Tropical Connections

South Florida's marine environment

William L. Kruczynski and Pamela J. Fletcher, Editors

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Finally, we thank our families for their understanding of our dedication to this project and for the many sacrifices that they made that allowed us to complete this book.

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Dedication

We dedicate this book in memory of Brian D. Keller (1949-2010), Science Coordinator, Southeast Atlantic, Gulf of Mexico, and Caribbean Region, the National Oceanic and Atmospheric Administration Office of National Marine Sanctuaries. Brian was a strong supporter for the development of this book and participated in many meetings and discussions that helped frame its form and content. With his passing, coral reef ecosystems around the world have lost a knowledgeable and strong advocate who worked tirelessly to understand these systems so that they can be better protected and conserved, and we have lost a dear and true friend.

Two historic figures in the American environmental movement also stand out as informed and outspoken critics of the consequences of environmental degradation and proponents of the importance of conservation and restoration of natural habitats for the enjoyment by future generations. We also dedicate this book to Rachel Carson (1907 – 1964) and Marjory Stoneman Douglas (1890 – 1998), whose writings taught humankind about the wonder and beauty of the living world. Both recognized the need to educate the public about the connectivity between biological and physical/chemical components of the south Florida marine ecosystem and the importance of conservation of its fragile and limited biological treasures.

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About this book

We prepared this book to summarize technical information on the south Florida marine ecosystem in a manner that is easy to read and understand. The target audiences of the book are students, educators, lay readers, and decision makers. The information presented in this book will further the understanding and appreciation of this diverse and complex ecosystem, correct any misconceptions about facts or ecological processes, and promote conservation and management decisions that are based upon sound, defensible scientific findings.

The book is unique in that it consists of fact pages that were prepared by 162 experts in their scientific disciplines. The fact pages can be used individually, but they are also organized into chapters that synthesize the information. Chapter introductions summarize and supplement information given in the chapter and sources are footnoted. Scientific citations are not included on the fact pages in order to make the text flow better for the targeted audiences. An annotated list of further readings is included at the end of each chapter. We had no intention of representing the thoughts and knowledge of others as our own in the introductions to the chapters or any place else in this book.

We anticipate that there will be several levels of readers of this book. Some will read every word, while others may browse through the pages. It is possible that the browsers may not completely receive the main messages of the book because they are spread across its chapters and pages. So, we are stating the main messages of the book explicitly here.

- South Florida is the lower portion of the Florida peninsula south of latitude 27. This area represents the southern limit of many temperate organisms and the northern limit of many tropical organisms, resulting in the amazing biodiversity of life forms in the area.

- The hydrology of south Florida is complex due to the influences of currents from the Caribbean Sea, Gulf of Mexico, and the Atlantic Ocean. It is an area of convergence of external influences and important internal circulation patterns, and both function to maintain biodiversity and populations of the flora and fauna.

- The marine environments discussed in this book include shallow-water habitats of the Atlantic Ocean and the Gulf of Mexico to the edge of the continental shelf, coastal bays and estuaries, and adjacent wetlands, including mangrove forests. All of these habitats are physically and biologically connected, and all are critical elements of the entire south Florida marine ecosystem. In order to maintain or restore the ecosystem, wise management of all components of the ecosystem is required.

- The human population of south Florida is growing. Declining water quality, physical damage to coral reefs, seagrass beds, mangrove forests, and decreased fish landings are symptoms of increasing impacts by humans to the south Florida marine ecosystem.

- Impacts to the ecosystem occur at local, regional, and global scales, and solutions must operate at all scales to be effective.

- In order to restore and maintain the marine ecosystem, we must first understand its complexity and the connectivity between aquatic habitats, and promote wise management based upon that understanding. Citizens play an important role in fostering and implementing conservation and restoration practices.

We titled this book "Tropical Connections" for several reasons. Classically, the tropics are located at latitudes near the equator, between the Tropic of Cancer (23.4° N) and the Tropic of Capricorn (23.4° S), and by that definition south Florida (about 25° N) is "subtropical." However, "tropical" can be used in a general sense to mean warm to hot and moist year-round conditions with lush vegetation. The southern Florida mainland and the Florida Keys meet that latter definition and support a prevalence of vegetation derived from the Caribbean tropics, including many species of palms and Caribbean tropical hardwood trees. The growth and survival of tropical plant species in south Florida are better near the coast because of the warming influence of the Florida Current and coastal waters. It is this maritime influence that allows tropical plants and animals to survive north of the Tropic of Cancer.

The title contains the word "connections" because the marine habitats of south Florida are interconnected physically, chemically, and biologically, as well as connected with other geographic areas. If you live, vacation, boat, swim, snorkel, SCUBA dive, fish, spear fish, bird watch, or eat marine fish or shellfish in south Florida, you are "connected" to the south Florida marine habitats. Also, people who read about, study, or enjoy knowing that the marine habitats of south Florida exist as natural wonders have a special connection to this place that may be no less significant than physical experiences.

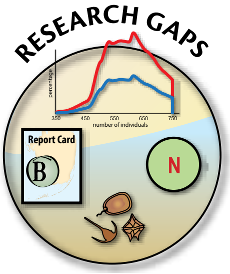
The synthesis of information contained in this book will result in an appreciation and understanding of this resource and will support conservation and management measures that will allow future generations the opportunity to share and enjoy its richness and beauty. We sincerely hope that you enjoy this book and find it useful.

Bill and Pamela

1. GEOGRAPHIC SETTING AND IMPACTS TO THE ENVIRONMENT

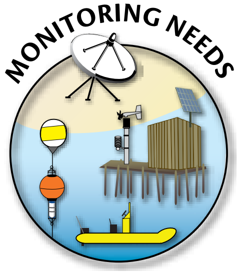
Geographic Setting and Impacts to the Environment Chapter Recommendations

- Recognize the vulnerability and impacts on south Florida marine habitats that are located adjacent to city centers and develop measures to **reduce local sources of pollution**.
- Identify and prioritize the **causes of ecosystem declines** and implement management actions to address and reverse the declines.
- Recognize the impacts of **global climate change** and sea-level rise in planning processes, and identify ways to reduce the local contributions to greenhouse gases.
- Include impacts from **farfield sources** to south Florida in planning.
- Promote the value of **ecosystem services** that benefit the south Florida economy and quality of life, such as tourism dollars generated from visitation to parks and natural areas, and incorporate those elements in regional and local planning.
- Apply the concepts of **"carrying capacity" and "smart growth"** to management decisions affecting the natural and "built" environments in south Florida.



- Conduct targeted research to separate ecosystem responses to **natural variability** from those caused by anthropogenic stresses.
- Further quantify the effects of **global warming and ocean acidification** to facilitate accurate predictions and to design appropriate management strategies and actions.
- Investigate the impacts of **African dust** on productivity of waters and public health in controlled laboratory experiments to improve the understanding of those impacts and determine how resource management and planning can minimize or reverse the impacts.
- Clarify the effect of the **elimination of top predator species** on ecosystem structure and function to facilitate setting scientifically defensible resource management goals.
- Quantify the effects of existing roadbeds and causeways that **impede flushing rates** and affect biological populations in coastal waterways.
- Identify parameters to rapidly **assess ecosystem health**.

Chapter title page: Hurricane Andrew approaching Florida (1992). NOAA.



- Develop and support monitoring programs required to assess **long-term impacts of episodic (infrequent) events**, such as tropical storms, shifts in ocean currents, and African dust.
- Design monitoring programs to **detect environmental changes** to support defensible management actions.
- Use effective and efficient monitoring methods, such as **remote sensing**, to provide broad-scale geographic evaluations that can be used to assess local, regional, and global conditions.
- Investigate the utility of developing a comprehensive water quality monitoring program along the Southwest Florida Shelf to provide an **early warning** of movement of pollutants or other adverse environmental conditions to downstream locales in south Florida to aid managers in planning response actions to environmental perturbations.

J. Luo - UM/RSMAS

Coral reefs provide habitat for a diverse assemblage of marine life in south Florida.

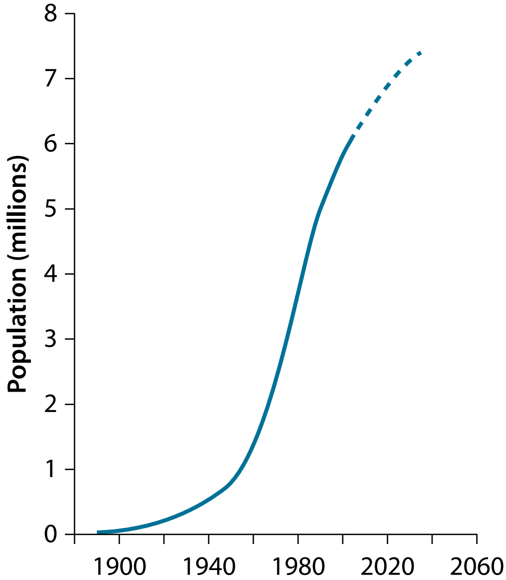
Introduction

The south Florida watershed begins in East Lake Tohopekaliga, Osceola County, and flows south via the Kissimmee River to Lake Okeechobee. Historically, overflow from Lake Okeechobee flowed through the Everglades to coastal areas and south to Florida Bay. This book encompasses those areas of the south Florida marine environments from Martin County on the Atlantic coast to Charlotte County on the Gulf of Mexico coast.

South Florida is a special place to live, work, and play. It is an area where climates, cultures, habitats, biogeography, and ocean currents converge. The mild, subtropical climate allows year-round outdoor activities that are enjoyed by residents and visitors alike. Evidence of south Florida popularity is reflected by the growing population. Palm Beach, Broward, and Miami-Dade Counties accounted for 27% of the overall growth in the State of Florida in the past several years, and the population of Collier County grew 25.4% from 2000 – 2008.[1,2] The resident population of south Florida is

South Florida marine environment is closely linked to upland and upstream influences. This book examines the coastal area from Martin County on the east coast to Charlotte County on the Gulf of Mexico coast.

projected to increase from approximately 4 million in 2004 to 7.2 million in 2035.[3,4,5] Residents of south Florida are a mix of many nationalities that results in a unique and attractive diversity of cultures and entertainment, dining, and recreation. Tourism is a main source of income to the local economy, and approximately 25 million people visit south Florida annually, spending approximately $19 billion.



Adapted from BEBR, UF.

The population of southeast Florida is projected to increase to approximately 7.2 million residents by 2035.

The multitude of natural communities found in south Florida is part of its uniqueness and allure. The resources are a diverse mix of upland, wetland, and aquatic habitats that include hardwood hammocks, mangrove communities, coastal lagoons and bays, and coral reefs and hardbottoms. Many consider the beaches of south Florida unparalleled in their beauty. The Florida Everglades is one of only three sites on Earth declared an International Biosphere Reserve, a World Heritage Site, and a Wetland of International Importance.[6,7] The Everglades offer many recreational opportunities, including bird watching, hiking, camping, boating, fishing, and exploring nature. Mangrove forests protect natural shorelines and provide habitat for birds and fish. Seagrass meadows abound in shallow, clear marine waters, and the seagrass area in south Florida is the most expansive documented seagrass bed on Earth.[8] Seagrasses support a diversity of life, including recreational and commercial species of fish. South Florida is the only place in the continental United States where one can visit a tropical coral reef or hardbottom habitat by boat or by swimming from shore.

The flora and fauna of south Florida are an interesting and unique mix of tropical and temperate species, many at the geographic limits of their range. On land, pineland forests, tropical hardwood

W. L. Kruczynski - EPA

Beaches of south Florida attract millions of visitors each year.

hammocks, sawgrass marshes, cypress swamps, and rockland communities exist in a mosaic of diverse habitats. In marine environments, biogeographic provinces describe assemblages of life adapted to particular geographic areas. In south Florida, organisms from the Carolinian, Louisianian, and West Indian biogeographic provinces live together and result in a biodiversity "hot spot." For example, more than 500 species of fish live in the coastal waters of south Florida.

Native American hunter-gatherers visited and occupied south Florida as early as 10,000 years ago and thrived on deer, bear, waterfowl, and the bounties of the sea. European explorers and slave hunters began arriving in the early 1500s. Juan Ponce de León was the first

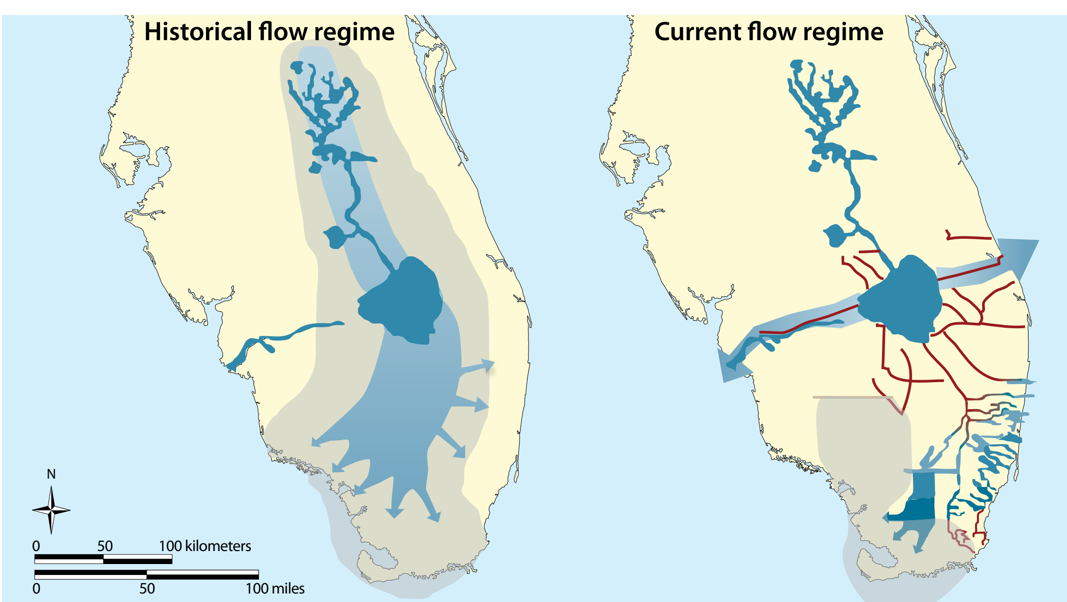
European to see the Miami area when he sailed into Biscayne Bay. At that time, freshwater springs in Biscayne Bay were a source of freshwater for sailing ships. Similar freshwater springs were reported in Florida Bay. In the short time span of approximately 250 years, Native Americans were all but eliminated from the area by swords, guns, disease, rum, and pitting of Indian nations against one another.[9] Taming the land by white settlers did not come easily, but eventually limiting factors were overcome: marshes and swamps were drained and converted to agriculture, mosquito populations carrying yellow fever and malaria were reduced, and refrigeration and air conditioning were invented.

Growth along the east coast of south Florida focused on conversion of Everglades wetlands to agriculture and, subsequently, to housing and industrial developments. Rock mines were constructed to obtain fill material for roads and other development requiring

Wikimedia

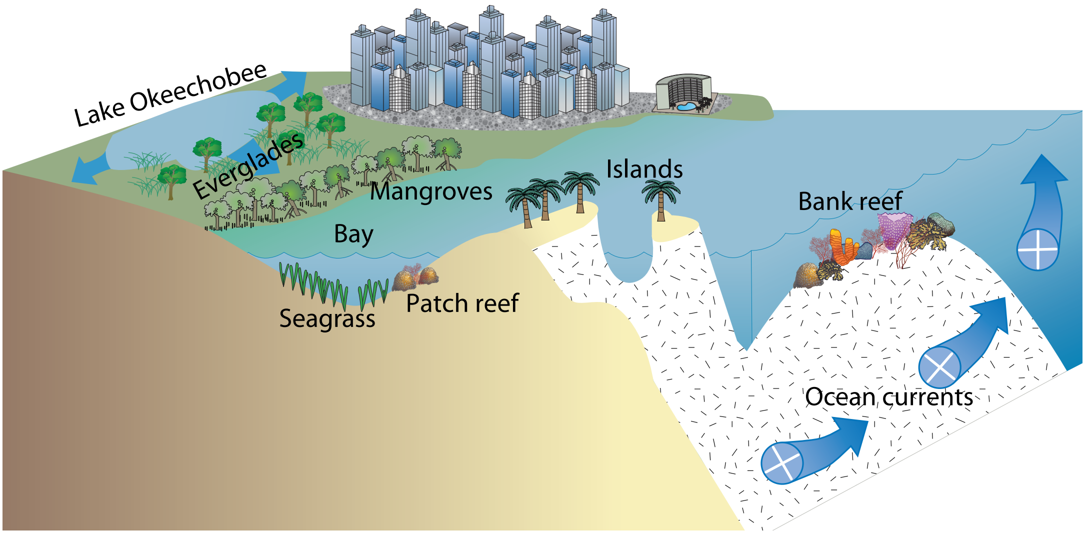
In 1907, the State of Florida established the Everglades Drainage District to "drain the abominable pestilence-ridden swamp." Construction of a network of drainage ditches, such as the one shown (ca. 1915), allowed the conversion of large portions of the Everglades to agricultural lands.

an increase in elevation to reduce the effects of seasonal flooding. In 1907, the construction of a vast network of inland drainage canals was initiated, and by 1928, the American winter vegetable kingdom was fashioned from the Everglades.[10] With plentiful crops, beef, and dairy products assured, the stage was set for the metropolitan and industrial expansion that characterizes south Florida



SFWMD

Historical (left) and current (right) freshwater flows in the south Florida watershed. Removal of water through a vast system of drainage canals (red lines in right image) converted wetlands into areas suitable for farming and land development and reduced the danger of flooding to low-lying development. It also dried out the Everglades and resulted in increased salinities in Florida Bay and Biscayne Bay and decreased salinities in the St. Lucie and Caloosahatchie estuaries.



The southern portion of the Florida peninsula includes: sawgrass prairies, mangrove-fringing shorelines, bays, seagrass meadows, islands, exposed relict reef, patch reefs, bank reefs, hardbottom habitats, and blue-water environments.

today.[11] Drainage of "excess" freshwater to the sea through the vast system of canals not only allowed conversion of large areas of the Everglades to agriculture, but also significantly altered the historical flow of freshwater to Biscayne Bay and Florida Bay. Rapid drainage also decreased the amount of freshwater that seeps into underground aquifers, which resulted in the reduction and the disappearance of freshwater springs in Biscayne Bay and Florida Bay.

Dense human populations living along a relatively narrow coastal strip in south Florida and the Florida Keys eventually led to additional conflicts between the growing population and natural communities as well as among various user groups. These conflicts were due to overuse of natural resources, such as hunting large wildlife to extinction (e.g., harbor seals) or near extinction (e.g., panthers, alligators), uncontrolled harvesting of fish and other marine resources (e.g., sea turtles, sharks, sawfish, large grouper, queen conch), and boat collisions with wildlife (e.g., manatees). Additional areas continued to be drained and filled to create more housing for the ever-growing population. Other conflicts were due to misuse of natural resources, such as treating nearshore waters as disposal sites for garbage and untreated stormwater and wastewater; the uncontrolled use of pesticides and other toxic materials; the intentional or accidental release of exotic species; anchoring and boat groundings on corals and seagrasses; and motoring through shallow seagrass meadows, causing long-lived propeller scars. All these examples are symptoms of too many people competing for limited space and resources as well as inadequate management and public awareness.

Global stressors are also impacting the region, including global warming, ocean acidification, hurricane frequency and intensity, and African dust. Sea-level rise is a result of global warming, and its rate is increasing over historical levels. Changes in water levels will have severe impacts in south Florida because of low elevations and dense shoreline development. Rising levels of carbon dioxide in the atmosphere are also causing changes in the acidity of the ocean. Marine organisms with calcium carbonate shells or skeletons rely on dissolved minerals in seawater. Changing ocean chemistry may decrease the ability of some organisms to effectively grow and reproduce.[12,13]

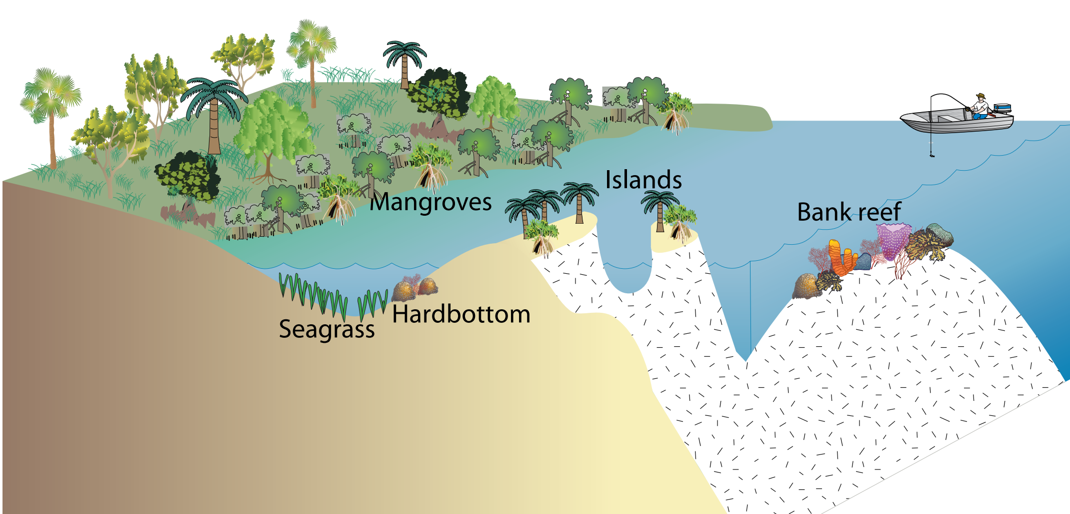
South Florida has many diverse habitats

Thomas E. Lodge

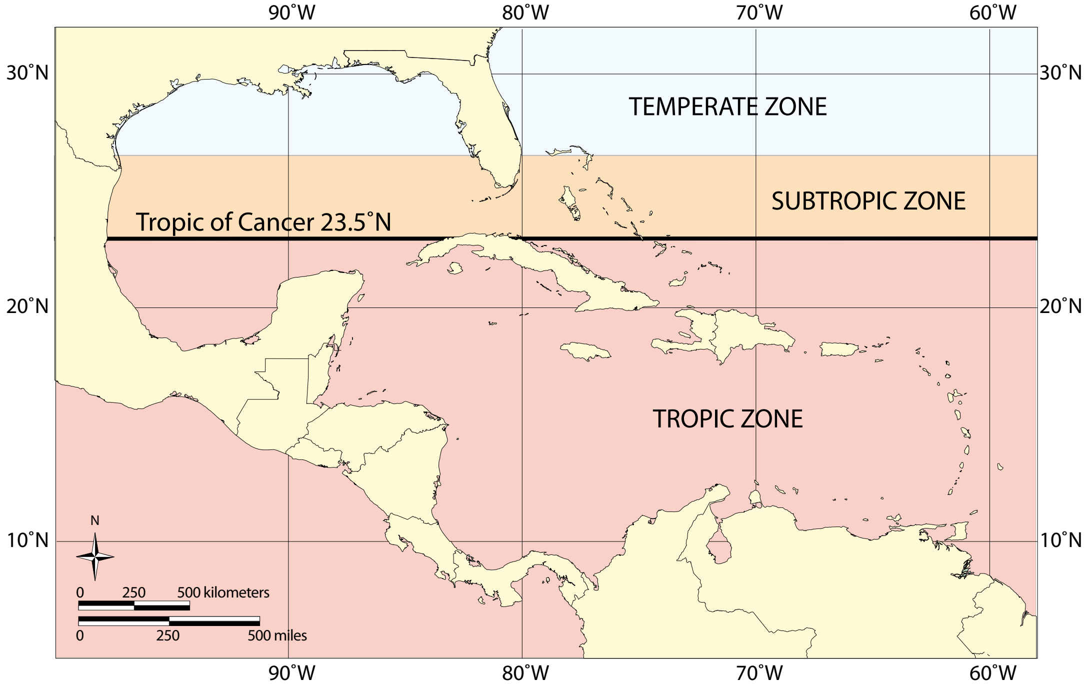
South Florida is the portion of the Florida peninsula from Lake Okeechobee southward through the Florida Keys. This area is unique in many ways. Around the world, at the same latitude as south Florida, there are vast areas of desert, including the Sahara in northern Africa and deserts in western Mexico. Despite being a peninsula of comparable configuration to Florida, Baja California in Mexico is a mountainous desert, whereas Florida has low elevation and high rainfall. The highest land in south Florida is about 12 meters (40 feet) above sea level, but the majority is less than 6 m (20 ft). Annual rainfall averages 130 – 150 centimeters (50 – 60 inches), 60% of which is from thunderstorms and tropical weather events in the warmest 4 months (June – September). Throughout the rainy summer, moisture-laden trade winds arrive from the Atlantic Ocean, resulting in abundant thunderstorms. If the rainfall pattern in south Florida followed that of northern Florida, where frontal-based weather systems bring spring rains and frequent summer droughts, the two large and unique physiographic features of the south Florida mainland—the Everglades and Big Cypress Swamp—would not exist. The abundant summer rainfalls provide a source of freshwater, but much of the historical flow is now intercepted by drainage canals that were constructed for flood control. These have disrupted the timing and distribution of freshwater to coastal areas.

The Florida peninsula extends from the temperate climate portion of North America into the northern limits of the West Indian tropics. In south Florida, tropical species commingle with warm-temperate species. This mixing makes south Florida unique from neighboring tropical marine waters, such as the Bahamas and Cuba, which largely lack the temperate component to their flora and fauna.

The physical and climatic setting of south Florida has resulted in many localized features. Because of the regional low elevations, surface waters move



South Florida is the portion of the Florida peninsula from Lake Okeechobee southward through the Florida Keys. Unique natural habitats include the Everglades, Big Cypress Swamp, Ten Thousand Islands, and tropical coral reefs. Flora and fauna are a unique mix of warm-temperate and tropical species.



South Florida is located along the southern margin of the temperate region of North America and the northern margin of the tropics.

as a shallow "blanket" of water called "sheetflow" across the Everglades and Big Cypress Swamp and not in defined creeks or rivers. Upon reaching coastal areas, the flows collect into countless tidal creeks and small rivers, creating highly productive estuarine habitats.

South Florida coastline includes three additional unique habitats: coral reefs and hardbottom, shallow coastal bays, and the Florida Keys. The Florida Keys comprised fossilized coral reefs and marine sediment deposits that were created during a time of higher sea level. Today, these islands, and the modern coral reefs found seaward of the islands, separate the oceanic environment from the protected shallow coastal environments to the west and northwest, including Florida Bay, Barnes Sound, Card Sound, and Biscayne Bay. Southern Biscayne Bay is loosely enclosed by islands formed of coral reef origin, but its northern portion is separated from the ocean by sand-based islands, Miami Beach and Key Biscayne, that are the southernmost barrier islands on the east coast of Florida.

Historically, bays and lagoons landward of the barrier islands benefited from diffuse freshwater flows through mangrove-fringed shorelines and tidal creeks. However, drainage canals have damaged these functions by periodically discharging large pulses of freshwater, which result in wide fluctuations in salinity in these habitats. Redfish (*Sciaenops ocellatus*), formerly common in Biscayne Bay, were apparently eliminated by damage to their nursery grounds shortly after drainage canals were built.

Many changes have been made to the unique habitats of south Florida. The Comprehensive Everglades Restoration Plan is designed to help redistribute canal flows diffusely through coastal mangrove swamps and into nearshore bay communities and increase flows through the entire Everglades system to the south and southwest coast. Biscayne Bay and Florida Bay are especially important recipients of these "restored" flows that should help to reestablish the ecological functions of the diverse habitats in the region.

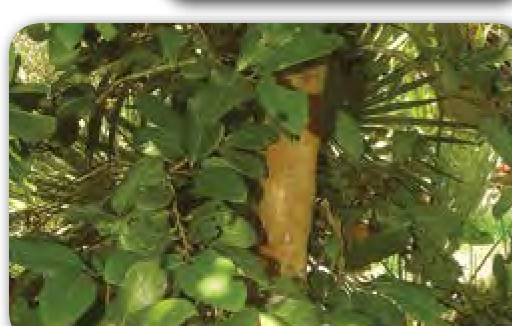
Tropical hardwood hammocks

Pamela J. Fletcher, William L. Kruczynski, and Thomas E. Lodge

A hammock is an upland area where the ground elevation is high enough to prevent seasonal flooding. A brief discussion of their composition is included here because of their proximity to the marine environment, their important habitat value, and the fact that many acres have been lost or fragmented by coastal development. Hammocks in south Florida, from about Miami southward, are dominated by tropical trees of West Indian origin intermixed with a few temperate species. This plant community was established in south Florida about 6000 years ago during postglacial warming. Tropical hardwood hammocks occur in Everglades National Park, the southern portion of Big Cypress National Preserve, and the Florida Keys as well as along the Atlantic coastline to about Pompano Beach. Only a short distance north, the majority of tropical species, such as Jamaican dogwood (*Piscidia piscipula*), blackbead (*Pithecellobium guadalupense*), gumbo limbo (*Bursera simaruba*), and pigeon plum (*Coccoloba diversifolia*) do not thrive, or are cold-pruned to short stature.

A.M. Molina Fletcher

W.L. Kruczynski - EPA



W.L. Kruczynski - EPA

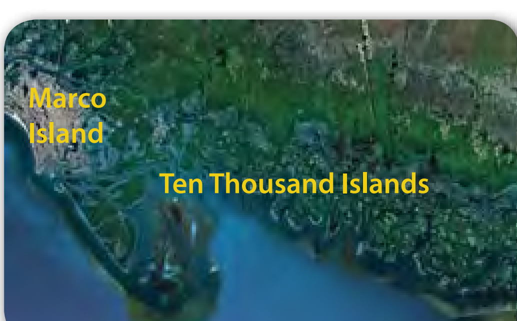
Blackbead (left) and pigeon plum (right) are common tropical hardwood hammock species.

Mangrove communities

Pamela J. Fletcher, William L. Kruczynski, and Thomas E. Lodge

Mangroves in Florida can be found as far north as St. Augustine on the east coast and Cedar Key on the west coast. In the northern portion of their range, they occur sparsely throughout broad temperate climate salt marshes, dominated by smooth cordgrass (*Spartina alterniflora*) and black needlerush (*Juncus roemerianus*). Mangrove recruits in northern reaches of their range die during periodic severe cold spells. In south Florida, mangroves dominate along tidal rivers and streams as well as in low energy coastal wetlands. There are three native mangrove species in south Florida: red (*Rhizophora mangle*), black (*Avicennia germinans*), and white (*Laguncularia racemosa*). Extensive mangrove forests occur along the southwest coast of Florida. The expanse of mangrove swamp in Everglades National Park measures approximately 1300 km^2 (500 mi^2) and constitutes a unique habitat of south Florida. Mangroves are prolific contributors to coastal fisheries because of their high productivity and nursery functions.

A.M. Molina Fletcher



GoogleEarth

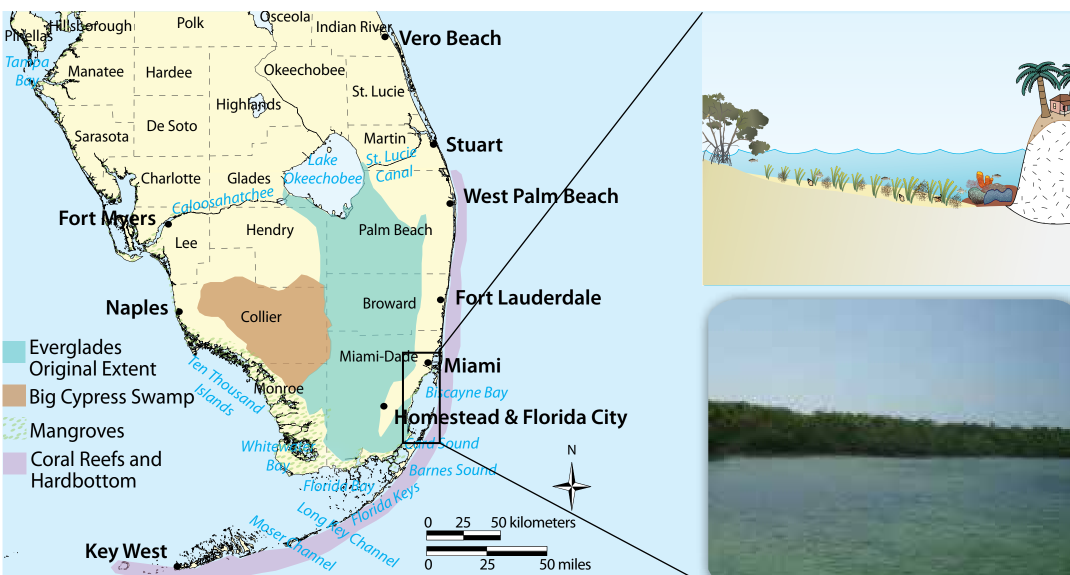
A.M. Molina Fletcher

Ten Thousand Islands on the southwest Florida Gulf coast (left) is a vast expanse of mangrove islands and tidal creeks. Red mangroves located on an intertidal shoreline (right).

Coastal lagoons and bays

Pamela J. Fletcher, William L. Kruczynski, and Thomas E. Lodge

Many lagoons and bays are found throughout rural and urban areas of south Florida where freshwater mixes with saltwater. Biscayne Bay and Florida Bay are two large embayments that are characterized as shallow inner-shelf lagoons. Biscayne Bay provides a natural playground for a large urban population. Florida Bay consists of shallow interconnected basins, seagrass meadows, mud banks, and mangrove islands. Each of these features provides habitat for birds, reptiles, fish, plants, and a variety of benthic organisms. Bays along the southern portion of the Florida peninsula are mixing zones that link uplands and coastal nearshore areas to the Gulf of Mexico on the southwest coast and to the Atlantic Ocean on the southern and southeastern coasts. Bays and lagoons are important nursery habitats for many marine organisms and are susceptible to discharges of excess nutrients and other pollutants from land-based sources.



