindicators). Changes in structural characteristics, such as leaf length, width, and shoot-specific leaf area, may indicate response to environmental conditions at intermediate time scales between acute and chronic stress. Also, leaf size and area may be affected by shoot density.

Leaf morphometrics and biomass of *Thalassia* short-shoots were examined in quantitative core samples taken from yearly spring sampling at more than 300 stations in ten basins of Florida Bay, which represent a continuous gradient of conditions across the bay. Shoot-specific characteristics, such as leaf length and width, and area-specific characteristics, such as standing crop (above-ground biomass) and leaf area index (a measure of leaf area and plant density), were examined to determine how these characteristics vary among basins within this system, and to determine how these characteristics are affected by density. Leaf length and width were shown to vary within this system, and the relationship between leaf length and width, leaf area, and leaf weight of *Thalassia* were described. These allometric relationships changed with plant density.

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## Seagrass Distribution and Cover Abundance in Northeast Florida Bay

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The Miami-Dade County Department of Environmental Resources Management has maintained a routine benthic vegetation monitoring program in northeast Florida Bay since October 1993. The program was established in cooperation with the South Florida Water Management District and was initiated to monitor the downstream affects of changes in water management practices for the east Everglades and Taylor Slough. The monitoring program has been modified over the last seven years to improve spatial coverage, standardize sampling methodologies, and to expand the study region. The study currently utilizes a probabilistic stratified random sampling methodology similar to methods used by other seagrass researchers working in the Florida Bay ecosystem.

The study area includes ten basins in the region from Little Madeira Bay east to U.S. Highway 1, as well as Manatee Bay and Barnes Sound located east of U.S. 1. Sampling is conducted bimonthly at a total of 96 randomly selected stations located in the following twelve basins: Little Madeira Bay, immediately south of Little Madeira Bay, Alligator Bay, Davis Cove, Trout Cove, Joe Bay, Highway Creek, Little Blackwater Sound, Long Sound, Blackwater Sound, Manatee Bay, and Barnes Sound. At each station benthic cover was evaluated at four randomly placed 0.25m<sup>2</sup> quadrats using a modified Braun-Blanquet Cover Abundance Scale (BBCA) (Table 1). When possible, additional measures of seagrass shoot and blade density were also collected. Physical water quality characteristics such as temperature, pH, dissolved oxygen, specific conductance, and salinity were also recorded at each site using a calibrated Hydrolab multi-meter.

Table 1:  
Braun-Blanquet Cover-Abundance (Magnitude) Scale

BBCA VALUE	OBSERVED % COVER	MEAN % COVER	ABUNDANCE
5	> 75	87.5	ANY
4	50 to 75	62.5	ANY
3	25 to 50	37.5	ANY
2	5 to 25	15	ANY
1	< 5	2.5*	NUMEROUS
0.5	< 5	2.5*	LOW
0.1	< 5	2.5*	SOLITARY
0	ABSENT	0	ABSENT

Represents an assigned value

Evaluation of data for the most recent one-year period ending December 31, 2000 shows that *Thalassia testudinum* was the most widely distributed seagrass in the study region. *T. testudinum* was found in ten of the twelve basins visited and at 430 of 573 (75%) stations sampled during this period. Average annual BBCA cover abundance values in basins where

*T. testudinum* was found ranged from 1.86 to 3.41 (estimated 15 – 37.5% cover). The highest average basin cover abundance for *T. testudinum* was noted in Manatee Bay while the lowest was observed in Long Sound (Table 2). *T. testudinum* was not present in Joe Bay or Highway Creek, which are somewhat isolated basins located in the extreme northern portion of the study area. *Halodule wrightii* was also widely distributed, being found in all twelve basins visited and at 383 of 573 (66.8%) stations sampled. Average annual BBCA cover abundance values for *H. wrightii* ranged from 0.3 to 2.09 (estimated 2 – 15% cover). The highest annual average basin cover abundance for *H. wrightii* was seen in Long Sound (Table 2). *Ruppia maritima* was very sparsely distributed, being found in only four of the twelve basins visited and at only 67 of 573 (11.7%) stations sampled. Average annual BBCA cover abundance values for *R. maritima* ranged from 0.13 – 1.16 (<5% cover) in basins where it was present. The highest annual average basin cover abundance for *R. maritima* was seen in Highway Creek (Table 2).

Beginning in August of 1999 an isolated area of *T. testudinum* die off was observed in the northern portion of Little Madiera Bay from the mouth of Taylor River extending out to the south and west. Historically, this area supported populations of very dense *T. testudinum* with green algae (*Batophora oerstedii*). This area experienced a rapid and catastrophic decline in both seagrass cover abundance and shoot density. In one affected sampling region, BBCA cover abundance and shoot density values for *T. testudinum* decreased from 5 and 868 shoots/m<sup>2</sup> in July of 1999, to 0.5 and 0 shoots/m<sup>2</sup> respectively, in August of the same year. Recent field surveys have shown a gradual re-colonization by *R. maritima* and *H. wrightii* in the area of the dieoff. The effects of this die off can be seen when comparing the average annual BBCA cover abundance values for the three seagrasses for 1999 and 2000. Average annual BBCA cover abundance for *T. testudinum* in Little Madeira Bay dropped from 3.74 in 1999 to 2.87 in 2000 while values for *H. wrightii* and *R. maritima* increased from 1.18 and 0.06 to 1.45 and 0.21. (Table 2 and Table 3)

Table 2:  
Average Annual BBCA Cover Abundance (January 2000 – December 2000)

Basin	<i>T. testudinum</i>	<i>H. wrightii</i>	<i>R. maritima</i>
AB	3.06	0.45	0.00
BS	2.55	0.66	0.00
BW	3.10	0.30	0.00
DC	2.83	0.91	0.00
FB	2.33	0.48	0.00
HC	0.00	1.33	1.16
JB	0.00	1.55	0.59
LB	2.03	1.34	0.00
LM	2.87	1.45	0.21
LS	1.86	2.09	0.13
MB	3.41	0.42	0.00
TC	3.03	0.82	0.00

Table 3:  
Average Annual BBCA Cover Abundance (January 1999 – December 1999)

Basin	<i>T. testudinum</i>	<i>H. wrightii</i>	<i>R. maritima</i>
AB	3.43	0.56	0.00
BS	2.72	0.56	0.00
BW	2.89	0.34	0.00
DC	2.91	0.83	0.00
FB	1.88	0.53	0.00
HC	0.00	0.72	0.55
JB	0.00	1.27	0.41
LB	2.25	0.85	0.00
LM	3.74	1.18	0.06
LS	2.09	1.94	0.04
MB	3.81	0.60	0.01
TC	2.98	0.88	0.00

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## **Phosphorus Uptake and Alkaline Phosphatase Kinetics of *Thalassia Testudinum* and Epiphytes in Florida Bay**

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### Introduction

Although phosphorus (P) limitation appears to control primary productivity and growth of *Thalassia testudinum* the dominant seagrass in Florida Bay, particularly in the NE region of the Bay, no data exists on P uptake kinetics. P uptake kinetics of *T. testudinum* epiphytes are also unknown. In addition to inorganic P acquisition, the ecological significance of surficial alkaline phosphatase activity (APA) as a source of bio-available phosphorus to *T. testudinum* and its associated epiphytic community has not been addressed. In a series of experiments, we determined the above components of seagrass P-uptake kinetics.

### Methods

#### Whole plant P-uptake Experiments

Whole-plant 2 compartment (shoot and root) microcosm chambers (50 cm height X 12 cm diameter; 4 L upper compartment, 2 L lower compartment) with five individual plants in each chamber were employed to quantify P uptake kinetics of roots and leaves over a wide range of P concentrations (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 5.0, 7.0, 10.0, 15.0, 25.0, and 30.0  $\mu\text{M PO}_4^{3-}$ ). This range allowed us to examine the affinity of leaves and roots for P at low Florida Bay ambient P concentrations, and quantify the saturation kinetics based on concentrations 2 orders of magnitude greater than ambient levels. P uptake rates were determined in the light and dark, and under opposite chamber high and low P levels. Uptake rates were calculated based on the slope of P concentration change over 10 hr incubations sampling each hour.

#### Epiphyte P-uptake Experiments

Epiphyte inorganic P uptake experiments were conducted with *T. testudinum* blades with attached epiphytes, *T. testudinum* blades free of epiphytes, and with detached epiphytes alone. Plants were spiked with similar inorganic P concentrations used in the above whole-plant experiments (0.5, 1.0, 1.5, 2.5, 5.0, 10.0, and 25.0  $\mu\text{M PO}_4^{3-}$ ) plus ambient Florida Bay water  $\sim 0.2 \mu\text{M PO}_4^{3-}$ . Each treatment was incubated under light and dark conditions. All treatment incubations were conducted using 300 ml BOD bottles and incubated for a total of 2 hours. In order to decipher between abiotic and biotic epiphytic P uptake, additional experiments were conducted amending bottles with Mercuric Chloride ( $\text{MgCl}_2$ ).

#### Leaf and Epiphyte APA Experiments

Two study sites were selected in eastern Florida Bay for analysis of APA kinetics of *T. testudinum* and its epiphytic community: Little Madeira Bay (LMB) considered an oligotrophic site and Sunset Cove (SC) considered a eutrophic site. Seagrass with attached epiphytes and surface water were collected at the LMB and SC sites on three occasions,

December 4, 1999, April 23, 2000, and Sept 19, 2000. Assays were conducted in 60 ml glass BOD bottles using an artificial seawater medium with *p*-nitrophenyl phosphate (*p*NPP) at 5, 50, 200, 350, 500, 650, 750, 800 and 1000  $\mu\text{M}$  *p*NPP levels for one hour. Ambient available phosphomonoesters (PME) in the water column were also assayed from the two sites.

#### *P*-uptake and Enzyme Kinetic

To calculate inorganic P uptake and APA kinetic parameters, Michaelis-Menten plots of P or APA ( $[S]$  vs  $v$ ) were linearized using both the Eadie-Hofstee transformation ( $v/[S]$  vs  $v$ ) and the Lineweaver-Burk double reciprocal plot. Enzyme kinetic parameters,  $K_m$  and  $V_{\max}$ , were calculated as the negative slope and y-axis intercept, respectively, for the Eadie-Hofstee transformation. In the Lineweaver Burk double reciprocal plot, the x-intercept is equal to  $-1/K_m$ , while the y-intercept is equal to  $1/V_{\max}$ . These parameters were then used in the Michaelis-Menten non-linear equation ( $v = V_{\max}[S]/K_m + [S]$ ) to recalculate P uptake parameters by reiteration and best fit. The Michaelis-Menten equation was also used with *in situ* PME concentration ( $[S]$ ) to calculate a theoretical hydrolytic velocity for APA of *T. testudinum* and its associated epiphytic community.

#### Results and Discussion

##### Whole plant *P*-uptake Experiments

Across a broad range of nutrient levels (0.5 to 25  $\mu\text{M}$  SRP), *P*-uptake ( $\mu\text{mol g DW h}^{-1}$ ) rates in the leaves were similar in the light ( $V_{\max}$  1.90-3.80;  $R^2=0.92$ ) and dark ( $V_{\max}$  2.10-3.60;  $R^2=0.94$ ). Under this same broad range of P, root *P* uptake rates declined slightly (30%) in the dark, and were significantly lower than the leaves under both light ( $V_{\max}$  0.57-0.96;  $R^2=0.82$ ) and dark ( $V_{\max}$  0.38-0.63;  $R^2=0.85$ ) conditions. Interestingly, at P concentrations more indicative of Florida Bay (0.05 - 5.0  $\mu\text{M}$  SRP), nutrient uptake rates ( $\mu\text{mol g DW h}^{-1}$ ) were similar between roots and leaves and, consistent with the above results, were not light-dependent. A lower  $V_{\max}$  was found for the low P range in both leaves (0.50-0.77;  $R^2 = 0.66$  light and 0.93 dark) and roots (0.38-0.63;  $R^2 = 0.77$  light and 0.92 dark), indicating a potential 2-phase kinetic, one under high and one under low P levels. Calculating the affinity for P, using the linear slope of the initial rise in uptake rates across the low P concentration range (0.5 - 2.0  $\mu\text{M}$ ), provided an indication of the potential for *P*-uptake in Florida Bay pore- and surface-waters characterized by very low ( $< 2.0 \mu\text{M}$ ) inorganic P availability. In the May experiments, leaf P affinities were 2-fold greater (slope = 0.19 and 0.23, dark and light respectively) than those of the roots (slope = 0.09 and 0.10, dark and light respectively), while in November non-significant differences in *P*-uptake rates were seen in the leaves compared to roots. When opposite compartment chambers were amended with 10-fold greater P concentrations (0.5 versus 5.0  $\mu\text{M}$  in root and 0.1 versus 10.0  $\mu\text{M}$  in leaf), no significant differences were observed in the uptake rates of either the leaves or roots.

##### Leaf and Epiphyte APA Experiments

Multiple standard units were used to compare P uptake rates between seagrass leaf blades and epiphytes, because of the high inorganic content of epiphytes (75%). Leaves, leaves + epiphytes, and epiphytes alone were normalized to biomass (g DW), organic carbon (mg C g DW<sup>-1</sup>), and blade area (nmol cm<sup>-2</sup> hr<sup>-1</sup>). Both leaf (6.7 to 13.6  $\mu\text{mol g DW h}^{-1}$ ) and epiphytes (5.6 to 15.7  $\mu\text{mol g DW h}^{-1}$ ) had similar ranges of  $V_{\max}$ , while the leaf+epiphytes together

consistently had a lower  $V_{\max}$  (2.8 to 5.6  $\mu\text{mol g DW h}^{-1}$ ), potentially a function of the greater weight associated with both biotic components without an increase in the P uptake rate. On a leaf area basis, P  $V_{\max}$  increased in the following order: leaves (34 to 79  $\text{nmol cm}^{-2} \text{h}^{-1}$ ), leaves + epiphytes (55 to 107  $\text{nmol cm}^{-2} \text{h}^{-1}$ ), then epiphytes alone (111 to 217  $\text{nmol cm}^{-2} \text{h}^{-1}$ ). Apparently, greater surface area of epiphyte to surface area of leaf area contribute to the high epiphyte uptake rates. High organic C associated with leaves versus epiphytes also gave a pronounced increase in epiphyte uptake compared to the leaves and leaves associated with epiphytes. A further examination of epiphytic P uptake with and without HgCl<sub>2</sub> indicated that the P uptake was biologically mediated, in fact, P was released when biotic activity halted.

#### P-uptake and Enzyme Kinetic

Average APA maximum reaction velocity ( $V_{\max}$ ) was higher in leaves with epiphytes (79  $\mu\text{mol g}^{-1} \text{AFDW hr}^{-1}$ ) than in leaves with epiphytes removed (50  $\mu\text{mol g}^{-1} \text{AFDW hr}^{-1}$ ), suggesting greater total enzyme concentration in the leaf-epiphyte consortium than in the seagrass leaves alone. APA and water column SRP concentrations, as well as ambient organic substrate PME concentrations were not significantly different between Sunset Cove and Little Madiera Bay sites. However, PME concentrations were found to vary considerably on a seasonal basis. The winter analysis showed average PME concentrations of  $0.372 \pm 0.076 \mu\text{M}$ , over three times those of ambient SRP ( $0.107 \pm 0.0076 \mu\text{M}$ ). *In situ* alkaline phosphatase P remineralization rates varied between 0.246 and 2.181  $\mu\text{mol P g}^{-1} \text{AFDW day}^{-1}$ , reflecting differences in the ambient PME concentrations and kinetic parameters utilized in the Michaelis-Menten equation. Seagrass leaves with epiphytes had phosphate regeneration rates two to three-fold higher than leaves without epiphytes.

#### Conclusion

The above studies, along with providing important kinetic data on seagrass P uptake in Florida Bay, show the important role of seagrass leaves and their associated epiphytic consortium in acquire inorganic and organic P from the water column, even at extremely low P concentrations.

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## **Seagrass Habitat Recovery and Everglades Restoration: Use of an Ecological Model to Assess Management Strategies in Florida Bay**

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An ecological model was developed of the *Thalassia testudinum* community in Florida Bay in order to investigate two questions: 1) what are the mechanisms by which *Thalassia* can thrive at high rates of productivity and levels of biomass in an oligotrophic environment?; and 2) what are the effects of single and multiple simultaneous environmental stressors on biogeochemical processes of the *Thalassia* community? It is known that vascular plant communities in temperate, mesotrophic systems are well supplied with nutrients required for their observed high productivity. It is less apparent how tropical plant communities growing in oligotrophic karstic systems can sustain productivity at levels as great or greater than their temperate counterparts. Similarly, aquatic vegetation in tropical systems is impacted by environmental factors, natural and anthropogenic, which are likely to differ from those in temperate systems, where impacts are better understood. We have developed a heuristic numerical model, spatially averaged, and configured to represent two distinct regions in northern Florida Bay, one receiving Everglades fresh water inflows, and the other more removed from Everglades influence. The model includes the primary flows and processes that are likely to bear on questions of *Thalassia* productivity and die-off.

Processes in the model include: *Thalassia* salinity and temperature optima, nutrient availability and uptake kinetics in roots and shoots, light requirements, light availability and utilization, epiphyte loading, and sulfide effect on production. State variables are: *Thalassia* above-ground biomass, below-ground biomass, epiphyte biomass, sediment organic carbon, porewater phosphorus, and porewater sulfide. Simulations were run for three years. The baseline model successfully reproduces the pattern of *Thalassia* growth and biomass observed in two regions (Little Madeira Bay and Rankin Lake) for 1996 and is robust within the observed range and variability of environmental parameters.

The mechanism by which *Thalassia* is able to grow well in oligotrophic environments was examined using the model to calculate nitrogen (N) and phosphorus (P) demand from observed productivity rates and determine likely pathways of nutrient supply and availability. Supply rates of porewater P and complexed P in sediments was varied to test responses in *Thalassia* growth. Relationships between environmental change and *Thalassia* productivity was also tested by varying salinity, temperature, porewater sulfide, and water column nutrient concentrations. Scenarios were developed along projected variations that may result from hydrological changes due to Everglades restoration activities, as well as potential climatic variations due to global warming.