R. Molina

P.J. Fletcher - FSG

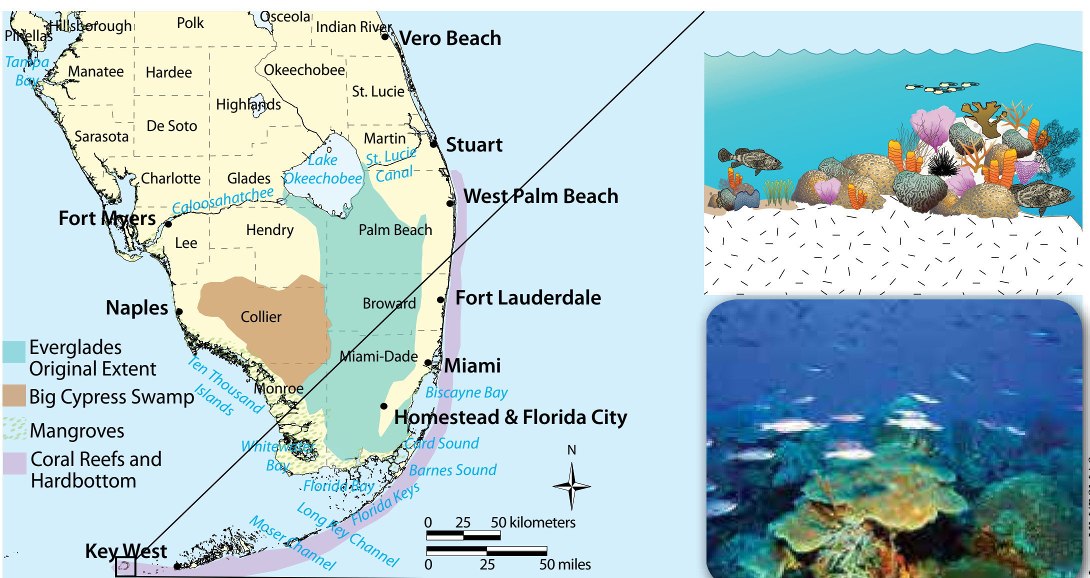
R. Molina

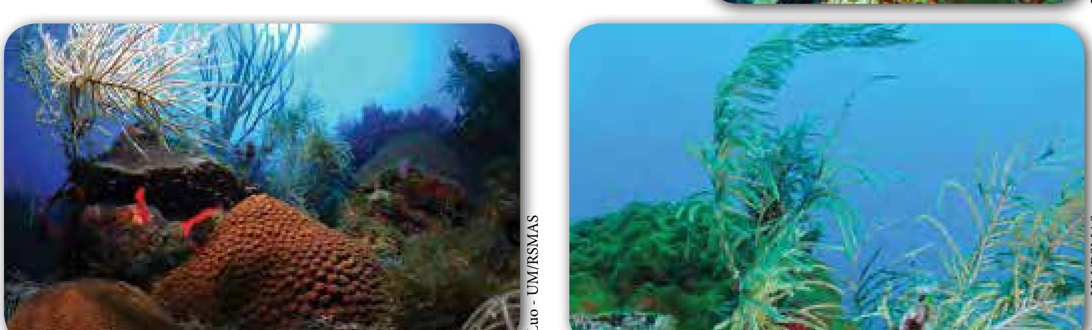
Bill Baggs Cape Florida State Park beach and lighthouse (left) attracts thousands of visitors each year to Biscayne Bay. View of Biscayne National Park from Elliott Key (right).

Coral reefs and hardbottom habitats

Pamela J. Fletcher, William L. Kruczynski

Coral reefs and hardbottom habitats are found throughout south Florida. Coral reefs are formed by reef-building corals that grow into vertical formations that provide habitat for a diverse flora and fauna that rivals tropical rainforests in biodiversity. Bank reefs occur at the continental margin in the Florida Keys and may consist of spur-and-groove formations. Patch reefs are small, roughly circular reefs that occur in nearshore waters. Coral reefs are important to the local economy and generate income by attracting tourists and supporting recreational and commercial fisheries. The Florida Keys Reef Tract is the only shallow water, tropical coral reef ecosystem in the continental United States. Hardbottoms are widely distributed and consist of limestone substrate that offers attachment sites for a variety of sea life, including sponges, soft corals, stony corals, bryozoans, and algae. Hardbottoms lack the vertical structure of reefs and are an important habitat for life stages of many organisms that make their way to coral reefs as adults.





Stony corals (left forefront) and soft corals (right) grow on the reefs and provide habitat for various life stages of fish and other marine animals.

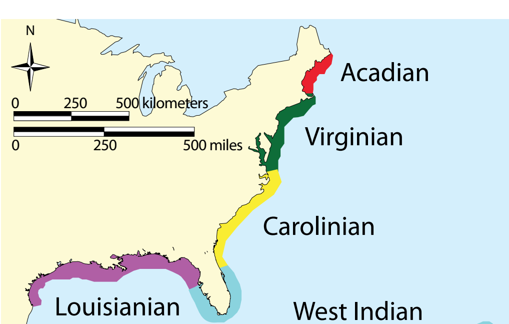
The Florida Keys are a unique environmental setting

Billy D. Causey

At the tip of south Florida lie the Florida Keys, one of the most diverse assemblages of terrestrial and marine life in North America. This unique environmental setting was best described by Rachel Carson in *The Edge of the Sea* (1955) when she wrote:

"I doubt that anyone can travel the length of the Florida Keys without having communicated to his mind a sense of the uniqueness of this land of sky and water and scattered mangrove covered islands. The atmosphere of the Keys is strongly and peculiarly their own. ... This world of the Keys has no counterpart elsewhere in the United States, and indeed few coasts of the Earth are like it."

Biogeography is the study of patterns of species distribution. Biogeographically, south Florida and the Florida Keys are situated between warm, temperate waters and tropical waters of the Caribbean. This area is inhabited by fauna and flora of the West Indian, Carolinian, and Louisianian Biogeographic Provinces. South Florida is also at the crossroads of water masses that transport larvae from the Gulf of Mexico and the wider Caribbean basin. This environmental setting results in higher biodiversity in south Florida compared with other marine areas on the Atlantic and Gulf coasts.



Adapted from Engle, Summers (2000)

South Florida is situated at the junction of the West Indian, Carolinian, and Louisianian Biogeographic Provinces, which results in a unique environmental setting and high biodiversity.

As visitors to the Florida Keys drive down U.S. Highway 1, the only highway connecting the Keys to the mainland, they may not realize that the marine environment is very different a short distance to the north in Florida Bay and the Gulf of Mexico compared with the south toward the coral reef tract and the Florida Straits. The marine environment in Florida Bay and the Gulf is influenced by the waters of the Southwest Florida Shelf. These waters are cooler in the winter and warmer in the summer than the more tropical waters of the Florida Current that bathe the coral reef tract to the south. There are many species of fish and invertebrates that live in Florida Bay or the Gulf that are not found on the coral reefs (e.g., speckled trout, *Cynoscion regalis*). Conversely, there are many species that live on Atlantic coral reefs that never make their way into the Bay waters (e.g., squirrelfish, *Holocentrus adscensionis*).

The Upper Keys are fossilized coral reefs that grew at the same time that the sand bars were forming in the Lower Keys, when the sea level was at least 6.1 meters (20 feet) above present. The current discontinuous chain of islands was formed when sea level fell and left the reefs (Upper Keys) and sand bars (Lower Keys) high and dry. The coral limestone substrate of the Upper Keys is called Key Largo Limestone. Newfound Harbor Keys, located seaward of Big Pine Key, are the western-most exposure of Key Largo Limestone. The highest elevation in the Keys is at Windley Key, 5.5 m (18 ft) above present sea level. Key Largo Limestone was once mined from Windley Key to build many of the old public buildings in Miami and the federal courthouse in Key West. The limestone quarry is now the Windley Key Fossil Reef Geological State Park, where visitors can walk on top of and inside the 125,000-year-old coral reef.

Strong ocean currents connect geographic regions

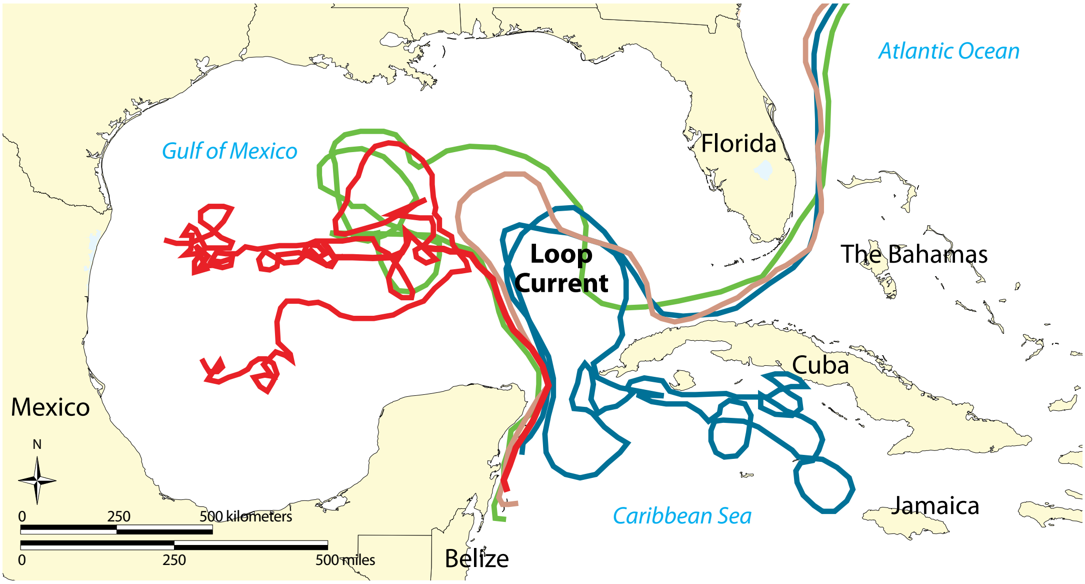
Brian D. Keller and Elizabeth Johns

Strong ocean currents connect south Florida with upstream waters of the western Caribbean Sea and the Gulf of Mexico. In particular, the Caribbean Current, emanating from the Caribbean Sea and flowing north past the Yucatán Peninsula, and the Loop Current in the Gulf of Mexico provide a rapid conduit for transport of materials from the Caribbean Sea, Mexico, and Belize into the coastal zones of northern Cuba, south Florida, and the Bahamas.

Planktonic larvae are dispersed by ocean currents. Thus, ocean currents between geographically separated reefs and marine habitats provide a means of biological connectivity between regional populations. This feature may have a direct influence on the ability of an ecosystem to recover from disturbances. For this reason, Marine Protected Areas should be strategically placed to maximize connectivity and protect biodiversity.

Dispersal of larvae can be simulated by computer models. At present, models are mainly useful in providing generalities and generating hypotheses. Studies of individual larval behavior, the ability of larvae to move up and down in the water column, and detailed life histories are required to produce more accurate simulations of population connectivity.

Currents also have the potential to carry pollutants, nutrients, diseases, and other stressors downstream to coral reef communities and other habitats. Cooperation between neighboring countries and an improved understanding of how external stressors degrade local marine resources are required to reduce negative impacts from upstream sources.



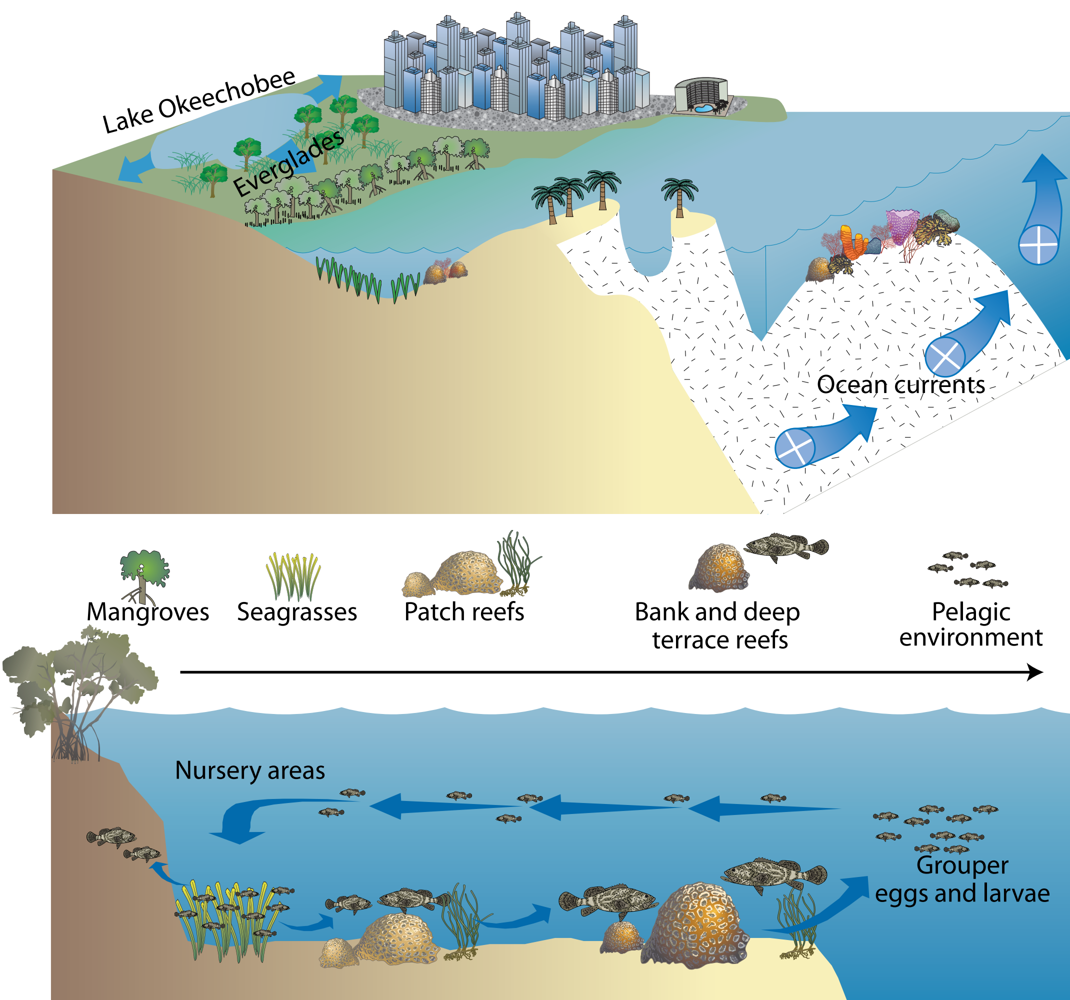
Trajectories of surface drifters deployed in March 2006 just east of the Yucatán Peninsula in Mexico show the complexity of regional currents. One drifter (red) became entrained in eddies in the western Gulf of Mexico and remained there. One (green) became entrained in eddies for a time and then joined the Loop Current and exited the Gulf of Mexico through the Florida Straits. One (orange) took a straightforward trip via the Loop Current, through the Florida Straits, and off to the North Atlantic. One (blue) meandered south of Cuba for several months before rejoining the Loop Current and rapidly exiting the area.

Marine and estuarine habitats in south Florida are physically and biologically connected

Jerald S. Ault

Unique bay-to-reef biological, topographic, and oceanographic conditions help to sustain the coral reef ecosystem of south Florida. Coastal benthic habitat types exhibit a distinct cross-shelf pattern from the shoreline to the deep reef, encompassing fringing mangrove forests, seagrass meadows, sponge and soft coral-covered hardbottoms, patch reefs, bank (i.e., barrier) reefs, and carbonate sediments. Many species of fish and invertebrates depend on this mosaic of environmental conditions and habitats found along the gradient from bays and lagoons to the bank coral reef.

South Florida is characterized by productive and highly diverse biological communities that include more than 500 species of fish and thousands of species of invertebrates, including corals, sponges, shrimps, crabs, and lobsters.



Schematic view of south Florida, including Miami and Biscayne Bay, showing physical connectivity of marine habitats and movement of life stages of grouper among habitat types.

Approximately 389 species of fish depend on a healthy coral reef ecosystem and support multi-billion dollar fisheries and tourism industries. The value of Florida recreational fisheries exceeds that of the state citrus industry and is 10 times more valuable than the state commercial fishing industry. Recognition of this fact contributed to the designation of Florida as the "fishing capital of the world" by the Florida State Legislature (1987).

South Florida is critically positioned at the nexus of complicated hydrodynamic influences. The seaward edge of the bank reef receives clear, low nutrient water from the Florida Current (that portion of the Gulf Stream current system in the Florida Straits) that provides conditions conducive to coral reef development. Periodically, the deep-reef margins receive pulses of nutrient-rich waters from locally intense upwelling events.

Gulf of Mexico waters mix with surface and groundwater from the Everglades and produce variable salinity regimes within an extensive network of coastal bays and lagoons with lush mangrove forests and seagrass meadows. The net movement of coastal waters along the Southwest Florida Shelf is southward through Florida Bay and toward the Atlantic Ocean and the fringing coral reefs.

Groupers and snappers are highly prized in commercial and recreational fisheries of south Florida. The bottom-dwelling stages of at least 50 species in the snapper-grouper complex use a broad array of habitats across the entire continental shelf. Most evidence suggests that strict estuarine dependence is a rare life history strategy among the species in the complex. However, many show some degree of habitat utilization and migration across the shelf as they mature. Habitat utilization patterns generally shift from coastal bays to offshore reef environments as individuals develop from juveniles to adults. Many species spawn at the seaward edge of bank reefs and sometimes form large spawning aggregations (e.g., goliath grouper). Pelagic eggs and developing larvae


NPS

Mangroves and seagrasses are important habitats in the life cycle of many marine species.

are transported from spawning sites to nursery habitats by a combination of tidal currents, seasonal wind-driven currents, and unique animal behaviors. Some of the most important nursery habitats are located in the coastal bays and near barrier islands and include mangrove and seagrass habitats.

Implications of habitat connectivity on fisheries management

Stressors to fisheries include overfishing, impacts of coastal development on habitats, and water quality degradation. The fact that many species depend on several coastal habitats throughout their life cycle complicates management strategies. It is important for management plans to consider protection for all habitat types used by the species throughout their life history to provide maximum protection to the fishery.

A major concern of fisheries management is the vast network of drainage canals in south Florida that were completed during the second half of the 20th century to facilitate rapid development of the coastal margin, conversion of wetlands for agriculture, and flood control. These canals have significantly altered the distribution of freshwater within the south Florida watershed and changed the historical quantity, quality, and timing of freshwater discharges to coastal bays. These alterations of natural drainage patterns have degraded marine habitats and resulted in dramatic environmental changes. A key management goal must be optimizing salinity gradients across the ecosystem, from mangrove shorelines to the coral reef, to ensure the ecological health of benthic habitats and the productive and diverse fisheries that they support.

Inputs from the Mississippi River, Southwest Florida Shelf, and other riverine sources can affect water quality, produce algal blooms, and reduce habitat suitability and fishery resources in south Florida. Thus, the geographic scale of future fisheries management actions may need further refinement from those historically used.

The need to unify coastal land management with fishery management was reinforced by the Essential Fish Habitat (EFH) provisions in the reauthorization of the Magnuson-Stevens Act. EFHs are "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." EFH guidelines recognized Habitat Areas of Particular Concern (HAPC) by at least four criteria:

1. Importance of ecological functions;
2. Sensitivity to degradation;
3. Probability and extent of effect from development; and
4. Rarity.

The Act provides that if a species is overfished, all habitats it uses are considered essential. Sites that consistently support spawning aggregations for multiple species require management as EFH-HAPC and potentially should be set aside as no-take protected areas.

Nursery habitats are particularly vulnerable to impacts from coastal development. Establishment of Marine Protected Areas (MPAs) can only be effective if connectivity among habitats is recognized, and the design of MPAs is coordinated among all agencies responsible for regulating development, water quality, fisheries, and habitat protection.

The Comprehensive Everglades Restoration Plan projects a 30-year implementation program to restore the Everglades ecosystem and adjacent estuaries. An important aspect of the restoration plan must be to optimize the expected changes to the entire coastal ecosystem.

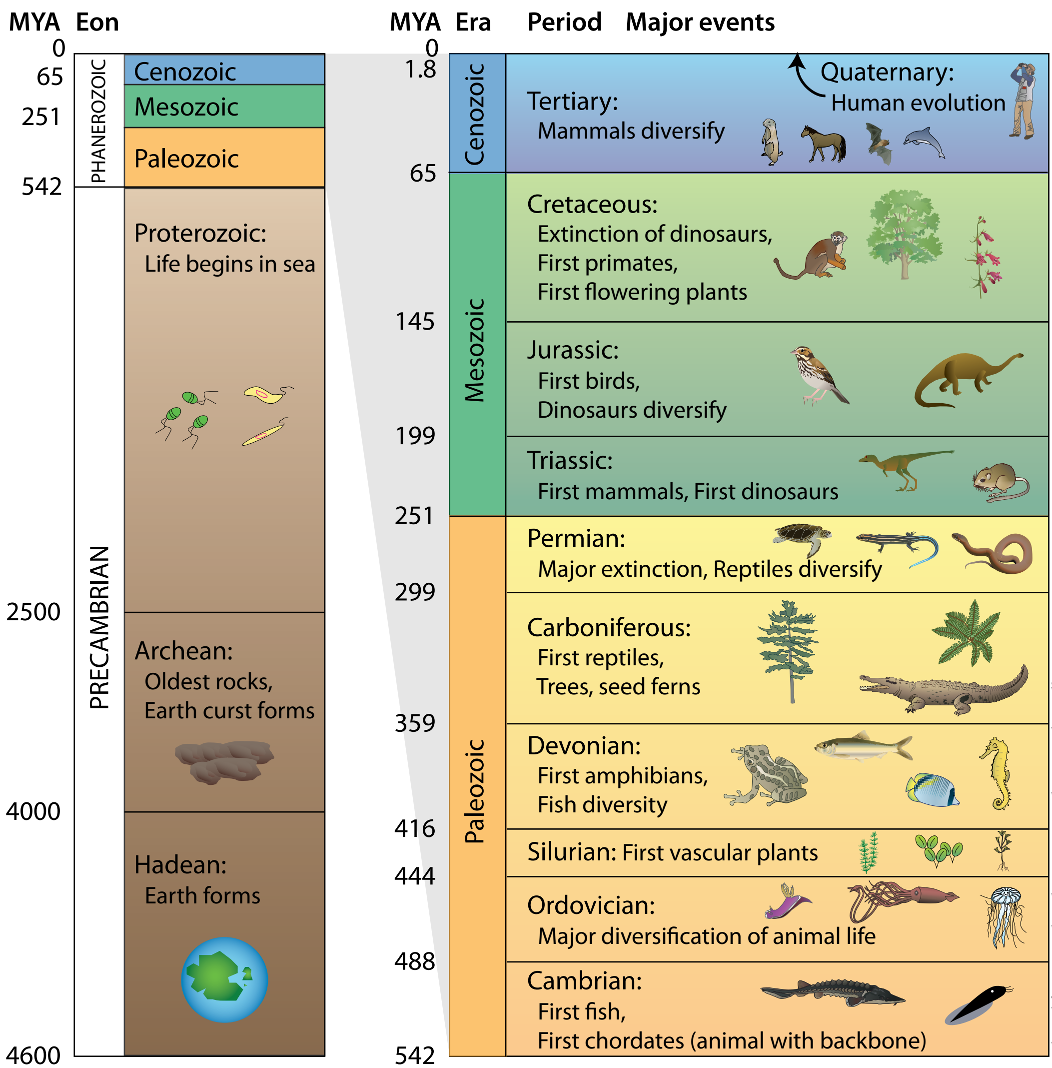
FDOT

FDOT

Example of coastal habitat loss in south Florida. Extensive coastal habitats, including mangrove forests that were present near the mouth of the Miami River in 1956 (left), are replaced today with extensive development (right).

Geological time with major evolutionary events in the fossil record

William L. Kruczynski and Pamela J. Fletcher



Adapted from Encyclopedia Britanica and www.enchantedlearning.com

The geological time scale is a method of relating the timing and relationship between events that have occurred during the history of the Earth. The Earth is more than 4.5 billion years old, and an appreciation of the expanse of geological time is difficult to visualize. This chart shows the sequence of major evolutionary events that appear in the geologic record. Geologists and earth scientists have used the relationship between layers and types of rocks, presence of plant and animal fossils, and radioactive dating to assemble a sequence of historical events that have occurred over geologic time.

Geologic time is divided into four large segments called Eons: Hadean, Archean, Proterozoic, and Phanerozoic. The Phanerozoic Eon is divided into Eras: Paleozoic, Mesozoic, and Cenozoic. The divisions among Eras reflect major changes in the fossil record, including the extinction and appearance of new life forms. Eras are divided into Periods, a unit of geologic time in which a single type of rock system is formed. Some Periods are divided into Epochs that are not shown on this chart, but a discussion of Epochs appears on subsequent pages in this chapter that summarize the creation of the Florida peninsula, the geology of south Florida and the Florida Keys, and the appearance and disappearance of shorelines and coral reefs.

Dates from the International Commission on Stratigraphy, 2010. MYA = Million years ago.

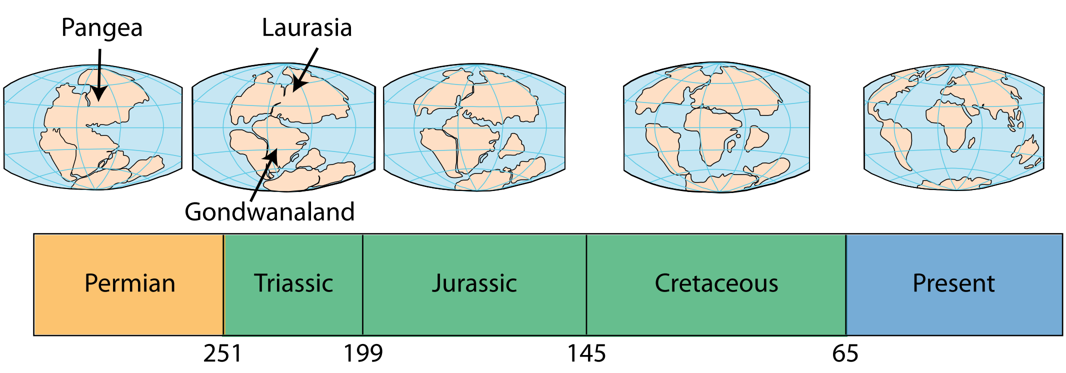
Florida has changed over millions of years

Guy H. Means

The Earth is more than 4.5 billion years old. During this unimaginable expanse of time, our planet has undergone drastic changes. For the earliest part of the history of the Earth, the planet was a molten inferno. As the planet slowly cooled, rocks and minerals began to form, and continents and ocean basins took shape. The continents today look nothing like they did hundreds of millions of years ago. In fact, the continents move around through a process called "plate tectonics." Continental crust, the thin outer skin of our planet, sits on top of hot rock material that behaves like cold syrup and is called the mantle. As the plates shift, they can collide, causing mountain ranges and deep ocean trenches to form. They can also slide past one another along long faults, like the San Andreas fault in California, and they can spread apart as seen along mid-ocean ridges. Plate tectonics describes the processes involved with plate movements and allows geologists to understand the changes in the Earth's landforms.

The geological history of south Florida can be traced back to the Paleozoic Era, 542 – 251 million years ago (mya), based on rock core samples retrieved from thousands of meters below the surface. These rocks, referred to as "basement rocks," consist of igneous and metamorphic rocks overlain by sandstones and shales. The sequences of rock layers record the events that were taking place as the Laurentian and Gondwanan landmasses were converging to create the supercontinent of Pangea. As these and other smaller landmasses converged, they created the foundation for the accumulation of vast thicknesses of carbonate (limestone) that would eventually become the Florida Platform.

During the early Mesozoic Era (251 – 65 mya) the supercontinent of Pangea began to rift and break apart. Florida, during this time, was located between what would later become the continents of Africa, South America, and North America. In fact, as North America separated from Africa, a small portion of the African plate remained "stuck" to North America and that provided some of the foundation upon which Florida now rests. Geologists can tell this by looking at the chemistry and fossil assemblage of Florida basement rocks. During the later part of the Mesozoic Era, the Florida landmass was beneath a warm, shallow ocean. As



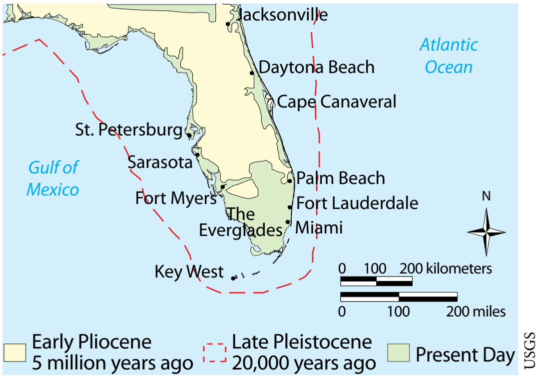
USGS

During the Permian Period (299 – 251 million years ago [mya]), the continental plates on Earth joined together to form the supercontinent Pangea. During the Triassic Period (251 – 199 mya), the supercontinent broke apart. As this happened, a small portion of Africa remained attached to North America, which created the foundation that Florida now rests upon.

marine organisms died and sank to the ocean floor they began to accumulate in great thickness. This sediment would later consolidate and become limestone. The end of the Mesozoic Era was brought about by a great cataclysm, when a large meteor impacted the Earth in what is now the Yucatán Peninsula. It is believed that this event caused mass extinction of many species, including the dinosaurs.

During the Cenozoic Era (65 mya – present), Florida slowly took its current shape. Warm, tropical oceans covered the state until the late Oligocene Epoch (34 – 23 mya). Large, voracious whales roamed the shallow seas hunting other marine vertebrates. Small patch reefs formed in the warm, clear, shallow waters of Florida during this time. The skeletons of billions of small creatures, called "foraminifera" accumulated on the seafloor. These skeletons would later become cemented together to form limestone, which underlies the entire state of Florida. Also during this time period, a marine current similar to the Gulf Stream swept across northern Florida and scoured the seafloor. This current deflected sediments, such as silicate sands, that were being eroded and transported from the north, and this is the reason why limestones from this time period in Florida are so pure (up to 99% calcium carbonate). At the end of the Oligocene Epoch, sea levels dropped, and Florida emerged from the sea. The first fossils of terrestrial vertebrates in Florida come from this time period and include animals like bats, horses, and carnivores. From this time period on, at least some portion of Florida would remain above sea level. Throughout the end of the Oligocene and into the Miocene Epoch, sea levels fluctuated, and clays and sands became common deposits.

The Miocene Epoch (23 – 5.3 mya) was a time of unique conditions across Florida. Large deposits of phosphorite accumulated as cool, nutrient-laden ocean water bathed southern Florida. These deposits are mined today and account for a significant portion of the phosphate produced in the United States. Unique creatures also existed in Florida at this time. Large sharks patrolled the nearshore marine environments preying on whales. Horses, saber-toothed cats, and elephants roamed the land. Many of these creatures left behind their bones in Miocene deposits. A prized fossil from this time period is the tooth from the giant extinct shark (*Carcharodon megalodon*). These teeth can exceed 180 centimeters (7 inches) in length and belonged to an animal that may have been 20 meters (67 feet) long!



Land area of Florida during the Early Pliocene, Late Pleistocene (red dotted line), and present-day Florida.

The Pliocene Epoch (5.3 – 2.6 mya) was an important time for land animals in Florida. North America became connected to South America, allowing animals to travel freely between both continents. North America became the home to animals like sloths, giant armadillos, and llamas that migrated north over the newly formed land connection. Ocean currents were also interrupted and the Gulf of Mexico became isolated from the influence of the Pacific Ocean. The exchange of flora and fauna from South America is known as the Great American Interchange. Sea levels were fluctuating, and marine deposits (limestone and shell beds) were accumulating in south Florida. Those shell beds contain some of the most diverse molluscan faunas in the world.

The Pleistocene Epoch (2.6 mya – 11,000 years ago), also known as the Ice Age, was a time of extreme climate and sea level changes. Sea levels were about 123 m (400 ft) lower and as much as 30 m (100 ft) higher than today. As the giant continental glaciers advanced and retreated, sea levels responded. During warm, interglacial periods, sea levels were sufficiently high to allow marine limestones to accumulate. During glacial periods, sea levels were much lower, and erosion and dissolution of limestone occurred. Giant Ice Age mammals roamed Florida at this time and included some of the largest land mammals to have ever existed. Some of these animals include mammoths, mastodons, giant lions, Dire wolves, saber-tooth cats, giant sloths, and giant beavers. At the end of the Pleistocene, another animal arrived in Florida: humans. This also coincided with the demise of the giant Ice Age mammals. Many large mammals went extinct at the end of the Pleistocene either as the result of climate change, human hunting, or a combination of both.

Sea level reached its current elevation during the Holocene Epoch (11,000 years ago – present). Human populations expanded and shaped the landscape to suit their needs. The Everglades of south Florida formed, and thick layers of peat were deposited. The Florida Keys became islands, and new coral reefs began to grow. Our modern climate developed, and Florida took the shape we are all used to seeing: a long peninsula.

MYA	Era	Period	Epoch	Major Events
0	Cenozoic	Quaternary	Holocene	Climate change and sea-level rise. Florida Keys become islands. Current bank reefs form. Everglades form. Sea level at present level.
0.011			Pleistocene	Humans arrive in Florida. Mastodons roam. Ice Age causes extreme changes in climate and sea level. Sea level drops about 123 meters (400 feet) below present level. During warm periods, sea level was about 30 m (100 ft) above present level and allowed exchange of Atlantic and Gulf of Mexico faunas. Coral reefs that would eventually become the Florida Keys grow and accumulate. Humans evolve.
2.6		Tertiary	Pliocene	North and South America joined. Giant sloths and llamas found in Florida. Gulf of Mexico isolated from Pacific Ocean.
5.3			Miocene	Phosphate deposits accumulate. Giant sharks (*Megalodon*) roam the seas. Horses, saber-toothed cats, and elephants roam landmass. Clays and sands deposited from north.
23			Oligocene	Thick deposits of limestone. Sea level drops, Florida landmass emerges. First land animal fossils.
33.9			Eocene	Warm period, oceans teem with fish. Palm trees range as far north as Alaska. Foraminifera accumulate on seafloor.
55.8			Palocene	Evaporite minerals accumulate in shallow, restricted marine water areas.
65	Mesozoic	Cretaceous		Extinction of dinosaurs. Marine sediments continue to accumulate.
145		Jurassic		Marine sediments form thick limestone deposits.
199		Triassic		Plate tectonics result in separation of Florida landmass from Africa.
251	Paleozoic			Basement rocks accumulate.
542				

Adapted from Lane (1994)

A brief geological history of Florida.

Geology of the Florida Keys

Eugene A. Shinn

The Florida Keys are approximately 125,000 years old. It is a common belief that the Keys landmass of today is just old exposed corals, but it is more complex than that. The Keys can be divided geologically into the Upper Keys, from Bahia Honda Key northward, and the Lower Keys, from Big Pine Key to Key West. The Lower Keys are cemented fossil tidal bars of ancient sands. These sand bars consisted of small concentric grains of calcium carbonate called ooids that precipitated from warm high-energy waters. When ooids are cemented together to form limestone, the resulting "rock" is called oolite. This formation is also found under the city of Miami. Similar ooid sand bars are currently forming in the Bahamas, but for unknown reasons ooids ceased precipitating in huge quantities in the Florida Keys after the fossil bars formed 125,000 years ago. The north-south shape of the Lower Keys from No Name Key to Key West is due to strong tidal currents that once raced between the Gulf of Mexico and the Atlantic Ocean when sea level was higher than present, and the currents eroded channels through the tidal bars.

The Upper Keys are fossil coral reefs. These reefs grew at the same time sand bars were forming in the Lower Keys when the sea level was at least 6 meters (20 feet) above present. The current discontinuous chain of islands was formed when sea level fell, leaving the reefs (Upper Keys) and sand bars (Lower Keys) high and dry. This coral limestone of the Upper Keys is called Key Largo Limestone. Newfound Harbor Keys are the westernmost exposure of the Key Largo reef. The highest elevation in the Keys is at Windley Key, 5.5 m (18 ft) above present sea level.

The fossil reef that forms the Upper Keys is much more permeable than the oolitic limestone in the Lower Keys. Big Pine Key is a large oolite island and has a 6 m (20

NASA

Satellite image showing the current shape of the Lower Florida Keys landmass.

Years ago	Period	Epoch	Major Events
50	Quaternary	Holocene	1950 -1970 Keys development increases and canals are built.
100			1912 Flagler's Railroad disrupts Gulf-Atlantic water exchanges.
200			1821 Indian Key becomes U.S. property. 1763 Native Indians no longer present in the Keys.
300			1733 First map of the Florida Keys.
500			1513 Ponce de Leon "discovers" the Keys.
2000			Oldest Indian shell midden dated.
11,000		Pleistocene	
12,000			Sea level begins rising rapidly.
13,000			Paleo Indians arrive.
17,000			Florida Keys and Florida Bay are forested; Hawk Channel is a swamp.
18,000			Last glacial period, warming begins and glaciers melt. Sea level 123 meters (400 feet) lower than present-day.
120,000			Coral reefs that form the Florida Keys landmass are dry. Sea level 6 m (20 ft) higher than present-day. Quaternary Units (Q1 – Q5) form during periods of low water. Reefs flourish during interglacial periods. During glacial periods, corals grow at the edge of the continental shelf.
1,800,000			Ice Age begins, and there are four periods of glaciation.

Adapted from Lane (1994) and Viele (1996)

A brief history of the Florida Keys during the Quaternary Period (time record is not to scale).

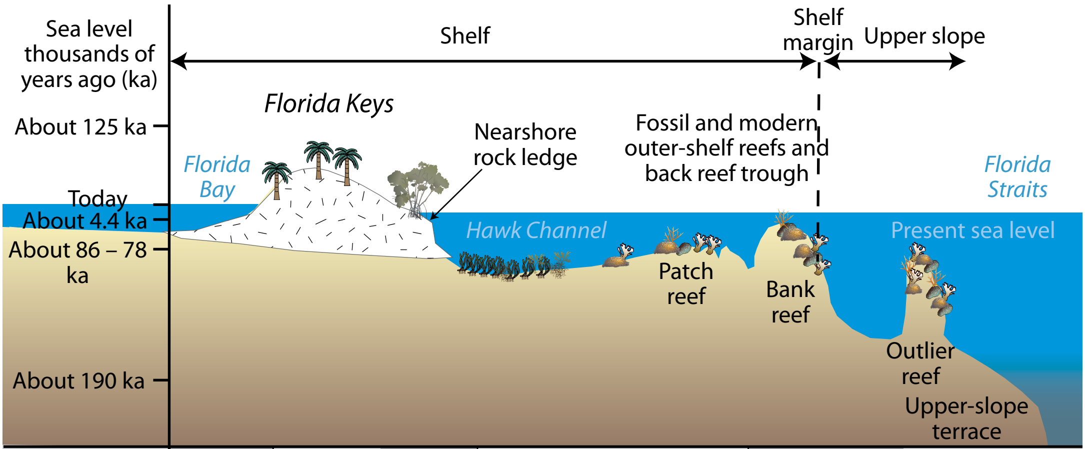
ft) thick freshwater lens just below the surface. The lens floats on the underlying salty groundwater and is not greatly affected by the tides because of the low permeability of the oolite. The south Florida slash pines (*Pinus elliotii* var. *densa*) for which the island is named depend on this freshwater lens to survive. Tides flush through the Key Largo Limestone more rapidly and remove any freshwater that accumulates beneath the surface. This is one reason that there are no pine trees in the Upper Keys.

The Florida Keys were formed in the Pleistocene Epoch, a time period from 1.8 million years before present until 11,000 years before present. It was a time that includes the most recent period of repeated glaciations in the world. During glacial times, sea level fell because water was locked up in the polar ice caps; during interglacial times, sea level rose as the ice caps melted. Each time the sea rose, rows of coral reefs formed on the shelf seaward of the present Florida Keys. Each time the sea fell, the reefs were left exposed, and rainwater dissolved and cemented them into hard limestone. The exposed reefs were also coated with a distinctive dense crust called Q1– Q5 Units (Q = Quaternary). That brown-colored crust can be seen in areas of exposed limestone. The last big drop in sea level was about 28,000 years ago, when the sea level fell more than 123 m (400 ft). About 10,000 years ago, the sea began rising fast and flooded the old offshore reef areas in about 3000 – 4000 years. Those older reef areas became the foundation of the present reef growth. The modern barrier reefs that make up the Florida Keys Reef Tract were formed in the Holocene Epoch, a time period from 11,000 years ago to the present, and are essentially a recolonized growth of corals, algaes, and other benthic organisms on old dead reef structures.

What lies below the Pleistocene rocks is, of course, much, much, older. The Pleistocene marine sequences accumulated on top of more than 4.6 kilometers (2.8 miles) of pre-existing limestone. About 3.4 km (2.1 mi) below the Pleistocene rocks are limestones that belong to the Cretaceous Period (the time of the dinosaurs) that ended about 65 million years before present. The limestone was dated from rock fragments recovered from the 14 oil wells drilled in the Keys since the 1940s (the last in 1961). Underneath the Cretaceous rocks are those belonging to the Jurassic Period.

A.S. 'Buddy' Wylie, Jr. - COGE

Key Largo Limestone consists of fossilized coral reef as seen in canals in the Florida Keys.



Pleistocene geomorphic features	*Shallow inland lagoons or embay-ments (Florida and Biscayne Bays)*	*Key Largo Lime-stone and Miami Lime-stone*	*Shallow near-shore rock ledge*	*Broad trough-like depression lined with soft sediments*	*Ridge of 86 – 78 ka corals underlying Holocene accumulations and forming shelf-margin edge*	*Upper-slope terrace (about 190 ka)* *1) Seismic profiles reveal outlier reefs on upper slope terrace 2) Facies and aerial photographs indicate high-relief outlier reefs and deep troughs on terrace off the Lower Keys 3) Youngest Pleistocene corals on the outlier reefs and shelf-margin reef are the same age (86 – 78 ka)*
Depth (relative to present sea level)	*-2 to -3 m*	*0 to +5.5 m above sea level*	*0 to -4 m*	*-8 to -16 m average*	*-6 to -15 m*	*-30 to -40 m*

Adapted from Lidz (2005)

Timeline of recent geologic events in the Florida Keys and reef tract.

Geographic Setting and Impacts to the Environment

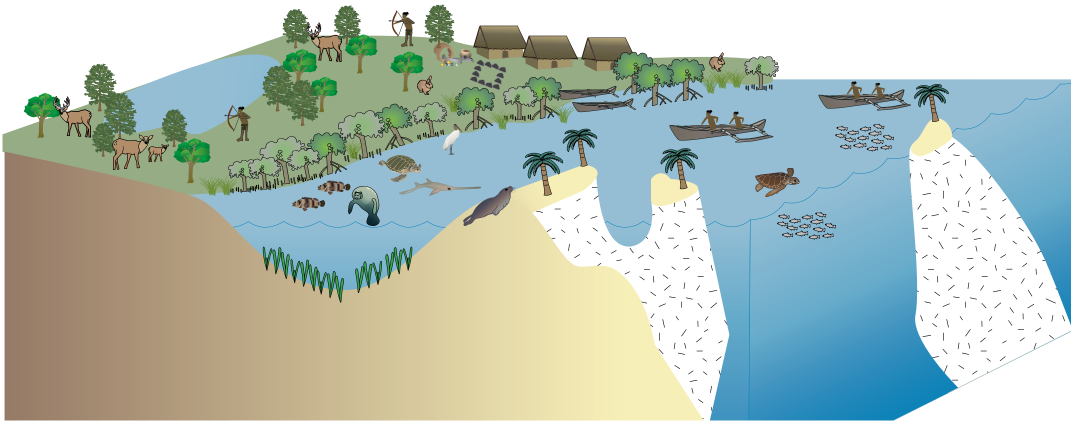
Humans have significantly impacted south Florida and the Florida Keys

William L. Kruczynski and Pamela J. Fletcher

BIRDS	Wood stork	*Mycteria americana*	Endangered
MAMMALS	Key deer	*Odocoileus virginianus clavium*	Endangered
	Florida panther	*Puma concolor coryi*	Endangered
	Silver rice rat	*Oryzomys palustris natator*	Endangered
	Florida manatee	*Trichechus manatus*	Endangered
	Caribbean monk seal	*Monachus tropicalis*	Extinct
	Key Largo woodrat	*Neotoma floridana smalli*	Endangered
	Lower Keys marsh rabbit	*Sylvilagus palustris hefneri*	Endangered
	Key Largo cotton mouse	*Peromyscus gossypinus*	Endangered
FISH	Largetooth sawfish	*Pristis perotteti*	Critically Endangered
	Smalltooth sawfish	*Pristis pectinata*	Critically Endangered
	Sandbar shark	*Carcharhinus plumbeus*	Threatened
	Goliath grouper	*Epinephelus itajara*	Critically Endangered
	Scalloped hammerhead	*Sphyrna lewini*	Endangered
REPTILES	American crocodile	*Crocodylus acutus*	Threatened
	Green turtle	*Chelonia mydas*	Endangered
	Kemp's ridley turtle	*Lepidochelys kempii*	Endangered
	Loggerhead turtle	*Caretta caretta*	Threatened
	Leatherback turtle	*Dermochelys coriacea*	Endangered
CORALS	Elkhorn coral	*Acorpora palmata*	Threatened
	Staghorn coral	*Acorpora cervicornis*	Threatened

U.S. Endangered Species Act list (yellow, orange, black) — International Union for Conservation of Nature (IUCN) list (red)

Before the arrival of humans, south Florida waters were a much different place than they are today. The region teemed with life, including large herbivores and predators. The land supported a diverse assemblage of wildlife, including deer, bear, panther, and their prey. The history of south Florida is a story of human attempts to conquer the land, resulting in habitat destruction, habitat fragmentation, overfishing, and pollution. Today, humankind is trying to manage a very different ecosystem than the one that existed in the past. There are few places on Earth that have as many endangered, threatened, and overfished species as south Florida.



By 100 A.D. the Native American population increased to about 1000 inhabitants. They were hunter-gatherers and obtained much of their food from the sea. Because of their small numbers, sustainable harvesting practices, and general respect for the Earth, they had negligible impacts on the environment.

1000 BC – 700 AD
Dates given to many Upper Keys Native American archaeological sites.

1700s – 1800s
White man's guns, disease, rum, and raids by northern Indian tribes wiped out Keys natives. Keys are deserted.

1513
Ponce de Leon expedition "discovered" the Florida Keys while searching for the Fountain of Youth.

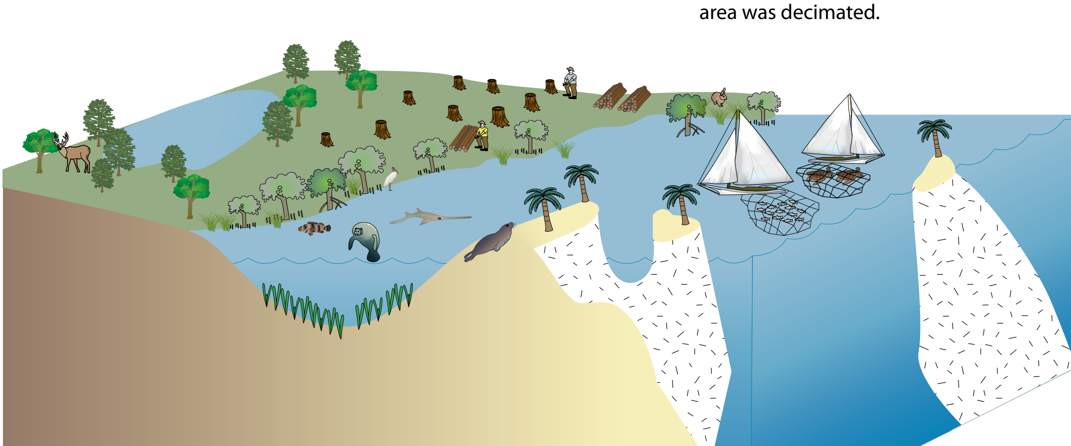
1821
Florida became a U.S. territory.

1825
Cape Florida lighthouse built on Key Biscayne to warn ships of dangerous coral reefs. The lighthouse was burned by the Seminoles in 1836.

1836 – 1842
Second Seminole War occurred over demand by U.S. government that Indians relocate to western reservations. Indian war parties raided Key Largo and Indian Key. Population of settlers in Miami area was decimated.

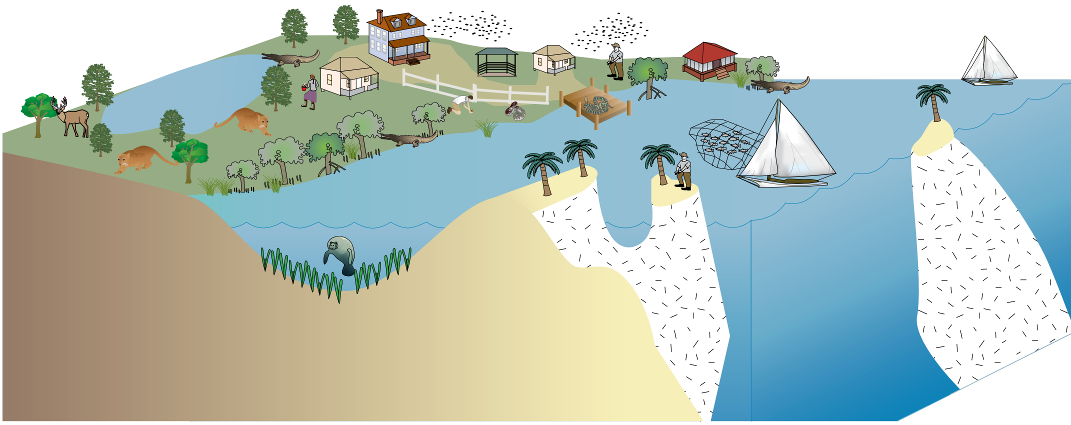
1845
Florida became a U.S. state.

1850
First census: 32 settlers lived among Summerland, Sugarloaf, and Boca Chica Keys; 40 settlers lived on Key Vaca.



Cubans and Bahamians visited the Keys to fish, catch turtles, harvest hardwood timber, and salvage shipwrecks. Most valuable timber was probably gone by 1760. After the War of 1812, New England fishermen came to the Keys in the winter to fish. They were among the first settlers of Key West.

Adapted from Viele (1996) and The Florida Keys Environmental Story (1997)



Heat, rattlesnakes, mosquitoes, no-see-ums, alligators, panthers, and scarcity of freshwater made life difficult in the Keys. Before the first highway, all inter-Keys commincation and communication with the mainland was by boat.

1870 — Population outside Key West was about 300 inhabitants.

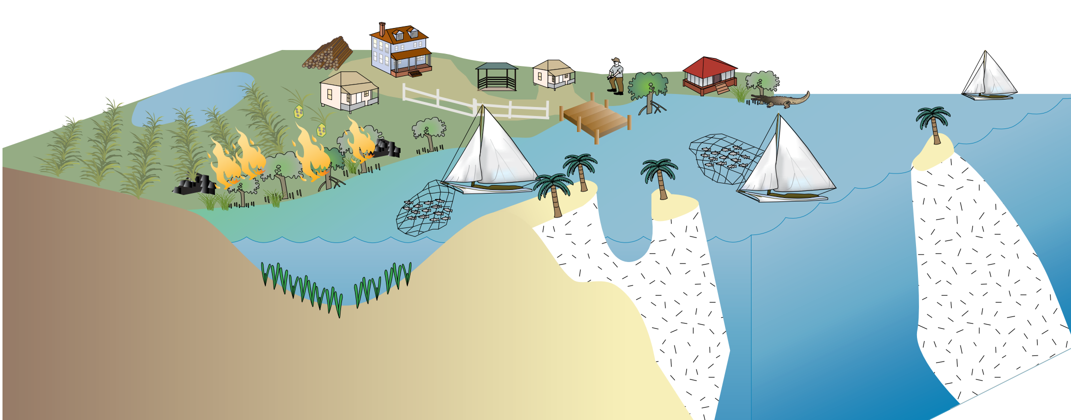
1890s — Key West was the largest city in Florida (18,000 people) with an economy based on the cigars, sponges, and shipwreck salvages.

1905 – 1912 — Henry Flagler financed the construction of the Overseas Railroad ($50 million in 1905 dollars). The Railroad spanned 171 km (106 mi), connected 31 islands, and included 27 km (17 mi) of bridges and 32 km (20 mi) of filled causeways. Turbidity negatively impacted seagrasses and corals and degraded sponging and fishing grounds.

1906 — Canals were dug to drain water from the Everglades for agriculture and to create land for development.

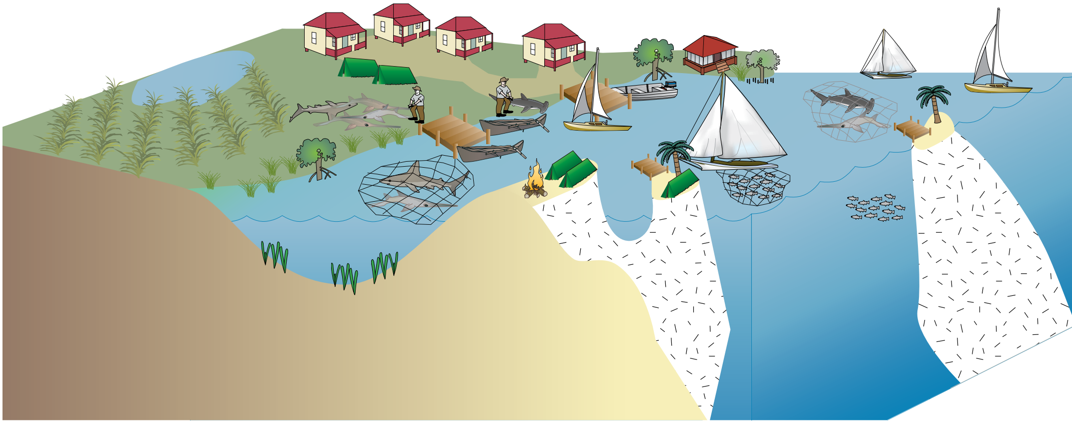
1917 – 1928 — First Overseas Highway was constructed, making it possible to ferry or drive by automobile from Miami to Key West. Ease of access brought many recreational fishermen to the Keys.

1918 — Seaplane base was established in Key West for training and anti-submarine patrol. After WWII ended, some military personnel stayed in the Keys.



Adapted from Viele (1996) and The Florida Keys Environmental Story (1997)

Many early settlers were farmers, and a main crop was pineapples in the Upper Keys and fruits and vegetables in the Lower Keys. Many made a living fishing, gathering sponges, or making charcoal for Key West stoves. Rampant habitat loss and fragmentation to "conquer" the Keys begins. Hardwood hammocks were cleared for farming.



By 1930, fishing camps were popular in the Keys. Big Pine Shark Camp commercially harvested up to 100 large sharks and sawfish per day. The long-lived and slow-reproducing fish were virtually eliminated from the Keys and have not recovered to this day.

1930
Mosquito ditches were constructed to control yellow fever and malaria.

1931 – 1934
Freight cars of pineapples were shipped from the Keys.

1935
Hurricane damaged the Overseas Railroad, and more than 400 people perished. The Railroad was not rebuilt because it was not profitable.

1937
A 210 km (130 mi)-long pipeline was constructed to deliver freshwater from Florida City to the Key West Naval Air Station and Key West.

1940
Key West Naval Air Station was created. After WWII, many military families stayed in the Keys or vacationed there.

1940s – 1960s
DDT sprayed for mosquito control.

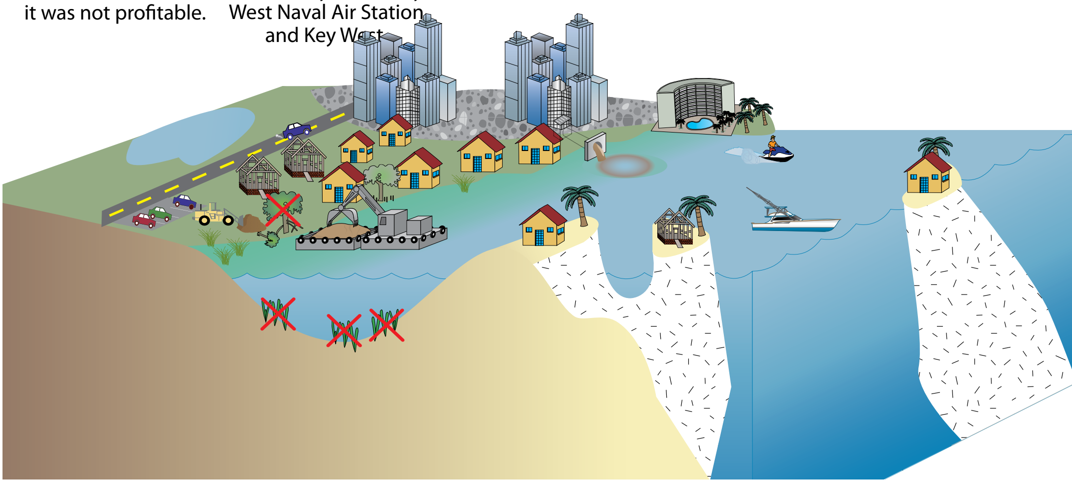
1947
Everglades National Park was established.

1950s
Sportfishing in the Keys was "discovered".

1970
The State of Florida banned new canal construction in Keys due to turbidity and other water quality concerns.

1980
Water pipeline replaced to deliver approximately 14 million gallons per day to Keys. U.S. Highway 1 improved and new bridges constructed. Seagrass suffered extensive damage.

1990
Florida Keys National Marine Sanctuary was established.



The period 1948 – 1970 marks a building boom to create waterfront housing by dredging and filling mangroves and seagrasses. Approximately one half of the mangroves in the Keys were destroyed. Turbidity was chronic and smothered seagrasses and corals. Sewage and stormwater controls were primitive or nonexistent.

Adapted from Viele (1996) and The Florida Keys Environmental Story (1997)

Paleoecologists interpret south Florida's past

C. Lynn Wingard

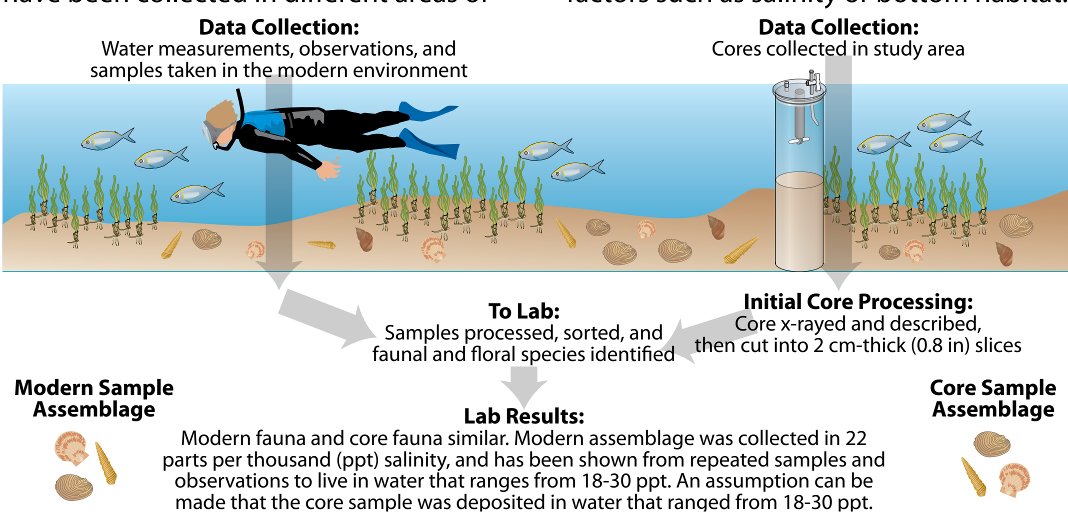
One way to understand what an environment looked like in the past is to examine the remains of plants and animals in samples collected throughout an area being studied. This is what paleoecologists do: they study the remains of plants and animals that lived in the past (paleontology) and they interpret the interaction of those plants and animals with their environment (ecology).

Paleoecologists need two types of information to interpret the history of an ecosystem: 1) the remains of plants and animals that lived in the past collected from sediment cores and 2) the ecological requirements of the living organisms found within the ecosystem.

Cores are used to collect layers of sediment with plant and animal remains while maintaining their vertical arrangement relative to each other. Each layer tells the "story" of what the ecosystem was like at a particular point in time. The most recent part of the story is preserved in the upper layers of the core; the lower layers of core material show older periods in time. By examining the changes from layer to layer, scientists can develop a picture of the changes that occurred over time. In south Florida, cores have been collected in different areas of the estuaries to compare what happened across the region at the same time.

Once a core is collected, it is X-rayed, photographed, described, and then sliced into approximately 2 centimeters (0.8 inches)-thick samples. The plant and animal remains are counted and identified, and the distribution of key organisms in the core is recorded. Changes in the number and types of plants and animals in the core reflect changes to the environment.

Paleoecologists work on the principle that "the present is the key to the past." In south Florida estuaries, factors that control the distribution of living species of plants and animals are salinity, water temperature, water depth, and type of bottom environment. Understanding the ecological requirements of the plants and animals alive today allows scientists to interpret the environmental conditions represented in the layers of the cores. Species found in the core samples that currently live in south Florida are assumed to have had the same set of environmental conditions observed today. Compiling the changes in the core assemblages over time illustrates the environmental changes over time of factors such as salinity or bottom habitat.



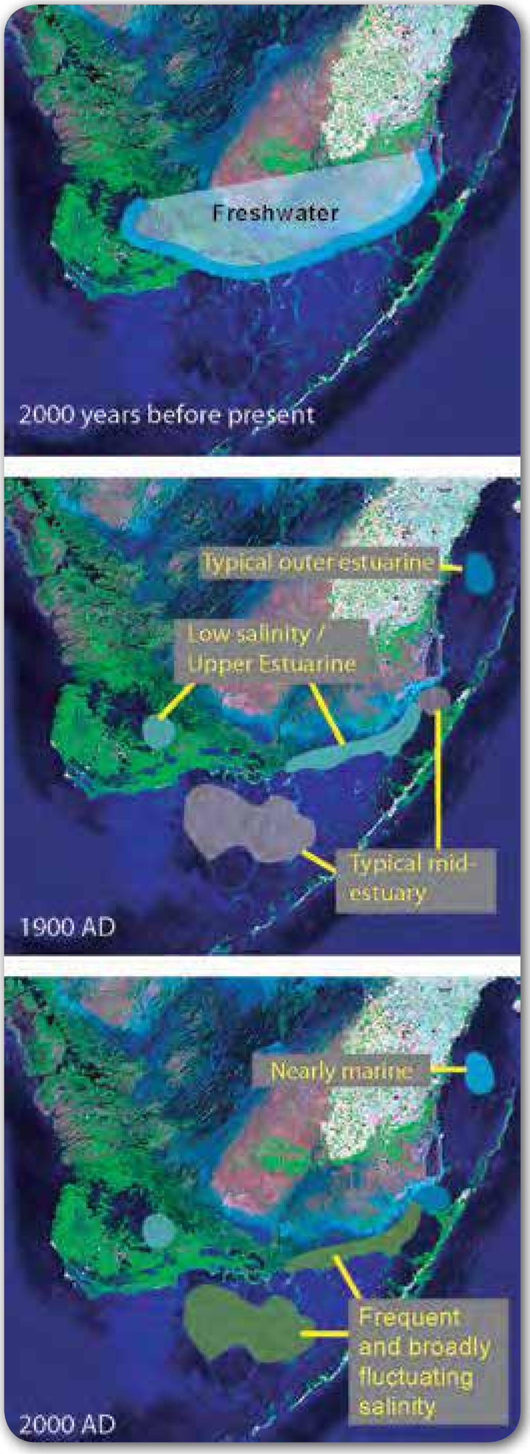
From Wingard (2004)

South Florida estuaries have changed over time

C. Lynn Wingard and Frank E. Marshall

South Florida estuaries may have been quite different in the past compared to present-day conditions. Analysis of sediment cores shows that over the past 2000 years, the salinity in south Florida estuaries has been gradually increasing due to rising relative sea level. During the 20th century, the rate of change in salinity increased significantly. Most scientists attribute this change in salinity to a combination of the increase in the rate of sea-level rise and a decrease in the supply of freshwater to the estuaries because of drainage modifications for agricultural and urban flood protection and for development.

Changes in salinity are critical to an ecosystem because salinity patterns within an estuary are one of the primary controls over distribution and diversity of living organisms. Approximately 2000 years ago, freshwater environments extended into nearshore areas that are currently estuarine along the transition zone of Florida Bay, Whitewater Bay, and the Shark River. By the beginning of the 20th century, evidence from sediment cores shows a change to relatively typical faunal patterns for a zoned estuarine ecosystem. In a zoned ecosystem, more marine salinities occur in open areas of the bays, and lower salinities occur in the upstream transition zones (e.g., between the Everglades wetlands and the estuaries).



From Wingard, Hudley, and Marshall (2010)

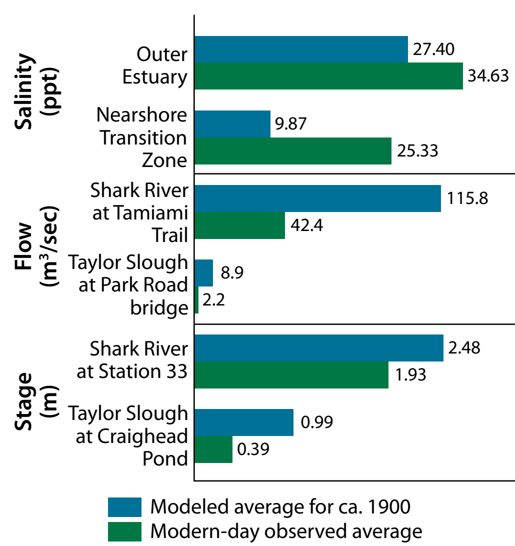
Salinities in Florida Bay and Biscayne Bay based on the fauna from core samples. Top: The minimal extent of freshwater environments approximately 2000 years ago. Middle: Around 1900, low salinity environments occurred along the northern margins of Florida Bay and Barnes Sound, typical mid-estuary condition in central regions, and outer estuary near the Safety Valve (tidal pass into Biscayne Bay). Bottom: By 2000, Florida Bay lost typical estuarine zones and is dominated by species that tolerate a wider range of salinities; Biscayne Bay has become more marine.

Preserved fauna in the cores show gradual changes over nearly 2000 years and are consistent with a rise in sea level relative to the position of the land. However, by the end of the 20th century, the typical estuarine pattern is not evident, and Florida Bay is dominated by species that tolerate frequently and widely fluctuating salinities. In Biscayne Bay, the environments also shifted during the 20th century. The region near the Safety Valve, where Biscayne Bay opens to the Atlantic Ocean, is dominated by marine organisms, and the estuarine fauna have migrated into areas closer to the shores of the bay.

Historical salinity, based on paleoecologic analysis of cores, has been combined with statistical analysis of hydrology and salinity data collected in south Florida since the 1950s to evaluate the changes that have occurred since 1900. Climatological data and anecdotal information indicate that rainfall patterns and salinity around 1900 were similar to the conditions in south Florida over the past 30 – 35 years. Statistical models (using linear regression equations) were developed from existing data that relate salinity in Florida Bay to freshwater depth and flow at different locations in the present-day Everglades. Salinity estimates based on the paleoecologic data for the beginning of the 20th century are used by the models to estimate the hydrology needed to produce the 1900 salinity values. The flow and depth at different locations in the Everglades are estimated from the 1900 conditions and compared to monitoring data over the past 36 years.