In order to test the importance of three potential pathways of P supply to the plants, each pathway (recycling/remineralization, dissolution of P-complexed carbonates, and P inputs from Everglades inflows), was sequentially set to zero and/or varied across a range in the model. Input of recycled P from decomposition of autochthonous organic material was the major factor contributing to growth of *Thalassia*. With complete removal of continuous inputs of recycled P, growth of *Thalassia* declined dramatically, reduced by over 45% in one year and 75% within 3 years. When recycled P inputs were reduced by half, biomass declined by 40% after three years. Dissolution of P from sediments and carbonate rock was also found to be a substantial factor contributing to *Thalassia* growth and biomass in the model. Lacking inputs of P from dissolution, *Thalassia* growth was reduced by 20% after one year and by 30% after three years. Inputs of P via Everglades inflows contributed minimally to *Thalassia* growth. Reductions in advective P supply at times resulted in increased *Thalassia* biomass as epiphyte growth became nutrient limited.

Responses of *Thalassia* to environmental parameters in Little Madeira Bay and Rankin Lake were evaluated. Two-fold increases in average salinity did not significantly impact *Thalassia* growth in Little Madeira Bay, as during most of the year, salinity levels remained within the optimal range for *Thalassia*. However, in Rankin Lake, where baseline salinity values were initially higher, a two-fold increase raised salinity beyond optimal limits, resulting in a biomass decline of 60% after one year and 75% after three years. Increasing water temperatures by six degrees C stimulated biomass production in winter months at both sites. This was compensated by decreased production in summer months, also a function of parameter shift with reference to the optimal range. Thus, although growth patterns were dramatically altered, total annual production remained unchanged. With a 10 degree C increase, representative of localized quiescent conditions occasionally observed in Florida Bay, annual production declined by 55%.

Model analysis showed *Thalassia* to be very sensitive to porewater concentrations of sulfide. At both sites, a 2.5-fold concentration increase caused annual biomass reductions of over 40%. When multiple stressors (temperature, salinity and porewater sulfide) were applied simultaneously, biomass was reduced by over 50%. In scenarios of increased advective inputs of P and N, epiphyte biomass could be stimulated significantly, reducing growth rates of *Thalassia* by attenuation of light. Epiphytes were highly responsive to advected P inputs and only minimally to N because P is present in limiting concentrations. However, the two sites exhibited different sensitivities to nutrient elevations. In Little Madeira Bay, a 5-fold increase resulted in a 20% reduction in *Thalassia* biomass in the first year, reaching a new equilibrium at that level over three-year simulations. In Rankin Lake, *Thalassia* was insensitive to nutrient multiples and even 10-fold increases resulted in no significant biomass decline. Examination of input data reveals that in 1996 in Rankin Lake, dissolved P was significantly lower than in Little Madeira Bay during the summer. Epiphyte increases did not exceed a critical density, allowing continued *Thalassia* growth even at elevated nutrient levels. An interesting corollary result in all scenarios was the strong impact of plant processes on phosphorus concentration in porewaters. Due to rapid recycling and uptake of P by plants in the model, reductions in *Thalassia* biomass and productivity resulted in reduced nutrient demand, and rapid accumulation of P in porewaters. Conversely, when

*Thalassia* productivity increased, porewater P concomitantly decreased, to potentially limiting levels.

We feel that simple models can be a powerful means by which to test hypotheses about ecological systems at both local and regional scales. Furthermore, employing fundamental physiological processes and ecological relationships allows the extrapolation of model responses over a broad range with relative confidence, and the accurate simulation of processes with time-sensitive responses. Such model simulations can be performed in hindcasting and forecasting modes. Hindcasting is of interest as part of the effort to understand the combination of factors that led to the well-known *Thalassia* die-off event beginning in 1987. Forecasting is valuable in assessing probable effects of changes in nutrient, organic and salinity regimes associated with restoration. In addition, the model can be employed in this mode as a tool for determining appropriate design of upstream restoration plans currently underway to optimize impacts on the downstream seagrass community.

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Research

## **Branching Frequency of *Thalassia testudinum* Banks ex Konig as an Indicator of Growth Potential within Ten Basins of Florida Bay**

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*Thalassia testudinum* Banks ex Konig (turtle grass) comprises a decreasing percentage of the marine angiosperms in Florida Bay within the Everglades National Park boundaries. Many factors have been attributed to the loss of this species since 1987. The Fish-Habitat Assessment Program (F-HAP) was established to provide insight into the temporal and spatial distribution of seagrasses and macroalgae as well as morphometrics and demography of *T. testudinum*. Each basin within the park boundaries has specific morphometric and geographic characteristics, which affect the growth of *T. testudinum*. Light penetration to the leaf blades varies as a function of depth and turbidity, and the occurrence of the marine slime mold *Labyrinthula* has been shown to affect photosynthetic characteristics of *T. testudinum*. Each of these factors plays an important role in the potential for growth into new or previously inhabited areas of these basins. This monopodial species is meristem dependent. Excess carbon is needed to proliferate the apical meristem for lateral growth and spread. Basin-specific characteristics provided information regarding the growth responses of this species as a function of available light or presence of *Labyrinthula*. Investigation of the apical meristem density has a potential use as an “ecoindicator,” giving insight to the potential for loss or gain of seagrass density within these basins.

Sampling in FHAP was conducted twice a year in the spring (April/May) and fall (October/November) from the Spring of 1998 to the Spring of 1999. The ten basins sampled represented a gradient of conditions across the Bay within the ENP boundaries. Each basin contained approximately thirty stations that were located within a tessellated hexagonal grid system. Stations were located through the Global Positioning System (GPS). Physical parameters, temperature, depth, salinity (conductance), secchi depth, and water depth were measured at each station. Ten short shoots were collected from every station to be examined by the Aquatic Health Team from the Florida Marine Research Institute for the presence of *Labyrinthula*. Core samples (15cm diameter) were taken from each station during the spring sampling provided morphometric and density data. Biomass is at its seasonal maximum due to the flowering of *Thalassia*. Apical and shoot density data were recorded. Branch frequency was calculated from the number of rhizome apicals/ number of short-shoots per station. The typical branching pattern was approximately .24 or one apical branch produced every four short-shoots. The relationship between rhizome branching and shoot density changes was examined. Advanced Very High Resolution Radiometer (AVHRR) satellite imagery was used to obtain the average surface reflectance (which corresponds to turbidity) for the corresponding spring sampling seasons. This may provide a more realistic assessment of depth in terms of its effect on available light.

Multiple regression and correlation were used to verify observed trends within each basin of the environmental and physical parameters indicated. Preliminary regressions ( $p < .0001$ )

indicate density dependence in both the Spring of 1998 and the Spring of 1999 among apical and shoot densities ( $R^2$  values of .61 and .42 respectively). Branch frequency from both the Spring of '98 and '99 was found to have significant dependence on shoot density ( $p = .0001$ ). Although the relationship of branch frequency as an indicator of density fluctuation from the spring of '98 to the spring of '99 was significant ( $p < .0001$ ), the R-Square value of .12 was low. These data together may indicate increases in branching only in areas of low short shoot densities. *Labyrinthula* was found to have significant influences on branching frequency ( $p = .03$ ), shoot density ( $p = .004$ ), and apical density ( $p = .033$ ). Low R-square values may also be affected by density dependence. Further investigation is needed. PCA and cluster analyses will be performed to determine the environmental or physical factors controlling *Thalassia* growth patterns within and between each basin.

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## A Landscape-Scale Seagrass Model for Florida Bay

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We are developing a hierarchical approach to modeling the interaction between plant and physical processes in the Florida Bay that involves two distinct spatial scales – the demographic unit (ca. 10 m<sup>2</sup>) and the landscape unit (ca km<sup>2</sup>).

Plant processes are modeled at a spatial scale ca. 10 m<sup>2</sup>, the spatial scale that we refer to as the demographic unit. We have developed a model of *Thalassia* that explicitly relates patterns of photosynthesis, respiration and carbon allocation to environmental conditions that include salinity, temperature, PAR and nutrient availability.

Physical processes such as sedimentation, decomposition and nutrient cycling are modeled on a spatial scale of km<sup>2</sup>, defined as the landscape unit.

The approach provides a hierarchical framework where the demographic units used to simulate plant processes exist in the context of the landscape units, which will define the underlying physical environment. The plant characteristics that are relevant to the feedbacks with the physical environment, such as primary productivity, inputs of dead organic matter, etc. are described statistically for the demographic units and used to define the biological environment for each landscape unit. In this manner, the framework functions as a dynamic, interactive GIS where each parameter and process is described and simulated at the appropriate time and space scale.

Initial simulations of Rabbit Key Basin will be presented that examine patterns of standing biomass and net primary productivity. Model experiments include longer-term responses of productivity and plant cover to temporal variations in environmental conditions, as well as, spatial analysis of recovery following simulated disturbances.

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## **Geochemical Monitoring of Productivity in Florida Bay**

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Monitoring changes in biogeochemical processes provides a mechanism for measuring early response of the Florida Bay ecosystem to environmental perturbations. We have performed seasonal measurements of productivity associated with representative benthic substrate types in Florida Bay to begin establishing baseline rates before significant changes occur during restoration. Monitoring changes in productivity during implementation of restoration plans will allow resource managers to evaluate the progress and success of South Florida restoration efforts. Carbonate environments such as Florida Bay are characterized by three primary biogeochemical processes including 1) carbonate sediment production by calcifying organisms and dissolution, 2) photosynthesis and 3) respiration (referred to collectively as productivity). These processes are sensitive to changes in water quality including salinity and nutrients, and show distinct rate changes before visual evidence of environmental disturbances such as seagrass die-off, algal blooms, and shifts in ecosystem success indicator species. Water management practices in South Florida have already been altered in an effort to restore the Everglades and Florida Bay. Resulting changes in water chemistry will first affect biogeochemical processes, and may, subsequently, result in changes in species distributions (such as seagrass, algae, etc.).

Carbonate sedimentation and organic productivity (calcification, photosynthesis, and respiration) are most effectively determined from precise, in situ measurements of alkalinity, pH, temperature, conductivity, and air:sea CO<sub>2</sub> and O<sub>2</sub> gas fluxes. Net productivity was determined on seagrass beds in basins located in the western bay near Buchanan Keys and in the central bay near Manatee Keys during March of 1999 and 2000 and during September of 1999, and on mud-bottom and hard-bottom (soft corals and small hard corals, sponges, calcareous algae) communities during March 2000. A large incubation chamber called the Submersible Habitat for Analyzing Reef Quality, or SHARQ, was used to isolate water over the substrate and to measure temporal changes in key geochemical parameters over 24 hour time periods. Productivity in the water column was determined in March 2000 by isolating a mass of water inside of the SHARQ from the substrate by placing a floor in the incubation chamber. Geochemical parameters including pH, dissolved oxygen and temperature were measured continuously using a flow-through analytical system throughout the duration of incubation periods. Water samples were removed every 4 hours from sample ports for total alkalinity measurements. Dissolved oxygen, pH and alkalinity data were used to calculate average rates of net calcification, photosynthesis, and respiration for light and dark hours. Productivity on mud-banks located at Russell Bank was measured during March and September of 1999 and March of 2000 using an upstream/downstream sampling strategy. Changes in key geochemical parameters were determined by identifying unidirectional currents across Russell Bank and establishing upstream and downstream sampling sites along 200-400 meter bank transects. Average rates of net calcification, photosynthesis and respiration were calculated from total alkalinity, pH, dissolved oxygen, air:sea CO<sub>2</sub> and O<sub>2</sub> gas fluxes, salinity, temperature, and wind measurements taken every 4 hours during 24 hour time periods at each sampling site.

Rates of calcification for Buchanan Keys Basin and Manatee Key Basin seagrass beds indicate net dissolution of carbonate sediments during March 1999 and 2000 and September 1999. The average rate of net photosynthesis during daylight hours for Buchanan Keys Basin seagrass beds is 0.071 g carbon/m<sup>2</sup>/hr with values ranging from 0.04 to 0.08 g carbon/m<sup>2</sup>/hour. Net photosynthesis values for Manatee Key Basin seagrass beds ranged from 0.005 to 0.13 g carbon/m<sup>2</sup>/hour with an average of 0.069 g carbon/m<sup>2</sup>/hour. Average rates of respiration during night hours were 2.5 x 10<sup>-4</sup> g carbon/m<sup>2</sup>/hour for Buchanan Keys Basin and 1.1 x 10<sup>-4</sup> g carbon/m<sup>2</sup>/hour for Manatee Key Basin seagrass beds.

Preliminary results of productivity measurements on representative substrate types during March 2000 indicate that the highest rates of net photosynthesis occurred on seagrass beds in Manatee Key Basin followed by seagrass and hard-bottom communities in Buchanan Keys Basin. Highest net calcification rates (day calcification – night dissolution) were associated with the hard-bottom community. Rates of calcification and photosynthesis for mud-bottom and water column in Manatee Key Basin were up to an order of magnitude less than rates for seagrass and hard-bottom communities. Generally, for all substrate types, net precipitation of carbonate sediments was observed during daylight hours, while net dissolution occurred at night. Relatively low respiration rates may result from consumption of respired CO<sub>2</sub> by carbonate sediment dissolution reactions.

Results of Russell Bank productivity measurements indicate net carbonate sediment production during March 1999 of 0.071 g carbon/m<sup>2</sup>/24 hours and net sediment dissolution during September 1999 of 0.014 g carbon/m<sup>2</sup>/24 hours. Average rates of photosynthesis were -0.061 g carbon/m<sup>2</sup>/hour for March and -0.042 g carbon/m<sup>2</sup>/hour for September indicating net oxygen consumption on the bank top. However, average rates of respiration were -7.0 x 10<sup>-4</sup> g carbon/m<sup>2</sup>/hour for March and -2.3 x 10<sup>-3</sup> g carbon/m<sup>2</sup>/hour for September indicating net carbon fixation. This suggests that oxygen may be consumed through inorganic oxidative processes (e.g. sulfide oxidation, etc.) and that additional nutrient measurements will be required to quantify these processes.

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Question 4 - Seagrass Research



## **Seagrass Dieoff in Florida Bay 1989-2001: Decadal Trends in Abundance and Growth of *Thalassia testudinum***

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Over a decade ago, beginning in late 1987 Florida Bay experienced a large and unprecedented dieoff of *Thalassia testudinum*, culminating in the initial loss of over 20,000 ha of seagrasses, and significantly greater losses in the years following.

Initially the dieoff occurred only in stands of dense *T. testudinum*. The largest dieoff zones were in western Florida Bay, but with some dieoff in the denser beds of the eastern Bay. The abundance and productivity of *Thalassia testudinum* was measured at 5 stations associated with the seagrass dieoff and 3 control stations, including one on the seaside of Key Largo, outside of Florida Bay, from 1989 to 1995. During the initial decline salinity was very high, exceeding 46 psu, and regional oceanic temperatures were higher than normal in the late summer thru late fall months. By 1991 salinities decreased to 29-38 psu. Temperature extremes were dampened but the patterning remained altered from long-term means. Seagrass standing crop and short shoot density declined at nearly all stations until 1994. Turnover rate was lower than the long-term Florida average during the years of high salinity, and progressively increased from 1989 to 1994.

At this point the data show three distinct phases. The first is the initial dieoff phase (primary dieoff - 1987-1991) where standing crop and areal productivity were high but then declined as dieoff progressed. In this phase water clarity was good but became progressively worse. A second phase occurred in 1992-1997 (secondary dieoff) where seagrasses continued to decline in response to deteriorated water quality. In 1998 a new phase seems to have begun with a significant upturn in both productivity and standing crop. This appears to be associated with progressively improving water quality.

In 1999 a new occurrence of primary seagrass dieoff was detected near Barnes key in southern Twin Key Basin, an area where dieoff had not previously been detected. This area was highly reminiscent of the first occurrence of primary dieoff, with excessively dense beds of *T. testudinum*. Patches appeared in these dense beds, and the same unusual seagrass morphologies ('twinning') were found in surviving shoots.

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## **Seagrass Dieoff in Florida Bay: Meristematic Anoxia, a Mechanism for the Initiation of Primary Seagrass Dieoff**

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Seagrasses were first observed to dieoff in Florida Bay in the fall of 1987. The dieoffs occurred only in the continentally influenced *Thalassia testudinum* beds, and then only in exceedingly dense beds. Sparse and medium density beds were not affected by the primary seagrass dieoff, although many succumbed during the secondary, eutrophic driven phase.

While the specific areas experiencing dieoff were subjected to a varying mix of environmental stresses, including high salinities, high temperatures in the late summer and throughout the fall, high BOD due to excessive blade loss from banks and subsequent decomposition, and chronically high sulfides in the sediments. A conceptual model formulated to organize these phenomena (Zieman, Fourqurean, and Robblee) noted that primary dieoff occurred largely in the fall and winter and not in the summer. This is a time when water temperatures and therefore respiration are held high by high water temperatures, while light intensity and day length are decreasing. Studies in Denmark linked *Zostera marina* dieoff to meristematic anoxia and a series of experiments were conducted to determine if this occurred in Florida Bay seagrasses.

Diel measurements were made in November *in situ* in stable *Thalassia* beds near Porjoe Key and in Rabbit Key Basin, and in a very dense beds experiencing primary dieoff in southern Twin Key Basin north of Barnes Key. Additionally detailed profiles from the water column to the sediments were made for oxygen, pH, and sulfide.