To date, the findings from this analysis indicate flow to the estuaries would be about 1.5 – 2 times greater than the current conditions if the volume and distribution of freshwater discharges to the estuaries of south Florida had not been modified. The statistical models show that observed salinities in the modern-day nearshore transition areas are between 12 – 20 parts per thousand (ppt) higher than estimated salinities from the 1900 data. The stations in Florida Bay that are closest to the Atlantic and Gulf influence have salinities of 5 – 8 ppt higher today than around 1900. The redistribution of freshwater discharges from the Everglades has also created unnatural conditions of lower salinity in extreme northeast Florida Bay, further complicating the understanding of ecosystem changes.

These changes in salinity have affected the diversity, density, distribution, and species composition of the algae, seagrasses, invertebrates, fish, mammals, and wading birds that use the estuaries. The sustainability of the ecosystem and the productive recreational and commercial fisheries are threatened. Scientists agree that freshwater supply and timing that mimic the conditions that existed prior to drainage modifications will result in salinity patterns that will improve the health of south Florida estuarine ecosystems and aid in resiliency in the face of increasing sea level change.



From Wingard, Hudley, and Marshall (2010)

This chart shows differences between the observed modern salinity, flow, and stage (depth of water) at different locations in Everglades National Park and the estimated values based on models using the paleo-salinity values. Modern observed salinity in outer estuary and nearshore (green) is higher than modeled average for 1900 (blue). Flows and water level (stage) at Shark River and Taylor Slough are less today than in 1900.

Geochemical records can be used to determine the history of Florida Bay

Peter K. Swart

In 1986, a large colony of the smooth star coral (*Solenastrea bournoni*) was discovered in Lignumvitae Basin (Florida Bay near Islamorada). Hard corals such as this have annual growth bands that are wider under favorable conditions and narrower under poorer conditions. Thus, the growth bands provide a record of water quality conditions under which the coral grew. This specimen was cored to reveal a growth record from 1825 – 1986. By measuring ratios of carbon and oxygen isotopes in the core bands, changes in salinity over time and other water conditions can be determined.

The extension of the Flagler Railroad from Miami to Key West from 1904 – 1912 blocked the tidal flow of major tidal channels connecting the Gulf of Mexico and the Atlantic Ocean. Observations from coral cores have shown that Indian Key Causeway (Islamorada) in particular blocked a major tidal connection between Florida Bay, an area of limited tidal circulation, and the Atlantic Ocean and changed salinity and circulation patterns in Florida Bay. Some believe that the historical decline in the Bay may be directly linked to this blockage in the tidal exchange.

P.K. Swart - UM/RSMAS

Large smooth star coral cored for use in assessing geochemical records. The inset map (dot) shows the approximate location of the coral in Florida Bay.

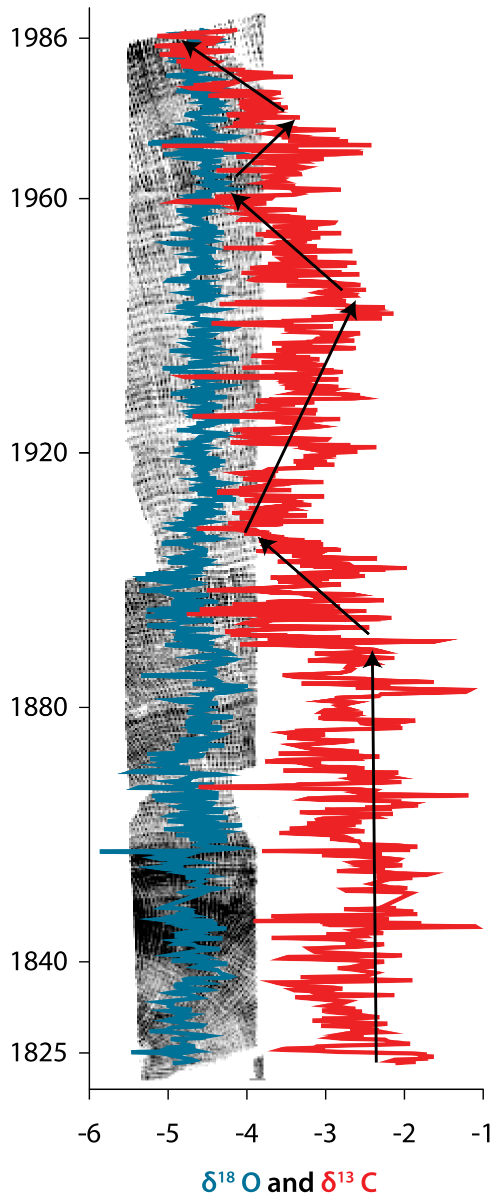
Flagler's Railroad

Henry M. Flagler changed the isolation of the Florida Keys by constructing a railroad from Miami to Key West, but it also blocked tidal exchange between the Gulf of Mexico and the Atlantic Ocean in many areas of the Keys. The railway made Key West a booming deep water port in anticipation of the growth in shipping commerce that would be generated by the opening of the Panama Canal. The 206 kilometer (128 mile)-long railway consisted of 27 km (17 mi) of viaducts and bridges and over 32 km (20 mi) of roadbed fill. With the completion of the railway in 1912, trade with the Caribbean increased, and Key West flourished for 23 years, thus recovering from the loss of the sponge and cigar industries to Tarpon Springs and Tampa, respectively. However, it is believed that the decline of Florida Bay water quality may be linked to a lack of tidal exchange brought about by construction of filled causeways for the railroad bed.

On Labor Day 1935, a major hurricane hit the Upper and Middle Keys, destroying much of the railroad. Hundreds of lives were lost when a 5.2 meter (17 foot) storm surge flooded Islamorada. Afterwards, Monroe County purchased the railroad right-of-way and converted the remaining railway bridges into a series of two-lane bridges for automobiles. The highway from Homestead to Key West was opened for traffic in 1938.

Coral skeletons reveal growth patterns

A cross-section of coral from 1825 – 1986 is shown below, with yearly growth bands superimposed with oxygen (blue) and carbon (red) isotope data. Black arrows depict trends in carbon isotope values. Salinities in the 1800s were somewhat stable and resulted in favorable growth rates of this coral. Construction of causeways impeded the flushing of Florida Bay, contributed to changed ratios of carbon and oxygen isotopes and reduced the coral growth rate. During periods of high hurricane activity, flushing improved, and the coral growth rate increased.



Between 1964 – 1986, no strong hurricanes affected Florida Bay. Hurricane Andrew (1992) passed to the north of Florida Bay and caused a significant amount of organic material to accumulate in the bay. Carbon isotope levels (red) decreased, and coral growth slowed.

Between 1959 – 1964, three strong hurricanes affected Florida Bay causing the carbon isotopic composition to become more positive.

After 1945, the number of hurricanes declined, the carbon isotopic value decreased once more, and coral growth slowed again.

After 1910, the carbon isotopic values gradually moved toward more positive values. This is believed to arise from numerous hurricanes in this period that caused increased exchange between Florida Bay and the Atlantic Ocean between 1910 – 1945.

The largest decrease in the carbon isotopic rate occurred between 1905 – 1910, coincident with the construction of the overland railway to Key West. The oxygen isotopic composition (blue) shows a slight increase over this period, indicating slightly higher salinity values, and coral growth declined.

The carbon isotopic composition decreased from about -2 at the start of the records to -5 by 1986. This decrease is a result of the increased oxidation of organic material within Florida Bay and less exchange with the open ocean. The oxygen isotopic composition, which is linked to salinity, shows no long-term trend but is more variable prior to 1910.

Coral annual growth bands can be revealed using X-ray and oxygen (blue) and carbon (red) isotope ratios measured using a mass spectrometer.

Climate change will have several potential impacts to south Florida

Harold Wanless, William L. Kruczynski, and Pamela J. Fletcher

NOAA

Temperature extremes

At continental, regional, and ocean basin scales, numerous long-term changes in weather and climate have been observed. These include increases in arctic temperatures and accelerating ice loss; widespread changes in precipitation amounts, ocean temperature, and salinity; wind patterns; and increased extreme weather, including droughts, heavy precipitation, and heat waves. Observations since 1961 show that the average temperature of the global ocean has increased from the surface to depths of at least 3000 meters (9800 feet). Excessively hot or cold water temperatures can result in death of organisms that are unable to move, such as corals, seagrasses, and other benthic organisms.

J.W. Porter - UGA

Ocean water chemistry

Carbon dioxide (CO_2) in the atmosphere dissolves in ocean waters, creating carbonic acid. Rising levels of CO_2 are making ocean water more acidic. Increased acidity makes it harder for coral polyps and other calcareous organisms to build their shells, may cause bleaching, and affects survival of coral larvae after settlement. There has been a steady drop in calcification rates by marine organisms over the past 20 years. Currently, atmospheric CO_2 levels are 387 parts per million (ppm), rising from 305 ppm in 1960. When CO_2 levels in the atmosphere reach about 500 ppm, calcification by sea life may diminish dramatically.

W. L. Kruczynski - EPA

Sea-level rise and coastal erosion

Global warming is resulting in rising sea levels due to thermal expansion of the oceans and melting of ice sheets. Deepening water will flood mangrove swamps and other coastal wetlands, and their ability to keep pace with rising waters is uncertain. Low-lying developed areas will be flooded, and property damage and loss will be immense. Coastal bays will become increasingly marine. Coasts will become more and more eroded and dissected by storms. Increased turbidity and nutrients from coastal erosion will further stress coral reefs and other benthic communities.

NOAA

Weather and climate patterns

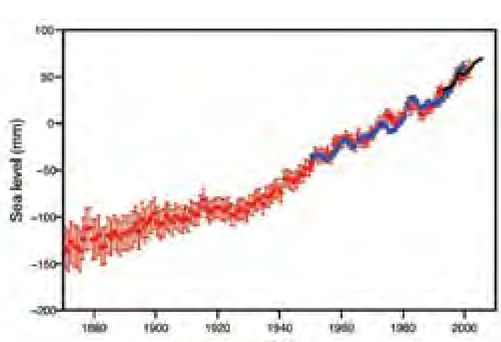
There is observational evidence of an increase in intense tropical cyclone (hurricane) activity in the North Atlantic since about 1970. A list of the 11 worst hurricanes to hit Florida in the past century includes five in the past 17 years. An increase in the severity of hurricanes will result in damage to developed areas and natural communities, particularly as sea level rises and contributes to increased flooding. Mangrove forests severely damaged by hurricanes are very slow to recover. Coral reefs already weakened by bleaching, disease, or pollution will be vulnerable.

Sea-level rise will have dramatic impacts on south Florida's landmass

Harold Wanless

Although some people continue to debate the issue, overwhelming scientific evidence supports the fact that climate is changing at an unprecedented rate because of human-induced warming. Sea-level rise is one of the most profound consequences of climate change. There is still some debate about how fast sea level will rise, but most scientists agree that there will be significant sea-level rise this century. Unless atmospheric and oceanic warming are quickly reversed, there will be catastrophic sea-level rise in the coming centuries. A rising sea will inundate not only south Florida, but also a significant portion of peninsular Florida. With each year that humankind does not reverse the causes of global warming, the coming catastrophic impacts on human and natural environments become increasingly likely and less reversible.

Greenhouse gases are driving human-induced global warming and include carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons. These gases act as a blanket around the globe, trapping back-radiating solar energy. The most abundant greenhouse gas is carbon dioxide; its main source is from burning fossil fuels (e.g., coal, oil, and natural gas).



From IPCC (2007)

Beginning in the 1930s, the rate of sea-level rise dramatically increased primarily due to warming and thermal expansion of the oceans. The present rate of sea-level rise in south Florida is about 30 cm (1 ft) every 100 years. Sea-level rise is accelerating due to melting polar ice.

Lag time

Even if humans stopped putting carbon dioxide into the atmosphere today, sea-level rise will continue because of the long lag period for decreasing the effects of emissions. Lowering the carbon dioxide levels in the atmosphere from the current level of 387 parts per million (ppm) to below 325 ppm will lower the heat imbalance between the atmosphere and the ocean but will probably not slow the first 90 – 150 cm (3 – 5 ft) of sea-level rise.

Florida has experienced sea-level rise and fall throughout geological time. About 125,000 years ago, the peak of the previous interglacial period, sea level was 6 meters (20 feet) higher than today, and most of south Florida was underwater. About 18,000 years ago, the peak of the subsequent Ice Age, sea level dropped 128 m (420 ft) below present-day levels. At that time, Florida and Biscayne Bays were high and dry. Sea level has been slowly increasing a few centimeters per century for the past 2000 years, but since the 1930s, the rate has dramatically increased. The current rate of rise in Florida is 30 centimeters (1 foot) every 100 years, about the same as the global rate.

There are two main causes of accelerated sea-level rise: melting of the polar ice sheets and thermal expansion of the oceans. Since the mid-1990s, warmed ocean water is accelerating the melting of the Greenland and Antarctic Ice Sheets, causing an increased rate in sea-level rise that is higher than earlier projections. This has sped the loss of the Arctic summer pack ice, the "refrigerant" of the Arctic. A portion of atmospheric heat is transferred to the oceans, which then become warmer and expand. Sea-level rise will accelerate through this century and beyond and is expected to reach 90 –180 cm (3 – 6 ft) by 2100.

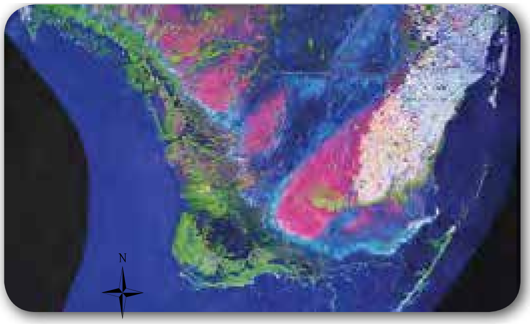
What does this mean for south Florida? The Miami-Dade County Climate Change Task Force provided more accurate predictions of rates of sea-level rise and their local consequences. In 2008, the Task Force predicted a rise of 50 cm (1.5 ft) in the next 50 years and a total of 90 – 150 cm (3 – 5 ft) by the end of the century. The upper projection has recently been raised to 180 cm (6 ft). Whatever the sea level is at the end of the century, it is important to understand that the rate of sea-level rise will continue to accelerate. For example, if sea level has risen 150 cm (5 ft) by 2100, the rate of sea-level rise will be 30 cm (1 ft) per decade.

A 60 cm (2 ft) rise in sea level will result in the Turkey Point Nuclear Power Plant becoming an island in a combined Biscayne-Florida Bay. All coastal wetlands will be flooded, and the coastal mangrove community will have shifted north to about Tamiami Trail (U.S. 41 between Miami and Naples). Only about 40% of presently developed Miami-Dade County will be above mean high water with a sea-level rise of 180 cm (6 ft), and marine waters will extend nearly to Lake Okeechobee.

Restoring the Everglades may slow the process of sea-level rise in south Florida. The Everglades historically has been drained over the past century, resulting in a loss of organic (peat) soils. As a result, the elevation of much of the Everglades has decreased. The loss of peat soils has lessened the ability of the Everglades to serve as a buffer to saltwater intrusion with rising seas, maintain a freshwater head (elevation above sea level) to recharge the drinking water aquifer, and stabilize the shoreline.

Meaningful restoration efforts include the reestablishment of a reliable southward flow of freshwater that can help rebuild peat soils. Research is needed to quickly learn how to most rapidly build resilient peat substrates that contribute to a healthy wetland environment. These restoration efforts will prolong both the survival of the Everglades and the time that the surficial, unconfined, freshwater aquifer is available for use. At the same time, efforts to reduce the levels of greenhouse gases in the atmosphere must be aggressively pursued.

The hurricanes of 1935, 1960 (Donna), and 1992 (Andrew) destroyed vast amounts of mangrove forests in south Florida. Large areas were converted to open water because of rapid erosion, and the subsidence of peat, combined with rising sea level, prevented the recovery of the mangrove community. With accelerating rates of sea-level rise, coastal mangrove wetland destruction during storms will occur over broad geographic areas. Restoration of storm-damaged wetlands is required to prolong the survival of coastal wetlands and protect sources of fresh groundwater.



A comparison of south Florida in 1995 (left) and south Florida with a sea-level rise of +120 cm (+4 ft) (right). Note the losses of all of the fringing mangrove coastline on the southwest coast, much of the southern Everglades, and all of the islands in Florida Bay. Most dramatically, the majority of developed Miami-Dade County and the Upper Keys will be either inundated or so low that they will be flooded by heavy rains and tropical storms. The Upper Keys will also be significantly reduced in size. South Florida will become an increasingly risky and inconvenient place to live.

Estimates of ecological and economic consequences of sea-level rise on the Florida Keys are staggering

Chris Bergh

Climate change is happening at a rate unprecedented in modern times. Some symptoms of climate change include:

- Certain species of migratory birds are now wintering further north than they did in the recent past;
- Glaciers around the world are shrinking;
- The amount of ice in the Arctic Ocean has significantly declined; and
- Sea level is rising, which is one of the more predictable consequences of climate change.

Although estimates vary, it is likely that sea-level rise will be at least 50 centimeters (20 inches) by the end of this century and could be twice that amount or more. To predict future impacts of sea-level rise on the environment and economy of the Florida Keys, The Nature Conservancy combined 2007 high resolution topography data for Big Pine Key, lower resolution data for the entire Keys, and Monroe County tax data using Geographic Information System computer software. "Bathtub modeling," a digital simulation of rising waters, was conducted using five published sea-level rise scenarios for the year 2100, ranging from 18 – 140 cm (7 – 55 in).

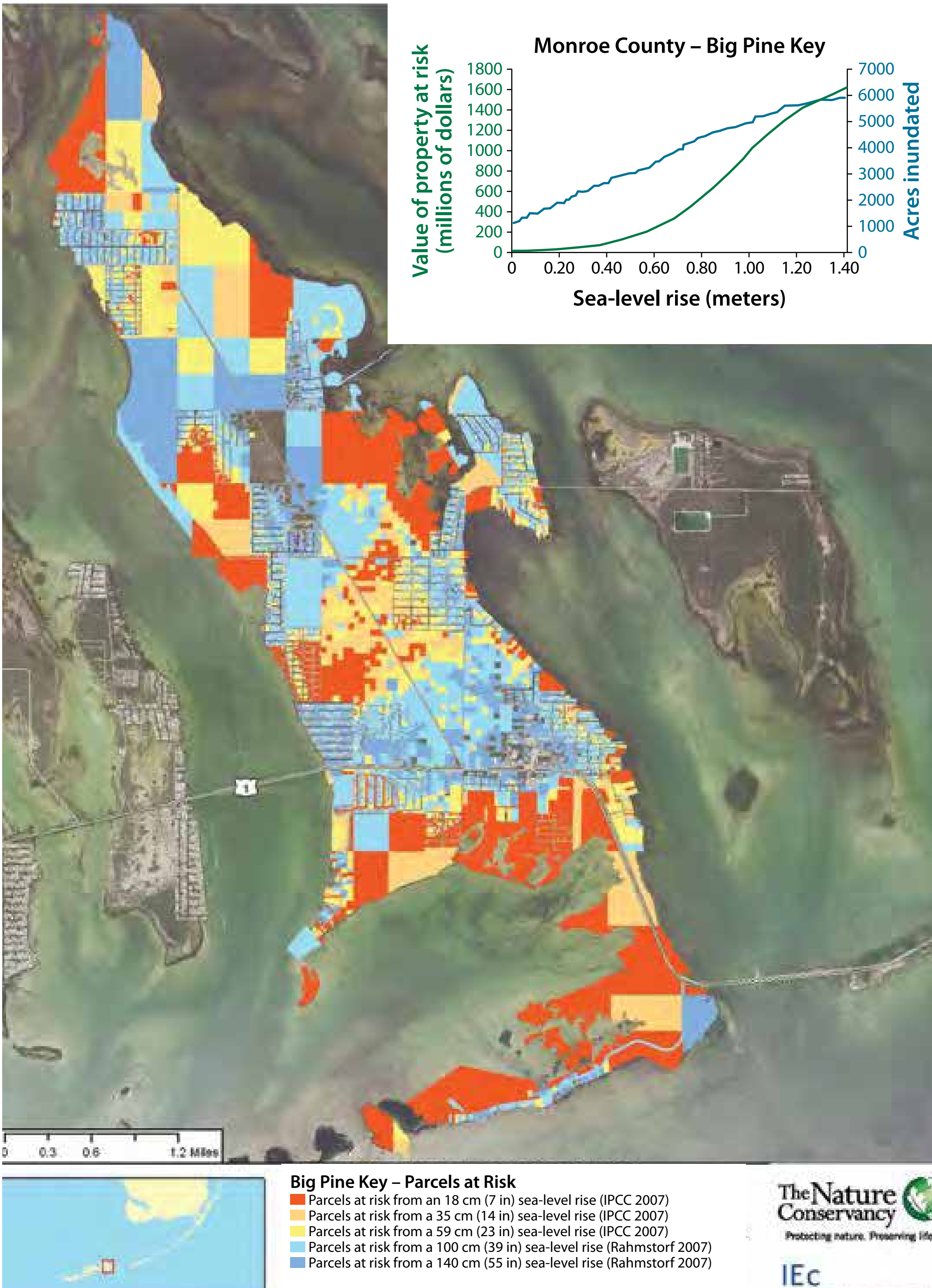
The high-resolution topography data enabled a detailed prediction of future shorelines, distribution of major terrestrial habitats, and property value losses for Big Pine Key. In every scenario, the island became smaller, marine and intertidal habitat moved upslope at the expense of terrestrial habitat, and property values diminished. In the best-case scenario (i.e., 18 cm [7 in] sea-level rise), 744 hectares (1840 acres) (34%) of Big Pine Key was flooded by the sea, resulting in the loss of 11% of the upland habitats on the island. This degree of inundation would displace native species dependent on upland habitat and threaten $40 million of property values. In the worst-case scenario (140 cm [55 in]), 2407 ha (5950 ac) (96%) of the island was inundated, resulting in the loss of all upland habitat and $1.6 billion in property values.

This modeling exercise demonstrates that in the next one to three centuries, sea-level rise is likely to jeopardize most, if not all, of the terrestrial plants, animals, and natural communities of the Florida Keys while creating new marine habitat. Developed areas and human communities will experience negative impacts, including lost property values.

Minimizing the consequences of sea-level rise will require marked decreases in greenhouse gas emissions and deforestation, the main causes of climate change. Also essential are careful planning and implementation of local actions to help terrestrial natural areas, native species, development, and human communities adapt to inevitable change.

	Lower Keys			***Florida Keys***		
Sea-level rise scenario	**Property value at risk (billions)**	**Hectares (ha)**	**Acres (ac)**	**Property value at risk (billions)**	**Hectares (ha)**	**Acres (ac)**
IPCC 18 cm	$2,610,000,000	4,450	11,000	$11,000,000,000	23,800	58,800
IPCC 35 cm	8,790,000,000	19,910	49,200	18,700,000,000	42,900	106,000
IPCC 59 cm	11,000,000,000	22,000	54,400	21,900,000,000	46,500	115,000
Rahmstorf 100 cm	13,000,000,000	22,800	56,300	26,700,000,000	50,200	124,000
Rahmstorf 140 cm	15,800,000,000	23,500	58,000	35,100,000,000	57,500	142,000

Year 2100 property value at risk and acreage lost to inundation by sea-level rise for the Lower Keys and for the entire Florida Keys predicted by a model using the best-available elevation data in 2009. IPCC = Intergovernmental Panel on Climate Change 2007; Rahmstorf = Rahmstorf 2007.



Industrial Economics, Incorporated and The Nature Conservancy

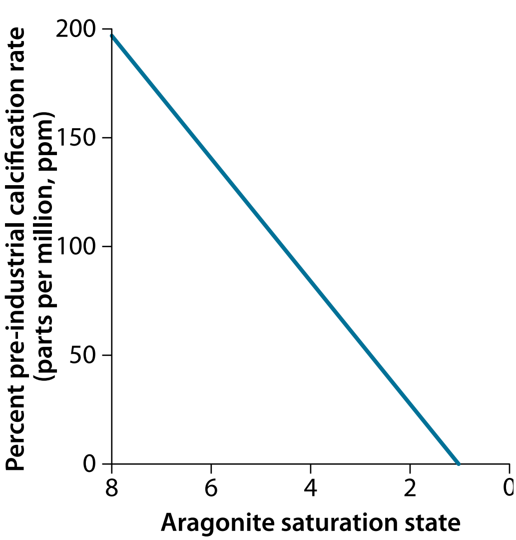
Aerial photograph of Big Pine Key with overlay showing cumulative land parcels at risk under various scenarios of sea-level rise. Sea-level rise scenarios tested are 18 cm (7 in) red; 35 cm (14 in) orange; 59 cm (23 in) yellow; 100 cm (39 in) light blue; and 140 cm (55 in) dark blue. Line graph inset: Green line on graph is an estimate of value of property at risk. Blue line is the number of acres inundated by seawater.

Ocean acidification may be a threat to the marine ecosystem

Christopher Langdon

Carbon dioxide (CO_2) is one of the most important gases in the atmosphere. It affects the radiant heat balance of the Earth and the calcium carbonate equilibrium of the oceans. Cores in glacial ice show that for 650,000 years prior to the Industrial Revolution, atmospheric CO_2 concentrations remained between 180 – 280 parts per million (ppm). Increased burning of fossil fuels, cement production, and changes in land use are causing atmospheric CO_2 to rise at increasing rates. The atmospheric CO_2 concentration in 2008 was about 387 ppm and is expected to continue to rise by about 1% per year. This increase is about 100 times faster than occurred over the past 650,000 years and possibly the past 25 million years.

"Ocean acidification" is the name given to the ongoing decrease in the pH of the oceans caused by their uptake of anthropogenic CO_2 from the atmosphere.



This graph is a summary of the growth of 12 coral species at different carbonate (aragonite) saturation states. Data demonstrate that as saturation declines (with decreasing pH) from a present-day value of 3.8 – 4.0, the calcification of corals declines significantly and will stop completely if saturation reaches 2.0 or below.

Carbonate chemistry

Changes in the chemistry of the ocean can have major impacts on organisms that precipitate calcium carbonate from seawater to make shells. As the pH of the seawater changes, the ability to precipitate calcium carbonate (calcification rate) is changed. As atmospheric carbon dioxide increases, more carbon dioxide dissolves in seawater, resulting in a lower pH. Lowering the pH decreases the amount of calcium carbonate that can be dissolved in seawater (saturation state). Decreasing the saturation state can lead to a decreased ability in marine organisms to produce shells from seawater because the carbonate ions that bond with calcium are less available.

About a third of the excess CO_2 released by anthropogenic activities has been stored in the oceans. The ocean is well buffered, but the present rate of input of CO_2 greatly exceeds the rate at which natural processes can neutralize the carbonic acid that is formed when the CO_2 from the atmosphere dissolves into the ocean. As a result, the ocean is becoming progressively more acidic (lower pH), and the saturation state of carbonate minerals is declining.

Carbonate minerals are used to form the supporting skeletal structures (biocalcification) of many groups of marine organisms, including corals. Controlled laboratory experiments on the effects of increased CO_2 conditions on biocalcification have documented that the calcification rate of many organisms decreases with a slight reduction in pH. Extrapolation of these results from the laboratory to the real world suggests that calcification rates in the oceans will decrease up to 60% within the 21st century.

What does this mean for corals and other marine organisms, such as calcareous algae, mollusks, and echinoderms, that have calcium carbonate skeletons? Not much is known about how decreased calcification will affect biological functioning or organism survival. However, it is widely accepted that marine organisms with calcareous skeletons will be significantly stressed. Analyses of coral skeletons have recently been reported to show that coral growth rates have declined by 11% – 21% in just the past 16 years. Other studies have shown that pH decreases of as little as 0.1 – 0.2 pH units result in a 50% – 78% reduction in postsettlement growth of mustard hill coral (*Porites astreoides*) larvae. In a world where the balance between production and loss of carbonate on many reefs is believed to be closely balanced and where replacement of new corals on many reefs is not keeping up with mortality, a reduction in fitness due to ocean acidification may have significant impacts. Acidification may not kill corals directly, but it does result in slower development of coral larvae into juvenile colonies and slower development of juvenile colonies to sexually mature colonies. Also, it is known that increased CO_2 in the atmosphere is raising the average temperature of the oceans, and warmer waters mean increased incidence of coral bleaching. Thus, it is possible that acidification may play a synergistic role in the lack of recovery of many reefs. Further research is required to quantify the impacts of increasing acidity on the structure and function of the south Florida marine ecosystem.

A change in ocean chemistry could impact the way marine organisms, such as the bay scallop (top left), hard and soft corals (bottom left), queen conch (top right), and the long-spined sea urchin (bottom right), build their skeletal structures.

Hurricanes and tropical storms are regular features in south Florida

William L. Kruczynski, Pamela J. Fletcher, and Neal M. Dorst

Hurricanes and tropical storms are regular summertime features in south Florida. The name "hurricane" comes from the Caribbean Taino Indian god, Huracan. Hurricanes develop over warm ocean waters from weak disturbances where moist air gets drawn into their low pressure areas. In many south Florida storms, the initial disturbance forms off the west coast of Africa, but storms can also develop from low pressure disturbances originating in the tropical Atlantic or Caribbean. The Coriolis effect causes winds to spiral inward and counterclockwise in the northern hemisphere. Within the low pressure system, rising moist air condenses as it cools, produces rain, and releases heat to the atmosphere, causing the air pressure to decrease further, which pulls more moist air into the system at the surface of the ocean. The storm intensifies as long as these processes continue. As a storm passes over land or cool water, it loses its source of energy and dissipates.

Saffir-Simpson Hurricane Wind Scale

1	74 – 95 mph
2	96 – 110
3	111 – 130
4	131 – 155
5	155+

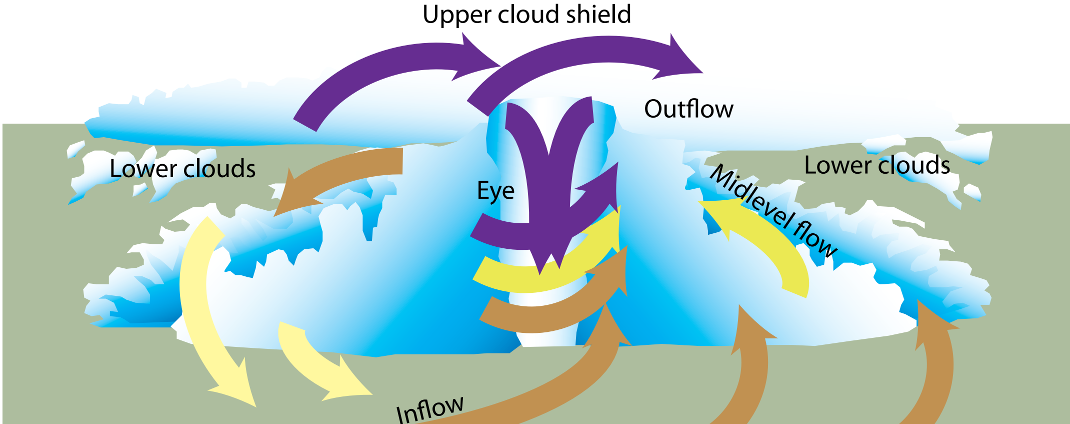
NOAA

The number of tropical storms that strike Florida varies from year to year but averages about 1.7 storms annually. The chances of hurricane-force winds striking Florida each year varies from 1:100 for Jacksonville to 1:7 for Miami and Key West. The longest period since 1885 without a major hurricane was 9 years, between 1951 – 1959.

Every storm is different, and it is hard to compare storms. Here are some of the worst to hit south Florida.

1919 Atlantic-Gulf Hurricane

This was the most powerful storm in Key West history. It was the only hurricane known to form in the Atlantic that year. It killed more than 800 people.



N.M. Dorst - NOAA

Hurricane structure and formation.

1926 Great Miami Hurricane

"The blow that broke the population boom" was described at the time as the most destructive hurricane ever to strike the United States. Storm surge of 4.6 meters (15 feet) was reported in Coconut Grove as the eye passed over Miami. Many of the 800 people killed had stepped outdoors during the lull of the passing eye and were swept away when the opposite side of the eyewall passed over the area.

1928 San Felipe-Okeechobee Hurricane

This hurricane came ashore near Palm Beach. When the eye passed over Lake Okeechobee, shifting winds pushed the lake waters against the southern dikes, causing them to fail, and sweeping away homes. Over 1800 Floridians perished.

1935 Florida Keys Labor Day Hurricane

This Category 5 hurricane struck the Middle Florida Keys, destroying the railroad and killing 408 people. Barometric pressure readings from Long Key reflect this to be the most intense hurricane on record in the region.

1960 Hurricane Donna

This Category 4 storm hit the Middle Florida Keys and Fort Myers. Heavy rainfall and storm surges impacted south Florida.

1964 Hurricane Cleo

This Category 2 storm hit Key Biscayne and passed over Miami, Opa-locka, West Hollywood, and Fort Lauderdale. The hurricane caused extensive power outages and water damage that impacted much of the southeast Florida coast.

1965 Hurricane Betsy

The area between Key Largo and Miami was impacted by this Category 3 storm. The storm appeared to be headed to South Carolina; however, it stopped 570 kilometers (350 miles) east of Jacksonville before heading back to south Florida.

1992 Hurricane Andrew

Andrew hit Homestead as a Category 5 storm and caused a 5.2 m (17 ft) storm surge. It is the second costliest storm in the mainland U.S. history.

2004 Hurricane Charley

This storm passed over the Dry Tortugas (177 km [110 mi] per hour winds) and then hit southwest Florida as a Category 4. Most of the damage from Charley was caused by high winds and tornadoes.

2004 Hurricane Frances

This was one of several large hurricanes that hit south Florida in a period of 6 weeks. It was a slow-moving, super-sized storm that covered the entire state of Florida. Upon making landfall near Stuart, the storm produced heavy rainfall and strong winds.

2004 Hurricane Jeanne

This Category 3 storm hit Stuart shortly after Frances. Impacts launched existing piles of storm debris and further weakened buildings, causing additional damage in the area.

2005 Hurricane Katrina

This storm hit the border of Miami-Dade and Broward Counties before moving westward to wreak havoc in Louisiana and Mississippi. Rainfall over southern Florida was estimated between 25.4 – 35.6 cm (10 – 14 in) and flooding and wind damage was extensive. The storm caused $81 billion in damages in the United States.

2005 Hurricane Wilma

It took 5 hours for this storm to pass over southern Florida, entering at Cape Romano and exiting north of Palm Beach as it changed from a Category 3 to a Category 2 hurricane. The storm caused five deaths in Florida and damages estimated at $16.8 billion.

Major hurricanes can have major impacts on marine environments

William L. Kruczynski and Pamela J. Fletcher

The loss of human life and property is well documented for major hurricanes. However, the environmental effects of hurricanes are less well-known.

On August 24, 1992, Hurricane Andrew struck near Homestead, Florida just before high tide, resulting in a storm surge of 5.2 meters (17 feet) on the Atlantic coast and 4.6 m (15 ft) on the Gulf coast. It was a relatively dry storm and resulted in approximately 5 centimeters (2 inches) of rain. Its path over land was approximately 100 kilometers (62 miles) long, and it partially or completely defoliated vegetation over a 50 km (31 mi)-wide swath. However, Andrew was a very fast moving storm, which may have reduced its potential damage to the marine environments.

Hurricane Andrew affected nearshore water quality by increasing nutrients from runoff and disturbing bottom sediments. Increased concentrations of phosphorus and nitrogen resulted in phytoplankton blooms and low levels of dissolved oxygen after the storm. Depleted oxygen levels in waterways resulted in the death of an estimated 7 million fish. In hardbottom communities, sponges, corals, and sea whips were sheared from their substrate and deposited in extensive wracks of debris along shorelines. Juvenile Caribbean spiny lobsters, normally found under sponges and in coral crevices in central Biscayne Bay, disappeared. Minimal losses of seagrasses were documented after Andrew, but seagrass meadows are not immune from storm damage. For example, three of the 30 permanent seagrass monitoring stations in the Florida Keys National Marine Sanctuary were deeply buried by sandy sediment during Hurricane Georges (1998); the seagrasses have yet to recover.

FKNMS

Pillar coral overturned by Hurricane Andrew in the Florida Keys.

J. Luo - UM/RSMAS

Hurricane Wilma destroyed a large area of mangrove forest near the mouth of Shark River, southwest Florida.

Hurricanes and tropical storms can be beneficial to coral reefs by breaking branching corals (*Acropora cervicornis* and *Acropora palmata*) into pieces, each of which can grow and form a new colony. However, the gains achieved by asexual proliferation of branching corals are likely to be offset by storm scouring and sediment smothering of other corals and turning over coral heads.

Hurricanes have been a central feature in the evolution of subtropical and tropical ecosystems; however, the natural ecosystems are not adapted to withstand additional impacts due to anthropogenic sources. For example, approximately 95,000 liters (25,000 gallons) of gas and oil were spilled into Biscayne Bay during Hurricane Andrew. The most severe damage noted to coral communities was from lobster and crab traps that smashed coral heads and reefs. A ship sunk as an artificial reef broke free and destroyed natural coral reefs as it was carried by strong waves generated by the hurricane. During heavy rains, canals rapidly drain freshwater to coastal areas, which results in rapid drops in salinity and untold impacts to marine biota.

Two weeks after Hurricane Andrew passed, the mangroves within the path resembled a deciduous forest in winter. Many trees that were completely defoliated have not recovered. At Highland Beach, where the hurricane eye left the west coast of Florida, more than 85% of the mangrove trees were blown over and uprooted.

Hurricane Donna (1960) spread the seeds of Australian pine (*Casuarina equisetifolia*), an invasive exotic plant, along the west coast of Everglades National Park, and the resulting vegetative overgrowth posed a threat to turtle nesting areas. Open patches in mangrove forests are threatened by the invasion of Brazilian pepper (*Schinus terebinthifolias*) because it can occupy open areas more quickly than native mangroves. In short, hurricanes may change the balance in favor of nonnative invasive vegetation that can have long-lasting impacts on the ecosystem.

African dust is an airborne pollutant in south Florida

Eugene A. Shinn

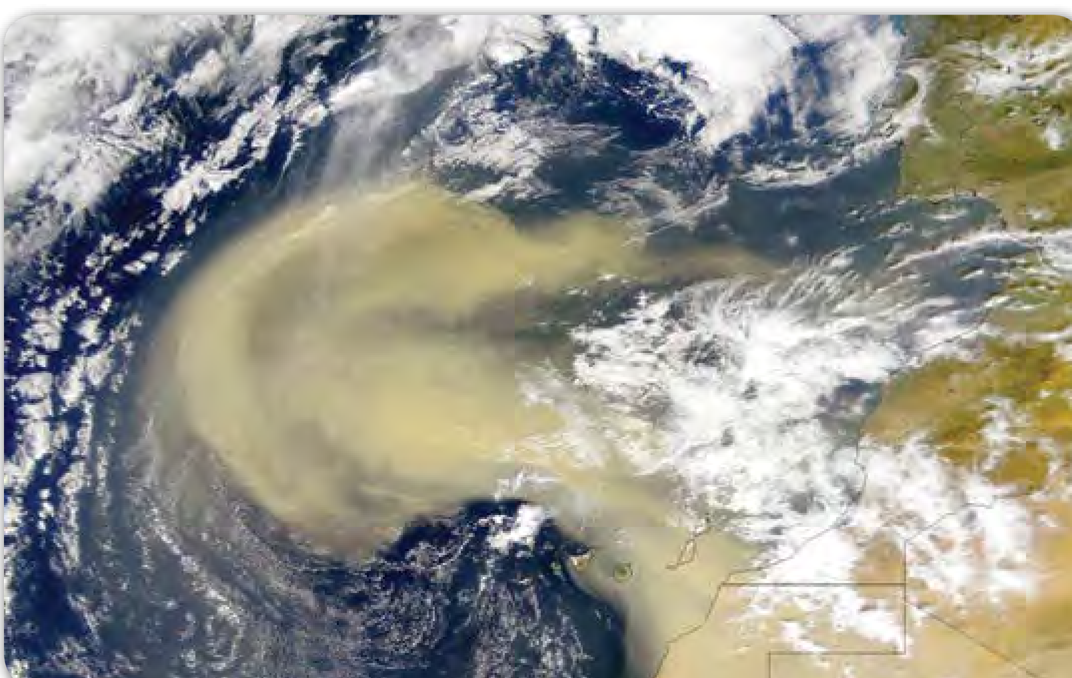
It is a small world

African dust is transported to Florida mainly during the summer months by trade winds blowing across the Atlantic Ocean. During the winter months, the dust is transported to South America where it has been shown to nurture the Amazon rainforest. Most dust clouds are transported during positive phases of the North Atlantic Oscillation (NAO), the meteorological equivalent of the Southern Oscillation in the Pacific called the El Niño. Positive NAO reduces rainfall in North Africa and accelerates trade winds. Major episodes of dust transport across the Atlantic occurred during NAO events in 1973, 1983, and 1997.

Why is this important?

African dust is a suspect in the Caribbean-wide loss of corals and other marine life. The dust has been found to contain DDT, a pesticide that is used legally in Africa but banned in the United States because it accumulates in aquatic food chains. Microbiologists captured dust on sterile filters in Africa, over the Atlantic Ocean, and in Florida during dust events and cultured bacterial and fungal spores present in the dust. To date, more than 200 microbes that ride the dust have been identified, including well-known human, animal, and plant pathogens.

Medical records show that asthma attacks in the Caribbean have increased 17 times since 1973 and that 25% of children in the eastern Caribbean today have asthma. The connection of asthma with African dust has not yet been medically proven, but it is known that people living in the eastern Caribbean start coughing during dust events and must frequently clean dust from boats, docks, and drinking water cisterns.



NASA

Major dust storm leaving the west coast of North Africa in February 2000.

E.A. Shinn - USGS

African dust in the atmosphere causes red-colored sunsets, such as this sunset over the Seven Mile Bridge, Florida Keys, on August 1, 2008.

Impacts of African dust

African dust may affect reefs by depositing nutrients, pollutants, or pathogens that:

- Interfere with the immune system of corals;
- Interfere with some stage of coral reproduction;
- Activate disease-causing microbes present in the reef environment;
- Trigger rapid increases in pathogens; and
- Fuel cyanobacteria, macroalgae, and phytoplankton growth.

What is different today?

Geological evidence from the past million years shows that African dust has periodically been deposited on Florida shores, especially during glacial periods when the air was extremely dry. If dust today is a problem to the marine ecosystem, did it have effects on ecosystems in the past? No one knows, but what is certain is that there were no pesticides, phosphate mining, or mercury mining in North Africa in geological times. Also, North Africa lacked the human population that exists there today. Along with the advent of vehicular traffic, open fire, waste disposal, and deforestation to feed the ever-expanding human and animal populations, the content of African dust is undoubtedly different today than in the past. An increase in domestic animal droppings and raw human sewage has resulted in a larger pool of microbes that can be carried across the Atlantic Ocean. All of these changes, including climate change, have loosened the delicate desert soils and have made them far more transportable by winds than in the past.

T. Hinson

African dust in the atmosphere can cause halos around clouds in south Florida.

There has been a loss of megafauna from south Florida waters

Dalal Al-Abdulrazzak

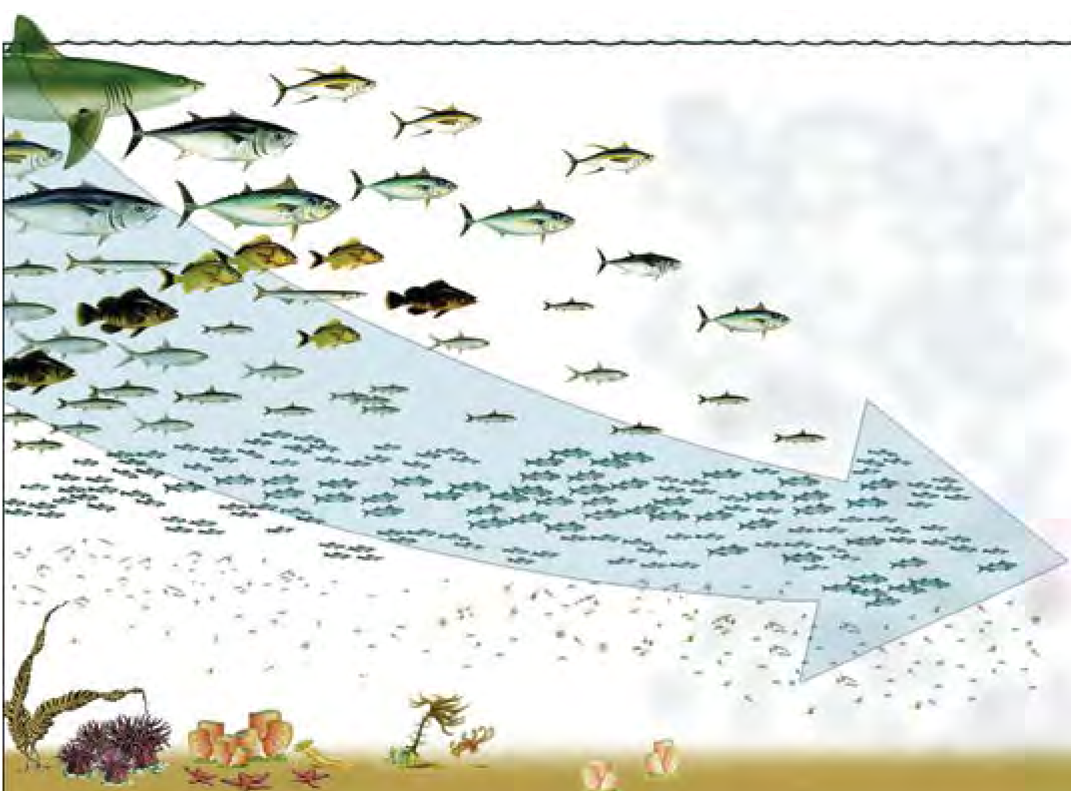
Large animals, or megafauna, such as manatees, sawfish, large sharks, and sea turtles, are all but extinct from south Florida. Their high numbers, ease of capture, and large size appeals to humans. Megafauna are especially vulnerable to overharvesting due to their slow maturity and low number of offspring. Female manatees, for example, reach sexual maturity between 6 – 10 years of age, after which they only bear a single offspring every 2 – 5 years.

After the near elimination of large tertiary consumers, people turned their attention to the secondary, and even primary, consumers of the sea. Unlike on land, where consumers at the top of food chains (e.g., lions, tigers) have never been an important part of the human diet, at sea, humans were attracted first to large predators (e.g., sharks, tuna, swordfish).

Megafauna are ecologically important to the marine environment not only

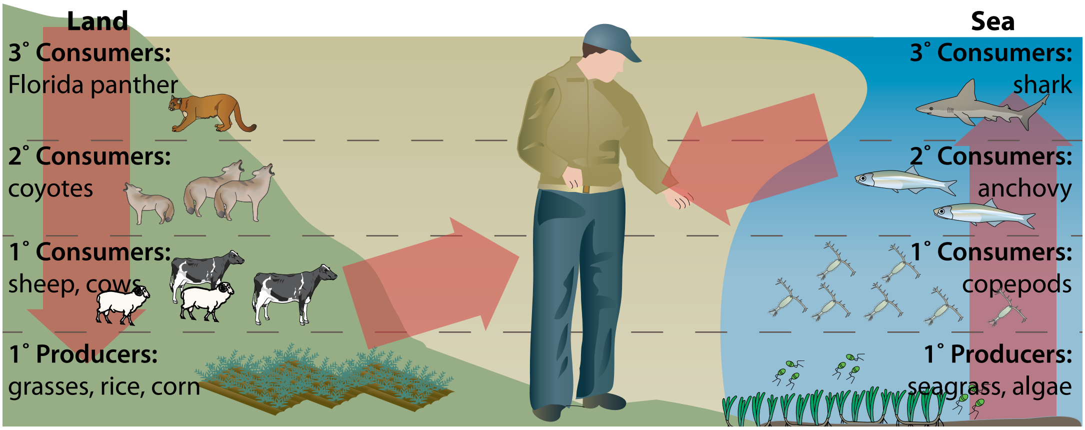
J. Luo - UM/RSMAS

Large animals (megafauna) that were commonly found in south Florida, such as sea turtles, are found in significantly fewer numbers or no longer exist.



Sea Around Us Project

Because most megafauan have been overfished in the past, people today are forced to fish farther and farther down the food chain, harvesting smaller and smaller sized species.



Human energy pyramid on land and sea. Humans gain most food energy from terrestrial primary producers, such as rice and corn, and primary consumers, such as cows and sheep. From the sea, humans harvest top predators in the marine food web, such as swordfish, tunas, sharks, and mackerels.

because of their place at the top of the food web, but also because of their specific physical and biological functions. For example, the loss of manatees and sea turtles has severely altered seagrass grazing, food web structure, and productivity in adjacent ecosystems. Nearshore marine environments today are very different from when manatees and sea turtles were common.

Today, small fishes and invertebrates dominate the coral reefs, but their presence cannot fully compensate for the loss and the unique role large vertebrates play in an ecosystem. Dr. Jeremy Jackson, a prominent marine ecologist, wrote,

"Studying grazing and predation on reefs today is like trying to understand the ecology of the Serengeti by studying the termites and the locusts while ignoring the elephants and the wildebeests."

J. Luo - UM/RSMAS

With the loss of large marine animals, small fishes typically dominate nearshore marine environments.

Overfishing has reduced fish stocks in south Florida

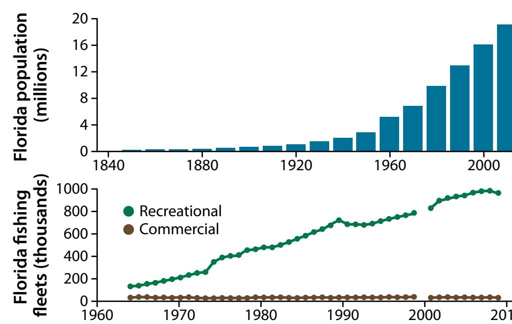
Jerald S. Ault

South Florida is home to a species-rich tropical marine ecosystem that supports a multibillion dollar tourist economy. The diverse fish community of the reefs and associated habitats is influenced by complicated biological and physical interactions, not the least of which is commercial and recreational fishing pressure. It is not surprising that catches of prized grouper and snapper have declined in numbers and size from historical levels given the 658% explosive growth in the number of recreational fishing boats, based on boater registrations, since the mid-1960s. Also, better design and the addition of modern hydroacoustic, navigation, and communication devices have resulted in greater fishing prowess than vessels and fishing techniques used in the recent past.

Monroe County Public Library

Fish stocks in the Florida Keys could not be sustained at historical fishing landings.

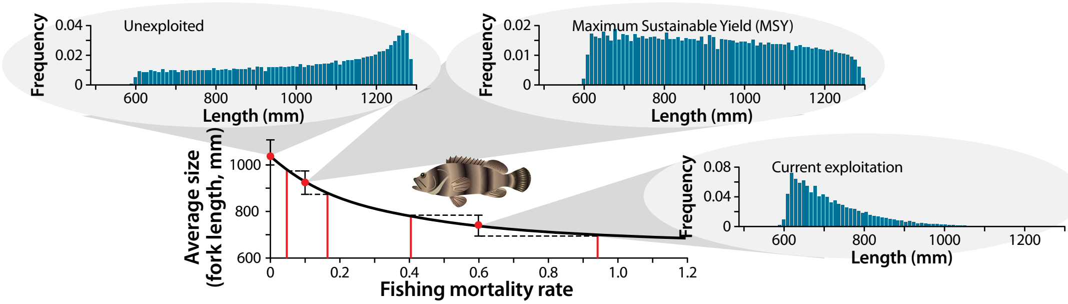
A comprehensive 26-year study (1979 – 2005) was performed to examine the effects of fishing and to establish a baseline of the status of the multi-species fishery in the Florida Keys. The results contributed to an accurate evaluation of the management actions in the Florida Keys National Marine Sanctuary. The average size of fish from visual observations at reefs throughout the Keys was compared with sizes from head boat catches to develop an indicator of the stock status for each of the fish species observed and caught. Heavy fishing pressure successively eliminates older, more reproductively active size classes and reduces the average size of fish over time, making the stock younger (juvenescence). Smaller fish have a substantially lower reproductive output compared to larger fish. Exploited species are considered overfished when the Spawning Potential Ratio (SPR) (ratio of a fished to an unfished stock) is reduced to 30% or less.



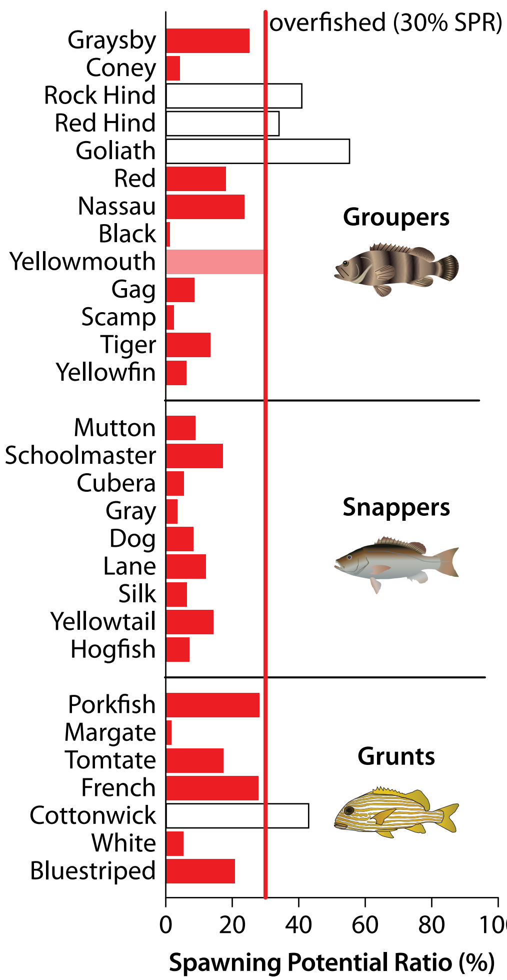
Aapted from Ault, Bohnsack, and Meester (1998)

The human population in Florida (top graph) and the number of registered fishing boats (bottom graph). The number of registered recreational fishing vessels in Florida has increased 658% since 1964.

Although 46 reef fish species were seen or captured by head boats, data for only 29 species were abundant enough for statistical comparisons. The data from the two independent sources were highly correlated for grouper, snappers, and grunts. It was found that the average size for many of the economically important reef fish populations was marginally above the minimum size of capture regulated by fishery management agencies (i.e., most fish were small and marginally legal). Nine of 13 grouper species, nine of nine snapper species, and six of seven grunt species for which there were data are below the 30% SPR, meaning that these species are



Population dynamics and fishery sustainability metrics for black grouper, a heavily overfished species at three levels (red dots) of fishing mortality. Heavy fishing pressure reduces the average size of individuals in the population over time, making the stock younger and successively eliminating older, more fecund size classes. Fecundity (i.e., number of eggs produced) increases exponentially with the size of fish. Protection of large fish is required to sustain fishery yields and maintain or improve fish spawning stock biomass.



Aapted from Ault, Bohnsack and Meester (1998)

Estimates of percent Spawning Potential Ratio (% SPR) for 29 species of Florida Keys reef fishes, comprising of groupers, snappers, and grunts. Red bars show species that are overfished (i.e., below 30% SPR). Open bars indicate stock that are not overfished.

overfished. Overall, 63% of the 29 stocks that could be analyzed were overfished. The Florida Keys reef fishery exhibits classic "serial overfishing" in which the largest, most desirable, and vulnerable species are exploited in the following order: exploitation is highest for groupers, followed by snappers, followed by grunts. Generally, the most valuable groupers and snappers currently have the lowest spawning potential.

Several factors led to the establishment of the Sanctuary and associated Marine Protected Areas, including concerns about the rapid growth in the human population in south Florida, habitat destruction, and declining water quality. Reversing adverse trends in the reef fishery in south Florida and the Florida Keys requires innovative approaches for controlling exploitation rates. The coupling of traditional management practices, such as fish size and capture limits, with a spatial network of adequately sized and strategically located no-take marine reserves may provide an ecosystem management strategy for achieving long-term goals of protecting biodiversity while maintaining sustainable fisheries. An important component required for the success of this effort is a conscientious, continuous assessment program for integrating fishery-independent and fishery-dependent data to evaluate the effectiveness of marine reserves. With adaptive management, improvements to fish stocks can be obtained over time.

Fishing patterns have changed over time

Loren E. McClenachan

Fishing has always been an important part of the culture and economy of south Florida and the Florida Keys. As early as the 18th century, the coast of Florida was "covered with fishermen's huts." Overfishing during the last century has reduced populations of once abundant fish, invertebrates, and reptiles in the Florida Keys. For example, green turtles, which historically nested and fed throughout the Keys, are rare today. Many fish are overexploited, and several fish that were commonly caught in the 18th and 19th centuries, such as sawfish, are listed by the International Union for Conservation of Nature as Critically Endangered or Endangered.

19th century

In the second half of the 19th century, new export fisheries were developed in the Keys. By the 1840s, more than 100 boatloads of fish were sent annually to Havana, Cuba, where the fish market was known for its variety and quantity of fresh fish. The Key West Green Turtle Cannery opened in 1849, and marine sponges were first exported in the same year. By 1890, turtles and sponges were the two major marine exports sent to northern markets, and populations of both had precipitously declined.

C. H. Anderson courtesy of D. Gallager

Historically, sharks were harvested commercially for their skins and oil. The average length of sharks found in the Florida Keys has declined by more than 50% in the past 50 years.

Shifting baselines

The debate about the status of fisheries in the Florida Keys is a classic example of the "shifting baselines syndrome." It has been mistakenly assumed that the abundance and sizes of fishes seen in the 1980s represented pristine conditions. However, most prized fishes had been reduced to a small fraction of their pristine abundance long before.

20th century

In the 20th century, both commercial and recreational fisheries grew in Florida. Sharks were harvested commercially in the 1920s – 1940s for their skins, which were turned into leather, and later for vitamin D, which was extracted from their liver oil. After World War II, the Keys became a major recreational fishing destination, and the infrastructure supporting recreational fisheries in the Keys increased rapidly. The landings of several commercial fisheries peaked in the 1970s – 1980s, and now many present-day fish stocks are considered to be overfished.

Back to the future

Fishing is not what it used to be, but the prospects for recovery are promising. Abundances of several fish species have increased within no-take marine reserves in the Florida Keys National Marine Sanctuary, providing hope for the future of fishing in the Keys.

Wil-Art Studio, courtesy of Monroe County Public Library

Wil-Art Studio, courtesy of Monroe County Public Library

L.E. McClenachan - SFU

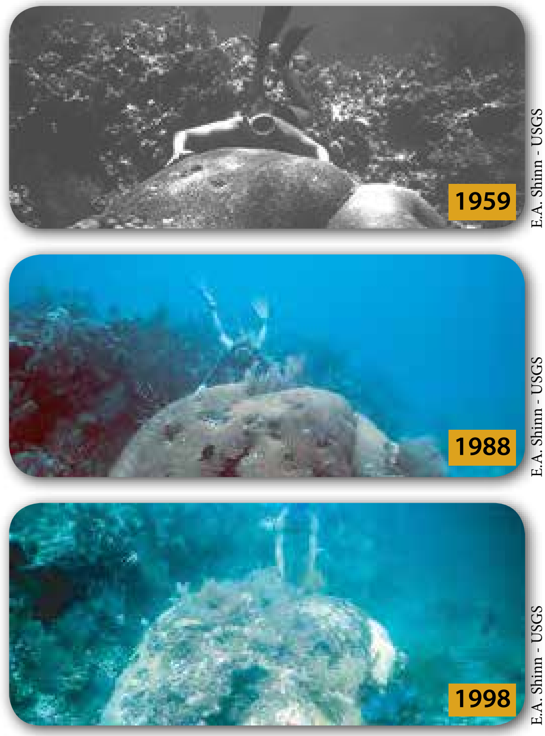
An example of a day's catch in 1957 (top), the 1980s (middle), and in 2007 (bottom).

Shifting baselines alter the public perception of the environment

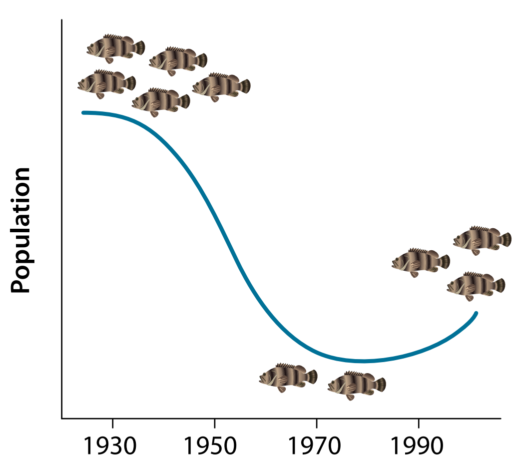
Dalal Al-Abdulrazzak

The concept of what is pristine in the oceans often is limited to the collective memory of observers. As each generation redefines according to personal experience what was "natural" in the oceans, degraded states can become accepted as normal. This loss of the perception of change is known as a "shifting baseline." The term was first used by fisheries scientist Dr. Daniel Pauly in reference to fisheries management in which scientists failed to correct baseline population size and, thus, worked from a shifted baseline. Scientists determine baseline conditions as reference points from which to evaluate changes in the health of populations, communities, and ecosystems. If the original baseline condition for a degraded ecosystem is known, measures can be taken to help restore the ecosystem to that target condition.

The lack of knowledge on baseline conditions of pristine marine ecosystems is especially a problem for coral reefs, which are both the most diverse marine ecosystem and the most threatened. Most of the tropical coastal oceans worldwide are so degraded that many pristine reefs have essentially disappeared. Because detailed study of coral reefs did not begin until the invention of SCUBA diving in the 1940s, most of our knowledge has been focused on coral reefs that were already moderately to severely degraded. Paleoecologists, geologists, and historical geologists attempt to characterize past conditions by studying biophysical conditions and historical evidence to describe changes to the environment and establish more accurate baselines.



Photographs of the same coral head at Grecian Rocks (Key Largo) in 1959, 1988, and 1998. A visitor to the reef in 1998 or later, who has never seen a coral reef before, may conclude that the reef is alive and healthy, even though present-day condition is not what a healthy, pristine coral reef actually looks like.



The biomass and population numbers of goliath groupers in south Florida have increased by more than 30% since the 1990s. Although it may seem like the population is recovering, a closer look at historical records indicates that goliath populations have been declining since at least the 1950s. The numbers from the 1990s represent a baseline that has shifted.

You can help to lessen impacts to the environment

William L. Kruczynski and Pamela J. Fletcher

The natural resources of planet Earth are finite and must be conserved for future generations. Do all that you can to leave a small human "footprint."

- Become educated about global warming and sea-level rise. Recognizing the reality of the problem is the first step.
- Encourage public officials to establish policies and programs that are good for the environment.
- Support the use of solar power and other alternatives to fossil fuels for production of energy.
- Reduce, reuse, recycle. Choose reusable products instead of disposables, such as single-use plastic water bottles.
- Buy products with minimal packaging. Recycling half of your household waste can save 1089 kilograms (2400 pounds) of carbon dioxide annually.
- Use less heat and air conditioning. Setting your thermostat 2°F (lower in winter and higher in summer) can save about 907 kg (2000 lbs) of carbon dioxide per household annually.
- Drive less and drive smart. Bicycle, walk, and use carpools when possible. Buy energy-efficient vehicles.
- Buy energy-efficient products and appliances. If every U.S. family replaced one regular bulb with a fluorescent bulb, it would eliminate 41 million metric tons (45 million tons) of greenhouse gases.
- Use less hot water. Washing clothes in warm or cold water can save more than 227 kg (500 lbs) of carbon dioxide per household annually.
- Hang clothes outside to dry instead of using a clothes dryer. Use a clothesline in your attic, garage, or basement during inclement weather.
- Turn off the lights when they are not needed. Turn off water when you are not using it.
- Plant a tree. A single long-lived tree will absorb over a ton of carbon dioxide during its lifetime.
- Landscape with native plants and water sparingly. Use drip irrigation if necessary. Mulched plants require less water.
- Plant a vegetable garden. Use containers if space is limited.
- Reduce use of pesticides, herbicides, and other toxic chemicals and do not apply near water.
- Use reusable bags when shopping for groceries or other items.
- Buy products from sustainable fisheries, including pond-reared fisheries products.
- Obey fishing and hunting regulations.

L. Perez - NPS

A single long-lived tree will absorb over a ton of carbon dioxide during its lifetime. Use native trees for landscaping to reduce water consumption and use of fertilizers.

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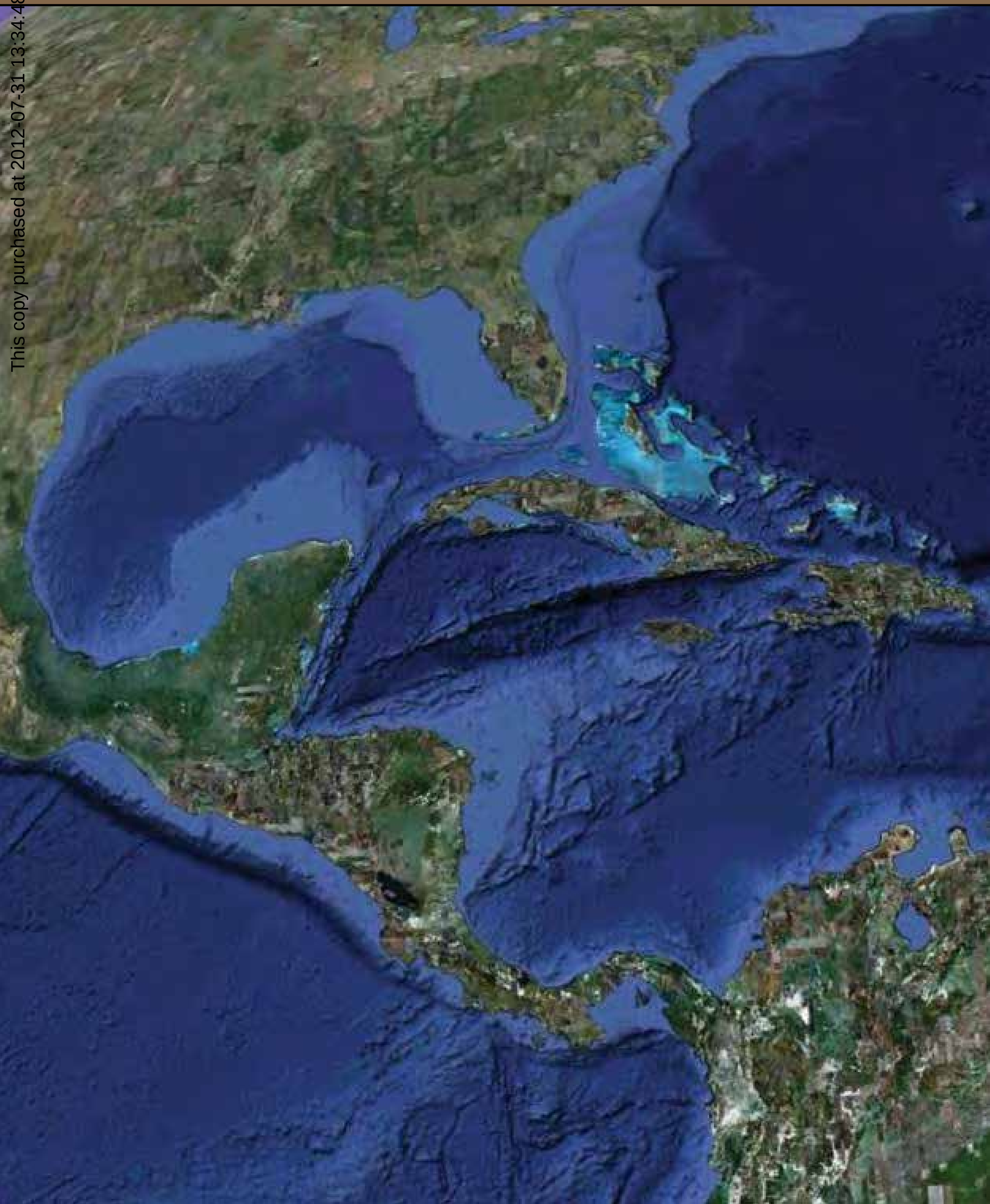
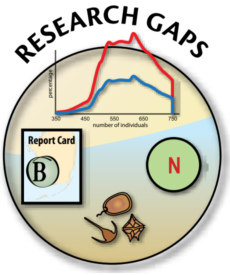
2. OCEANOGRAPHIC CONNECTIVITY

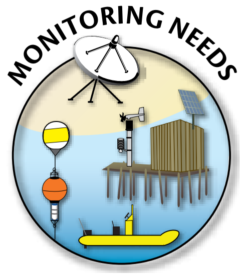


Oceanographic Connectivity Chapter Recommendations

- Recognize the importance of **communication and cooperation** across political boundaries to effectively manage a large, hydrologically open system.
- Acknowledge **regional and global threats** when developing management plans to address local actions.
- Practice **adaptive management** to improve decision making using the best available science.