In at all stations meristematic oxygen pressure showed typical diel patterns. At this latitude and time of the year, oxygen pressure declined with decreasing light in the late afternoon, and reached a minimum near 06:00. After that values rose sharply as the light increased and reached atmospheric oxygen pressure between 09:00 and 11:00. At Barnes Key and Porjoe Key, all meristematic values remained positive and oxygen was present at all times. At Barnes Key two of the samples were taken at the periphery of a dieoff site and one at the center of the site. The Barnes Key sites showed much more rapid decline of oxygen in the evening than the other stations and all reached anoxia. The peripheral sites were near anoxic for five hours and anoxic for at least one hour. The sample in the middle of the dieoff zone was near anoxic for over 1.5 hours and anoxic for five hours. In the morning these stations

on average were much slower to show positive oxygen production, and by 14:00, two of the samples did not reach equilibrium oxygen pressure of 0.21 atm. At no time did the water column oxygen pressure decline lower than 50% atmospheric pressure.

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## *Question 5*



## **Advances in Reeffish Monitoring and Assessment in the Florida Keys**

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Reef fish monitoring of species presence, abundance, and sizes has been conducted in the Florida Keys, USA for over 20 years using the circular plot sample technique with a centrally located stationary diver described by Bohnsack and Bannerot in 1986. Statistical power has been significantly improved by using a habitat-based stratified random sample design in which effort is allocated based on sample variance. Other improvements involve sampling more sites with fewer samples per site, combining data for buddy pairs for analysis, and using nitrox for divers. These changes have significantly increased the sample size, geographical coverage, and habitat types that can be monitored. Further technological developments could potentially increase the accuracy of size estimates and biomass projections. This monitoring is being used to evaluate habitat importance to individual species, changes in reef fish communities due to no-take protection, and regional changes in management and water quality. In addition, the fishery-independent data generated can be used to do traditional fishery stock assessments with several advantages over using only fishery-dependent data.

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Question 5 - High Trophic Level

## Molluscan Fauna as Indicators of Change in Florida Bay and Biscayne Bay

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Analysis of seven cores from Florida Bay and Biscayne Bay has indicated significant changes in the molluscan fauna during the latter half of the 20<sup>th</sup> century. *Brachidontes exustus* comprises >80% of the molluscan fauna in the upper portions of six cores. In four of the cores, this increased dominance of *Brachidontes* is unprecedented. *Brachidontes exustus*, a nearly ubiquitous mussel at current sites in eastern and central Florida Bay, can tolerate diminished water quality and a wide range of salinities. Five cores also show dramatic decreases in molluscan abundance and diversity during the last forty years. These findings indicate a system under stress.

Molluscs as a group possess many characteristics that make them ideal as proxies for the general health of estuarine ecosystems. They occupy a number of trophic levels as primary, secondary, and tertiary consumers and they are an integral part of an estuarine food web. A number of feeding strategies are utilized by molluscs, including filter feeding, grazing, scavenging, and carnivory. Throughout their lifetime, some species of molluscs may pass from the planktonic to the benthic realm, and they move from micro-, to meio-, to macro-fauna as they mature. A decrease in molluscan diversity and abundance may be an indication of a disrupted system.

Molluscs generally live in equilibrium with the surrounding water, but have the ability to tolerate water outside their normal range for brief periods by halting their exchange with the water column. Because they typically exist at equilibrium with seawater, they record the composition of seawater at the time the shell is deposited. Molluscs generally are tolerant of short-term perturbations in their environment, but they will respond to seasonal and annual changes in salinity. Thus, changes in salinity and other measures of water quality indicated by molluscan shell chemistry or molluscan assemblages, represent significant changes to the environment.

Key molluscan indicator species and whole assemblages therefore provide vital historical data on the following:

1. salinity and proximity to freshwater outflow;
2. water quality;
3. substrate, including the density and distribution of seagrass and macrobenthic algae;
4. estimates of overall diversity and health of the ecosystem;
5. sea level and/or proximity to shoreline.

In addition, the shells of individual molluscs serve as archives of changing water chemistry. Experimental work has begun this year on extracting monthly and seasonal salinity and other water chemistry data from mollusc shells, with emphasis on the relatively thick-shelled species, *Chione cancellata*.



Analyses of molluscan assemblages to date have contributed the following historical information.

- The environments at the mouth of Taylor Creek in Florida Bay (core T24), and in Manatee Bay (core MB1) show distinct shifts from oligohaline/mesohaline assemblages with a strong freshwater influence, to polyhaline assemblages with very little freshwater influence. Yet the changes have not been enough to displace *Anomalocardia auberiana*, a species typical of the northern transition zone in Florida Bay; this species is present throughout both cores.
- Pass Key (core PK37), southeast of Little Madeira Bay, shows significant fluctuations in species indicative of the northern transition zone, probably indicating fluctuations in salinity at the site.
- Between 1910 and 1930, distinctive changes occur in the molluscan assemblage at Russell Bank (core RB19B). *Anomalocardia auberiana*, consistently present in low percentages prior to 1920, is not present in the upper portion of the core, which may indicate a decreasing influence from Taylor slough and the northern transitional area.
- The dominance of *Brachidontes exustus*, beginning around 1980 at Russell and Bob Allen, around 1950 in Whipray (core 25B), and in the upper portion of the cores from Pass Key, Taylor, and Manatee Bay (core MB1), could be an indicator of diminished water quality, increased fluctuations in salinity, or any combination of factors stressing the molluscan fauna of the region. The only core examined that does not show an increase in *Brachidontes* dominance in the upper portion of the core is FB1 from Featherbed Bank in Biscayne Bay. *Brachidontes* is very rare at this site, which is dominated by more euhaline faunas.
- The four cores from central and eastern Florida Bay, and from Featherbed Bank in Biscayne Bay all show decreases in measures of molluscan faunal diversity and absolute abundance that may have begun in the 1960's or earlier, and reached a low in the early 1970's. Interestingly the transition zone cores from the mouth of Taylor Creek and in Manatee Bay do not show this decline.

Experimental work with living molluscs will provide additional data to interpret changes in the downcore assemblages, and is providing the framework for future work analyzing the change in shell chemistry within an individual mollusc shell. If successful, the planned analyses of mollusc shells from well-dated cores will allow determination of monthly, seasonal and annual changes in water chemistry. These data will provide target data for the restoration efforts to restore historical seasonal flow into Florida Bay and Biscayne Bay.

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## Immigration Pathways of Pink Shrimp Postlarvae into Florida Bay

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Understanding and predicting the connectivity between larval supply and recruitment to fisheries is crucial to modeling and managing fisheries in South Florida ecosystems. The pink shrimp (*Farfantepenaeus duorarum*), one of the most important commercial and recreational species in South Florida, migrates between offshore spawning grounds and nursery grounds in Florida Bay and lower southwest coast estuaries. Adult pink shrimp spawn northeast of the Dry Tortugas about 150 km southwest of Florida Bay. Larval stages develop offshore close to the spawning grounds, and postlarvae migrate into Florida Bay, where juveniles settle for several months before recruiting to the Tortugas fishery.

Our recent modeling results suggest that large year-to-year variations in recruitment to the Tortugas fishery could potentially be caused by observed year-to-year differences in the salinity regime of interior Florida Bay. The model simulates recruitment on the basis of growth and survival as functions of salinity and temperature. Interior Florida Bay experiences persistent hypersalinity some years because of limited freshwater inflow and tidal exchange. Water management in the upstream Everglades may influence the frequency, duration, and severity of hypersaline conditions. Reduced tidal amplitude and, presumably, tidal flow, may limit postlarval transport to the Bay's interior, making conditions on potential nursery grounds there less relevant. Therefore, the modeling results raise questions about postlarval transport to interior Florida Bay. Principal questions being addressed with present research are: (1) What are the dominant postlarval transport pathways to Florida Bay? (2) Do postlarval shrimp reach the interior of Florida Bay? (3) If so, by what pathways? (4) What oceanographic and environmental factors affect transport to the Bay and penetration into the Bay's interior? This information is crucial to evaluate the relevance of modeling results and to expand the model to include larval shrimp immigration and major affecting oceanographic and environmental factors.

At least three pathways have been hypothesized for pink shrimp postlarvae entering Florida Bay: west (across the southwest shelf), southeast (through the Lower and Middle Keys), and east (through the Upper Keys). These pathways may be affected differently by physical oceanographic processes. Larval influx across the Lower and Middle Keys has been the most recognized path because local winds, Florida Current flow, and coastal eddies interact to influence the onshore transport and recirculation of larvae in the Florida Keys. Prevailing southeast and east winds favor onshore Ekman surface transport in this east-west aligned coastline. Furthermore the Middle and Lower Keys coastal zone is frequented by gyres

formed in the Dry Tortugas. Recirculation in these coastal cyclonic gyres facilitates cross-shore transport of postlarvae into Florida Bay. In the Upper Keys, insufficient space is available for gyre formation because the shelf is narrow and the Florida Current approaches close to shore. Onshore transport of larvae arriving in the Florida Current at the Upper Keys may instead be facilitated by frequent inshore meanders and onshore frontal convergence of the Florida Current. Onshore transport mechanisms are less studied in the Southwest Florida Shelf than in the Florida Straits but may be mainly affected by winds, tides and Loop Current frontal eddies. Dominant prevailing southeasterly winds in summer enhance northward Ekman transport of the upper layer, providing an onshore movement for postlarvae. Close to shore, tidal currents seem to be the most effective transport mechanism across the western shelf.

In zooplankton samples collected in Florida Bay by P. Ortner et al. (NOAA/AOML), we found pink shrimp postlarvae near Sandy Key in the western Bay, near Shell Key and Cross Key in the eastern Bay, and near Roscoe Key (Whipray Basin) in the northcentral Bay. Highest numbers were found at Sandy and Shell Keys. None were found near Eagle Key and Duck Key. Interestingly, postlarvae from the western sites were significantly younger (fewer rostral spines) than those from the eastern sites, although roughly the same size (total length and carapace length), possibly suggesting faster growth and a shorter journey.

Our monthly sampling to quantify pink shrimp postlarvae entering Florida Bay started in January, 2000, at two channels connecting Florida Bay with the Atlantic Ocean (Whale Harbor, at the Bay's edge, and Captain Key, a possible interior pathway) and two channels connecting the Bay with the Gulf of Mexico (Sandy Key Channel and Conchie Channel). Sampling was relocated to Panhandle Key Channel, another interior site, from Captain Key Channel in June because sites selected near the mouth of the Captain Key channel had insufficient water flow ( $<0.01$  m/s) for effective sampling. Moored subsurface plankton channel nets ( $0.75$  m<sup>2</sup> mouth, 2.5 m long) are set simultaneously at the four sites on two consecutive nights over the new moon period. Nets are moored to concrete blocks and suspended with floats at roughly 0.5 m depth. Cod ends are placed on the nets before dusk and removed shortly after dawn each day to target the optimal dark-flood time window for larval migration into the Bay. We use two nets per channel (a sampling pair), which makes a total of 8 samples per night of sampling.

Intensive sorting and identification of postlarval and juvenile penaeid shrimps is in progress on the 205 samples collected to date. Samples sorted and processed through June suggest that the influx of *F. duorarum* postlarvae through the Atlantic Ocean and through the Gulf of Mexico are of comparable magnitude at their peaks and that, therefore, both eastern and western pathways are important. Seasonal patterns differ, however. Pink shrimp postlarvae at the western stations showed two peaks, one in February and another in June, while the greatest influx through the two Whale Harbor stations occurred in May. The relatively high current speed in all months sampled at Panhandle Key (comparable to that at Whale Harbor) and the relatively large number of pink shrimp postlarvae collected in the one month of samples sorted and identified thus far suggest we may have found a significant pathway for postlarval migration into the interior Bay. Completion of the sorting and processing of two years of samples will make it possible to confirm these preliminary results and to relate them to physical factors. Incidentally, a great abundance of pre- and post-settlement stages of

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*Rimapenaeus* sp. were found at Sandy Key and Conchie Channels. This species is closely related to *F. duorarum* and has been previously reported only as an occasional species in the Bay; however in our samples, the number of *Rimapenaeus* sp. juveniles is about three times that of *F. duorarum* juveniles.

Postlarval influx into the Bay has begun to be analyzed in relation to physical parameters. Wind, salinity, and temperature data have been obtained by the SEAKEYS/C-MAN meteorological stations. Current data, ARGOS-buoy trajectories, and prevailing circulation patterns will be obtained from physical oceanographers in SFERPM. AVHRR satellite imagery will be used to characterize upstream oceanography. Postlarval influx will also be analyzed in relation to juvenile pink shrimp density in western Florida Bay and fishery data. These analyses will provide important clues as to which factors (*e.g.* supply, transport, habitat, salinity, or food) limit the abundance of pink shrimp in Florida Bay.

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## **Pink Shrimp Dynamics in Florida Bay: Effects of Salinity and Temperature on Growth, Survival, and Recruitment to the Tortugas Fishery**

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A simulation model has been developed to predict pink shrimp recruitment from Florida Bay as a function of temperature and salinity through their effect on growth and survival. While preliminary modeling results with the limited data available at the time has been published, further work with the model requires a more thorough knowledge of these effects. Therefore, a series of trials have been conducted to determine the response of young pink shrimp growth and survival to temperature and salinity in interaction. The series of temperatures and salinities tested extended across the full range of temperature and salinity found in Florida Bay and nearby Whitewater Bay. Tested temperature ranged from 15° C to 33° C, and tested salinity ranged from 2 ppt to 55 ppt. A series of addition trials were conducted to determine the effect of conditioning the shrimp in intermediate salinity before moving to extreme salinity.

New equations and parameters have been developed for the model based on the trials, and new simulations will be produced with the new information. The updated model will hindcast relative recruitment from the distinct regions of Florida Bay using temperature and salinity observations specific to each Bay area. Site-specific information about bottom structure (i.e., bank, basin, and island intertidal area) and seagrass coverage will be used to refine model results.

The temperature and salinity trials were conducted with 2,000 small juvenile shrimp (average capture length 36.625 mm) from Florida Bay. Data from the trials were used to produce parabolic regression equations for survival and growth. Survival curves calculated with the survival equation indicated a maximum survival rate at 20° C temperature and 30 ppt salinity. Measured growth and survival rates with and without conditioning at salinity extremes (5, 10, 45, 50, and 55 ppt) were compared with G-tests. Only at 55 ppt were survival rates significantly greater with conditioning than without it. Length measurements from the trials were used to estimate growth rate. The trials were conducted over a 28-day period, and individual shrimp were measured weekly. Weekly data for individuals were fit to exponential growth equations. A parabolic regression equation was prepared from individual

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growth rates across the range of temperature and salinity covered by the trials. The equation predicted maximum growth rate at 32°C temperature and 30 ppt salinity. Survival and growth coefficients for use in the simulation model were obtained from the regression equations.

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## **The Potential Effects of Changing Salinity on Hard-Bottom Habitat and Spiny Lobster Recruitment in Florida Bay, FL**

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Sustainable use and conservation of intensively fished species such as the Caribbean Spiny Lobster (*Panulirus argus*) requires accurate recruitment forecasting tools, especially in environments like the Florida Keys that are dynamic and subject to severe disturbances. The successful recruitment of spiny lobsters in south Florida is intimately linked to the condition of hard-bottom habitat in the region. Especially important for juvenile lobsters are the availability of macroalgal settlement habitat and crevice shelters, primarily sponges, corals, and rock crevices. Proposed changes in water management in the Everglades are likely to profoundly change the spatial and temporal patterns of salinity in Florida Bay, with unknown consequences for hard-bottom communities and the important fishery resources they nurture. Spiny lobster, for example, support both commercial and recreational fisheries that combined make this one of the most economically valuable fishery in the state of Florida.

For nearly two decades, we have studied the ecology of spiny lobster in the Florida Keys with particular emphasis on processes affecting recruitment. The effects of changing water conditions, variable postlarval supply, and degradation of hard-bottom nursery habitat on the recruitment of juvenile lobsters have figured prominently in that research. In 1993, we developed a spatially-explicit individual based model describing lobster recruitment in south Florida. It was the first spatial model for the region wherein processes acting at different ecosystem levels (e.g., phytoplankton blooms → hard-bottom habitat structure → spiny lobster) were integrated to predict recruitment of a species of ecological and economic significance.

The research in which we are now engaged explores more fully the impact of changing salinity on hard-bottom habitats, with special emphasis on impacts to spiny lobster and the sponge community. Our objectives are to:

- (1) Conduct field surveys of habitat structure in the shallow hard-bottom areas of Florida Bay and adjacent areas of the Florida Keys for ground-truthing our spatial model and to establish a better baseline data set for this under-studied habitat.
- (2) Conduct laboratory studies that experimentally test the tolerance of selected hard bottom-dwelling species (e.g., lobster, sponges, and perhaps other species) to different salinities at summer and winter water temperatures.
- (3) Use the data generated from Objectives 1 and 2, along with new fine-scale spatial depictions of habitat coverage, to refine our existing model and generate predictions of changes in hard-bottom habitat structure and lobster recruitment under specified salinity and water management regimes.

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## Past and Present Trophic Structure of Florida Bay: Stable Isotope Analyses

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This study is an ongoing, multi-year project designed to investigate possible change in the dependence of Florida Bay consumers (e.g., invertebrates, juvenile and adult fishes) on various sources of primary production (e.g. plankton, mangroves, seagrasses, detritus, epibenthic algae). Our working hypothesis is that the trophic structure of Florida Bay has shifted to some degree from a benthic system dependent on primary production by seagrasses and/or epiphytic and benthic algae to a pelagic system dependent upon planktonic algae.

Trophic relationships within an ecosystem may be established by analyzing the carbon, nitrogen and sulfur stable isotopic composition ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ,  $\delta^{34}\text{S}$ ) of the tissues of both producers and consumers. We have conducted field collections and completed multiple stable isotopic analyses of seston, seagrasses, seagrass epiphytes, benthic and epibenthic invertebrates, and fishes across a transect from the Gulf region of Florida Bay to its interior over the past three years (1997, 1998, 1999). Our sites include: Schooner Bank, Oyster Keys, Rabbit Key, Coon Key, Rankin Basin/Dump Key, and a control site in the relatively pristine seagrass beds of lower Biscayne Bay. Our collections have been augmented by specimens from other sites which have been donated by researchers working in Florida Bay during the same time period (Paul Carlson, DEP-FMRI; David Evans, Beaufort NMFS; and Tom Schmidt, ENP), specifically from areas along the mainland, east central and north east regions of the bay. In addition to the general surveys of producers and consumers conducted for all three years, sampling trips in 1998 and 1999 targeted endmember species (e.g., primary consumers and apex predators). Results to date indicate that there is a strongly seagrass-based system within the bay with a gradient toward a more pelagic (or marine) system for the Gulf stations. One of the questions which we are addressing with our current work is whether this shift toward pelagic stable isotope values for the Gulf sites is due to change in trophic structure with time or is attributable to a natural spatial variation which has existed historically.

In addition to establishing the trophic structure of extant communities, we have developed methods which will allow us to access the trophic status of the extensive historical collections of fish from Florida Bay which are held by the Florida Museum of Natural History and FMRI and which extend back to the 1950's. It has long been assumed that preserved tissue is compromised with respect to a dietary carbon isotopic signal (via direct incorporation of isotopically  $^{13}\text{C}$ -depleted or "light" carbon from formalin). Our intended approach to determining the trophic status of preserved specimens was to evaluate bone carbon (in the form of biogenic apatite) which should be unaffected by preservation, and we have indeed established a strong correlation between the  $\delta^{13}\text{C}$  of tissue carbon and bone carbon ( $r^2=0.7$ , across all species collected). Several long-term preservation experiments conducted with whole fish either preserved in formalin or fixed in formalin and preserved in ethanol have recently been concluded. For preserved specimens we analyzed bone  $\delta^{13}\text{C}$  and



tissue  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and  $\delta^{34}\text{S}$  at several time points from 0 to 12 months. While preliminary results from stable carbon isotopic analyses of preserved bone appear promising, i.e. there is no trend in  $^{13}\text{C}$ -depletion with preservation, the variation in the data is high. Surprisingly, we did find that preserved tissue will be useful for dietary analysis. Although our preservation methods (formalin, formalin/ethanol) significantly altered the  $\delta^{13}\text{C}$  of tissue, this effect is relatively small and highly predictable. For experiments with fish preserved in formalin, tissue had a total isotopic shift in  $\delta^{13}\text{C}$  of  $-0.81 \pm 0.26$  ‰. The shift in tissue  $\delta^{13}\text{C}$  from fish fixed in formalin and then preserved in ethanol is  $-1.0 \pm 0.13$  ‰. Storage time did not affect the impact of preservation on carbon isotopic composition, as tissue sampled at 3 weeks evidenced the total 1‰ shift while tissue sampled from all specimens from 3 weeks to 12 months showed no further increase in  $^{13}\text{C}$ -depletion (with an average change in  $\delta^{13}\text{C} \leq 0.1$ ‰, within the range of experimental error). There was no significant effect of preservation on tissue  $\delta^{15}\text{N}$  and  $\delta^{34}\text{S}$ , with differences between time points well within the range of experimental error (i.e.,  $\leq 0.3$ ‰ for nitrogen and  $\leq 0.5$ ‰ for sulfur), indicating that these stable isotopes will also be useful in establishing the trophic status of preserved specimens.

Utilizing the multiple stable isotope ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and  $\delta^{34}\text{S}$ ) approach described above to compare contemporary collections with historical collections, we will now be able to evaluate changes in the trophic relationships in Florida Bay as the ecology of the bay has shifted over the years with respect to seagrass distribution, seagrass biomass, species abundance and distribution of consumers, freshwater input, salinity and temperature.

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Question 5 - Higher Trophic Levels

## **ALFISHES: A Size-Structured and Spatially-Explicit Model for Predicting the Impact of Hydrology on the Resident Fishes of the Everglades Mangrove Zone of Florida Bay**

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A model (ALFISH) for functional fish groups in fresh-water marshes in the Greater Everglades area of Southern Florida is extended to create a new model (ALFISHES) to evaluate the spatial and temporal patterns of fish densities in the community of resident fishes of the Everglades mangrove zone of Florida Bay. These fish constitute an important prey base for large fish, reptiles, and birds that are important indicators of ecosystem health. Results from a long-term study (Lorenz 1997) suggest that historic changes in water delivery may have altered the mangrove fish community and lowered prey availability to higher trophic levels.

The model utilizes the object-oriented modeling framework provided by the Across Trophic Level System Simulation (ATLSS) to implement a dynamic, agent-based simulation of fish from a single functional group, small fish (<110 mm in length). The model is size-structured and spatially-explicit. The model combines field data assessing the impact of salinity of fish biomass with hydrology data from the USGS Southern Inland Coastal Systems (SICS) numerical model. The estuarine landscape consists of a spatial grid of 500×500 meter cells across the coastal areas of the Florida Bay. Each cell is divided into two habitat types, flats, which are flooded only during the wet season, and creeks, which are always wet and serve as refugia during the dry season. Daily predictions of water level and salinity are obtained from the SICS model. The fish spread out into the flats during flooded conditions. As the cells dry out, the fish either retreat by moving into creeks, move to other spatial cells, or die if their cell dries out. The model output may be used to assess the impact of changes in hydrology on fish biomass and its availability to wading bird and other consumer populations.

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## Supply of Pink Shrimp Postlarvae through Intertidal Channels into Florida Bay

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The pink shrimp (*Farfantepenaeus duorarum*), one of the most important commercial and recreational species in South Florida, spawns offshore in the Dry Tortugas. With the help of physical transport processes, larvae migrate into Florida Bay where they settle as juveniles for several months before returning to offshore habitats to complete their adult life cycle. Larval supply, a major determining factor of the strength of the adult year-class, is therefore strongly linked to physical processes. Through this research we examine the coastal larval transport processes and the inshore supply of postlarval pink shrimp into Florida Bay through inter-island channels. This information is crucial to link in the transport component of the recruitment model for pink shrimp in South Florida.

Larval distribution in the southern Straits of Florida is affected by the Florida Current, winds, and the mesoscale gyres propagating along the shelf between the Dry Tortugas and the lower Florida Keys. These gyres are instrumental in the retention and concentration of larvae near the coast. Local winds and Florida Current flow interacting with the bathymetry can affect the onshore entry and recirculation of larvae. In the Gulf of Mexico, the variable Loop Current connects upstream larval sources to the Florida Keys, and also modulates the formation of gyres within the Straits of Florida.

*Farfantepenaeus* spp. postlarvae were collected with moored channel nets from October 1997 through June 1999 at two inter-tidal channels of the Florida Keys, Whale Harbor (WH) and Long Key (LK) Channels. These two passes from the Atlantic Ocean into Florida Bay are located at the east and west end of the Middle Keys respectively. Channel nets were moored on the Bay side near the mouth of the channels and sampled monthly at each site on three consecutive nights around the new moon. Nets were deployed before dusk and emptied shortly after the following dawn each day to target the optimal dark-flood time window for postlarval migration into the Bay.

The physical correlates collected concurrently with the biotic sampling were temperature and volume flow. Other important physical parameters were collected from different sources. Hours of darkness during flood were calculated for each night of sampling based on predicted tide tables and current meter data from WH (N. Smith, Harbor Branch).

Current and temperature data were provided from sensors moored at Tennessee Reef as

part of the Florida Bay Circulation and Exchange Study (T. N. Lee, E. Williams, RSMAS and L. Johns, NOAA). Temperature and wind data were obtained from the Coastal Marine Automated Network (CMAN) station at Sombrero Light, situated 2 km offshore and midway between LK and WH. ARGOS satellite-tracked surface drifters were also set out periodically. AVHRR (Advanced Very High Resolution Radiometer) satellite SST imagery (Johns Hopkins University and United States Geological Survey) were used to characterize the oceanography of the upstream (Gulf of Mexico) and local (coastal Florida Keys) pelagic environments. These complementary data allowed us to determine the position, extent, and variability of oceanographic fronts and recirculation features that could affect the origin, transport, and retention of pelagic larval stages that subsequently recruit into Florida Bay.

Winds and currents are the major physical driving forces often invoked in larval transport. The components of these variables that are most favorable to larval recruitment are those contributing to onshore and countercurrent transport. The average magnitudes of onshore current ( $-u$ ) and countercurrent ( $-v$ ) components, and wind stress components that induce onshore ( $-\tau_y$ ) and countercurrent ( $+\tau_x$ ) Ekman transport were respectively calculated for the pre-sampling period (14 days prior and 3 days during the sampling) as indices of transport. The percentage frequencies of occurrence of onshore currents and countercurrents were also calculated.

Density of postlarvae were analyzed together with these indicators of transport and other important factors involved in the supply process such as hours of darkness during flood, precipitation and temperature. Postlarval influx through LK channel showed a seasonal pattern with peaks in late spring-summer (July-August/98 and May/99). Because of this larval influx seasonality the highest correlation found was with the temperature ( $p < 0.05$ ). Density of postlarvae at WH was very patchy. Extremely low densities were observed during Oct/97-June/98, while three large peaks occurred during July/98-June/99. The smallest one was in December/98 (79.6 postlarvae per 1000 m<sup>-3</sup>) the largest in March/99 (424.7 postlarvae per 1000 m<sup>-3</sup>) and the intermediate in May/99 (141.7 postlarvae per 1000 m<sup>-3</sup>). The three peaks of postlarvae correlated with the frequencies of occurrence of onshore currents and countercurrents peaks. Coastal countercurrents are usually driven by winds but in the Florida Keys can also result from the passage of mesoscale, cyclonic eddies offshore. In this case countercurrent events were more often associated with eddy presence than with countercurrent-inducing upstream wind stress. AVHRR satellite imagery and ARGOS buoy trajectories confirmed the presence of gyres prior to sampling in Dec/98, March and May/99.

Postlarvae showed a significant seasonal variation in size and number of rostral spines. Postlarvae captured during the winter months at both channels were larger (mean size=10.67 mm total length) than those captured during the summer months (mean size=9.03 mm total length) for the two periods of sampling. The number of rostral spines, a morphological feature generally correlating with the number of moults, size and age, also varied seasonally but with an opposite trend as the body size. The largest postlarvae collected in January–February had an average of 3.4 rostral spines, while smaller postlarvae collected from May–June/99 had an average of 4.3. Surface water temperature proved to be a determining factor in this seasonal size variation. The body size of postlarvae was found to have a high negative correlation with water temperature, and a positive correlation with the number of rostral

spines ( $p < 0.05$ ). These results suggest that winter postlarvae have been in the plankton for a prolonged period of time because of the extended time they need to grow between moults at low temperatures. If it is the case, oceanographic conditions at the Tortugas grounds should be more favorable for larval retention during the cold months than in the summer months. The alternative would be that the Florida Keys receives a portion of its recruits from larvae which originate upstream of the Gulf of Mexico and are transported via the Loop Current. These postulates need to be proved.

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Question Number/Research #5

## **Mangrove Prop-Root Habitat as Essential Fish Habitat in Northeastern Florida Bay**

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The red mangrove prop-root is the primary interface between the freshwater Everglades system and marine Florida Bay. This habitat has been proposed as a nursery area for several fish species, but little is known about habitat use under varying salinity conditions. Changes in freshwater flow into northeastern Florida Bay may affect the use of the prop-root habitat there.

We assessed the use of the prop-root habitat in northeastern Florida Bay where previous water diversion had potentially altered salinity conditions and recent rediversion has increased freshwater input. We used diver visual census to identify and enumerate fish using the prop roots in Little Madeira Bay, Trout Cove and Manatee Bay. This method has the advantage of being non-destructive but limited to areas with adequate water clarity. Another bias that has not been examined is the influence of the diver on fish behavior. Some fish tend to flee or avoid the diver leading to potential density (or diversity) underestimation. We developed a remotely operated video platform (RVP) to assess the diver bias inherent in the method.

Preliminary analysis indicates that some species such as cichlids, sheepshead, and grunts may be underestimated due to flight response elicited from the diver. Other species, such as mangrove snapper and gerreids, may be adequately enumerated. One surprising observation was the very limited number of forage based fishes in the prop roots. The RVP confirmed the relative absence of this important trophic group was not due to diver bias. In addition, the number of juvenile fishes was very low when compared to mangroves in the Bahamas and Puerto Rico.

The low juvenile abundance lead to secondary sampling of larval fish to see if recruitment or habitat limitation might explain the low abundance. Light traps were used to sample in the prop roots and compared to nearshore and bay locations in Madeira Bay, Little Madeira Bay, and Trout Cove. A sampling site on the leeward side of Key Largo near potential recruit sources was used as a control site. In comparison to the Key Largo site larval abundance was very low in northeastern Florida Bay. Among the northeastern Bay sites the prop root sites had significantly more larvae than nearshore (but away from mangroves) and bay sites. This sampling suggests that northeastern Florida Bay is depauperate in larval fishes. Whether this is due to poor circulation from potential offshore recruit sources or the altered salinity regime still needs to be explored.

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## **Linking Everglades Restoration and Enhanced Freshwater Flows to Elevated Concentrations of Mercury in Florida Bay Fish**

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Since 1995, Florida Bay has been under a health advisory recommending limited consumption of fish caught in the bay due to elevated levels of mercury. Yet, little is known about the sources of mercury contamination to Florida Bay. Limited studies done to date suggest that surface water flows from the mainland may contribute significant loads of total mercury (THg) and methylmercury (MeHg) to eastern Florida Bay. However, it is equally plausible that atmospheric deposition of inorganic mercury to the Bay is sufficient to feed *in situ* production of enough MeHg to account for the observed mercury bioaccumulation. Because we were constrained in our ability to predict the effects of increased Everglades inflows to eastern Florida Bay, our two existing programs were integrated into a single multiagency study in 2000 to assess the impact of hydrologic restoration on the Bay's mercury problem.

In February and July-August 2000, we collected surface water and sediment cores at 12 stations along two transects into eastern Florida Bay and at one station near Dump Keys and analyzed them for THg and MeHg. Total Hg concentrations in unfiltered surface water ranged from 0.36 ng/L to 4.16 ng/L. MeHg concentrations in unfiltered water samples ranged from <0.016 ng/L to 1.06 ng/L. On average, MeHg as a percent of THg was 13%. Filterable THg accounted for 69% of unfiltered THg and filterable MeHg accounted for 71% of unfiltered MeHg. All mercury species exhibited non-conservative mixing with maximal concentrations occurring in the northern transition zone near the mouths of Taylor River and a creek flowing into Joe Bay.

THg and MeHg in sediments from Florida Bay and upstream canals ranged from 9.9 to 63 ng/g and 0.063 to 2.33 ng/g dry weight, respectively. As was the case with surface water, highest sediment-THg concentrations occurred in the transition zone near the mouth of Taylor River and in sediments from the creek flowing into Joe Bay. Maximum concentration of MeHg also occurred in sediments at the mouth of Taylor River; however, MeHg was relatively low in sediments from the creek flowing into Joe Bay.

In addition to water and sediments, different fishes, including both forage and game fish species, were collected and analyzed for THg to augment our existing data base on mercury bioaccumulation. Total Hg in fishes ranged up to 0.62 mg/kg in forage fish and 2.96 mg/kg in game fish. Highest mercury concentrations were observed in fish from the interior region in the central and eastern zones of Florida Bay. Spotted seatrout, *Cynoscion nebulosus*, almost always exceeded the 0.5 ppm advisory level in this region. Mercury concentrations in red drum, *Sciaenops ocellatus*, frequently exceeded this level, while mercury concentrations in gray snapper, *Lutjanus griseus*, rarely exceeded this level. However, many of the gray snappers were undersized and, thus, this sampled population may underestimate human health risk from ingesting snappers of legally harvestable size.

Current research centers on integrating tissue mercury levels with stable isotope measurements in biota to infer the important trophic (food web) pathways and to quantify the relative importance of watershed-derived methylmercury from that generated within Florida Bay proper. Preliminary findings reveal distinct patterns in bioaccumulated mercury, stable carbon and nitrogen isotope ratios. Gray snapper in western Florida Bay had  $\delta^{13}\text{C}$  ratios indicative of a seagrass source, while gray snapper in the Everglades/Northern Transition Zone had  $\delta^{13}\text{C}$  ratios increasingly dependent on a mangrove or terrestrial-wetland sawgrass source. Gray snapper in eastern Florida Bay were intermediate. The  $\delta^{15}\text{N}$  ratios differ as well. Gray snapper in eastern Florida Bay and the Everglades/Northern Transition had distinctly higher values than in the western bay. Highest mercury concentrations in gray snapper were associated with these higher  $\delta^{15}\text{N}$  ratios. These patterns were also observed for spotted seatrout and red drum. The association of high mercury levels with high  $\delta^{15}\text{N}$  ratios in fish may indicate a linkage between methylmercury formation and denitrification in the sediments of eastern Florida Bay.

Preliminary results of surface water and sediment analyses show gradients in THg and MeHg that continue to implicate runoff from the mainland as a significant source. However, loading of THg and MeHg will likely vary seasonally and, thus, must be interpreted using a mass budget approach. Further, mercury bioaccumulation in fishes did not follow this simple geographic pattern. Future results from this on-going study, particularly when the two programs become fully integrated, will allow us to better understand the factors responsible for geographic patterns in mercury bioaccumulation. This information should improve our ability to make informed decisions about the proper management of Everglades inflows for the restoration of the sport fishery and the protection of fish-eating wildlife in eastern Florida Bay.

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## **Size-Structure of Gray Snapper (*Lutjanus Griseus*) within a Mangrove “No-Take” Sanctuary**

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In an ongoing study designed to examine the fish utilization of red mangrove (*Rhizophora mangle*) shorelines in southeastern Florida, we detected differences in the size structure of gray snapper (*Lutjanus griseus*), between an area closed to fishing and surrounding waters.