- Continue to update, develop, and test **hydrographic models** to predict influences of farfield sources of pollution on ecological processes.
- Assess **effects of restricted movement of water** from the Gulf of Mexico and Florida Bay to the Atlantic Ocean in areas with restricted flows.



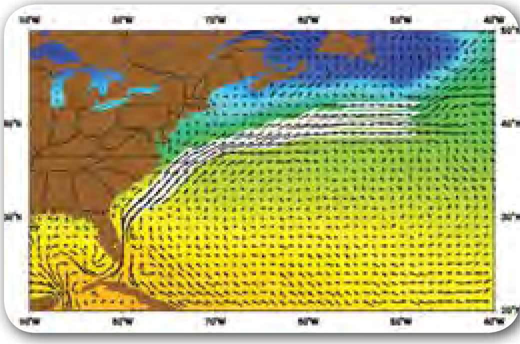
- Continue to collect long-term data of current speed and direction, water temperature, salinity, and other **water quality** parameters that are required to validate and update oceanographic models.
- Incorporate **remote sensing** where applicable to gather synoptic data over large geographic areas.
- Quantify the frequency and length of **upwelling events** to allow the development of more accurate nutrient loading models to coral reef habitats.
- Maintain or increase the number of Sustained Ecological Research Related to Management of the Florida Keys Seascape Coastal-Marine Automated Network (**SEAKEYS C-MAN**) stations to provide cost effective real-time oceanographic and meteorological data.

Chapter title page: The Caribbean Sea, Gulf of Mexico, and Atlantic Ocean are hydrologically connected. Google Earth.

Introduction

Oceanography is a multifaceted branch of science that studies the ocean. Because 71% of the Earth is covered in seawater, it is essential to understand worldwide oceanic interactions across the air-sea interface. The atmosphere and ocean are linked because of evaporation, precipitation, and exchange and absorption of gases as well as thermal flux and solar insolation. The effects of these factors occur at varying geographic scales.

South Florida is an area of complex oceanographic patterns because it is located at the confluence of the Atlantic Ocean and Gulf of Mexico, which results in dynamic tidal and surface current patterns. The Gulf Stream system sweeps past south Florida as the Florida Current and connects the area to upstream sources in the Caribbean Sea and Gulf of Mexico. Larval, juvenile, and adult forms of marine life "ride" the Gulf Stream currents, are delivered to south Florida, and help to maintain the diverse and abundant sea life in Florida.[1] Pollutants can also be entrained in the currents and may be delivered far downstream from their sources. For example, pesticides and fertilizers used on corn fields in the Midwest of the United States can be carried downstream by the Mississippi River, entrained in the Loop Current, and delivered to south Florida.



From Gyory, Mariano, and Ryan (2001-2008)

A computer model of the Gulf Stream current system represented by the Mariano Global Surface Velocity Analysis. The Gulf Stream transports a significant amount of warm water poleward. Water from the Caribbean Sea is funneled into the Gulf of Mexico, past the Yucatán Peninsula, and forms the Loop Current in the Gulf. The Loop Current becomes the Florida Current as the water sweeps through the Florida Straits.

Oceanography

Major divisions of oceanography include: geological oceanography, the study of the structure, formation, and movement of the ocean floor; physical oceanography, the study of physical attributes of ocean water, such as waves, tides, currents, salinity, and temperature; chemical oceanography, the study of the chemistry of ocean water; biological oceanography, the study of the animals and plants that live in the sea; and meteorology, the study of the interactions between the atmosphere and the ocean. Oceanographers may specialize in one or more disciplines or blend several disciplines to further the understanding of the oceans, their inhabitants, and biophysical and biochemical processes.

The south Florida coastal region comprises oceanographic subregions defined by their physical characteristics, flow properties, and species composition. The oceanographic linkage between the subregions depends on the degree of transport and interaction of currents connecting the subregions as well as on connections over the whole coastal region provided by the surrounding Gulf Stream currents and eddies. Periodic tropical storms and hurricanes can strongly influence salinity, water quality, and the circulation of water within and among the subregions, as can oceanic forcing functions such as deep ocean upwelling and freshwater pulses from terrestrial sources.[2]

The south Florida marine environment is the receiving body of water for the Greater Everglades Ecosystem, including but not limited to the Kissimmee River, Lake Okeechobee, St. Lucie River, Shark River, Taylor Slough, and the Caloosahatchee. Historically, freshwater flowed unimpeded through the system into Biscayne Bay and Florida

Bay. Hydrologic modifications to the watershed have affected the quantity, quality, timing, and distribution of freshwater to downstream areas and have shunted much of the freshwater drainage to the sea via the Caloosahatchee (Gulf side) and St. Lucie Canal (Atlantic side). As a result, salinity and other water chemistry parameters have been altered in downstream areas.

Seasonal changes in rain (wet and dry season patterns) and wind direction and speed further add to the oceanographic complexity of the area. Wind direction and speed are major drivers of ocean currents. Strong and persistent southeasterly winds can raise water levels on the Atlantic side of the Florida Keys, resulting in nontidal current reversals toward the Gulf side of the Keys. Wind forcing is especially important in the shallow waters of Florida Bay, providing the connecting link between inflow from the Gulf and outflow to the Atlantic and vice versa. Causeways constructed in the Florida Keys for Flagler's Railroad disrupted the normal exchange of surface waters between Atlantic and Gulf sides of the Keys and affected salinity patterns and flushing times in Florida Bay.[3]

A historical perspective of oceanographic science and research in south Florida

Humankind has been interested in the oceans since prehistoric times. Early exploration of the oceans was primarily for map making and describing the creatures that fishermen sighted or brought up in their nets.[4] Modern oceanography began as a field of science less than 130 years ago, in the late 19th century, when Americans, British, and other Europeans launched expeditions to explore ocean currents, ocean life, and the seafloor adjacent to their coastlines. The first scientific expedition to explore the oceans and seafloor was the Challenger Expedition. From 1872 – 1876, Charles Wyville Thompson and Sir John Murray led the research cruise onboard the British three-masted warship HMS *Challenger*. The results of that hallmark voyage were published in 50 volumes covering biological, physical, and geological oceanographic findings, and approximately 4700 species of new flora and fauna were described. The Challenger Expedition established oceanography as a quantifiable science.[5]

NOAA

HMS *Challenger*, a British Navy corvette (small warship), was converted into an oceanographic ship with laboratories and scientific equipment. The Challenger Expedition (1872 – 1876) was the first worldwide study of the oceans and seafloor.

The first ship built specifically for oceanographic purposes was the *Albatross* in 1882. Its 4-month voyage in 1910 in the North Atlantic Ocean, headed by Sir John Murray and Johan Hjort, was the most ambitious oceanographic and marine zoological project undertaken at that time.[6]

At the end of the 19th century and the beginning of the 20th century, several notable oceanographic institutes were founded in the United States, including the Scripps Institution of Oceanography (1892) and Woods Hole Oceanographic Institution (1930). The first acoustic measurements of the depth of the seafloor were made in 1914, and between 1925 – 1927 the German Meteor Expedition gathered over 70,000 ocean depth measurements using an echo sounder between Europe and the United States, leading to the discovery of the Mid-Atlantic Ridge.[4] In 1942, Harald Ulrik Sverdrup, Martin Johnson, and Richard Fleming published *The Oceans*, which was widely used as a textbook of oceanography. In the 1950s, August Piccard invented the bathyscape and used the *Trieste* to investigate the ocean depths. The nuclear submarine *Nautilus* made the first journey under ice to the North Pole in 1958. The theory of seafloor spreading and plate tectonics was developed by Harry Hammond Hess in 1960. The Ocean Drilling Project was started in 1966, and deep sea vents were discovered in 1977 by John Corlis and Robert Ballard in the submersible *Alvin*. In 1966, the National Oceanic and Atmospheric Administration was put in charge of exploring and studying all aspects of oceanography in the United States, and the National Sea Grant College Program was established to fund multidisciplinary researchers in the field of oceanography.[4,5,7]

The long coastline of Florida (3663 kilometers [2276 miles]), coupled with the uniqueness and complexity of its marine habitats, prompted the establishment of many oceanographic centers in south Florida. The Carnegie Institute Laboratory for Marine Biology was located in the Dry Tortugas from 1905 – 1939.

USGS

The Carnegie Institute Laboratory for Marine Biology was established on Loggerhead Key, Dry Tortugas, in 1905 and was one of the best-equipped tropical marine laboratories in the world. The facility closed in 1939.

In that laboratory, the foundations of tropical marine science in the Western Hemisphere were established. Pioneering researchers in the Dry Tortugas, led by the visionary Alfred G. Mayer, described and illustrated species of marine invertebrates, fish, and algae of the nearby coral reefs. Remarkably, these major accomplishments were made with relatively primitive field and laboratory equipment.

Other more recent centers of oceanographic excellence were established in south Florida, including the Rosenstiel School of Marine and Atmospheric Science (University of Miami), Harbor Branch Oceanographic Institute (Florida Atlantic University), Nova Southeastern University Oceanographic Center, and the National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory. In addition, the Florida Institute of Oceanography was founded by the State of Florida University System to support and enhance Florida coastal marine science, oceanography, and related management programs through education, research, and public outreach.[8]

In recent years, emphasis has been placed on the development and application of computer models to further our understanding of oceanographic processes. The use of models allows numerical predictions of future ocean conditions based on past patterns.[9] Models have been used to predict ocean currents, algal blooms, distribution of fish and fish larvae, flushing times, salinity patterns, and coral bleaching. The development of new technologies, such as satellite tracked drifters and remotely operated vehicles, has opened new areas of exploration in the sea.

The deployment of arrays of oceanographic buoys and platforms and the use of remote sensing satellite technology have resulted in the availability of near real-time data and have facilitated modeling and forecasting of events, such as El Niño, algal blooms, and coral bleaching.[10] The Sustained Ecological Research Related to Management of the Florida Keys Seascape (SEAKEYS) Coastal-Marine Automated Network (C-MAN) stations were located throughout the Florida Keys and Florida Bay and provided an hourly record of wind speed, wind direction, air temperature, barometric pressure, sea temperature, salinity and solar irradiance. NOAA currently only supports the station located at Molasses Reef Lighthouse.

Oceanographic data are collected in many different ways

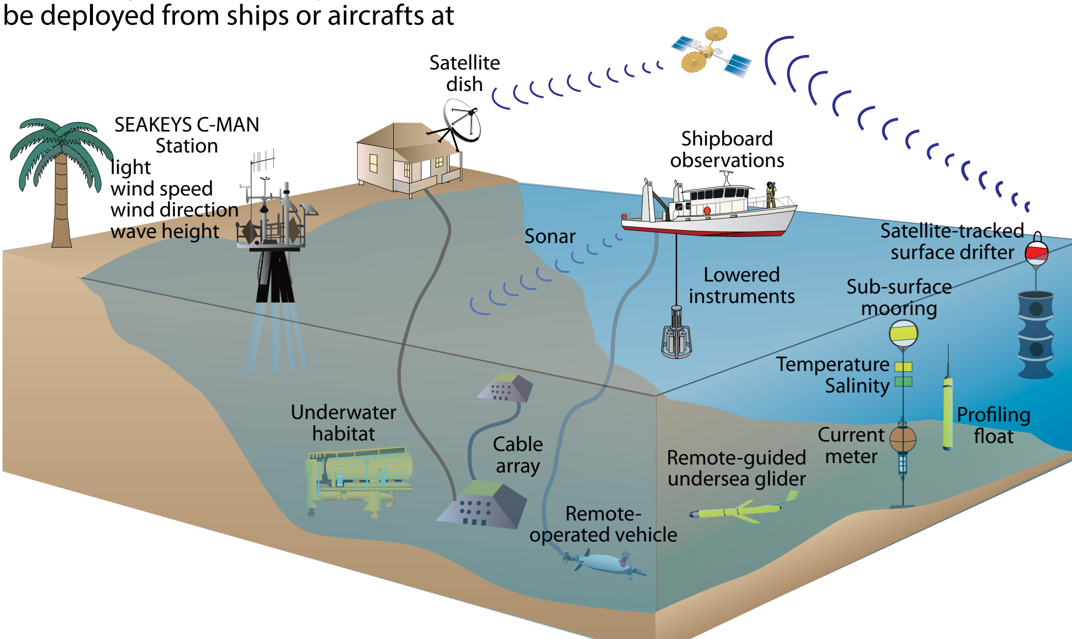
Ryan H. Smith and Elizabeth Johns

Scientists study the ocean in many ways. Seagoing oceanographers have historically conducted observations from research vessels. However, examining the physical, chemical, and biological properties of the ocean in that manner can be very expensive. Today, thanks in part to new technologies, scientists employ multiple tools to monitor our oceans. These methods are more economical and often provide greater coverage than traditional shipboard surveys. Although shipboard surveys are still important, they are one component in an ever increasing integrated ocean observing system.

Moored instrumentation arrays can provide long-term time series measurements at a fixed location. Other types of equipment designed to move freely through the ocean gathering data, such as surface drifters, Argo floats (i.e., broad-scale global array of temperature and salinity monitors), or gliders, can be deployed from ships or aircrafts at minimal cost. As these instruments gather data, they transmit this information back to scientists on land in real-time via satellite.

Scientists also gather data about the ocean remotely utilizing sensors affixed to orbiting satellites. Measurements such as sea surface temperature, ocean color, and sea surface height are collected continuously as these satellites pass over ocean regions.

Modeling is a very important component of modern oceanographic research. Scientists utilize computers to develop environmental models that mimic or reproduce the ocean conditions measured by the means just described. Accurate models, groundtruthed with real data, provide a tool for understanding ocean processes. Using these data (i.e., direct and remote measurements and model results), ocean scientists work to accurately describe the processes occurring in the marine environment and make predictions about the future.



Oceanographic data are collected in many different ways using instruments on the seafloor, throughout the water column, at the ocean surface, on land, and from space.

Oceanographic monitoring data are used to prepare ecoforecasts

James C. Hendee and Lewis J. Gramer

From the early 1990s – 2012, the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory (AOML) collaborated with the Florida Institute of Oceanography and the Florida Fish and Wildlife Research Institute in the management of data from the Sustained Ecological Research Related to the Management of the Florida Keys Seascape (SEAKEYS) Network. The network consisted of seven instrument-enhanced Coastal-Marine Automated Network (C-MAN) stations, cooperatively managed with the NOAA National Data Buoy Center (NDBC).

Instruments and data transmission equipment are still attached to all stations to measure standard meteorological variables such as wind velocity and direction, gusts, and air and dew point temperatures. Oceanographic variables, including salinity, sea temperature, tide height, and light attenuation (related to visibility) were formerly also measured throughout the network. However, due to budget constraints, the SEAKEYS components of the program have been decommissioned as of 2012, and only the station at Molasses Reef Lighthouse is still fully instrumented by AOML and NDBC. Data are collected hourly and transmitted to AOML from these stations via satellite. Scientists process and archive these data, then integrate them in time and space with other sources, such as satellite-derived sea surface temperatures and chlorophyll, and outputs from numerical computer models of the atmosphere and the coastal ocean.

Integrated data are used to develop marine ecosystem models called ecoforecasts, which assess changes in environmental conditions that trigger events such as coral bleaching, coral spawning, changes in water clarity and quality, larval drift, and other ecosystem phenomena. Ecoforecasts are validated, whenever possible, through observations from personnel in the field. Ecoforecasts allow managers at the Florida Keys National Marine Sanctuary to anticipate and understand changes to the ecosystem due to climatic and meteorological events. The knowledge gained from these forecasts support informed management decisions. These stations also provide the public with high quality, real-time information on air temperature, wind speed and direction (ndbc.noaa.gov), including sea temperature, salinity, and light data from Molasses Reef. To learn more about the network and to access the ecological forecasting database, please visit ecoforecast.coral.noaa.gov.

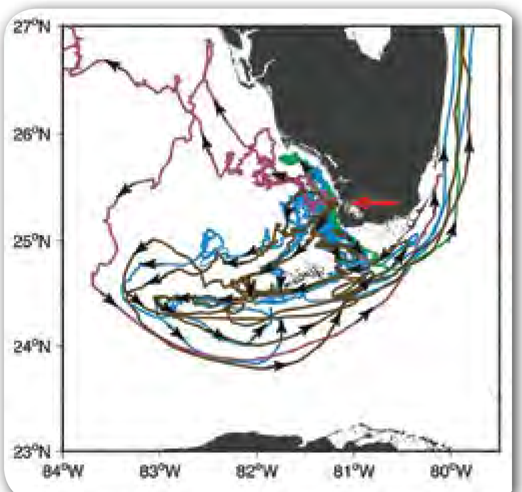
L. Myhre - Creative Commons

Real-time oceanographic data are collected from instruments fastened to the Molasses Reef Lighthouse and transmitted by satellite to the NOAA Atlantic Oceanographic and Meteorological Laboratory for analysis.

Ocean current circulation pathways are monitored by satellite tracking of drifters

Thomas N. Lee

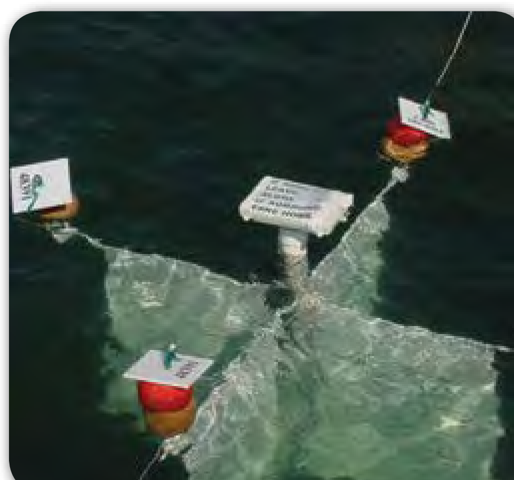
Oceanographers deploy neutrally buoyant devices called "drifters" that are moved by ocean currents. Satellite tracking of drifters released in the surface waters of the Shark River discharge plume indicate that three common circulation pathways connect the upper level waters of the entire south Florida coastal system.



From Lee et al. (2002)

Combined plot of surface paths of drifters placed in the Shark River discharge plume (red arrow) during September 1994 – February 2000. Colors show seasonal pathways of flow: winter is blue; spring green; summer lavender; fall brown. The 20 drifter paths were distributed evenly over the seasons and tracked by satellite.

The primary pathways are either to the southeast and through the passes of the Middle Keys, which is most common during winter and spring, or southwest to the Tortugas during the fall. The time to reach the Florida Keys Atlantic Coastal Zone is 1 – 2 months for both routes. The third pathway is to the northwest in the summer and the eventual merger with the Loop Current segment of the Gulf Stream, followed by southward transport to the Tortugas. This movement takes place over a 3 – 6 month period. Drifter movements on the Southwest Florida Shelf for periods longer than 1 day result primarily from currents induced by the local winds combined with a mean southward flow toward the Keys. Surprisingly, all the drifters deployed in the Shark River discharge plume eventually entered the Florida Keys Atlantic Coastal Zone. After drifters reach the Keys Coastal Zone, they tend to either recirculate in Florida Current frontal eddies and wind-driven countercurrents for periods of 1 – 3 months or are caught up by the Florida Current and are rapidly removed from the south Florida coastal system.



NOAA

Oceanographers use drifters to track ocean current circulation patterns and pathways.

Knowledge of local current patterns is important in designing and locating Marine Protected Areas to maximize the retention of larval and juvenile forms of marine organisms within the region. In addition, larval and juvenile recruits are transported to south Florida from the Gulf of Mexico and Caribbean Sea via the Gulf Stream "conveyor" current system.

Living underwater allows scientists to collect data, test technologies, and make important observations

Ellen Prager

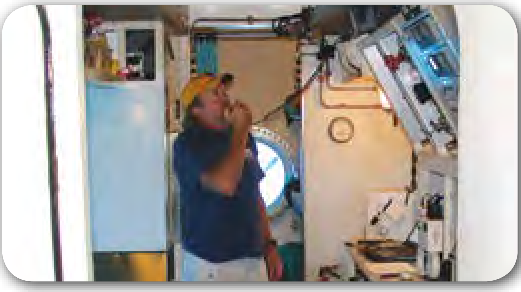
Aquarius is the only operating undersea research laboratory in the world. It is located in approximately 18.3 m (60 ft) of water in a sand patch at Conch Reef, about 5.6 kilometers (3.5 miles) offshore of Key Largo, Florida. Using saturation diving techniques, scientists can live and work underwater during 1 – 2 week missions, allowing them to make observations and conduct research that would be difficult or impossible by repeated dives from the sea surface. The undersea laboratory is part of the *Aquarius* Reef Base, which also includes an ocean observing station with real-time access via the Internet, and a shore base. The National Oceanic and Atmospheric Administration (NOAA) owns *Aquarius* and provides major funding for the facility through a grant to the operator, the University of North Carolina at Wilmington.

D.J. Roller - NURC

Aquarius provides state-of-the-art facilities for scientific research, technology testing, ocean observations, training, and education.

The mission of *Aquarius* Reef Base is as follows:

Scientific research: Research projects are performed to assess long-term change, study effectiveness of protected areas and restoration techniques, and further fundamental understanding of Florida coral reefs.



B. Campoli - NURC

Operations Manager Mark Hulsbeck inside Aquarius.

Technology testing: The facility serves as a test site for developing and applying new undersea technologies.

Ocean observations: Salinity, temperature, oxygen, waves, currents, and optical properties of the ocean are measured to provide valuable environmental data accessible in real-time over the Internet.

National training facility: The facility is used in training graduate and undergraduate students, U.S. Navy teams, and National Aeronautics and Space Administration astronauts.

Ocean education and outreach: The laboratory provides an exciting window into the underwater world and learning opportunities that students and the public can access at uncw.edu/aquarius.

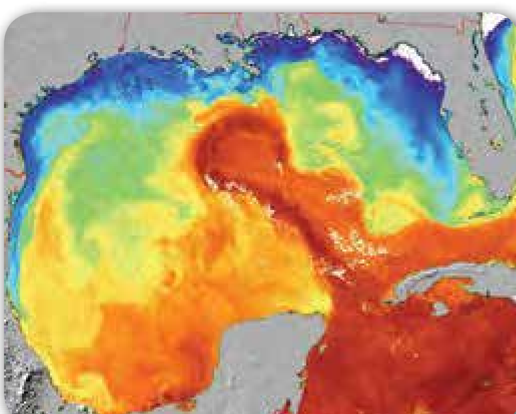
M. Ward - NURC

Aquarius Undersea Laboratory and ocean observing platform located off Key Largo. Scientists can live underwater for up to 2 weeks and transmit real-time data to a shore station or anywhere in the world via the Internet.

Frontal eddies are an important oceanographic feature in south Florida

Thomas N. Lee

Ocean eddies are rotating swirls of water that form along the boundaries of major ocean currents, such as the Gulf Stream. They come in different sizes, shapes, and rotation directions, ranging from large separations of the parent oceanic flows that form into warm- or cold-core rings several hundred miles across to small-scale turbulent vortices that engage in mixing fluids across the current boundary. Warm eddies have a clockwise rotation, and cold eddies rotate counterclockwise in the northern hemisphere.



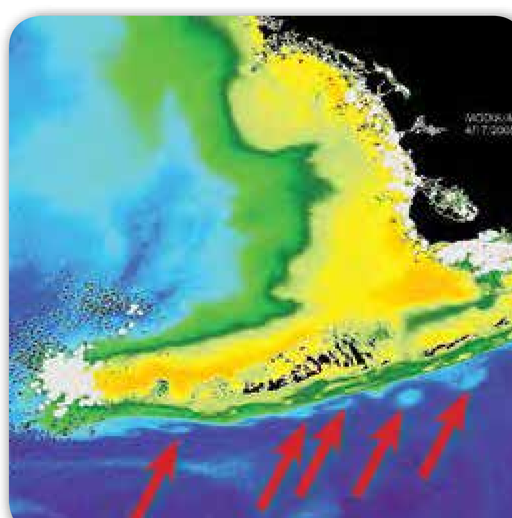
Courtesy of Johns Hopkins University

Satellite view of sea surface temperature in the Gulf of Mexico, March 21, 2001, showing Loop Current (dark red "finger") and cold water eddies (yellow swirls) from a 3-day composite image of sea surface temperature.

Eddies are particularly important to the health and wellbeing of the marine life and coastal waters of Florida because of the location and the peninsular shape of the Florida landmass. Florida is surrounded by one of the major ocean current systems in the world, the Gulf Stream system. A continuous stream of eddies move downstream along the shoreward boundary of the Gulf Stream system from the Gulf of Mexico, through the Florida Straits, and along the southeast coast of the United States to Cape Hatteras. These eddies are visible from space as cold, counterclockwise-rotating water masses that interact with the coastal waters of Florida and other southeastern states.

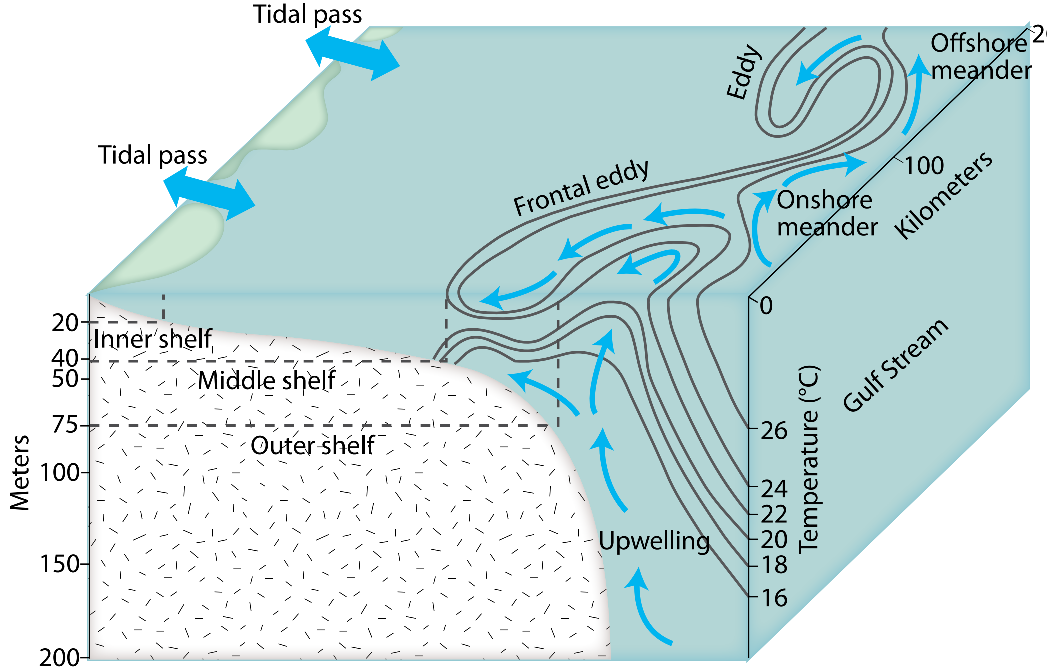
The eddies develop from growing disturbances of the Gulf Stream frontal boundary and hence are termed "frontal eddies." As the eddies grow within the space between the shallow coastal waters and the deep offshore waters of the Gulf Stream, the frontal boundary must shift offshore. The section of the Gulf Stream system that flows through the Gulf of Mexico from the Yucatán Channel to the Florida Straits is known as the Loop Current.

The Loop Current moves over deep, offshore water depths. Frontal eddies off the Loop Current reach diameters of 160 kilometers (100 miles) and move slowly toward the Florida Straits at only a few kilometers per day. On entering the



C. Hu - USF

NASA satellite image of south Florida showing frontal eddies that are spun off the Florida Current after it passes through the Florida Keys April 17, 2005.



Schematic cross section of frontal eddy formation of the Gulf Stream system, showing onshore meander; offshore meander; and upwelling of cold, nutrient-rich water. Upwelling provides nutrients to surface waters, and eddies provide a retention mechanism for planktonic larvae.

Straits near the Dry Tortugas, the size of the eddies begins to decrease, and the forward speed increases. Reaching the Middle Florida Keys, where the Florida Straits channel turns to the north and decreases in width, the Florida Current (the section of the Gulf Stream system through the Florida Straits) is forced to converge toward shore, causing the eddies to undergo rapid elongation and downstream acceleration, reaching average speeds of 24 km (15 mi) per day. This represents the final decay stage for these large frontal eddies, some of which were born in the Gulf of Mexico near the Yucatán coast nearly 5 months previously only to shear apart into small-scale vortices in the Middle and Upper Florida Keys. However, the energy associated with their evolution is not destroyed and is later transformed into a rebirth of the larger frontal eddies north of Jupiter, Florida, as the Florida Current leaves the channel confines of the Florida Straits.

The cold interior waters of the eddies stem from upwelling of deeper, nutrient-rich waters of the Gulf Stream. Upwelling provides a basic food supply and nutrients that support ecosystem productivity within the eddies and adjacent coastal environments. Circulation within the eddies provides a retention mechanism for newly spawned larvae, which, combined with the available food supply, enhances the survival and condition of new recruits to the Florida Keys coastal waters and reef communities, including shrimp, lobster, and commercially and recreationally important fish species. For example, larvae spawned in the Tortugas Ecological Reserve can be spread all along the Florida Keys by the movement and evolution of the frontal eddies. Passage of frontal eddies also increases exchange of offshore waters of the Gulf Stream with coastal waters and thereby helps to maintain the clear, low nutrient waters of the coastal ecosystem.

Weather and climate strongly influence salinity, water quality, and circulation of south Florida coastal waters and bays

Elizabeth Johns and Thomas N. Lee

Weather and climate affect south Florida coastal waters and bays over a wide range of geographic space and time scales. The coastal system, made up of waters from the Gulf of Mexico, Atlantic Ocean, Florida Bay, Biscayne Bay, and other estuaries, is highly coupled. As a result, local meteorological processes, such as precipitation, evaporation, wind events, and direct inflows of freshwater through streamflow and runoff, strongly influence the salinity, water quality, and circulation of coastal waters.

Seasonal weather patterns

The south Florida climate is subtropical, with a relatively small annual temperature range but pronounced wet (summer/fall) and dry (winter/spring) seasons. During the wet season, showers occur virtually daily with the afternoon sea breeze, and tropical cyclones with counterclockwise winds are transient occurrences. During the dry season, cold fronts pass through the region approximately weekly with accompanying increased wind speeds and clockwise-rotating wind directions. This annual wet season/dry season pattern causes noticeable changes in the regional sea surface salinity, most pronounced in the coastal zone along the Southwest Florida Shelf near the river mouths and along the onshore edges of Florida and Biscayne Bays.

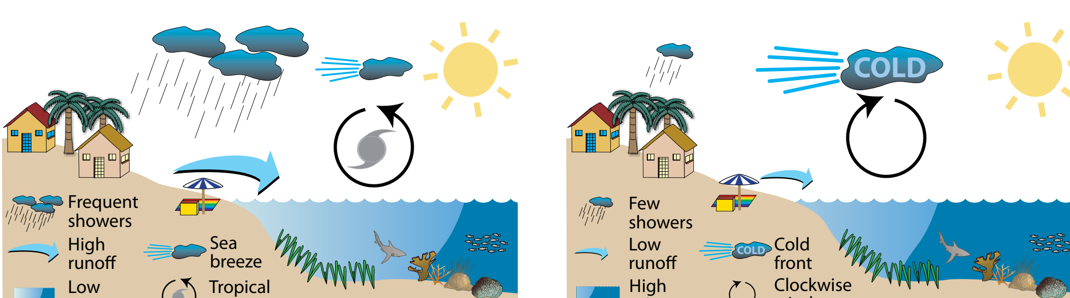
The seasonally changing regional winds, in conjunction with the geometry and bottom topography of the south Florida coastline, cause changes in the surface currents through direct forcing and by their effect on sea-level slopes. This subtidal circulation in response to the wind tends to be southward toward the Florida Keys in winter/spring, northwestward toward the Gulf of Mexico in the summer, and southwestward toward the Dry Tortugas in the fall. These seasonally episodic transport processes can affect the water quality of the Florida Keys coral reefs by delivering excessively warm, salty water to the reef tract from Florida Bay through the Keys passages in the spring and early summer, whereas relatively cold, turbid intrusions can occur in the winter.

Interannual to multidecadal weather patterns

Superimposed on the annual climatic cycle of south Florida are changes induced by longer-term and larger-scale influences, such as the interannual global phenomena known as the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO).

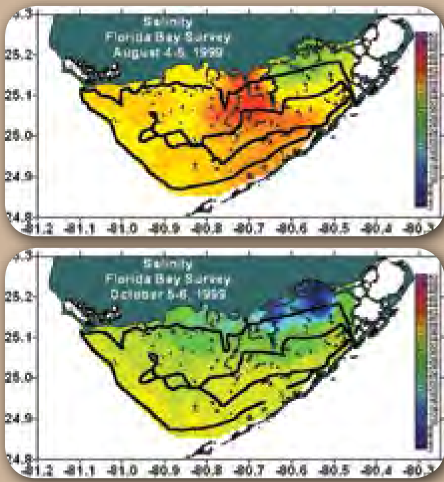
El Niño Southern Oscillation

The ENSO is a global ocean-atmosphere



Wet season (left) and dry season (right) variations in south Florida weather patterns.

Hurricanes and tropical storms



The most extreme meteorological events that affect south Florida are, as all Floridians well know, hurricanes and tropical storms. These episodic events cause rapid changes in barometric pressure; air and sea temperature; wind speed and direction; wave and swell amplitude, frequency, and direction; sea level height and slope; and coastal current speeds and directions. These changes also are accompanied by increased precipitation, more or less extreme depending on the size of the storms and the time that they spend over any given area of land or sea. All of these factors cause dramatic changes in oceanographic properties, including salinity of south Florida coastal waters, and tend to dominate time series records of meteorological and oceanographic parameters.

Surface salinity in Florida Bay before Hurricane Irene (1999) (top) and after Hurricane Irene (bottom). Red/orange shades indicate high salinities, and blue/green shades indicate low salinities.

phenomenon characterized by anomalously warm equatorial Pacific Ocean waters. It occurs roughly every 2 – 7 years. During its warm phase (El Niño), south Florida tends to experience a reversal of the normal wet/dry season and has cooler, rainier winters than usual. Conversely, during the opposite phase of ENSO (La Niña), when the equatorial Pacific is anomalously cool, south Florida tends to have warmer, drier conditions that often result in droughts and wildfires.

North Atlantic Oscillation

The NAO is an interannual north-south fluctuation in the sea level pressure difference between the Icelandic Low and the Azores High pressure systems. The NAO can cause noticeable variability in wind speed and direction, air and sea surface temperature, precipitation patterns, and the frequency and severity of storms.

Atlantic Multidecadal Oscillation

The AMO is a mode of sea surface temperature variability that occurs in the North Atlantic on a multidecadal time scale. The AMO is correlated with air temperature and precipitation variability over much of Europe and North America as well as with drought patterns and hurricane severity.

The ENSO, NAO, and AMO affect south Florida primarily by altering the usual seasonal temperature and precipitation cycles and have been shown to correlate with such variables as Florida stream flows, water depths in Lake Okeechobee, and coastal surface salinities.

Global climate change and implications for south Florida

Long-term changes in sea surface temperature, sea-level rise, hurricane severity and frequency, and other more recently discovered phenomena, such as a rise in ocean acidification, are expected to occur as a result of natural and anthropogenic global climate variability. South Florida likely will be dramatically affected by these changes due to its low elevation, high coastal population density, and unique sensitive ecosystems including the Everglades and the coral reefs. It remains to be seen how and to what extent the salinity, water quality, and coastal circulation of south Florida coastal waters, bays, and estuaries will be affected by global climate change.

Ocean currents connect south Florida coastal waters and link remote regions

Thomas N. Lee

South Florida coastal waters are highly connected throughout the region by a combination of locally produced circulation patterns and interactions with the surrounding large-scale Gulf Stream current system. The Gulf Stream system provides connections to remote upstream areas of the Gulf of Mexico and Caribbean.

The south Florida coastal region comprises subregions defined by their different physical characteristics, flow properties, and species composition. The subregions are the Southwest Florida Shelf, Ten Thousand Islands, Florida Bay, Florida Keys Atlantic Coastal Zone, and the Southeast Florida Shelf. The oceanographic linkage among the subregions depends on the degree of transport and interaction of currents connecting those subregions as well as on connections over the whole coastal region provided by the surrounding Gulf Stream currents and eddies. With the exception of the interior of Florida Bay, which is somewhat isolated by shallow banks, recent measurements of currents have shown a high degree of connectivity over the whole region as well as with remote upstream regions of the Gulf of Mexico.

Coastal water movements occur on time scales ranging from minutes to seasons to years. Tidal currents often account for a large part of the variation

Bathymetry of south Florida coastal waters and identification of coastal regions. Typical boundary of the Gulf Stream system surrounding south Florida is shown and identified as the Loop Current in the Gulf of Mexico and Florida Current in the Florida Straits. Evolution of frontal eddies is characterized along the Gulf Stream boundary.

in coastal currents and are important for local mixing and dispersion of materials. However, because of the reversing pattern of tidal currents, they are not effective transport mechanisms over distances longer than a few kilometers. Therefore, to understand transport by currents, oceanographers focus on currents that vary slowly and exist for periods of days to seasons. These are technically referred to as "subtidal currents." Subtidal currents are primarily responsible for linking adjacent, as well as remote regions to the south Florida ecosystem. These subtidal currents are mainly produced by interactions between local wind-forced currents, river runoff, and the large-scale Gulf Stream current system that encloses the south Florida coastal region. Subtidal coastal currents also are strongly influenced by local depth contours and coastline orientations. The major components of coastal currents within each of the subregions of the south Florida coastal ecosystem are described here.

Southwest Florida Shelf

The Southwest Florida Shelf is the southern extension of the wide, shallow West Florida Shelf that has smoothly changing depth contours aligned in a northwest-to-southeast direction. Similar to the West Florida Shelf, this region undergoes seasonal layering of the water column that is well mixed in fall and winter and vertically layered in spring and summer due to seasonal changes in the strength of wind mixing, atmospheric heating, and river runoff along its eastern border. The water on this wide shelf responds as a unit to alongshore (north or south) winds, with winds leading currents by less than 1 day. In other words, if the winds shift direction and come from the north, then shelf currents will start to move from north to south within 1 day.

Seasonal changes in wind strength and direction also produce seasonal differences in the strength of the currents, with greater strength of current variations in winter in response to passages of cold fronts and weaker currents in summer.

W.L. Kruczynski - EPA

The Dry Tortugas lie at the southern boundary of the Southwest Florida Shelf and are a main crossroads of ocean currents.

There is also a seasonal pattern in the upper layer currents, which are more southward in the winter, spring, and fall, changing to northward in the summer when winds shift to a northwesterly direction. The deeper lower layer currents are generally southward throughout the year. This is partly due to the Loop Current flow at the outer shelf, which is toward the south in this region following the Gulf Stream loop into the eastern Gulf of Mexico. The southward flow at the outer shelf creates sea-level slopes over the shelf that help to maintain the southward coastal currents and transport West Florida Shelf waters, including river discharges and harmful algal blooms, toward the sensitive habitats of the Florida Keys and Dry Tortugas.

At the southern extremity of the southwest coastal region lie the Florida Keys, including their westward extension out to the Dry Tortugas. The open passages between the Keys provide pathways to connect the Southwest Florida Shelf with the Florida Keys Atlantic Coastal Zone. The mean southward flow in the Southwest Florida Shelf coastal region discharges through the passages in the Middle Keys, predominantly Long Key

Channel and Moser Channel (Seven Mile Bridge), and onward toward the Florida Keys Reef Tract at a mean rate of about 28,000 cubic feet per second (cfs). This is a very large flow for a long-term average. The mean southward flow through the Keys passages appears to occur because mean sea level is higher in the eastern Gulf of Mexico than on the Atlantic side of the Keys, causing a cross-Key slope in sea level that forces flow through the passages. Recent measurements have shown a seasonal cycle in the southward mean flow, with strongest transports occurring during winter and spring, weak southward flow in summer, and mean northwestward flows into Florida Bay and the Southwest Florida Shelf region in fall. This seasonal cycle is the result of seasonal changes in local winds, which are the primary mechanism controlling the variability of sea-level slope across the Keys.

Ten Thousand Islands

The Ten Thousand Islands area is a shallow, complex system of small rivers, tidal creeks, and mangrove islands that receive freshwater runoff from the Everglades, primarily through Shark River, Broad River, and Lostmans River. Their combined discharges form a nearshore band of low salinity water that follows the curved shoreline northwest to Cape Romano. This low salinity band is transported toward the southeast and into western Florida Bay by the mean southward coastal flow and helps to prevent high salt concentrations (hypersalinity) from developing within western Florida Bay.

W.L. Kruczynski - EPA

Mangrove islands are found throughout Florida Bay.

Florida Bay

Florida Bay is made up of a complex maze of shallow basins separated by mud banks and mangrove islands. The Bay is openly connected to the Southwest Florida Shelf along its wide western boundary, but exchange with the Florida Keys Atlantic Coastal Zone is restricted to a few narrow tidal channels through the Keys island chain. The northern boundary of the Bay is mangrove fringed, with freshwater input into the northeastern region predominantly through Taylor Slough and Trout Creek.

The rapid decrease in tidal range in Florida Bay with distance from the western boundary and the dramatic increases in salinities observed in the north-central interior basins are indicative of poor water exchange between basins. Thus, it takes a long period of time for basin waters to be renewed. Freshwater flows from the Everglades directly into the northeast subregion of Florida Bay. These lower-salinity waters are mostly trapped by the enclosing shallow banks and have minimal influence on the high salinities of the surrounding subregions. Western basins receive Everglades discharge from Shark River and the Ten Thousand Islands, but in a diluted form mixed with waters from the Southwest Florida Shelf.

The amount of freshwater flow discharging from the Everglades through the Ten Thousand Islands and Florida Bay averages about 3000 cfs, which is small compared with the estimate of the mean southward flow connecting the Southwest Florida Shelf and Florida Keys Atlantic Coastal Zones. Therefore, it is unlikely that increasing the freshwater flow to the Everglades will have a substantial impact on waters of the Southwest Florida Shelf or Florida Keys Atlantic Coastal Zone. However, an increased Everglades flow should cause considerable modification of salinity within Florida Bay from increased discharges into northeast Florida Bay via Taylor Slough and Trout Creek and into western Florida Bay through the southeastward movement of the Shark River low salinity plume. Diverting a portion of the increased Everglades discharge into McCormick Creek that connects to the north central region of the Bay would greatly aid in reducing hypersaline conditions that develop in the central Bay during the dry season.

W.L. Kruczynski - EPA

Water moves from the Southwest Florida Shelf to the Florida Keys Atlantic Coastal Zone through tidal passes, such as Bahia Honda Pass.

Florida Keys Atlantic Coastal Zone

This zone consists of a narrow, curving shelf with complex topography associated with the Florida Keys Reef Tract. The curving shoreline causes regional differences in current patterns in response to prevailing easterly winds and influences of the Florida Current, the portion of the Gulf Stream system from the Florida Straits to Cape Hatteras. Westward currents are persistent at the bank reef tract and Hawk Channel areas of the Lower Keys in response to winds from the east. In the Upper Keys region, these same winds blow onshore and have little effect on alongshore currents. The Middle Keys are a transition region.

The seasonal cycle of the winds results in a seasonal change in coastal currents that is most pronounced in the Upper and Middle Keys where northward flows occur in the summer during southeasterly winds, and southward flows occur in fall, winter, and spring due to winds from the northeast and east. Mean coastal flows in the Lower Keys are toward the west throughout the year because the westward-oriented coastline aligns with the prevailing winds from the east and southeast.

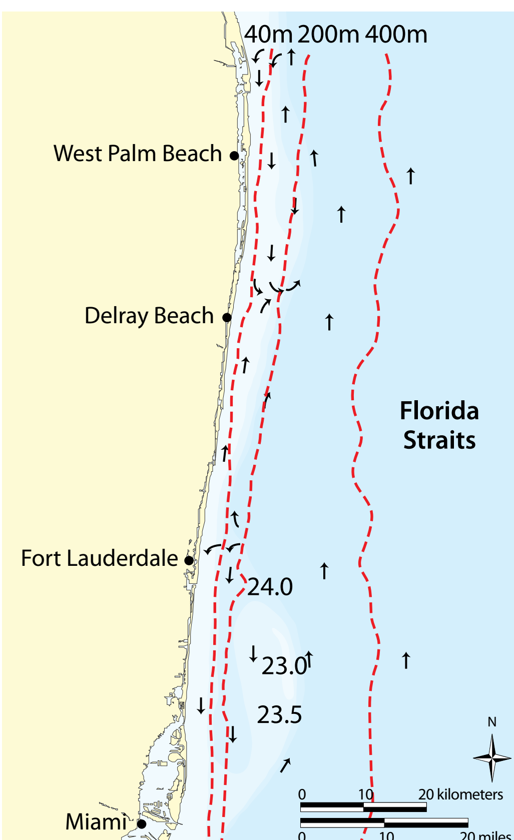
Water properties and currents in the Florida Keys Atlantic Coastal Zone are also highly influenced by the interaction with the Gulf Stream system (Florida Current) and the evolution of eddies that travel downstream along its shoreward boundary. Large, counterclockwise-rotating eddies with diameters of 100 – 200 kilometers (62 –124 miles) move downstream along the frontal boundary of the Loop Current in the eastern Gulf of Mexico. On reaching the Dry Tortugas region, these eddies can remain nearly stationary for several months and are sometimes referred to as Tortugas Eddies. After this period, they continue their movement into the Lower Keys and follow the northward curve of the Florida Current toward the Upper Keys with decreasing size and increasing forward speed. These features can occur any time of year, intensifying the westward countercurrents in the Keys. Mean flows at the seaward edge of the reef tract are directly related to the offshore distance of the Florida Current. Stronger downstream (northward) flows occur in the Upper Keys because of the proximity of the strong northward-flowing Florida Current along the outer shelf. Greater upstream (countercurrent) flows occur in the Lower Keys because of three factors: the Florida Current is located farther offshore on average, there are larger and more persistent eddies, and the winds are predominantly toward the west in the same direction as the countercurrent and align with the shelf topography.

Southeast Florida Shelf

The Southeast Florida Shelf is made up of a long, narrow coastal zone squeezed between the highly developed southeast

Florida metropolis at the shore and the strong northward flowing Florida Current at the shelf break. The shelf stretches north to south 100 km (62 mi) from Biscayne Bay to Palm Beach. The shelf configuration is unusual in that it is extremely narrow, varying in width from 1 – 3 km (0.6 – 1.9 mi) and quite shallow, with only a 30 meters (100 feet) water depth at the shelf break.

In nearshore waters of less than 10 m (33 ft), flow and temperature variations are controlled by tidal and atmospheric influences, typical of most shallow shelves. Northerly or southerly winds have the greatest influence on the direction of currents of this north-south-oriented coastline. The current response is in the same direction as the wind (north or south) with a lag of less than 12 hours. Typically in the summer, the nearshore mean current is toward the north due to the prevailing southeast winds. Prolonged north wind events in the fall result in southward mean flows at the coast. Winter and spring cold front passages cause variable alongshore flows without a consistent pattern.



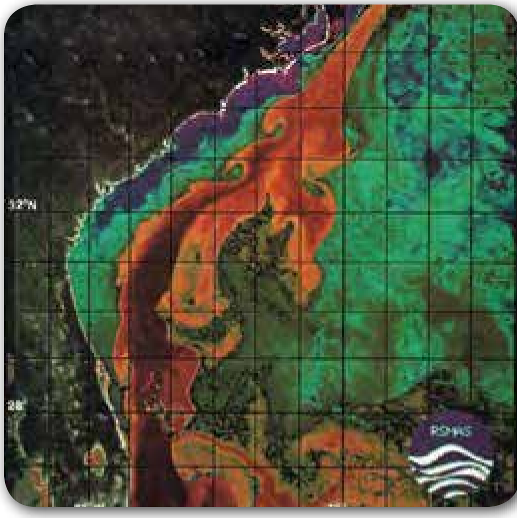
Lee, Yoder, Atkinson (1991)

Composite map of sea surface temperature (°C) from continuous shipboard measurements for the period February 20 – 23, 1973, showing two Florida Current frontal eddies interacting with coastal waters of the Southeast Florida Shelf. Arrows indicate observed current directions. Red lines are depth contours.

Current and water properties of the mid- to outer-shelf regions tend to be strongly influenced by the nearby Florida Current. Seaward of the shelf break, there occurs a submerged terrace at depths of 200 – 300 m (656 – 984 ft) that extends eastward for another 20 km (12 mi) before plunging to the 700 m (2300 ft) depths of the Florida Straits. The width of the Florida Straits along this shelf domain is only about 75 km (47 mi) and behaves as a channel to restrain the meandering movements of the Florida Current to typically 5 – 10 km (3 – 6 mi) and generally less than 20 km (12 mi). However, the Miami Terrace, which extends into the body of the Florida Current flow, can perturb the flow, causing meandering and eddy development along the shoreward boundary of the current, resulting in strong interactions between the Florida Current and adjacent shelf waters.

Typically the shoreward front of the Florida Current follows the shelf break northward, causing strong northward mean flows over the outer shelf ranging 25 – 50 centimeters per second (0.5 – 1.0 knots). Flow and temperature variabilities within the mid- to outer-shelf regions are dominated by the northward passage of small, counterclockwise-rotating frontal eddies that occur at an average frequency of once per week throughout the year with little seasonal change. Eddy diameters range from 5 – 30 km (3 – 19 mi) and their passage through the outer shelf can cause upwelling of deeper, nutrient-rich waters of the Florida Current that stimulate primary production in surface waters along the continental slope. Eddy passages normally take 1 – 2 days and result in considerable exchange between resident shelf waters and

Florida Current waters within the eddy. Displacement of shelf waters by eddies at an average weekly interval represents a flushing mechanism that results in mean residence time of shelf waters of 1 week.



Lee, Yoder, and Atkinson (1991) prepared by O. Brown and R. Evans - UM/RSMAS

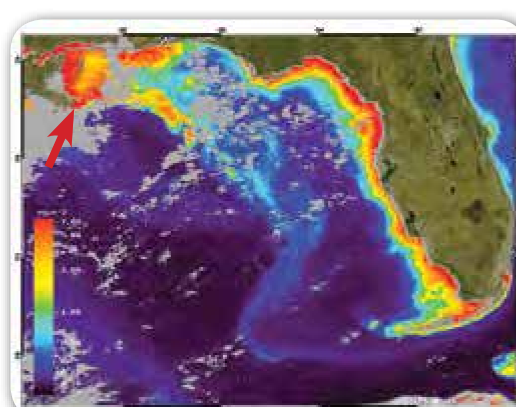
Satellite Advanced Very High Resolution Radiometer thermal image of the Gulf Stream on April 23, 1980, showing eddy development off the Florida Current along the Southeast Florida Shelf.

At times, these eddies have their origins on the Gulf Stream front in the Gulf of Mexico and together with the background flows of the Florida Current and coastal regions serve to connect the Southeast Florida Shelf with the previously mentioned shelf domains of the Florida Keys Atlantic Coastal Zone and the Southwest Florida Shelf as well as with other upstream sources such as river discharges. At other times, the eddies can be generated locally by unstable meander motions of the Florida Current. As the eddies leave the Southeast Florida Shelf region and move northward along the Southeast United States Continental Shelf, they leave the confines of the Florida Straits and the Gulf Stream frontal meanders are free to grow, resulting in explosive eddy growth that can reach dimensions of 100 – 200 km (62 – 124 mi) in a matter of days. Eddy development and migration along the shelf serve as a nutrient pump to outer shelf waters from Florida to Cape Hatteras, stimulating primary production.

Subregions are connected and linked to remote regions

The south Florida regional current patterns form a tightly coupled recirculation system. This recirculation system provides an excellent opportunity for successful recruitment of locally spawned larvae. Foreign recruits can also arrive via the Gulf Stream "conveyor" from upstream locations in the Gulf of Mexico and Caribbean.

The rapid movement of the Gulf Stream Current can also bring unwanted pollutants from the Mississippi River watershed and the wider Caribbean. Occasionally, Mississippi River discharge is transported south to the Keys in a low salinity band on the shoreward side of the Florida Current. The southward transport occurs when either the Loop Current or a large eddy separated from the Loop Current interacts with the river discharge off the Mississippi delta. Transport time to the Keys is less than 1 month and can result in decreased salinities and increased turbidity at the Florida Keys Reef Tract. Toxic chemicals, such as pesticides, were found in an intrusion of Mississippi River water following the 1993 Mississippi flood event.



C. Hu - USF

Satellite image showing chlorophyll concentrations. Water from the Mississippi River Delta (red arrow) can be traced flowing through the Florida Straits and past the Florida Keys Reef Tract. High chlorophyll concentrations shown in red, and low chlorophyll concentrations are shown in black to violet hues.

Water circulation and renewal in Florida Bay is influenced by flows from the Southwest Florida Shelf and tidal passes

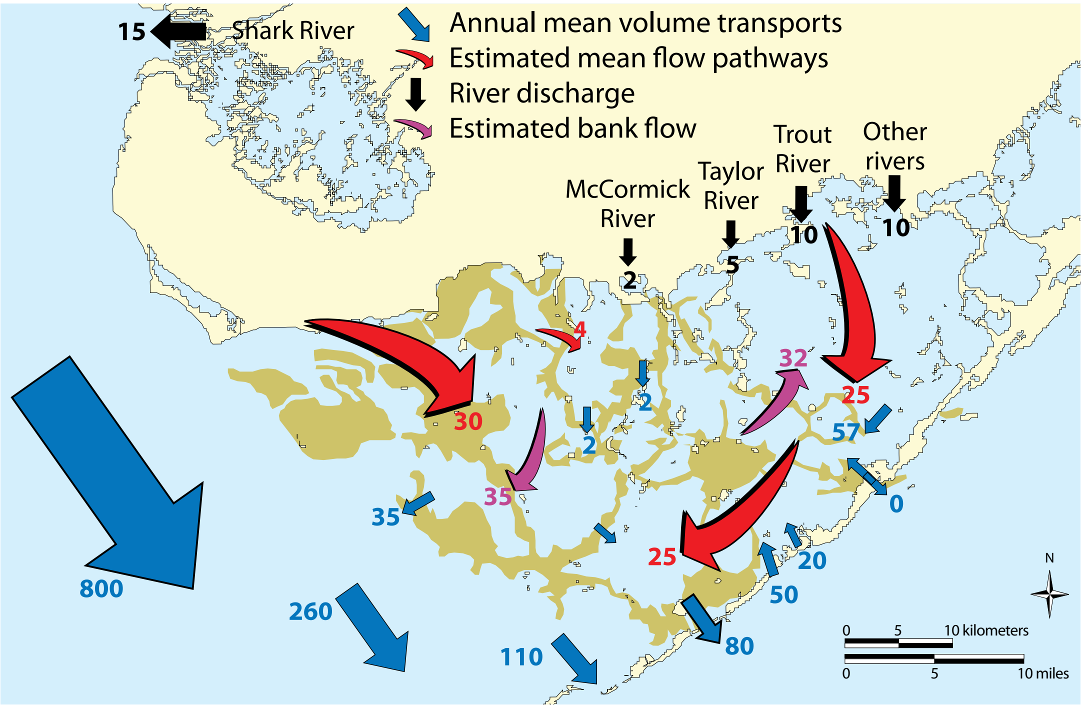
Nelson Melo and Thomas N. Lee

Florida Bay is located at the southern end of Everglades National Park between the mainland and the Florida Keys. The Bay waters interact with adjacent coastal waters of the Southwest Florida Shelf to the west and Florida Keys Atlantic Coastal Zone to the east and southeast. Exchange of Bay interior waters with the Florida Keys Atlantic Coastal Zone is restricted to a few narrow tidal channels in the Keys island chain between Key Largo and Islamorada, whereas water exchange with the Southwest Florida Shelf region takes place across a 40 kilometer (25 mile)-wide open boundary. The combined tidal harmonics of the Gulf of Mexico and the Atlantic produce a mixed tide along this wide western boundary with a tidal range of 1 – 1.5 meters (3 – 5 feet).

Surprisingly, the largest tide in the Gulf of Mexico or on the eastern seaboard of the United States south of Brunswick, Georgia, occurs at the mouth of Shark River. There the tidal range can reach over 2 m (6.5 ft) during spring tides. Not surprising then, Flamingo Channel, which is the northwest entrance to the Bay and only about 10 km (6 mi) from the mouth of Shark River, is the largest open channel to the Bay and has the greatest tidal exchange. The northern boundary of the Bay is fringed with mangroves and coastal lagoons. Freshwater discharge to the Bay is primarily confined to the northeastern region through Taylor Slough and Trout Creek.

The interior of the Bay is made up of a complex network of shallow basins with depths ranging from 1 – 3 m (3 – 10 ft) deep separated by mud banks and mangrove islands. Connection between basins occurs through narrow channels and over the shallow banks. Water depths over the banks are typically less than 0.3 m (1 ft) deep. During periods of low sea level (e.g., winter dry season or strong winds toward the west or southwest), the banks can become exposed, causing

Satellite image of Florida Bay showing the four subregions based on water circulation patterns and water quality.



Annual mean volume transports (m^3/s) in Florida Bay and through the Keys (blue arrows) and estimated mean flow pathways (red arrows) between Florida Bay subregions. River discharge is shown by black arrows. Estimated bankflow is shown by magenta arrows.

further isolation of the interior basins. The mud banks are also primarily responsible for the large landward falloff in tidal range, which decreases from 1.5 m (5 ft) at the open western connection of the Bay to a few centimeters (1 inch) near the northeast boundary of the Bay.

The typical climate of south Florida consists primarily of two seasons: a dry season during winter/spring and a wet season during summer/fall. The balance of freshwater flux, controlled by river discharge, precipitation, and evaporation, is negative during the dry season and positive over the wet season. This leads to increasing salinities in Florida Bay during the dry season and decreasing salinities in the wet season.

The configuration of mud banks and mangrove islands within Florida Bay and differences in the magnitude of volume exchange with adjacent waterbodies together with the isolation of river discharge into the northeast portion of the Bay tend to separate the Bay into four subregions: northeast, north central, southeast, and western.

The subregions of Florida Bay are characterized by prolonged hypersalinity in the north central part and persistent lower salinity in the northeast, with both subregions displaying a large seasonal range of salinity. Salinity of the southeast and western subregions is more typical of the adjacent coastal areas, indicating enhanced water exchange with these regions.

Recent direct measurement of volume transports through channels connecting interior basins have been used together with time series of basin total volume transport derived from sea level measurements to estimate basin flushing rates and residence times and to identify the important physical processes regulating the water renewal. The measurement strategy was applied to the north central, northeast, and western subregions and clearly shows that local wind forcing is the primary flushing mechanism controlling basin residence times. South Florida winds typically are weak from the east and southeast during the summer, shifting to be more from the northeast during the fall, with increased strength of wind events that can last several days. During the winter and spring seasons, cold fronts move through the region within a period of 3 – 7 days, causing increased winds that rotate clockwise from southwest through northwest to northeast. The cumulative effect from the passage of these wind events drives a mean flow through the basins, with net inflows over the banks and net outflows through the channels. The resulting net basin throughflows are weak and require on the order of 1 year to replace an equivalent mean volume of the north-central and northeast basins.

T. Scott - FGS

Florida Bay comprises a complex network of shallow basins with depths ranging from 1 – 3 m (3 – 10 ft) deep. These basins are separated by mud banks and mangrove islands and are connected by narrow channels through the shallow banks.

Net basin throughflows were found to be significantly larger in the western basin, which resulted in enhanced water exchange with the adjacent coastal waters, moderation of seasonal changes in salinity, and short residence times ranging from 0.5 – 2 months. Estimates of seasonal water balance indicate that groundwater discharge to Florida Bay is negligible.

Florida Bay mean flow pathways were estimated from annual mean volume transport measurements, river discharges, and derived bank flow estimates. The annual river discharge to the Bay of 27 cubic meters per second essentially is trapped in the eastern part with little diluting influence on hypersalinity of the north central Bay. Reduction of hypersalinity events in the Bay and corresponding degradation of water quality will require a diversion of a portion of the river discharge to the central region via McCormick Creek. There is a weak mean flow pathway from Flamingo Channel eastward across the northern banks and then southward through the north central basin of 4 m^3/s. There is also a much stronger clockwise mean flow pattern of about 30 m^3/s from the major arm of Flamingo Channel that feeds an outflow through Rabbit Key basin and through the channels of Nine Mile Bank. However, this recirculation through the western basins is small compared with the 800 m^3/s net southward coastal flow that provides the connection to transport riverine discharges from the Southwest Florida Shelf and Ten Thousand Islands area (including Shark River) to the western basins of Florida Bay and ultimately the Florida Keys Reef Tract.

T.A. Frankovich - FIU

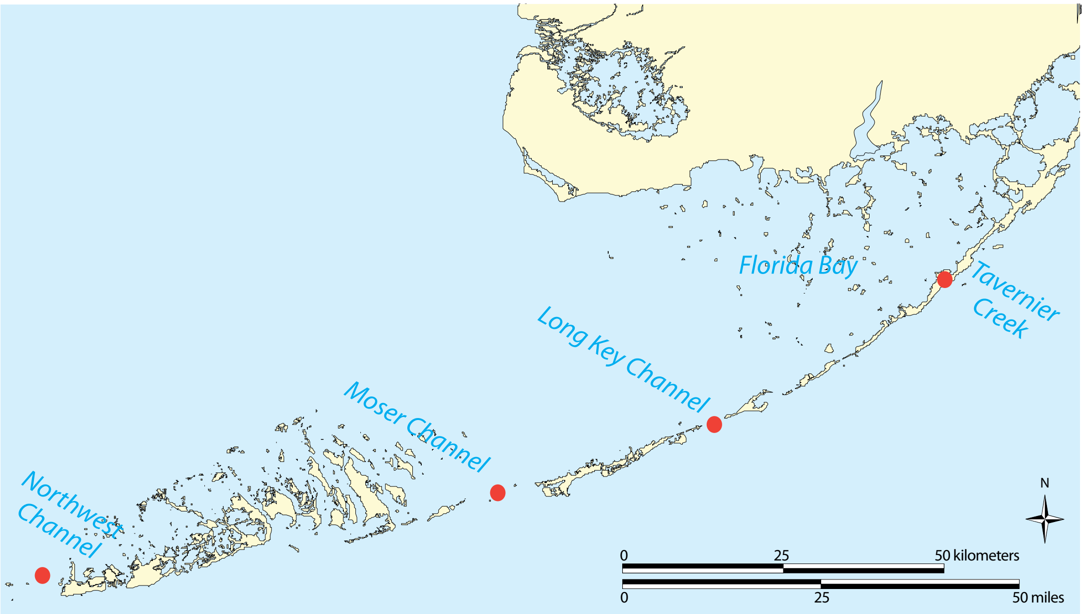
Narrow channels through the shallow banks are marked with paired aids to navigation within Everglades National Park.

Tidal flow and current reversals transport larvae spawned in the Atlantic Ocean to nursery grounds in the Gulf of Mexico

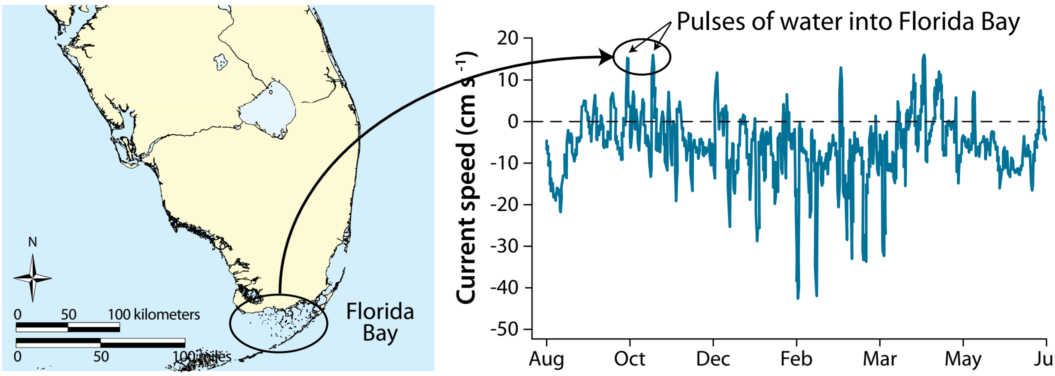
Ned Smith

Slightly higher water levels on the Gulf side of the Florida Keys result in a persistent, long-term net flow of water from the Gulf of Mexico to the Atlantic Ocean through the tidal passes between the Keys. Many animals, including spiny lobsters, pink shrimp, tarpon, and goliath grouper spawn in the Atlantic Ocean but have nursery grounds on the Gulf side of the Florida Keys and in Florida Bay. How do their planktonic larvae travel against the long-term net outflow of water from the Gulf to the Atlantic? There are two mechanisms that allow this transport to occur. One involves the ebb and flood of the tide, and the second involves temporary wind-driven reversals of the Gulf-to-Atlantic flow.

Strong ebb and flood tidal currents occur through all the major channels in the Upper and Middle Keys every 12.4 hours. Thus, although the long-term net flow is toward the Atlantic, Atlantic water, including any larvae suspended in the water column, is carried several kilometers into Florida Bay on the Gulf side of the Keys with each flood tide. Mixing of Atlantic and Bay waters during the flood half of the tidal cycle causes some Atlantic water to remain in the Bay. In its place, Bay water leaves on the following ebb. With this exchange, larvae are transported in the direction of the nursery areas. On the next flood tide, the larvae within Florida Bay are carried still further into the Bay, and with more mixing, some of them will be left behind on the following ebb. By entering the Bay with the flood currents from the Atlantic and then exiting with the ebb currents to the Gulf, larvae can move upstream against the long-term net Gulf-to-Atlantic movement of water. This transport mechanism is in operation throughout the year, and the cumulative effect on larval movement is believed to be significant.



Location of tidal passes where wind-driven reversals of nontidal currents were observed (red dots). Reversals result in inflow into Florida Bay at Moser Channel, Long Key Channel, and Tavernier Creek. Wind reversal temporarily halts movement toward Florida Bay in the Northwest Channel.



Nontidal current speeds (tidal floods and ebbs removed) recorded in Long Key Channel (August 20, 1995, to July 21, 1996). Negative speeds (below the dashed line) represent water leaving Florida Bay. Arrows point to two of the 30 pulses of Atlantic water entering Florida Bay. For comparison, flood and ebb current speeds are commonly 45 – 55 centimeters per second (approximately 1 knot). The total current speed is the sum of tidal and nontidal components. Major periods of wind-induced reversals occur in late fall and spring when many species are spawning.