Data on fishes and habitat was obtained from waters managed by Biscayne National Park (BNP), Everglades National Park (ENP), and the Florida Keys National Marine Sanctuary (FKNMS) through underwater visual surveys and biological sampling (Figure 1). Despite national park and “sanctuary” designations, fishing is permitted within the majority of these management areas. Within the ENP however, public access (and therefore fishing), has been forbidden within the Crocodile Sanctuary (CS-ENP) since 1980. Length-frequency distributions for *L. griseus* within BNP, ENP, and the CS-ENP were generated from 438 visual fish censuses conducted between September 1996 and March 2000 (Figure 2). The modal 5-cm size class for fish in Biscayne (BNP) and northeastern Florida Bays (ENP) was below the minimum legal size of 25.4 cm TL at 15-20 cm TL. In contrast, the modal length for fish in the CS-ENP, where fishing has been prohibited for over 20 years, was two size-classes larger at 25-30 cm TL. Differences in the percentage of legal-sized individuals were also apparent: the percentage of legal-sized fish was 15.6% in Biscayne Bay, 29.6% in Florida Bay, and 66.2% in the CS-ENP.

Our study is an important example whereby a nearshore area with restricted public access, albeit for purposes other than fish stock protection, has benefited exploited species. For many reef-associated species, the protection of offshore spawning areas has been a major priority in the effort to prevent stock collapse. However, for overexploited *L. griseus*, the protection of offshore reef habitat alone may not be enough. For this species, locally known as “mangrove snapper”, we suggest due consideration should also be given to increasing the number and size of nearshore refuges, especially those dominated by mangroves. Based on our data, it would seem prudent for the CS-ENP to remain a restricted-access, “no-take” area for the sake of both crocodiles and fishes.

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## **Analysis and Synthesis of Existing Information on Higher Trophic Levels: Factors Affecting the Abundance of Fishes and Macro-invertebrates in Florida Bay**

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A data base was assembled for Florida Bay that integrates six independent forage fish and macro-invertebrate studies that sampled between 1974-1997 using trawls, throw traps, or seines. To these data was added information on major forcing functions: ambient and lagged data on rainfall, water discharges, salinity, tidal amplitude, sea level, temperature, wind, El Nino events, bathymetry, and habitat (seagrass type and density). Sogard and Matheson collected throw trap data at overlapping stations on banks during the 1980's and 1990's, while Robblee provided throw trap shrimp data for Johnson Key banks and basins (1983-1999). Trawl data were provided by Schmidt (1970's), Thayer and Powell (1980's and 1990's), and Colvocoresses (1990's). Seine data were provided by Schmidt (1970's) and Colvocoresses (1990's). For each sample and gear type, the number of each species was converted to density per hectare.

The data base was used to examine the dynamics of 20 key species selected by consensus by researchers who had conducted fishery studies within Florida Bay. General additive models are being constructed to determine which major forcing functions were controlling the abundance of key species within the Bay. The data base will be used to examine spatial and temporal changes in fish densities intra-annually (seasonal), inter-annually (between years) and decadal.

Preliminary analyses suggest that the most important variables for determining the abundance of selected Florida Bay forage species were as follows, by species: *Hippocampus zosterae* (habitat, seagrass type, gear, salinity, month), *Lucania parva* (gear, salinity, seagrass

type, habitat, seagrass density, and temperature), *Syngnathus scovelli* (habitat, seagrass type, salinity, gear, seagrass density), *Eucinostomus spp.* (seagrass type, gear, habitat), *Farfantepenaeus duorarum* (gear, tidal amplitude, seagrass type, depth, month), *Floridichthys carpio* (depth, salinity, habitat, and tidal amplitude), *Opsanus beta* (gear, seagrass type, seagrass density, and temperature), *Anchoa mitchelli* (salinity, gear, sea level, habitat, and depth), and *Lagodon rhomboides* (gear, habitat, tidal amplitude, seagrass density, and depth).

A second data base, providing creel census data collected at the Flamingo boat ramp in Everglades National Park (1983-1999), was used to evaluate adult fish populations for the North, South, and Western portions of Florida Bay. Creel census data was linked to average salinities and monthly temperatures at water quality monitoring stations within the North, South and Western portions of the Bay and other environmental factors such as rainfall, water discharges into the Bay, and well levels. The relationship between the abundances of predatory fish and prey species was also examined.

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Question 5 – High Trophic Level

## Offshore Larval Supply of Snapper Larvae (Pisces: Lutjanidae) into Florida Bay

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Snappers (Family Lutjanidae) are an economically and recreationally important group of fishes that inhabit Florida Bay as juveniles and the Florida Keys reef tract as adults. Adult snappers form spawning aggregations at specific offshore reefs located off the Dry Tortugas and west of Key West during the full moon periods of the summer months (May – August); the subsequent larvae then enter Florida Bay through inter-island channels.

The influx of snapper larvae into Florida Bay from offshore waters of the Straits of Florida was monitored to determine the spatial and temporal variability in larval supply and to examine the relationship between larval supply and environmental and oceanographic variables. Supply of settlement stage snapper larvae into the Florida Bay juvenile habitat was monitored over a two year period from July 1997 to June 1999 at two inter-island channels in the Florida Keys: Long Key Viaduct and Whale Harbor Channel. Larvae were collected with plankton nets moored 1 – 3 m below the surface on the bayside of each channel; nets were fished between dusk and dawn on three consecutive nights around the new moon of each month.

Six species of snapper larvae were collected from a total of 249 samples; species composition and percent relative abundance were as follows: *Lutjanus analis* (0.3%), *L. apodus* (5.4%), *L. chrysurus* (26.4%), *L. griseus* (34.1%), *L. synagris* (32.7%) and *L. mahogoni* (1.1%). Larval duration and back-calculated birthdates were estimated from daily lapillar otolith increment counts. Based on data collected from 92 specimens from the first year of collection mean larval duration varied slightly across species and ranged from 35.50 – 41.45 days. Otoliths from 100 specimens of four species from the second year's collection were prepared for analysis. Preliminary data from this second year of samples indicates that larval durations during the second year differ from those of the first year. Size and age at settlement of fish collected during the first year (El Niño) with those collected during the second year (La Niña) of the study are also compared.

The position, extent, and variability of offshore fronts and recirculation features were obtained from two sources of remotely sensed measurements: AVHRR (Advanced Very High Resolution Radiometer) satellite SST imagery (Johns-Hopkins University) and TOPEX/ERS-2 satellite altimetry plots created by the Colorado Center for Astrodynamic

Research. Analysis of these complementary data allow identification of factors affecting the origin, retention, and transport of larval snappers and subsequent regulation of recruitment to Florida Bay.

The Loop Current penetrates into the northeastern Gulf of Mexico to varying degrees throughout the year and from year to year. During high latitudinal intrusion it loops anticyclonically through the Gulf before entering the southern Straits of Florida where it becomes the Florida Current. Periodically, anticyclonic rings separate from it, initiating a rapid decline of latitudinal intrusion, and results in direct flow from the Yucatan Channel into the southern Straits of Florida. The Tortugas Gyre evolves from Loop Current frontal eddies which become trapped offshore of the Dry Tortugas during periods of high latitudinal intrusion of the Loop Current. This gyre can act as a mechanism for the retention and dispersal of larvae along the eastern coast of Florida.

Peak abundances of snapper larvae entering Florida Bay occurred in the summer of 1997. This was coincident with a well developed Loop Current (high latitudinal extent) favoring gyre formation off the Dry Tortugas where snapper spawning aggregations occur. We hypothesize that gyre presence during the spawning season enhances year class strength in Florida Bay via 1) larval retention and 2) nutrient-enrichment of the larval pelagic habitat through gyre-induced upwelling. In contrast, during the second year of the study the Loop Current was relatively underdeveloped (characterized by low latitudinal intrusion) and abundances of snapper larvae were correspondingly lower in that year. If, in addition to this difference in larval abundances, differences in larval duration and size are found, this could be related to the difference in physical conditions characterizing each of the years of the study and may indicate variability in settlement behavior under different physical conditions.

Back-calculated spawning dates estimated from otolith increment analysis together with the timing of peaks in larval supply to Florida Bay indicate that spawning occurred around the time of the full moon and during periods in which spawning aggregations are known to occur off the Dry Tortugas.

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## **The Effects of Water Management on Roseate Spoonbills and their Piscine Prey I. Responses to a Multi-Year High Rainfall Period: Implications for the Restoration of Taylor Slough**

**Jerome J. Lorenz**

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Historical evidence indicates that, prior to drainage of the Everglades, the wetlands that fringe northeastern Florida Bay on the mainland were primarily freshwater or oligohaline. Operation of the C-111 canal/South Dade Conveyance System over the last four decades has likely played a role in the progressive conversion of these marshes into mangrove wetlands. Under present water management operations, these wetlands fluctuate between freshwater and marine conditions within the annual wet/dry season cycle. If Everglades restoration efforts are successful, the quantity of freshwater flows to the northeastern Florida Bay estuary should resemble that which occurred prior to 1960, resulting in a 'restored' freshwater/oligohaline coastal wetland. If this restoration is accomplished, higher trophic levels, such as Roseate Spoonbills, should be expected to return to former numbers as well. Between June 1992 and May 1996, record amounts of rainfall in southern Florida resulted in freshwater discharges into northeastern Florida Bay that may have been similar in quantity to historic flows. By examining the effects of this increased flow, I have attempted to assess the impact of restoration on the prey base fish community and Roseate Spoonbill nesting.

A critical link in the estuarine food web of these wetlands are the demersal forage fish community. Although, there are no accounts of the fish community in the coastal wetlands prior to 1960, the composition of the vegetative community were documented. Therefore, marshes that had similar vegetation patterns to those described for the coastal wetlands in the 1950's were identified just upstream from the existing mangrove wetlands. I have assumed the fish community at these locations to be a good representation of the historic/restored community in the coastal wetlands. Fish samples were collected at two freshwater sites from 1993 -1998 using the same methods as collections made at four locations in the coastal wetlands from 1990-1999. Correspondence Analysis of these fish collections indicated that the coastal wetland fish community more closely resembled the freshwater fish community during and immediately following the high rainfall period than samples collected under normal conditions. Furthermore, community samples from the freshwater sites and during the low salinity period had more fish and greater biomass per unit area than samples collected during higher salinity periods. These results indicate that, prior to water management, the prey base community was more robust than the current community. Therefore, restoration of flow should result in a recovery of this more robust community.

Historically, spoonbills feeding in these wetlands successfully nested in more than 70% of the years. However, prior to the low salinity period, spoonbills were successful in only 5 of the 11 years (45%). This lowered success was believed to have been due to a reduction in prey availability in the coastal wetlands caused by water management practices. Therefore, the higher prey abundance during the low salinity period would have been expected to result in higher spoonbill nesting success. However, spoonbill nesting colonies were observed to

fail during this period. Although the quantity of freshwater flow to the estuary was restored and prey fish populations responded, the timing of these flows probably kept water levels too high for the prey concentration effect to occur during the spoonbill nesting season (see abstract entitled The Effects of Water Management on Roseate Spoonbills and Their Piscine Prey II. Water depth and Hydroperiod Effects on Prey Availability and Spoonbill Nesting Success). These results suggest that both quantity and timing of freshwater flows are critical if predator populations are to recover.

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Question 5 - Higher Trophic Levels

## **The Effects of Water Management on Roseate Spoonbills and Their Piscine Prey II. Water Depth and Hydroperiod Effects on Prey Availability and Spoonbill Nesting Success**

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Multiple studies regarding trophodynamics in the Everglades have postulated that food resources are linked to the annual hydrologic cycle. According to paradigm; fish and aquatic invertebrate communities utilize ephemeral wetlands as foraging grounds and refugia from predation during high water periods thereby increasing in abundance during the wet season. During low water periods, these fish become highly concentrated in the remaining wetted areas of the wetland, thereby serving as an abundant food resource for wading birds and other predators during the dry season. Progressively falling water levels sequentially dry out ephemeral wetlands as the drying front passes across the topographic elevation gradient. These conditions produce a succession of high quality foraging patches as prey base fishes are concentrated along the drying front. Wading birds move from one patch to another as each successive patch becomes depleted, and thereby, have continuous access to a highly abundant food resource throughout the breeding period. This study examines nine years of hydrologic and fish abundance data from the mainland coastal wetlands of northeastern Florida Bay in conjunction with nesting parameters of Roseate Spoonbills that feed in these wetlands to see if seasonal changes follow the proposed paradigm.

Fish were collected in each of two sub-habitats (creeks and flats) at four locations within the coastal wetlands. The creek sub-habitat represented that part of the wetland that was continuously inundated, thereby representing the deep water refugia during low water periods. The flats sub-habitat was only seasonally inundated, thereby representing the ephemeral wetlands proposed in the paradigm. Seasonal fluctuations in fish abundance within the sub-habitats and in total fish abundance (stratified mean for both sub-habitats combined) occurred and were clearly related to the annual hydrologic cycle. Results of ANOVA revealed that fish start to become concentrated when water levels fell to about 12.5 cm relative to the depth at which the flats sub-habitat is completely dry. Therefore, samples collected at 12.5 cm or lower were analyzed separately from samples collected at higher water levels.

During periods when water level was above 12.5 cm relative depth (i.e., when the wetland was fully inundated) fish abundance in the flats sub-habitat tended to be positively related to the depth of water prior to sample collection. Presumably, greater depth provided increased three dimensional foraging space thereby resulting in larger populations. Seasonal analyses of fish abundance on the flats also indicated that increased hydroperiod resulted in greater abundance, presumably by allowing time for multiple generations to be spawned.

During periods when water levels were lower than 12.5 cm, mean fish biomass in the creek sub-habitat was about double compared to periods when water levels were higher. Seasonal analyses of the two sub-habitats indicated that this increase was caused by fish being forced



from the flats sub-habitat into the creeks by receding water levels. Differences in topography and timing of low water events within the coastal wetlands appeared to provide patches of concentrated prey in different locations through time. Potentially, this temporal and spatial mosaic in fish abundance would result in high quality foraging for wading birds somewhere in the coastal wetland throughout the reproductive season. However, reversals in the drying progression frequently disrupted the concentration process.

Spoonbills traditionally nested during the dry season presumably to take advantage of a highly concentrated and readily available food resource as indicated above. Water level and prey availability during spoonbill nesting periods were compared between successful and failed nesting attempts. Mean water levels at the fish sampling sites were found to be lower than 12.5 cm during successful nesting periods and higher than 12.5 cm during failed nesting periods. Furthermore, during successful nestings, prey availability at the sites was twice that of failed nesting periods. These results supported the proposed paradigm.

Out-of-season pulse-releases of water from the canal system have been shown to raise water levels in the coastal wetlands. If such releases occurred during spoonbill nesting, prey would become dispersed and nesting spoonbills would be unable to capture enough prey to meet the energetic demands of their rapidly growing young. The inability of water managers to limit canal discharges that are out of phase with pre-drainage conditions likely explains the increased frequency in spoonbill nesting failure in recent years.

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Question 5 - Higher Trophic Levels

## **Distribution and Abundance of Seagrass-Associated Fauna in Florida Bay: The Effects of Salinity and Other Habitat Variables on Resident Fish and Selected Decapod Crustaceans**

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Seagrasses provide food and shelter for vast numbers of resident fish and crustaceans throughout Florida Bay. The distribution and abundance of these animals are related to various habitat parameters, including seagrass-bed structural complexity, salinity, turbidity, current patterns, sediment depth, and water depth. Previous quantitative studies of this faunal community have been limited in both geographic scope and habitat coverage. We used a synoptic approach and one type of gear (1-m<sup>2</sup> throw-traps) to sample fish and selected crustaceans (penaeoid and caridean shrimps plus portunid crabs) in three seagrass-habitat strata (shoreline or near-key, bank, and basin) at 18 sites located throughout Florida Bay. Between October 1998 and April 2000, we collected approximately 900 throw-trap samples during both wet (fall) and dry (spring) seasons. The primary goal of our ongoing research is to quantify the relationships between faunal abundance and important habitat variables. These data will be available for incorporation into predictive models used to assess the effects of habitat changes (whether due to restoration efforts or to natural phenomena) on the Florida Bay ecosystem. Because we are still in the process of identifying animals and analyzing data, this presentation is based on only a portion of our data. Fish data included in our presentation are from bank and basin strata sampled during October 1998 and April 1999 and from the shoreline stratum sampled during April 1999. Crustacean data are from bank and basin strata sampled during October 1998.

Our 18 sample sites represent a complex mixture of habitat types but can be grouped based on salinity, sediment depth, and seagrass community. In a principal component analysis based on measurements of these habitat variables taken on banks at each site, the first two principle components (PC's) explained 76% of the variation in the data and separated the sites into these three geographic groups: 1) northeastern (NE)—Deer Key, Eagle Key, Black Betsy Keys, and Nest Keys; 2) south-central (SC)—Butternut Key, Bob Keys, Crab Keys, Bob Allen Keys, Spy Key, Whipray Keys, Buttonwood Keys, Roscoe Key, Barnes Key, Rabbit Key, and Johnson Key; and 3) northwestern (NW)—Palm Key, Joe Kemp Key, and Sandy Key. Heaviest loadings on PC1 were for total seagrass shoots and non-*Thalassia testudinum* shoots (*i.e.*, *Halodule wrightii* shoots plus *Syringodium filiforme* shoots), and heaviest loadings on PC2 were for salinity and sediment depth. Seagrass beds were least developed at NE sites (mean=513 shoots m<sup>-2</sup>), intermediate at SC sites (mean=838 shoots m<sup>-2</sup>), and most developed at NW sites (mean=3,350 shoots m<sup>-2</sup>). The average proportion of

*T. testudinum* in seagrass beds ranged from 99% at NE sites to 89% at SC sites to 8% at NW sites. The average density of *H. wrightii* shoots increased from NE to SC to NW sites, and *Syringodium filiforme* was present only at NW sites. Salinity averaged 24 ppt at NE sites and 34 ppt at SC and NW sites; sediment depths averaged 50 cm at NE sites, 141 cm at SC sites, and 182 cm at NW sites.

Overall crustacean abundance followed the salinity-sediment-seagrass gradient with mean densities least at the NE sites (29 m<sup>-2</sup>), intermediate at the SC sites (90 m<sup>-2</sup>), and highest at the NW sites (194 m<sup>-2</sup>). Numerically dominant taxa were *Thor floridanus*, *Hippolyte zostericola*, and *Farfantepenaeus duorarum* at SC and NW sites and *T. floridanus*, *H. zostericola*, and alpheid shrimp (*A. heterochaelis*, *Alpheus normanni*, and unidentified incomplete juveniles) at NE sites.

Abundances of the four dominant crustacean taxa showed similar patterns of correlation (Spearman correlations) with environmental variables. Densities of all four taxa were negatively correlated with water depth and positively correlated with sediment depth and total seagrass shoots. Abundances of all but alpheids were also positively correlated with salinity. Thus, *T. floridanus*, *H. zostericola*, and *F. duorarum* were most abundant at NW sites and least abundant at NE sites. Alpheids were also most abundant at NW sites, but their abundances at SC and NE sites were similar to each other. On a site-specific basis, these correlations indicate that all four taxa are more abundant on banks than within basins. Crustacean associations with seagrass species varied among taxa: *Thor floridanus* abundance was positively associated with *T. testudinum* density, whereas alpheid, *H. zostericola*, and *F. duorarum* abundances were positively associated with *H. wrightii* and/or *S. filiforme* density.

The distribution of non-pelagic fishes among geographic areas was similar to that observed for crustaceans, although fishes were much less abundant than crustaceans. The few pelagic fish collected during this study (*e.g.*, *Anchoa mitchilli* and *Harengula jaguana*) were not considered to be strongly associated with seagrasses and were eliminated from all analyses. Northeastern sites averaged 4 non-pelagic fish m<sup>-2</sup>, and the community was dominated by *Floridichthys carpio*, *Microgobius gulosus*, and *Lucania parva*. South-central sites averaged 8 non-pelagic fish m<sup>-2</sup>, and dominant species were *Gobiosoma robustum*, *Lucania parva*, and *Floridichthys carpio*. Northwestern sites averaged 9 non-pelagic fish m<sup>-2</sup>, and the dominant species were *G. robustum*, *L. parva*, and *F. carpio*. Of the three habitat strata at each site, fish were usually most abundant along the shoreline and least abundant within the basins. Fish densities were often similar for the bank and shoreline strata.

The densities of the four numerically dominant non-pelagic fish species exhibited different patterns of correlation with environmental variables. Densities of *F. carpio* and *M. gulosus* were negatively correlated with salinity, whereas densities of *G. robustum* and *L. parva* were positively correlated with salinity. The density of *M. gulosus* was negatively correlated with sediment depth, but the densities of the other three species was positively correlated with sediment depth; correlations with water depth were the opposite. Overall, *M. gulosus* densities were similar on banks and within basins; this species was absent at NW sites. The densities of the other three species were greater on banks than within basins (*i.e.*, more abundant at sites with shallow water and deep sediments). Correlations of fish density with

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seagrass shoot density ranged from positive for *G. robustum* and *L. parva* to negative for *M. gulosus*. The density of *F. carpio* was not correlated with total seagrass shoot density but was positively correlated with *T. testudinum* density.

Based on these preliminary analyses, we conclude that changes in salinity and seagrass species composition or shoot density in Florida Bay will likely lead to changes in seagrass-associated fish and crustacean communities and may affect populations of predators that feed on these small animals. Most of the dominant species in this system are euryhaline, but changes in freshwater inflow patterns could directly affect some species because of their salinity preferences. Moreover, changes in freshwater inflow patterns that alter the shoot density and species composition of seagrass beds could substantially alter faunal communities indirectly. Both positive and negative responses by faunal populations to such changes are possible, and the response direction will be species-specific.

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## Mesozooplankton Abundance Variability within Florida Bay (1994-2000)

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Since 1994, NOAA's South Florida Ecosystem Restoration Prediction and Modeling (SFERPM) program has supported regular monitoring of plankton populations in Florida Bay and adjacent coastal waters along the west Florida shelf and seaward of the Florida Keys. One reason is that the zooplankton of Florida Bay had received comparatively little attention prior to this work with not a single published report quantitatively characterizing the resident population. Another impetus for doing so was the relationship between zooplankton grazing and phytoplankton blooms. However, bloom incidence might be but one aspect of a more general phenomenon, ecosystem shift and habitat change. A change of state in the Bay ecosystem could have enormous consequence to the commercially and recreationally significant living resources to which the Bay represents a nursery ground and was therefore a particularly important issue to NOAA. Initial results supported this notion. However, as additional data have accumulated we now have little doubt that these initial hypotheses were over-simplified. The ecosystem in Florida Bay does not appear to be undergoing a monotonic change to a more pelagic state. In this respect the results appear consistent with the SERC surveys indicating that over the same time period plankton blooms have in general not systematically increased throughout Florida Bay. By coincidence we may have initiated our study close to the apex of phytoplankton bloom intensity.

Based on enumerations from 64um net tows the abundance of copepods and other holoplanktonic macroplankton was moderate in the Fall of 1994 through mid-winter 1995 but declined markedly thereafter to exceedingly low levels until ca. Spring 1996 when it returned to similar levels. Thereafter through the present it has increased markedly. Taxa vary but values more than five times higher than those present in 1994 have become common. The increase has occurred without any apparent increase in their apparent food source, the phytoplankton. This is not however surprising. In shallow subtropical estuaries like Florida Bay, a substantial fraction of the trophic base supporting zooplankton populations may be derived from primary production by seagrass and benthic algae rather than phytoplankton vitiating any direct positive relationship between the abundances of zooplankton and phytoplankton. Interestingly a similar trend was observed in the Western, Central and Eastern regions of the Bay despite their systematic differences in salinity, water column chlorophyll, bloom incidence etc. In contrast, the abundance of a dominant water column planktivore, *Anchovia mitchelli*, the bay anchovy, varied almost inversely with the abundance of its prey. Bay anchovy abundance in the same regions was high until 1996, when it dominated the forage fish community, but has declined precipitously thereafter to

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levels observed during the mid-1980's. Sampling has been insufficient to provide rigorous estimates of bay anchovy abundance, however, concentrations sufficient to appreciably reduce zooplankton numbers were observed with some regularity.

In short, the recent history of phytoplankton, zooplankton and planktivorous fish abundance provides little or no support for the concept of a fundamental persistent Bay shift from a demersal benthic production based ecosystem to a pelagic water column production based ecosystem.

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Question 3 - Algal Blooms

## The Potential for Filter Feeding Sponges to Control Phytoplankton Blooms in Florida Bay

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An unprecedented series of ecological disturbances has been recurring within Florida Bay (USA) since the summer of 1987. The most dramatic perturbation to this system has been the widespread mortality of turtlegrass, *Thalassia testudinum*, which has resulted in elevated inorganic and organic nutrient levels in the normally oligotrophic waters of Florida Bay and in increased turbidity in areas of exposed, easily resuspended sediments. The indirect eutrophication and increased turbidity resulting from the demise of *T. testudinum* have caused a general deterioration of the Florida Bay ecosystem, as evidenced by persistent and widespread phytoplankton and cyanobacteria blooms. These blooms have been responsible for a continued decline in seagrass communities as a result of increased light attenuation in the water column, and coincided with the large scale decimation of sponge communities.

Since the initial seagrass die-off, blooms have swept over extensive portions of the bay north of the middle Keys and have persisted for months at a time. The proliferation of the cyanobacterium *Synechococcus* and diatom *Rhizosolenia* blooms in the only region of the continental United States containing sensitive coral reef ecosystems has caused widespread concern among scientists and water managers. These blooms have the potential for disrupting the ecology of the bay through associated anoxia, toxin production and the reduction of light availability for benthic plant communities. Some regions of Florida Bay exhibit high levels of algal and/or non-algal suspended solids resulting in low light penetration. One factor which may be contributing to this unprecedented seagrass die-off is the reduction in light availability caused by high phytoplankton standing crops. One hypothesis is that the large scale loss of suspension feeding sponges has rendered the Florida Bay ecosystem susceptible to these recurring phytoplankton blooms.

Sponges are a particularly dominant structural feature of Florida Bay seagrass and hardbottom habitats, functioning as efficient filters of small (< 5  $\mu\text{m}$ ) planktonic particles. Previous studies have illustrated that the grazing pressure of filter feeding bivalves may control phytoplankton abundance. These studies generated great interest in the role that filter feeding bivalves have on phytoplankton growth dynamics and biomass. However, the influence that suspension feeding sponges have on phytoplankton biomass is relatively unknown. If the presence of sponges increases light availability to the benthic plant communities, then sponges may play an important role in reducing the shading effects of phytoplankton blooms, and the loss of this organism in Florida Bay may have cascading effects on the associated seagrass community.

A stratified random sampling design was used to identify 224 sites throughout the extent of the Florida Bay. This presentation will present data on current densities and biomass abundances of sponges at these sites. In addition, *in situ* grazing rates of the two sponge species which accounted for a dominant portion (69%) of total sponge community biomass prior to the sponge die-off (*Sphaciospongia vesparia*, loggerhead sponge and *Ircinia*

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*campana*, vase sponge) will be used to assess the impact of the large scale mortality of sponges that has occurred in Florida Bay. We will speculate if the system-wide trophic dysfunction, a consequence of the documented sponge die-off, has potentially contributed to the magnitude of the nuisance blooms and if the loss of these organisms can explain why this system remains susceptible to recurrent blooms of phytoplankton and cyanobacteria.

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## Interannual Changes in Juvenile and Small Resident Fish Assemblages, and Seagrass Densities in Florida Bay

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Five series of bi-monthly sampling for juvenile and small resident fishes have been conducted since 1984-1985. From May 1984 through January 1999, sampling was conducted with a two-boat otter trawl (Thayer et al., 1999). Sampling was conducted at 18 stations divided among three strata. In March 1999, we modified our sampling design to conform with the South Florida Ecosystem Restoration Prediction and Modeling (SFERPM), Program Management Committee's (PMC) subdivision designations. Florida Bay was stratified into six subdivisions that were divided into one nautical mile squares. Because the number of trawlable squares in each subdivision were not equal, the number of stations to be sampled were weighted by trawlable area. Thirty-six stations were randomly chosen (Gulf Transition: 4; Western: 3; Central: 10; Atlantic Transition: 7; Northern Transition: 3; Eastern: 9). Sampling was conducted with a 5.5 m boat and the same 3- m otter trawl previously used. The habitat monitoring of this work was directed at water column and seagrass characterization. Temperature, salinity, water clarity (secchi disk) and water depth were recorded. Three 0.008 m<sup>2</sup> cores were taken along a transect adjacent to the trawled area for seagrass short-shoot densities, composition, blade length, and standing crop.

The recent juvenile and small resident fish assemblage (especially 1998 collections) differed markedly than observed in 1994-1995 and resembled the assemblage observed in 1984-1985. There appeared to be a change in dominance from canopy dwelling fishes (1984-1985) to pelagic zooplanktivores (1994-1995) back to canopy dwelling fishes (1998-present). The bay anchovy (*Anchoa mitchilli*), a pelagic zooplanktivore, was rarely collected in 1984-1985, dominated collections in 1994-1996, rarely collected in 1998, and moderately abundant in 1999-2000. Even when this species was dominant, it was rarely collected in the Atlantic Transition Subdivision. Mean densities of two commonly collected canopy dwelling fishes (*Lucania parva*, rainwater killifish; *Eucinostomus gula*, silver jenny) were dissimilar to bay anchovy. The silver jenny, which is a transient species, was abundant in 1984-1985 (except at the Atlantic Transition Subdivision where this species is not commonly collected), but mean densities declined notably from 1994-1996. Presently, mean densities of silver jenny are similar to those observed in 1984-1985, except densities remain low (4.1 1000 m<sup>-2</sup>) in the Gulf Transition Subdivision compared to 1984-1985 (82.6 1000 m<sup>-2</sup>). Mean densities of the rainwater killifish, which is a resident species, were similar to those observed for the silver jenny. Rainwater killifish were abundant in 1984-1985 (except at Eastern and Atlantic Transition Subdivisions where they are not commonly collected), densities declined from 1994-1996, and in recent collections, densities in the Central and Western Subdivisions mirrored those of 1984-1985. Like the silver jenny, mean densities of the rainwater killifish in the Gulf Transition Subdivision were low in 1999-2000 (0.2 1000 m<sup>-2</sup>) compared to 1984-1985 (67.3 1000 m<sup>-2</sup>). Similarly, in the Gulf Transition Subdivision, mean densities of other commonly collected species (*Haemulon plumeri*, white grunt; *Lagodon rhomboides*, pinfish; *Floridichthys carpio*, goldspotted killifish; *Bairdiella chrysoura*, silver perch; *Hippocampus*

*zosteræ*, dwarf seahorse; and *Orthopristis chrysoptera*, pigfish) that represent diverse life history types were low in present collections relative to 1984-1985.

The assemblage of juvenile and small resident fishes that presently mirrors that of 1984-1985 appeared to be greatly influenced by the cyclical dominance of pelagic zooplanktivorous clupeiforms (anchovies and sardines), that might be related to chlorophyll a concentrations, which have been reported to be dynamic and spatially heterogenous.<sup>1</sup> The present assemblage that is dominated by canopy dwelling juvenile and small resident fishes can not be entirely explained by the recovery of seagrasses, especially in the Western Subdivision. Our observations indicate that on a subdivision wide basis, presently there is no evidence for recovery relative to our 1994-1996 observations, and seagrass standing crop and densities are much lower than observed in 1984-1985. In the Western Subdivision where seagrass die-off was most pronounced we have observed notable increases in mean densities (numbers 1000 m<sup>-2</sup>) of commonly collected canopy-dwelling juvenile and small resident fishes in 1999-2000 collections relative to 1984-1985 collections. This is exhibited (1984-1985 vs 1999-2000) by silver jenny (71.2 vs 96.7), white grunt (7.9 vs 20.7), silver perch (9.0 vs 26.5), rainwater killifish (91.5 vs 101.2) and pigfish (9.7 vs 39.9). In addition, mean densities for the recreationally important spotted seatrout, *Cynoscion nebulosus* were 1.1 and 9.3 for 1984-1985 and 1999-2000, respectively. Mean total fish densities in any yearly sampling series were highest in the Western subdivision, where seagrass composition is most diverse and manatee grass (*Syringodium filiforme*) is most dense. Yet, mean total densities in 1984-1985 (395.3 1000 m<sup>-2</sup>) were much lower than observed in 1999-2000 samples (692.1 1000 m<sup>-2</sup>). Total mean fish densities (numbers 1000 m<sup>-2</sup>) in 1999-2000 collections were also higher than those observed in 1984-1985 (1984-1985 vs 1999-2000) in Atlantic Transition (28.8 vs 43.0) and Central (85.5 vs 196.9) Subdivisions, but lower in East (105.8 vs 69.7) and Gulf Transition (316.6 vs 454.1) subdivisions. In neither of these two sampling periods were bay anchovy dominant.

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## **Early Life History of Spotted Seatrout (*Cynoscion nebulosus*) in Florida Bay**

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The early life history of spotted seatrout was studied from 1994 to present. In 1994-1995, 14 stations covering most of Florida Bay were sampled with standard ichthyoplankton bongo nets fitted with 0.333 mm mesh (Figure 1). In 1996, ichthyoplankton sampling was conducted at only those stations where spotted seatrout were collected in 1994-1995. In September, 1997 we decreased our ichthyoplankton sampling coverage to monitor spotted seatrout at four stations—Little Madeira Bay, Whipray Basin, Palm and Bradley Keys. Spawning had only recently been observed at two stations (entrance to Little Madeira Bay and Whipray Basin) whereas spawning has historically been observed at Palm and Bradley Keys. Stations were sampled with a paired 60 cm diameter bow-mounted push net with 0.333  $\mu\text{m}$  mesh for ichthyoplankton and a 0.3 x 0.7 m sled (July 1997-September, 1998) or a 1.0 x 0.5 m sled from May -Nov 1999 for recently settled larvae or juveniles.

Juvenile spotted seatrout used for otolith microstructure analysis were obtained from collections made in 1995 by Florida Marine Research Institute staff to examine: (1) size at age data to determine if growth differed by location; (2) hatchdate distributions to infer temporal spawning; and (3) the influence of temperature and salinity on otolith growth, a surrogate for somatic growth. Otolith methodology consisted of using polished, transverse sagittal sections from juvenile spotted seatrout. Increment counts, examined under immersion oil at 1000x magnification, were used to estimate size at age, and hatchdates. Standard regression analysis was used to compare growth (size at age) among subdivisions. Hatchdate distributions were standardized to account for mortality. Sagittal otoliths from 347 fish were aged and daily otolith increment measurements were obtained using image analysis. The counting path changed at 21 increments. Therefore the analysis was divided into two sets associated with each of the counting paths. Age estimates differed significantly between the standard counting method and image analysis for some fish. To eliminate inaccurate growth estimates due to ageing errors, any otolith that differed by greater than 7 days or 10% was excluded from the analysis. One-hundred and seventeen otoliths were removed using these criteria. To compare growth across distinct intervals and reduce noise the observations for otolith increment width, salinity and temperature were averaged across calendar weeks for 1995. A random coefficient model was used to determine a relationship between temperature or salinity and the natural log of otolith increment width. This model was implemented using SAS Proc Mixed procedures (SAS 1997). An age interaction was included to account for differences in growth across ages. Autocorrelation between observations from the same fish was modeled using a Markov covariance structure. Observations between fish were assumed to be independent.

Daily salinity and temperature values in 1995 were obtained from the Everglades National Park Service for Johnson Key basin, Little Madeira Bay, and Little Blackwater Sound. Values for other stations were estimated for 1995 using a relationship derived between stations from 1997-1998 data and applying to 1995. The values for Murray/Bradley Key were then predicted from the 1995 Johnson Key Basin values using the regression obtained. When there was not a monitoring station close to the sampling station, temperature and salinity were predicted using a relationship between values obtained when fish samples were taken and the closest monitoring station where 1995 data were available. In some cases a good relationship could not be determined and these fish were excluded from the study.

Spawning habitat for spotted seatrout in Florida Bay was determined. This species spawns mainly in Gulf Transition, Western, and Central Subdivisions (subdivision designations follow South Florida Ecosystem Restoration Prediction and Modeling Program, Program Management Committee), but spawning has also been reported in Little Blackwater and Blackwater Sounds in the far northeastern portion of the bay (Rutherford et al., 1989). Early larvae of spotted seatrout were mainly collected from May through September, but we collected larvae on one occasion in November and February and two occasions in April. Based on hatchdate estimates from 1995 juvenile collections, spawning peaks were observed in May and June with 50% and 100% of the total spawning occurring in mid-July and October, 1995, respectively. Larvae were collected over a wide range of bottom types with and without seagrass, in waters with temperatures between 20 and 35°C (majority between 26 and 34°C, and salinities between 12 and 41 ppt (majority between 25 and 40 ppt). Collections of larvae below 15 ppt, which occurred twice at the entrance to Little Madeira Bay, are notable as spotted seatrout pelagic eggs sink to the bottom at salinities below 20-25 ppt and are not viable. Although the majority of larvae were >1.5 mm and could have been transported into the area, one recently hatched larvae (1.3 mm) was collected. Still it is highly unlikely that a significant number of viable eggs could be produced at those low salinities. Spotted seatrout larvae were consistently collected at relatively high densities in Whipray Basin and the presence of larvae <1.5 mm indicated spawning occurs in this area. Yet we rarely collected recently settled larvae, and juveniles in Whipray Basin. This site has relatively sparse *Thalassia testudinum* standing crop (12 gms/m<sup>2</sup>) compared to Palm Key (28 gms/m<sup>2</sup> *T. testudinum* and 14 gms/m<sup>2</sup> *Halodule wrightii*). Although spotted seatrout appeared to spawn intensively throughout the spawning season in Whipray Basin, the value of this basin as a nursery area for spotted seatrout could be minimal.

Growth of juvenile spotted seatrout among three subdivisions (Gulf Transition, Western and Central) was not significantly different. The regression model that best describes juvenile growth (25-95 mm) was  $\text{Length} = -10.1414 + 0.8758 \text{ Age}$  ( $n = 346$ ). The regression that best describes larval and juvenile growth (1.2-100.0 mm) was  $\text{Log}_e \text{ Length} = 0.98406 + 0.04629 \text{ Age}$ . Otolith microstructure analysis indicated there was only a significant relationship between increment width and salinity for the  $\leq 21$  increment group. Salinities at five stations (Bradley, Sandy Roscoe Palm and Buoy Keys, and Johnson Key Basin) averaged across weeks ranged between 27-35 ppt. Salinities at two stations (Little Madeira Bay and Little Blackwater Sound) were considerably lower (5-10 ppt).

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Question 5 - High Trophic Level

## Habitat Use of Bottlenose Dolphins in Florida Bay

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### Background

Until recently, little research or monitoring effort has focused on a highly visible component of an upper trophic fauna in the Florida Bay system – the bottlenose dolphin. As upper trophic level predators in this system, dolphins depend on the health of prey populations for their survival and are potentially impacted by any stressors that affect their prey base, including salinity changes, nutrient inputs and habitat degradation. Between July 1999 and April 2000, we initiated a pilot research project to examine patterns of habitat use and behavior of bottlenose dolphins in Florida Bay. Our objectives were to: (1) assess the impact of current patterns of prey distribution on the distribution of bottlenose dolphins; and (2) evaluate the effects of habitat degradation on bottlenose dolphins as mediated through their prey.

### Methods

We assessed the distribution of bottlenose dolphins in relation to the distribution of their prey and water quality by conducting surveys and focal animal follows from small, outboard-powered vessels. These surveys and follows were conducted throughout the year, allowing us to capture seasonal variation in dolphin distribution and patterns of habitat use. The study area was divided into strata representing habitats of varying composition and quality. Visual surveys were conducted in each strata to locate dolphins. At 30-minute intervals during these surveys we measured salinity, turbidity and water depth and once an hour we sampled prey using a small research trawl. When we encountered a group of dolphins, we recorded the sighting location using a differential GPS unit and took photographs of the dorsal fin of each dolphin in the group. One distinctive individual was selected as a focal animal and that dolphin was followed from a distance of <100m. During each follow, the focal animal's location, habitat type, behavior, group composition and size was recorded at three-minute intervals. If a dolphin was observed feeding, we sampled prey and water quality using the research trawl, YSI probe and secchi disc. Thus, we obtained samples of the relative abundance and species composition of prey and water quality at sites where dolphins were observed feeding. At regular intervals throughout the follow we sampled prey and water quality data to obtain control data. We incorporated distribution, movement and behavioral data collected in the field to test the hypothesis that dolphins feed preferentially in habitats where prey densities are high.

## Distribution of Dolphins

We conducted 20 surveys of bottlenose dolphins in all four seasons. During these surveys we encountered 23 groups of bottlenose dolphins comprising 133 individuals. Dolphins were seen in every season, but were not found throughout the entire survey area. Most sightings occurred in the east-central and southwestern portions of Florida Bay; we found very few dolphins in the northeastern portion. We encountered groups of one to 20 individuals, with a mean group size of 5.8 (SD 4.9). Water temperatures and salinities ranged from 20.8-31.1 C and 12.3 to 36.9ppt, respectively during surveys. We collected a large quantity of water quality during these surveys and plan to correlate the distribution of dolphins with these environmental parameters in future analyses. During the 20 field days, we conducted 10 focal follows, with a maximum follow duration of 6 hours and 54 minutes. We observed focal animals engaging in various behaviors, including feeding. Our analyses of these behavioral data are not yet complete.

## Distribution and Composition of Prey

We conducted 63 trawls for potential prey of bottlenose dolphins, which yielded a total of 746 fish of 39 species, excluding small fishes such as anchovies. Water temperatures and salinities ranged from 20.8 to 32.7 C and 12.3 to 37.3 ppt, respectively at trawl locations. In all seasons and areas, the trawl samples were dominated by mojarras (Family Gerreidae). In general, the trawls produced a relatively low density and diversity of potential prey items, with a mean of 12 fish and two species per trawl. Ten trawls were conducted in the vicinity of feeding dolphins, primarily during the course of focal follows. There were significantly more fish captured in trawls made in the vicinity of feeding dolphins than in trawls made during surveys when no dolphins were present. The diversity of potential prey was not significantly different between trawls made around feeding dolphins and those made during surveys. We examined the stomach of one bottlenose dolphin that stranded in Florida Bay during the summer of 1999. Unfortunately, the forestomach of this specimen was completely empty. We will continue to collect stomachs from other specimens as they become available.

## Discussion

Our analysis of the first year of work is far from complete, but we can make some preliminary assessment of the distribution and behavior of bottlenose dolphins in Florida Bay. We wish to note, however, that much analytical work remains to be completed and that any conclusion presented here should be regarded as provisional, pending further analysis. Our surveys confirm that bottlenose dolphins are present in Florida Bay throughout the year. The density of dolphins in this area does not appear to be particularly high and it seems likely that the community of animals inhabiting this area is likely comprised of a relatively small number of individuals. Our photographic analysis, once completed and compared with the SEFSC catalog from Biscayne Bay and adjacent waters (Contillo et al. 1997), will provide important information in this regard.

A qualitative examination of the distribution of sightings and follows reveals that most dolphins were found in the east-central and southwestern portion of the Bay, where the

environment is influenced by exchange with the Atlantic Ocean. Our analysis of the spatial variation of potential prey is not yet complete, but other studies have found that fish densities are relatively low in eastern and northern Florida Bay (Sogard et al. 1989; Thayer and Chester 1989). We believe that the distribution of bottlenose dolphins in this area is driven primarily by the distribution of prey which, in turn, is determined by environmental factors such as temperature, salinity and habitat type. It is apparent from a cursory examination of our data, for example, that the low number of sightings in the northeastern portion of the Bay is correlated with relatively low salinities in that area.

Dolphins were observed feeding in areas where the density of potential prey was high. That we were able to draw this conclusion, despite a relatively low sampling effort, suggests to us that important linkages exist between dolphins and their prey in this environment. Florida Bay is characterized by strong environmental gradients, particularly with regard to salinity, and a diversity of habitat types. In such environments, fish are likely to be patchily distributed, associated with environments which fall within physiological tolerances and provide suitable habitat. Piscivorous predators, such as bottlenose dolphins, will respond to the patchy distribution of prey by concentrating their foraging efforts in areas where prey are abundant. Due to their visibility, bottlenose dolphins are a good indicator of the distribution of prey and, in turn, of the quality of the habitat and environment which support these fishes.

The work described here represents some of the first dedicated research on bottlenose dolphins in Florida Bay. We believe that continuation of this research will provide a rich baseline of information from which we will be able to assess the responses of bottlenose dolphins to future changes in the South Florida ecosystem.

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Question 5 – Higher Trophic Level



## **Population Modeling of the American Crocodile (*Crocodylus acutus*) for Conservation and Management in South Florida**

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An individual-based model of the American crocodile (*Crocodylus acutus*) in South Florida was constructed. This model is part of a larger modeling project, ATLSS (Across Trophic Level System Simulation), which attempts to predict the effects of restoration scenarios on the flora and fauna of the Florida Everglades. Altering the hydrology will result in altered salinity and water levels in estuaries areas, or core crocodile habitat. The crocodile modeling effort seeks to predict the effects of upstream hydrology on population size, population viability, breeding success and habitat utilization. The crocodile model utilizes a simulated spatial environment and incorporates information on individual movement, behavior, growth, and reproduction. The results of sensitivity analysis demonstrates the usefulness of such modeling techniques in the effective management and study of rare, endangered or otherwise difficult to study species.

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## Response of Seagrass Fish and Invertebrates to Habitat Changes in Johnson Key Basin, Western Florida Bay (1985 – 1995)

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In the fall of 1987, a widespread, rapid die-off of the dominant seagrass, *Thalassia testudinum*, began in Florida Bay. Increasingly extensive and persistent turbidity and algal blooms, apparently linked to the loss of turtle grass, have been associated with active seagrass die-off sites since 1988 and have characterized generally western and central Florida Bay since 1991. Recolonization of denuded areas by shoal grass, *Halodule wrightii*, has followed the loss of turtle grass.

In 1985 thirty sampling stations had been established in Johnson Key Basin. Stations had been located generally with no *a priori* consideration of the seagrass habitat present and were evenly stratified among the principal seagrass macro-habitat types present in Florida Bay: bank, basin, and near key. These thirty stations have been sampled on an approximately five-year interval (January 1985, May 1985, May 1989, January 1990, January 1995 and May 1995) providing the opportunity to observe faunal responses in numbers and species composition to change in seagrass habitat structure within the basin. Quantitative animal samples of seagrass associated fish and invertebrates, including the pink shrimp, were collected using a throw-trap; the area sampled by the throw-trap was 1 m<sup>2</sup> of bottom. The throw-trap operated over the full range of water depths occurring in Johnson Key Basin with a sampling efficiency estimated to exceed 95% as deployed for grass bed fish and invertebrates. Each animal sample was associated with quantitative measurements estimating microhabitat structure of the seagrass canopy: standing crops by seagrass species and associated macroalgae, seagrass blade densities by species, sediment texture and organic content, water and sediment depth, compaction, water salinity and temperature.

Unlike some areas in western Florida Bay, seagrass die-off in Johnson Key Basin was patchy and seagrass habitat change was most dramatic between 1990 and 1995 when algal blooms were always present in the basin. The cumulative affect of seagrass loss and recovery and reduced water clarity between 1985 and 1995 was a shift away from a turtle grass dominated seagrass meadow to one exhibiting greater habitat heterogeneity. Over this decade the standing crop of *Thalassia* had declined by 71% in Johnson Key Basin; standing crop of *Halodule* had increased by 24% in the basin; and *Syringodium* had disappeared from the thirty stations sampled though it was reported as present in basin. *Thalassia*, the dominant seagrass in 1985 at 17 stations in Johnson Key Basin was the dominant at only 9 in 1995. *Halodule*, present at 13 stations in 1985, was found at 18 by 1995. By 1995 bare sediment, not present as an appreciable habitat type in 1985, characterized the bottom in Johnson Key Basin at 4 of the thirty stations.

Accompanying these habitat changes faunal changes were observed. Comparing 1985 to 1995 the abundance (January and May averaged) of seagrass associated caridean shrimps had declined by about 65% while seagrass fishes had declined by 81%. Densities of pink shrimp, *Farfantepenaeus duorarum*, in 1995 were half that observed in 1985, (1.9/m<sup>2</sup> vs 4.0/mfs24<sup>2</sup>,

respectively). Salinity and water temperature conditions during sampling did not differ appreciably (31.5‰ vs 28.4‰; 25 C vs 24.9 C, respectively).

The fish and shrimp communities changed dramatically over the decade in Johnson Key Basin. In 1985, the killifish, *Lucania parva* and the caridean shrimp, *Thor floridanus* dominated numerically (62% and 81% of individuals, January and May averaged, respectively). By 1995 these populations had declined to 3% and 27% of fish and caridean shrimp collected, respectively. Six fishes, *Anchoa mitchilli*, *Sardinella aurita*, *Achirus lineatus*, *Gobiosoma robustum*, and *Hippocampus zosterae*. were numerically more abundant in 1995 and accounted for 65% of fish collected. Five caridean shrimps, *Periclimenes americanus*, *Alpheus heterochaelis*, *Thor floridanus*, *Hippolyte plueracanthus*, and *Hippolyte zostericola*, accounted for 81% of the caridean shrimps collected in 1995.

A preliminary factor analysis (non-rotated PCA) was used to reduce 9 habitat variables and year to 4 interpretable components. PC1 accounting for 25.3% of the variability among the original habitat variables was interpreted as a *Thalassia* gradient. *Halodule* is negatively correlated with *Thalassia* on PC1. PC2 (16%) was interpreted as a shallow water *Halodule* gradient. PC3 (12.4%) was interpreted as a *Syringodium* gradient. PC4 (10.4%) was interpreted as a macro algal gradient. Interpretation of PC's 1-3 indicate *Thalassia* and *Syringodium* decline in abundance with time while *Halodule* increases over time.

Individual species and species groups relate to habitat differently in Johnson Key Basin. The pink shrimp, an abundant penaeid shrimp, is significantly correlated to PC2 and 3 indicating an affinity for shallow water shoal grass and manatee grass habitats. The killifish, *Lucania parva*, was significantly correlated to PC1 and 2. In Johnson Key basin this fish is associated seagrass generally and is most abundant, as is the pink shrimp, in shallow water shoal grass habitats. The dominant caridean shrimp, *Thor floridanus*, is a ubiquitous species in the Johnson Key Basin grass beds, abundant in 1985 and scarce in 1995. It was positively associated with each of the 4 principal components.

These analyses are only exploratory at this point. Future efforts will focus on defining better the seagrass canopy and seagrass habitat changes with time (year and season) in Johnson Key Basin. The relationship between pink shrimp size and seagrass habitat preference will be evaluated. Last, species relationships with seagrass habitat will be evaluated in relation to declining dominance by *Lucania parva* and *Thor floridanus*.

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## **Recruitment, Growth and Survival of Offshore Spawning Upper Trophic Level Fishes in Florida Bay**

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We are seeking to determine if differences in snapper (Lutjanidae), grunt (Haemulidae) and barracuda (Sphyraenidae) recruitment and survivorship are related to habitat and environmental changes in Florida Bay, or planktonic processes outside the bay using an analysis of survivors approach. We emphasize unique life history attributes (i.e., hatchdates, size and age at settlement, growth rates, areal abundance) of surviving juveniles in the bay. This work will provide a framework for managers to assess the role of anthropogenic and natural processes in affecting fish growth, recruitment and survivorship in Florida Bay.

The juvenile stages of these fishes encounter similar abiotic and biotic environments as the juveniles of Florida Bay resident species such as spotted seatrout (*Cynoscion nebulosus*), but because they spawn outside the bay, offshore processes affect their recruitment to those bay environments. Because prevailing currents on the inner southwestern Florida shelf are to the south and southeast, larvae spawned there are transported to nursery habitats in Florida Bay and may represent an important source for juvenile recruits to reef habitats in the lower Florida Keys. To interpret observed patterns of variability in the recruitment of these fishes in the bay, it is necessary to understand planktonic processes that affect larval growth, transport, survivorship and in-bay processes that affect juvenile growth, recruitment and survivorship. This is critical in understanding the affects of anthropogenic changes in habitat on fishes within Florida Bay.

Over the last 15 years, we have observed large inter-annual differences in juvenile snapper and grunt abundance. We have also observed seasonal and regional differences in juvenile abundance, which is partially attributable to patterns in spawning and larval survival; these two combine to create patterns in back-calculated hatchdates. Also observed are seasonal differences in juvenile growth rate, which may also contribute to seasonal patterns in survivorship. We are examining the distribution, abundance, growth and survival of larvae on the southwest Florida shelf to understand how oceanic processes affect patterns of juvenile growth, recruitment and survivorship in Florida Bay.

In October 1998 we initiated a separately funded study of ichthyoplankton on the inner continental shelf west of Florida Bay during the peak spawning seasons of several species of grunts and snappers. Depth-stratified samples are collected with a Multiple Opening/Closing Net and Environmental Sensing System and a Tucker Trawl bottom sled along three transects extending for 50 nautical miles over depths ranging from 10 to 30 m. Ichthyoplankton samples are initially sorted at the Polish Sorting Center. Subsequently, larvae will be identified at the Beaufort Laboratory (see below). Otoliths will be removed and hatchdate distributions and growth rates will be determined. Hydrographic data will be analyzed to provide cross-shelf sections of temperature, salinity and density. Vertical distributions of larvae will be analyzed to provide preliminary biological data for input into physical circulation models. In addition, spatial and temporal patterns in larval growth rate will be

analyzed to begin to define water column habitat quality relative to the transport of larvae through this habitat.

Six weeks after each offshore cruise, juveniles which successfully recruited to Florida Bay habitats are sampled with a 3-m otter trawl. In the lab, fish are measured, weighed and their sagittae (otoliths) are removed. Otoliths are sectioned on a transverse plane and examined under immersion oil using light microscopy. All counts are made on the ventral lobe along the sulcus at 1000X magnification. Hatchdates are estimated by subtracting increment count from collection date. Growth rates are estimated from regression models. Through the use of otolith analysis, we will examine growth prior to, and after, ingress to Florida Bay nursery habitats and compare the hatchdate distributions of larvae with those of the juveniles that successfully recruited. This information will provide insight on the sources of variability in species-specific patterns of growth and survival among and between cohorts that use Florida Bay.

Accurate species-level identification of larval snappers is prerequisite for the success of this research. Through collaboration with the NOAA Charleston Laboratory, we will use genetic characters to positively identify problematic larvae. Two approaches will be used: (1) link discernable types of larvae with adults of known species based on genetic characters, and (2) use genetic characters to identify larvae where traditional characters are not useful and types can not be distinguished. Approach (1) is preferred, but both approaches might be required. We are currently examining sequences from multiple individuals to verify the ability to identify *Lutjanus* larvae to species using 12s mtDNA sequences. We will determine larval types through classic meristic and morphometric analysis. Each larvae will be digitally photographed and notes on ontogeny, spination, pigmentation will be made. We will then conduct genetic characterization of representatives of each larval type. If larval type proves to be mono-specific, all larvae previously assigned to that type can be identified to species and future specimens can be identified using traditional characters of the type (e.g., pigmentation and spination). If a larval type is not species-specific, genetic analysis will be conducted on an individual larval basis to determine species identity.

We have so far examined otoliths from 224 juvenile lane snappers (*Lutjanus synagris*) to determine spawning distributions and growth rates of surviving recruits to Florida Bay. Spawning is protracted with a peak in June and July and a second smaller peak during the late fall. We looked at the average growth rates for each of these cohorts and found that the late spring - summer spawned fish grew 75% faster than the fall cohort. Size at a given age was also more variable for the fall fish. These spring-summer fish first enter Florida Bay at a size of about 20 mm and an age of about 45 days. Upon completion of the processing of our remaining lane snapper we will begin processing our gray snapper (*L. griseus*) samples.

This project seeks to define processes that cause variability in juvenile numbers for important upper trophic level fishes that spawn outside the bay, but use bay habitats as nursery areas. Information will assist in distinguishing anthropogenic induced change due to restoration efforts versus natural variability in fish abundance. Links between larvae in pelagic habitats on the shelf and juveniles in benthic habitats within the bay will allow us to elucidate the natural processes that act outside of Florida Bay that effect the number, distributions and

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diversity of fishes in the bay as well as to provide measures of ecosystem health through the estimation of fish growth. When results of this study are integrated with those obtained from the larval fish immigration study being conducted by NMFS, Southeast Fisheries Science Center (SEFSC), and regional circulation studies conducted by the University of Miami, a more complete picture of reef fish early-life history and recruitment to Florida Bay will emerge.

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Question 5 - High Trophic Level

## The Recovery of Sponge Populations in Florida Bay and the Upper Keys Following a Widespread Sponge Mortality

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During 1992 and 1993, widespread sponge mortalities significantly impacted sponges in an area that encompasses Florida Bay and the upper and middle Keys. The extent of the impacted area has been estimated to be approximately 1000 km<sup>2</sup>. The cause of the mortalities has been attributed to cyanobacteria blooms. It has been hypothesized that the sponge mortalities resulted from clogging of the sponges' filter feeding mechanism, bloom toxicity, or perhaps lowered dissolved oxygen levels. However, at this point the exact cause has not been documented.

The work described here was initiated in response to concerns regarding the ecological and fishery impacts resulting from increase commercial sponge harvesting effort in the late 1980's and early 1990's. The objective of the initial phase of the work (conducted in 1991 and 1992) was to document and quantify the contribution of commercial sponges (sponges of the genera *Hippospongia* and *Spongia*) to total sponge community biomass. The data collected during this initial phase provided an invaluable baseline data set of sponge abundance and biomass in the affected area prior to the sponge mortalities and documented the severity of the impact on sponge biomass. A total of 15 areas were sampled (five areas north of Long Key, four areas within Everglades National Par, two areas west of Everglades National Park, and four areas north of Marathon). The total area surveyed was 34600 m<sup>2</sup>.

Beginning in 1994, the work entered a second phase: the documentation of the magnitude of the impact of the sponge mortalities on sponge biomass, and the long-term analysis of the recovery of the total sponge community. Two of the original 15 survey areas (one north to Long Key, and one north of Marathon) have been sampled in 1993, 1994, 1995, 1997, 1998, 1999 and 2000. Sampling of a third area in Everglades National Park was begun in 1995. Additionally, as resources have allowed, sporadic field observations have been conducted at two other sites.

Results of the 1994 field work documented highly significant declines in sponge numerical abundance, with even more significant reductions (up to 90%) in a sponge community volumetric biomass. However, the severity of the mortality varied significantly over the affected area. Sponges of the genera *Ircinia*, *Spongia*, and *Hippospongia* appeared to be the most susceptible to the mortalities. The loggerhead sponge (*Sphaciospongia vesparia*) appeared to be more resistant than many other species, but was completely eliminated throughout extensive areas. One species, *Cinachyra* sp., appeared to be particularly resistant, but subsequent sampling suggests that the possibility that this species is particularly opportunistic and was able to rapidly colonize cannot be ruled out.

As work has progressed a more comprehensive description of the sponge faunas at each area has been undertaken. A total of 30 sponge taxa were recorded during the 1997 survey and we now have a reasonable complete description of the sponge fauna and relative abundance

of sponge species found at the three survey areas. Furthermore, a more complete, long-term picture is beginning to emerge regarding the extent and description of the sponge community recovery.

Recently collected data (1998-2000) has documented a highly significant recovery in certain species of the genera *Hippospongia*, *Spongia* - the commercial sponges - and *Ircinia*. However, the extent of the recovery of these sponges is not uniform throughout the sampled areas. For example, the commercial sponge *Spongia barbara* has fully recovered at the Long Key site while the commercial sponge *Hippospongia lachne* has not yet been found at this site. In contrast, observations in other areas have shown a rapid recovery of *H. Lachne*.

Two species of the genus *Ircinia* (*Ircinia strobilina*, and *Ircinia sp.*) have recovered rapidly in recent years. In contrast, *Ircinia campana* (a large, formerly abundant sponge commonly referred to as the vase sponge) has shown no indications of any recovery.

The most conspicuous sponge, *Sphaciospongia vesparia* (loggerhead sponge), in terms of volumetric biomass contribution to the total sponge community biomass, has shown limited signs of recovery. Recent data (1999 and 2000) indicate that signs of recovery are becoming apparent at the Marathon sampling site. Prior to the sponge mortalities *Sphaciospongia vesparia* accounted for approximately 59% of the total sponge community volumetric biomass and *Ircinia campana* (vase sponge) contributed approximately 10%. Therefore, these two species taken together accounted for almost 70% of the total sponge community biomass prior to the mortalities. Based on the data collected to date, these two dominant species (in terms of sponge biomass) may take many years to recover to abundances observed prior to the sponge mortalities.

As the project evolves into a truly long-term evaluation of the recovery sponge populations, data is being collected that indicate that there are several sponge species that have exhibited rather dramatic fluctuations in abundance since the sponge mortalities. These data may indicate that certain sponge species (*Halichondria melandocia*, *Adocia sp.*, *Hytrios sp.*, *Cinachyra sp.*) can undergo significant “natural” fluctuations in abundance. It is also possible that these population fluctuations either represent a long-term response to the initial sponge mortalities or changing environmental conditions.

Project plans call for continued sampling in future years. Future data will document and assess the long-term recovery of hard bottom sponge communities. These data will also assist in monitoring ecological conditions and modeling Florida Bay food webs. Furthermore, such long-term analysis may provide insights into differences in the life histories and ecology of certain sponge species

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5 - High Trophic Level



## **Bioenergetics of Larval Spotted Seatrout (*Cynoscion nebulosus*) in Florida Bay**

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Larval spotted seatrout (*Cynoscion nebulosus*) occur over a wide range of temperatures and salinities in Florida Bay. We studied experimentally the relative importance of these variables on bioenergetic parameters (routine metabolism, ad libitum feeding rate, and growth rate). Routine oxygen consumption rates of larval spotted seatrout were measured over a range of temperatures (24, 28, 30 and 32°C) and salinities (5, 10, 20, 35 and 45psu). Oxygen consumption ( $\mu\text{L O}_2 \text{ larva}^{-1} \text{ hr}^{-1}$ ) scaled isometrically with body mass (slope=1.07) for larvae <6.8 mm TL and allometrically (slope=0.80) thereafter. The inflection in the mass-metabolism relationship coincided with the formation of the hypural plate and a change in the hydrodynamic regime experienced by the larvae. Analysis of covariance, using dry weight as a covariate, indicated the effect of salinity was temperature dependent, evident by the significant interaction between temperature and salinity at 30 and 32°C. A response surface describing the interactive effects of temperature and salinity on the routine metabolism is presented (Figure 1).

The metabolic response to temperature and salinity itself does not fully explain the energy partitioning of young spotted seatrout. Euryhaline fishes are known to use flexible strategies for the allocation of energy for maintenance, activity and growth in response to changing environmental conditions. Therefore, additional laboratory experiments examined the ad libitum feeding and growth rates at three temperatures (24, 28, and 32°C) and the same five salinities. Response surfaces developed for consumption and growth allow us to take into account the interactive effects of salinity and temperature on the physiology and behavior. If consumption and activity are constant across salinities, we would expect the growth to mirror routine metabolism. Results indicate that this is not the case: rather, spotted seatrout altered their consumption and or activity over the salinities tested. Detailed knowledge of these components of the energy budget allow us to model the environmental constraints on growth of spotted seatrout larvae in Florida Bay (historical or hypothetical).

A bioenergetic model is developed incorporating these response surfaces and additional data obtained from field samples. The model is evaluated using independent estimates of spotted seatrout growth from otolith analysis. Using the bioenergetic model, estimates of consumption can be obtained based on observed growth. This consumption, as a proportion of the maximum, is used to evaluate potential impacts on prey populations.

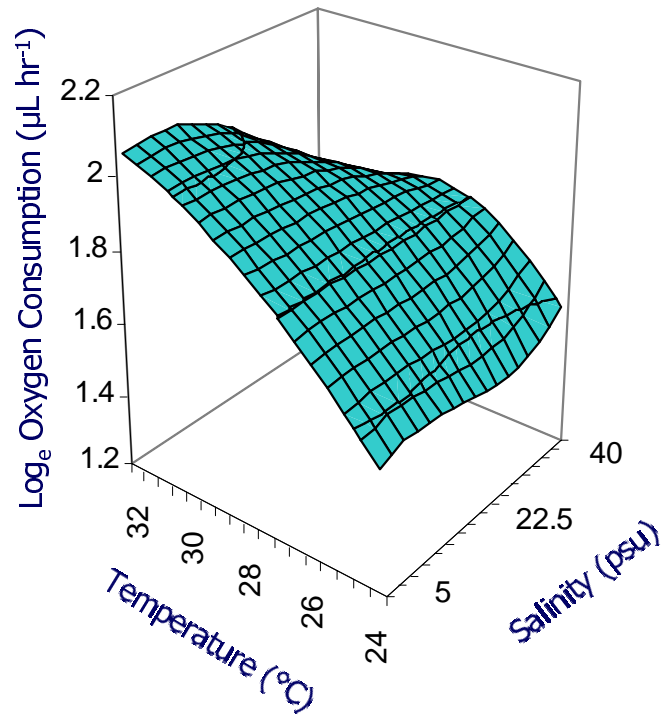


Figure 1. Response surface showing the predicted metabolic rate for spotted seatrout larvae (1mg dry weight) over a range of temperatures and salinities.

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## **Influence of Coastal Eddies and Countercurrents on the Influx of Spiny Lobster, *Panulirus argus*, Postlarvae into Florida Bay**

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The Florida spiny lobster population is concentrated in the coastal reefs that lie about 10 km offshore and stretch from the Florida Keys west to the Dry Tortugas. Offshore in the Straits of Florida, the strong Florida Current comes in close to the reef tract. The local population spawns offshore in the reefs, and the larvae are likely to be entrained and expatriated by the dispersive boundary current. The juvenile nursery is on the other side of the Florida Keys in Florida Bay, which is connected to the coastal ocean through inter-island tidal channels. Transport of the postlarvae from offshore to the juvenile habitat on the bayside is a necessary process in the recruitment of the Florida spiny lobster.

Local winds, Florida Current flow, and coastal eddies interact to influence the onshore transport and recirculation of larvae in the Florida Keys coastal zone. The objective of our study conducted in 1997-1999 was to examine the correlations between these coastal larval transport processes and the inshore supply of postlarval spiny lobster into their Florida Bay juvenile habitat through inter-island channels. We sampled the influx of postlarvae into Florida Bay at Long Key and Whale Harbor channels from July 1997 to June 1999. Channel nets were moored on the bayside of the channels to sample monthly on three consecutive nights around the new moon, fishing 1-3 m below the surface between dusk and dawn.

Although the channels were only 30 km apart, there were significant differences in the influx patterns. At Long Key, influx peaked every 2-3 months on the average, whereas at Whale Harbor the peaks were in winter and of higher magnitudes. The influx pattern at Long Key was highly significantly correlated with the average magnitude of countercurrent transport in the two weeks preceding sampling at the channels.

Countercurrent flow on the shallow continental shelf is usually induced by upstream wind stress, but during our study upstream wind stress did not sufficiently explain all the strong countercurrent events, nor was it correlated with larval influx. Coastal countercurrents in the Florida Keys can also result from the passage of mesoscale, cyclonic eddies offshore. These eddies are associated with the development of the Tortugas Gyre. The Tortugas Gyre evolves from Loop Current frontal eddies which become trapped offshore of the Dry Tortugas during periods of high latitudinal intrusion of the Loop Current. It usually remains there for a period of 1-3 months, until impacted by another approaching frontal eddy or released after

significant southward retreat of the Loop Current. Upon release it propagates as an eddy downstream towards the Florida Keys. Enhanced onshore surface Ekman convergence and cyclonic circulation due to the eddy can concentrate passive drifters within the eddy and at its inshore cyclonic edge. With their connection to Loop Current frontal eddies, the coastal eddies in the Keys may also be vehicles for transporting larvae from upstream locations to the Florida Keys. As the eddy disintegrates past the Middle Keys, entrained larvae may be released into the coastal zone and move inshore with the aid of wind-driven onshore transport.

Wind-driven transport should be coherent over the short distance separating the two channels where we sampled. On the other hand, the variable progress and development of the eddy relative to the positions of the channels and to the time of sampling can affect the pattern of transport over a small spatial scale. Satellite imagery showed that an eddy was often present in the vicinity when strong countercurrent events were detected off the Middle Keys. This was exemplified in the March 1998 period, where satellite imagery showed strong eddy activities in the Straits of Florida prior to sampling, but upstream wind stress was not strong in the same period. This suggests that eddy transport may be a major factor in the postlarval recruitment of spiny lobsters into the Florida Bay nursery area.

Variability in Loop Current frontal dynamics upstream in the Gulf of Mexico could affect eddy formation in the Straits of Florida on annual and inter-annual scales. The Loop Current penetrates into the northeastern Gulf of Mexico to varying degrees throughout the year. High latitudinal intrusion of the Loop Current is expected to favor the formation of the Tortugas Gyre. Periodically, anticyclonic rings separate from it, initiating a rapid decline of latitudinal intrusion. The result is direct flow from the Yucatan Channel into the southern Straits of Florida, a condition not conducive to gyre formation. Long-term climatic variability can precipitate into recruitment fluctuations through modulations on the large-scale circulation and mesoscale eddy transport processes. For an entire year between Mar 1998 and Feb 1999, the Loop Current was persistently at a low latitudinal intrusion. As a result, fewer eddies may propagate downstream, which in turn may reduce the supply of postlarval recruits into Florida Bay. It is unclear whether Loop Current development during the 1997-1998 period was affected by the strong 1997-1998 El Niño. A longer data time series would be necessary to capture inter-annual variabilities.

Eddy events could be instrumental in larval transport and recruitment into Florida Bay. The complexities of eddy dynamics and their interactions with the ecology and behavior of the pelagic phase of marine resources have yet to be investigated and may constitute a key component in the ecosystem model of South Florida.

Continuing on from this study, in 2000-2002 we will be specifically investigating the influence of eddies on the supply of recruits into Florida Bay. We will compare the densities of incoming recruits in the Middle and Lower Keys during the presence and absence of an eddy. Sampling will occur simultaneously at the Long Key channel and the Seven-Mile Bridge and directly offshore in the Middle and Lower Keys. With the cooperation of the Physical Science Team, coastal oceanographic data, especially that enabling detection of gyre conditions, will be collected with *in-situ* and remote sensing instruments. We also plan

to deploy a shore-based Ocean Surface Current Radar (OSCR) system within the area of proposed sampling to measure the surface current vector fields in near-real-time at a 1-km resolution extending 40 km offshore. This high resolution system has already proved to be extremely useful in guiding the biological sampling of larval fishes associated with small scale, ephemeral oceanographic features. Thus, mesoscale gyre features associated with the Florida Current should be clearly resolved in the coastal current structure using OSCR technology. The time-series of the surface flow fields will help us model particle trajectories from coast to channel in realistic transport scenarios. This continuing research will bring us closer to establishing the transport link in the South Florida aquatic ecosystem model.

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