The second mechanism involves temporary reversals of the Gulf-to-Atlantic movement of water due in part to changing wind conditions. The nontidal flow of water through the passes separating the Keys reverses over time periods of a few days, sending pulses of Atlantic water to the Gulf side of the Keys. Strong southeasterly winds raise water levels on the Atlantic side and reinforce the flood currents. On the Gulf side, the same southeasterly winds lower water levels and help to draw water out of the Bay on the ebb tide. Wind forcing is especially important in the shallow waters of Florida Bay.

In a study conducted in Long Key Channel, numerous reversals of the nontidal current were observed over a 336-day period. The net movement of water was consistent with the Gulf-to-Atlantic transport, but 18% of the observations recorded an inflow to Florida Bay. The nontidal current reversed 30 times during the study to send pulses of Atlantic water into the Bay. Reversals occurred throughout the study, but they were more frequent in late fall and late spring, times when larvae of many species are numerous.

Studies conducted in other channels in the Middle and Upper Keys revealed inflow to be even more common. For example, during a 339-day study in Tavernier Creek, a nontidal inflow to the northeast corner of Florida Bay was found in 33% of the observations. During a 254-day study conducted in Moser Channel under the Seven Mile Bridge, a nontidal inflow was recorded 47% of the time.

The long-term net outflow found in the Upper and Middle Keys does not occur in the Lower Keys. In a 348-day study conducted in the Northwest Channel just west of Key West, a northward nontidal transport toward Florida Bay occurred 73% of the time. At this location, larvae are transported to Gulf nursery areas with the mean flow. Wind events play an important role, but in Northwest Channel, they temporarily halt the import of water to the Bay.

In summary, the average west-to-east movement of water is an important feature of the regional circulation. A closer look at nontidal flow through the channels that separate the Florida Keys reveals that temporary reversals occur regularly. In the Upper and Middle Keys, these reversals can help to explain the apparent upstream movement of larvae into and through Florida Bay. Wind-driven transport together with the stepwise tidal transport play a crucial role in the life cycles of species that are spawned in the Atlantic Ocean and grow up on the Gulf side of the Florida Keys.

Many planktonic larvae use tidal currents to migrate or maintain their position

William L. Kruczynski and Pamela J. Fletcher

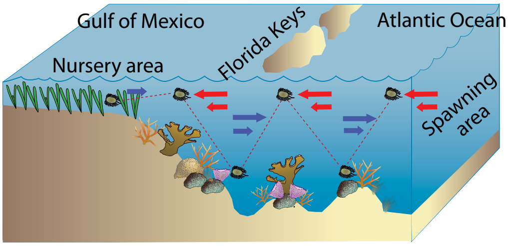
Many planktonic forms have limited mobility and are at the mercy of currents to control their distribution. However, other planktonic forms have the ability to migrate vertically and horizontally in the sea in response to environmental cues.

Vertical migration

Zooplankton, including adult and larval forms of crustaceans, salps, jellyfish, fish, squid, and other animals that live in the open ocean (blue water) perform daily vertical migrations by adjusting their buoyancy in response to light cues. They spend daylight hours at depths with little or no light penetration (aphotic zone) and migrate to the surface to feed during dark hours. This activity concentrates food sources at night and makes the surface waters an "eat or be eaten" environment. Also, excretion of nitrogenous wastes by the nightly migrants at the surface stimulates new primary production by phytoplankton during daylight hours.

Horizontal migration

Many organisms, including lobster, goliath grouper, and shrimp, spawn in the open ocean and settle out of the water column as juveniles in hardbottom, seagrass, and mangrove habitats on the Gulf of Mexico side of the Florida Keys. How do they get there? Larvae and postlarval forms are passively moved toward the Gulf by riding daily tidal currents and during times of periodic, wind-driven current reversals. But, how do they hold their position during unfavorable current conditions? The larvae are not as passive as once believed. They are able to adjust their buoyancy in response to current cues and seek refuge from unfavorable currents by migrating to protected benthic shelters, such as sponges and reefs. When currents become favorable again, they rise toward the surface to continue their migration to nursery habitats. This same mechanism allows larvae spawned in shallow waters to stay in the home range of their parents during daily tidal reversals.



Animals, such as Caribbean spiny lobster and goliath grouper, spawn in the Atlantic Ocean near the bank reef. Larvae are planktonic (i.e., float with the currents) but are capable of raising and lowering their position in the water column to "ride" tidal currents flowing toward the Gulf of Mexico. They find shelter near the bottom, out of the current, during periods of unfavorable flow direction and rise in the water column when the flow direction again becomes favorable. In this stepwise progression, they are capable of moving against the long-term flow and toward their nursery areas in seagrass, sponge, and mangrove communities on the Gulf side of Florida Keys and Florida Bay. Red arrows represent flooding tides toward the Gulf; blue arrows ebbing tides flowing to the Atlantic.

Implications for planning Marine Protected Areas

The movement of larvae into and out of no-take marine reserves plays an integral role in determining whether reserves can sustain themselves, exchange larvae with other protected sites, or supplement surrounding fished areas. A thorough scientific understanding of the larval dispersal methods of species protected in reserves is required in the effective design and placement of protected areas. Are larvae coming from long distances? Do they require protected habitats en route? Or are larvae "self-seeding" from local sources? For species capable of horizontal migration, it does not make sense to protect spawning habitat but not protect nursery habitat when both are required for the conservation of the species.

Hydrodynamic models provide insight into regional circulation patterns

Villy H. Kourafalou

The Florida Keys and the adjacent coral reefs are on a narrow continental shelf that quickly deepens to the Florida Straits located between south Florida and Cuba. The Gulf Stream is the dominant feature of oceanic circulation near the Keys and has several geographic names. Along the Keys it is appropriately called the Florida Current, and it receives flow from the Loop Current from the Gulf of Mexico. These currents are part of a larger-scale oceanic current system that enters the Gulf from the Caribbean Sea through the Yucatán Strait.

Sea surface height maps graphically show variability due to oceanic currents and depict highs and lows of the ocean surface, which give important clues about the circulation. Frontal areas have strong contrasts of sea surface height, and closed highs or lows mark recirculating features, the so-called eddies that are cyclonic (rotate counterclockwise) around a low and anticyclonic (rotate clockwise) around a high.

Understanding ocean circulation

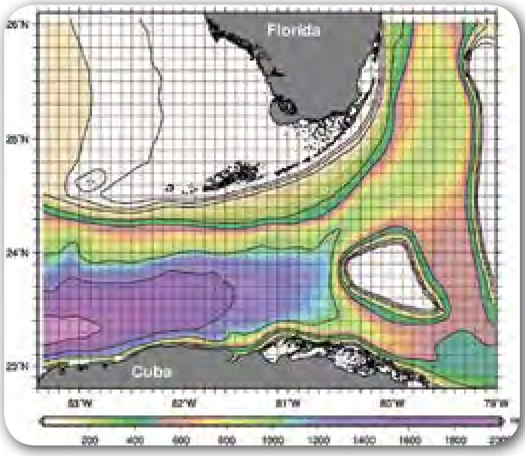
Two mechanisms are of utmost importance for marine life and water quality along the Florida Keys Reef Tract. First, because the Keys shelf is narrow and it neighbors the Florida Straits, the waters around the Keys are strongly influenced by the Florida Current, which is influenced by the Loop Current and by a much larger oceanic current system. Second, eddies traveling along the ocean currents carry nutrients, larvae, and sometimes pollutants from upstream sources that can be from hundreds of kilometers away. As these enter the Straits, they interact with the rough topography of the Keys that often causes them to break apart, delivering the substances and particles that have been traveling along entrapped in their recirculation. Both mechanisms are of utmost importance for marine life and water quality along the Florida Keys Reef Tract. Oceanographers observe these phenomena through *in situ* and satellite measurements and have developed hydrodynamic numerical models using these data.

Hydrodynamic numerical models

Hydrodynamics deal with the physics of the waters (e.g., motions, circulation); numerical means that equations are used to describe these phenomena and are solved through computer coding; and model means that a series of equations and coding methods are used to describe (i.e., model) the physical system. There are many different models that the oceanographic community uses widely, and they differ in the phenomena they target, the methods of solution they use, the ways they describe the interactions of the ocean with the atmosphere, and the ways they "discretize" (i.e., divide in smaller parts) the model domain. A local example is the Florida Keys Hybrid Coordinate Ocean Model (FKEYS-HYCOM), which covers all coastal areas around the Florida Keys and the deep Florida Straits, extending to Cuba and the Bahamas. The FKEYS-HYCOM is coupled with a biological model that allows the study of coral fish recruitment in the Florida Keys. There are also biogeochemical models that deal with the nonphysical phenomena and coupled physical and biogeochemical models (or full ecosystem models) that deal with all possible phenomena in oceanography.

Hydrodynamic models simulate environmental conditions

Hydrodynamic models simulate (i.e., model) natural phenomena. They synthesize the observations and theories and provide information for areas where data do not exist at a given time based on simulations that were calibrated with existing data. Thus, they provide a wealth of information for any time during the model simulation period and for any location within the model domain. Most importantly, hydrodynamic models can forecast future conditions and analyze scenarios of change due to either climate or anthropogenic influences, such as sea level changes; coastal inundation and flooding; or the construction or removal of a river dam, a sewage outfall, or an ocean inlet. A local example is using the FKEYS-HYCOM to predict changes in circulation around Florida Bay and the Florida Keys associated with the Comprehensive Everglades Restoration Plan.



Model grid map prepared by H.S. Kang - UM/RSMAS.

Models use grids and color for analyzing and illustrating ocean conditions, such as this FKEYS-HYCOM model domain and bathymetry map. Color scale shows depths in meters. White areas are less than 50 meters (164 feet) deep; purple color indicates the deepest areas in the Florida Straits. Rectangles depict the model gridding, where each box is actually divided into 10 more boxes in the model grid.

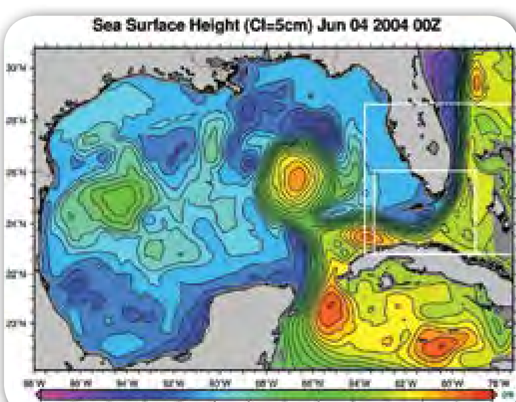
How are models created?

First, the modelers select the model domain, which covers the area of interest. Then the domain is divided into small gridded areas. The selected grid size depends on the phenomena modelers want to study and on the computer resources available to process all the data in the model and solve the equations of motion on every model grid. The coastal domains require smaller grids, and the smaller the grid, the greater the number of cells for a given study area and the more expensive it is to run the model, because it requires more computer power. The FKEYS-HYCOM has a high resolution (very small) rectangular grid of about a half mile in each direction. The model domain is large, and it has a total of 437 by 361 boxes, which is quite a lot when solving a very complex code every few minutes for years of simulation and at many different depths in the water column. For instance, the FKEYS-HYCOM model has 26 vertical layers. High performance computing resources (supercomputers) are required, and lots of storage space (many terabytes) is necessary to archive the results. Each grid box is given information about the latitude and longitude; the depth; and the forcing functions, such as wind, heating/cooling, evaporation, and precipitation. These forces change over time, creating different circulation patterns. In addition, grids near the land might receive river runoff, whereas grids near the model boundaries require information on currents and water properties (e.g., temperature, salinity) from larger-scale models.

Models connect circulation around the Florida Keys with the ocean currents

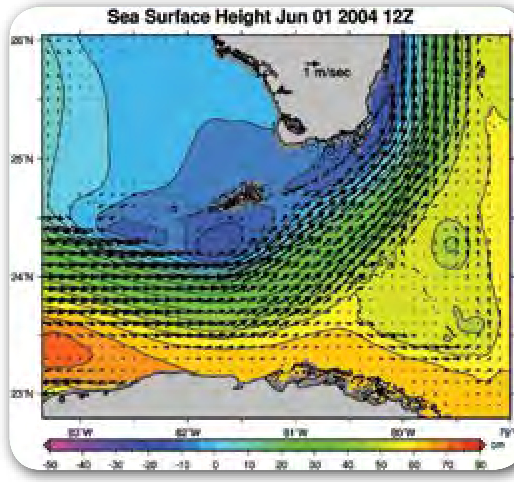
The FKEYS-HYCOM model is nested (embedded) in a hierarchy of larger-scale models, such as South Florida, the Gulf of Mexico, and the full North Atlantic Ocean, which, in itself, is embedded in a global model that covers the entire worldwide oceans. This particular modeling system is based on code used in the HYCOM model (hycom.org); other modeling systems use a different code. The larger-scale models are coarser (i.e., lower resolution or larger grid cells, which means less detail in topography), going up to several kilometers at each side of their grid. Using this downscaling approach, simulations with the FKEYS-HYCOM properly represent coastal flows and their interaction with the neighboring and remote oceanic currents.

An example of modeling, shown in the figures, illustrates the influence of eddies along the Florida Keys. Sea surface height was mapped by the Gulf of Mexico-HYCOM model for June 4, 2004. The Loop Current-Florida Current system is a dominant circulation feature as the continuation of the Caribbean Current that enters at Yucatán. Many cyclonic and anticyclonic eddies fill the Gulf of Mexico domain and enter the Florida Straits. The same features are present in the embedded FKEYS-HYCOM model, but many more details can be revealed, especially near and around the Keys, because this model has higher resolution that allows for more topographic details. An eddy was observed as a rounded feature off the Lower Keys on June 1, 2004. This eddy became an elongated feature by June 10, 2004, as the Florida Current meandered closer to the Keys. These are favorable conditions for eddy breakup, which results in delivery of nutrients and larvae from upstream spawning grounds. Note that there are times that the Loop Current is extended all the way to the northern Gulf of Mexico and can interact with the Mississippi River, potentially carrying agricultural runoff from the midwestern United States all the way to the Florida Keys.



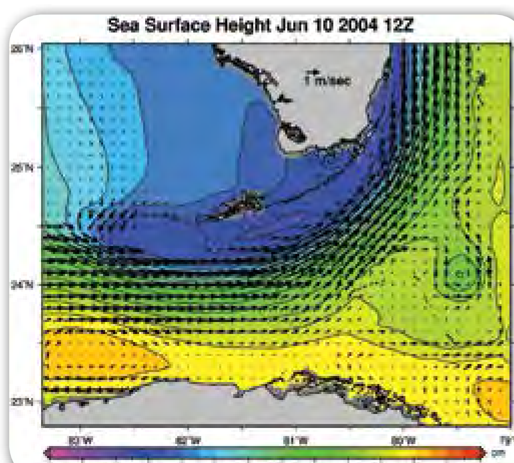
Model grid map prepared by H.S. Kang - UM/RSMAS.

Sea surface height for the Gulf of Mexico-HYCOM model on June 4, 2004. Color scale gives sea surface height in centimeters. High values (red and green) show the oceanic current system and clockwise eddies. Blue-colored eddies rotate counterclockwise. The white boxes mark the domains of the embedded south Florida-HYCOM (large box) and FKEYS-HYCOM (small box) models. Model fields provided by Pat Hogan and Ole-Martin Smedstad, Naval Research Laboratory, Stennis Space Center.



Model grid map prepared by H.S. Kang - UM/RSMAS.

Sea surface height map for the FKEYS-HYCOM model on June 1, 2004. Color scale gives sea surface height in centimeters. High values (red, orange, and green) show the oceanic current system and clockwise eddies. The blue-colored eddies rotate counterclockwise. Black arrows show the strongest currents (greater than 50 cm/s) along the Florida Current and around the eddies. Note the large, circular eddy (dark blue) off the Lower Keys.



Model grid map prepared by H.S. Kang - UM/RSMAS.

Sea surface height map for the FKEYS-HYCOM model on June 10, 2004. Color scale gives sea surface height in centimeters. High values (orange and green) show the oceanic current system and clockwise eddies. Blue colored eddies rotate counterclockwise. Black arrows show the strongest currents (greater than 50 cm/s) along the Florida Current and around eddies. Note how the eddy off the Lower Keys (dark blue) has elongated, a favorable condition for eddy breakup and delivery of nutrients and larvae from upstream sources.

A hydrodynamic and mass transport model has been developed for Biscayne Bay

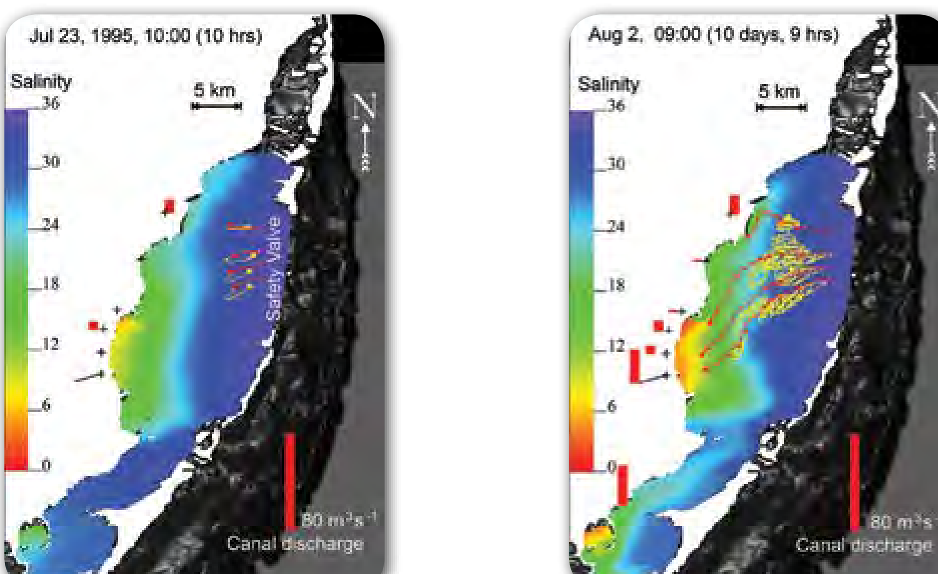
John D. Wang

A hydrodynamic and mass transport model is a predictive tool used to forecast or hindcast circulation patterns and transport of materials in a waterbody. Such information is useful to a broad range of potential users, such as sailors, pollution control managers, ecologists, and public health officials. All of these users may need knowledge of the water current velocities, water surface fluctuations, and transport of materials dissolved or suspended in the water. Supported by observations in the field that are limited by the cost, effort, and time required to collect them, a hydrodynamic numerical model can provide predictive information on spatial and temporal patterns on which informed decisions can be made.

For example, competitive sailors are interested in water currents as forced by tides and wind to gain an advantage over other sailors. Substantial changes in both magnitude and direction of currents occur throughout south Biscayne Bay and could be used advantageously to plan a sailing route. The model used to calculate this information is a finite element numerical model that expresses fundamental physical principles in a step by step fashion that are then used to calculate water current velocities and water surface fluctuations.

Adding a mass transport module to the hydrodynamic model allows the investigation of the pathways and travel times of substances in the water, such as fish larvae, polluted water discharged from the canals distributed along the western edge of the Bay, or microbes that are introduced into the water point and nonpoint sources.

The model also can simulate paths of fish larvae that arrive at the eastern opening of the Bay and are subsequently transported into the Bay toward suitable nursery grounds by surface currents.



Model simulation of dispersal of fish larvae that arrive at the eastern opening of the Biscayne Bay (Safety Valve). The model predicts paths of larvae without swimming behavior (yellow) and with swimming behavior (red) 10 hours (left) and 10.4 days (right) after time of arrival at the eastern opening of the Bay. The effect of canal discharge (red bars) on salinity of the Bay is also shown.

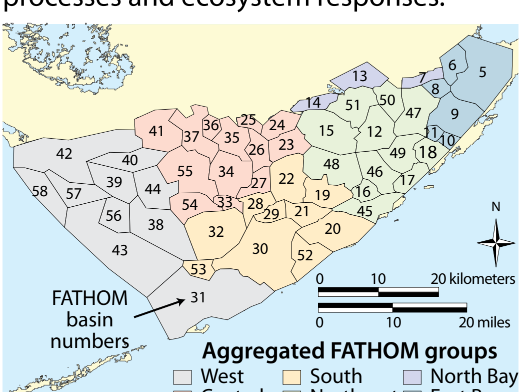
Hydrologic models predict salinity in Florida Bay

Frank E. Marshall and William K. Nuttle

Salinity and its pattern of variation define estuarine and coastal ecosystems. Salinity is a major factor in determining the types of plants and animals present and where they live. Salinity varies spatially and over time in response to fluctuations in the quantity and location of freshwater inflows. Models are capable of predicting how salinity changes and allow water managers to evaluate different ways of delivering freshwater to Florida Bay as part of the Comprehensive Everglades Restoration Plan.

Two general approaches have been used for constructing salinity models of Florida Bay. The first is empirical and relies on accurately describing observed salinity variations. The second is mechanistic and depends on accurately accounting for the physical processes (e.g., flow rates, tidal exchange, evaporation) that drive changes in salinity. In both approaches, the accuracy of the forecasts is limited by the data available for describing patterns of salinity variation and the ability to quantify the driving processes.

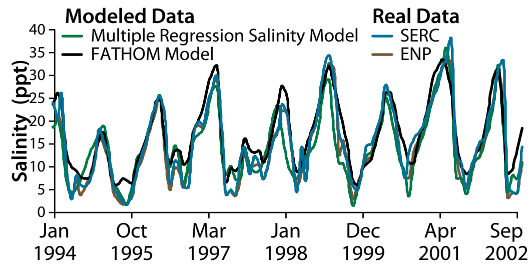
The empirical approach is simpler, using descriptive analyses to formulate models that confirm statistical relationships. Regression models are a method to explain the relationships between driving processes and ecosystem responses.



Map identifying Florida Bay basins and the aggregated regions used in FATHOM for salinity calculations.

A Multiple Regression Salinity Model has been developed for Florida Bay to evaluate freshwater delivery alternatives and for paleoecological investigations.

Mechanistic salinity models are mass balance models that provide a comparison of the inputs and outputs



A comparison of observed salinity data (real data) from Everglades National Park (ENP) and Southeast Environmental Research Center (SERC) and forecasts made by Multiple Regression Salinity Model and Fathom Salinity Models (FATHOM) in Long Sound. Results show that models accurately predict salinity variations used to guide water management decisions to restore natural freshwater inflows and salinity to Florida Bay.

of water and salt between basins. Mass balance models can be simple (box) models or more complex hydraulic and hydrodynamic models. FATHOM is a hydraulic model that accurately accounts for the exchanges between water and salt in basins delineated by geographic features (mud banks) in Florida Bay in a manner similar to creek flow. By design, hydrodynamic models are intended for more detailed and spatially discrete applications because of the effort and high cost to run large-scale hydrodynamic models for regional scenarios.

To date, the most widely used models for developing historical re-creations and simulating future salinity regimes for evaluating water management alternatives are the FATHOM hydraulic model and the Multiple Regression Salinity Model. These models have proven useful for planning-level decisions on a regional basis.

Sea surface temperature can be used to predict coral bleaching events

Lewis J. Gramer and James C. Hendee

Coral bleaching is the loss of color in corals due to stress-induced expulsion of unicellular algae (i.e., zooxanthellae) that live within coral tissues. Zooxanthellae give corals their particular color, and under stress those cells are expelled, leading to a lighter or completely white appearance in corals.

High sea surface temperature along with high incident radiation are the primary causes of summer coral bleaching. Because reef-building corals live near their upper thermal tolerance limits, small increases in the temperature of the ocean over several weeks, or a large increase over a few days, can cause bleaching events and ultimately may lead to coral death.

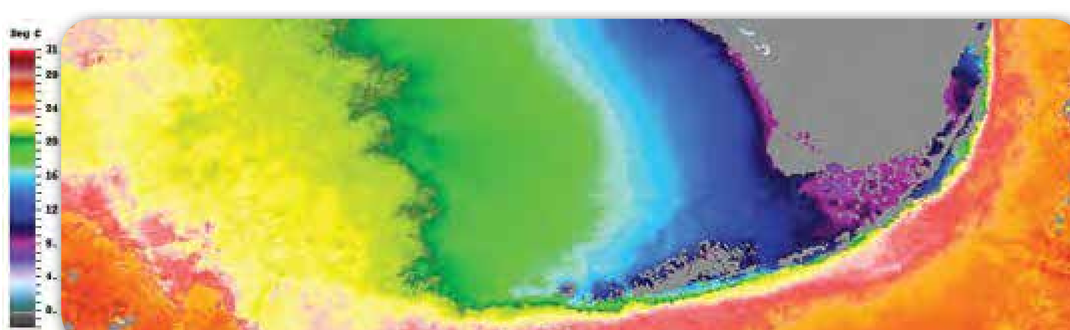
The ability to provide advanced warning of possible major coral bleaching events is important in sustaining healthy reefs. When coral reef managers and stakeholders are alerted to potential bleaching events, they can mobilize monitoring efforts, implement response strategies, and educate reef users and the general public on coral bleaching and the possible effects on the reef ecosystem.

The National Oceanic and Atmospheric Administration (NOAA) has partnered with researchers at the University of South Florida to develop a system for forecasting potential coral bleaching events. The NOAA Integrated Coral Observing Network system uses data (e.g., sea temperature, winds, light penetration) from local lighthouse stations and satellites to alert managers and scientists of the risk of coral bleaching. The forecasting system takes a page from artificial intelligence research, using a program called an expert system to model the way coral reefs respond to environmental extremes. As sea temperature extremes become more frequent and other stressors like pollution and other human activities affect coral reefs, forecasting coral bleaching becomes even more critical to managers. The goal of NOAA is to issue bleaching forecasts for coral reefs worldwide based on global high resolution satellite data.

Coral bleaching

Coral bleaching can be induced by:

- Increased or reduced water temperature;
- Increased solar radiation;
- Changes in water chemistry;
- Changes in local water circulation;
- Sedimentation; and
- Pathogenic infections.



C. Hu - USF

Satellite sea surface temperature composite for January 8 – 14, 2010, when extreme cold sea temperatures in shallow nearshore waters of the Florida Keys (blue color immediately adjacent to the Atlantic side of the Florida Keys) caused significant bleaching and mortality of corals. This image shows that reefs separated from one and another by only a few miles may experience very different temperatures.

Oceanic processes affect south Florida coral reefs

James J. Leichter

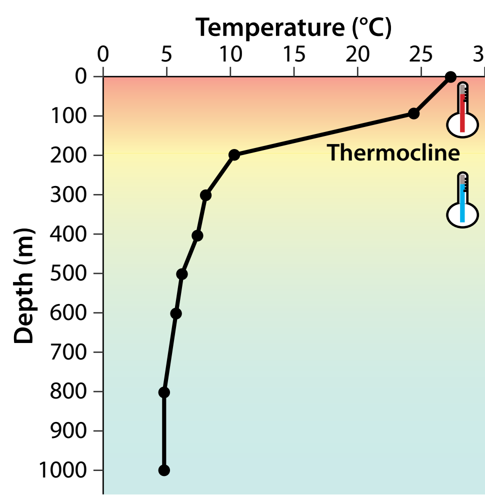
The oceanic environment plays a central role in shaping the biological communities of south Florida and the Florida Keys. A dominant feature of the system is the presence of strong and highly variable currents. The extensive flushing of water through the system is believed to contribute to high productivity and high rates of fish and invertebrate recruitment.

Close to shore (within a few kilometers of the shoreline), winds and tides drive circulation and exchange of water with inshore regions. The effects of freshwater runoff associated with strong rains and the tidal exchange of water from Florida Bay can be significant in the Florida Keys Atlantic Coastal Zone.

Further offshore, oceanic currents sweep over the shallow bank reefs and provide an oceanic influence and rapid alongshore transport of dissolved and suspended materials. The central axis of the Florida Current that sweeps past the Florida Keys and Atlantic coast of south Florida typically lies anywhere from 10 – 70 kilometers (6 – 43 miles) offshore because of the strongly meandering nature of the flow. Numerous eddies embedded in the northward flow can result in local reversals of the direction of the alongshore flow, lasting one to several days, and have been shown to be locally important in providing pulses of animal larvae arriving on shallow reefs. The total volume transported by the Florida Current varies seasonally (strongest in spring/ summer) and interannually.

Other important features of the oceanic environment that strongly influence the reefs of south Florida and the Florida Keys are the vertical stratification of water column temperature and density and subsurface internal waves. A typical vertical profile of the offshore water column shows warm surface temperatures separated from significantly cooler deeper waters by a region of rapid change in temperature with depth called a "thermocline." This thermocline typically is observed at depths of 50 – 80 meters (164 – 262 feet) in the Florida Keys.

The combination of vertical stratification, strong currents, and topographic features of the Florida Straits produces numerous internal waves at tidal and faster frequencies. Internal waves are vertical oscillations of the thermocline with amplitudes of up to tens of meters. These subsurface phenomena have a surface manifestation of parallel "slicks" separated by roughly 100 – 200 m (328 – 656 ft) and propagate toward shore. The slicks often contain surface concentrations of seaweeds and debris.

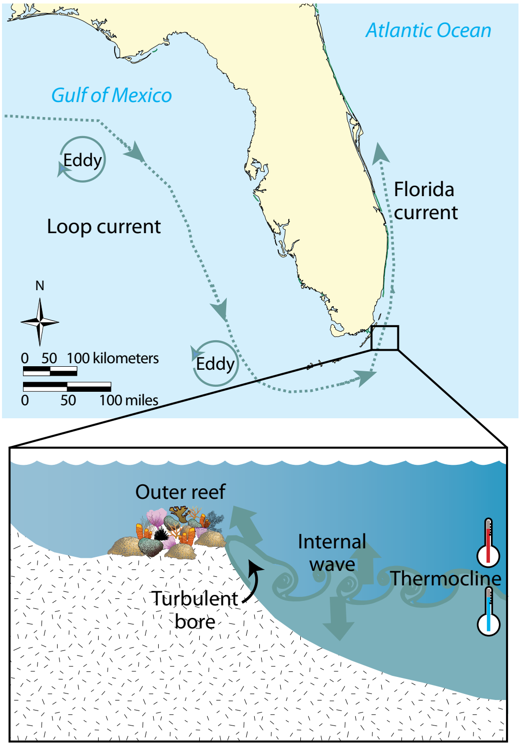


A thermocline is an area where the temperature changes rapidly with depth. Note the rapid change in temperature between approximately 50 – 150 m (165 – 500 ft). A thermocline causes vertical stratification of the water column, which means that it takes energy to mix the water from top to bottom.

When internal waves travel into shallow water, typically at depths of 10 – 30 m (33 – 98 ft) along the reef margin in the Florida Keys, they can strongly affect the temperatures and nutrient concentrations through upwelling of cold, nutrient-rich deep water. Temperature fluctuations as large as 5° – 8° C (9° – 14° F) on time frames ranging from minutes to a few hours are common along the entire region, especially during May – September. Drops in temperature are accompanied by marked increases in concentrations of dissolved inorganic nutrients and suspended particles. The upwelled water is rich in nutrients because of natural processes. When plankton and other organisms produced or living in surface waters die, they often sink toward the bottom. As these materials sink, they break down and get eaten and excreted, and the end result is the slow and continuous addition of nitrogen and phosphorus to waters with increasing depth.

Upwelled water flows onto the reef more often than people realize, sometimes several times a day. Although the biological effects of upwelling along the reef tract are not well understood, the presence of this cold, nutrient-rich water on the reef for extended periods of time has the potential to cause significant affects on ecological structure and biodiversity of the south Florida coral reef community. One indication of the prevalence of nutrient upwelling is widely distributed communities of large, densely packed macroalgae (seaweeds) observed at depths of 40 – 60 m (130 – 200 ft) on the slopes seaward of the bank reefs of the Florida Keys.

Strong bouts of internal tidal upwelling can deliver as much as 20 – 40 times more nitrogen and phosphorus to the outer reef tract than estimates of land-based nutrient pollution from sewage and stormwater runoff. However, this finding does not contradict that there are nearshore pollution problems in south Florida or that there is a need to better understand the dynamics of nearshore pollutants making their way offshore. Also, there are significant periods between upwellings and long periods in each year, particularly in October – December, when internal tidal upwelling is minimal. It is possible that



Internal tidal bores deliver cool, nutrient-rich water from the ocean depths to the outer reefs of the Florida Keys.

anthropogenic nutrient inputs may cause subtle alterations in baseline nutrient concentrations and shifts toward a more continuous, chronic nutrient availability in a system that is naturally characterized by large, but highly episodic inputs.

Global warming of surface waters may lead to increased water column stratification. A possible effect of increased stratification is an increase in the number of internal bores reaching Florida reef slopes and significant increases in reef slope nutrient availability. Another possible effect of climate change is a deepening of the surface mixed layer, which might result in internal bores occurring deeper on the reef slopes with reduced nutrient delivery into shallower water. Although the impacts of humans on the marine environments of south Florida are dramatic and complex, it is important to accurately assess effects of natural processes on the ecosystem.

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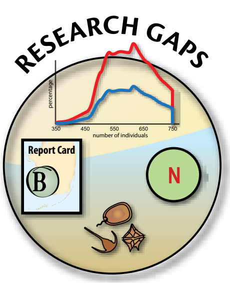
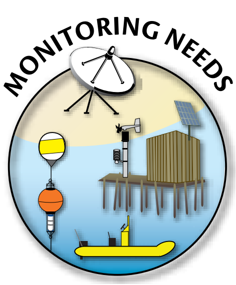
3. WATER QUALITY

Water Quality Chapter Recommendations

- Design management plans and actions to **address local priorities** with an awareness of potential impacts to other portions of the ecosystem.
- Support scientific research and monitoring to provide critical and current information required for effective **adaptive management**.
- Recognize that the ecosystem is affected by events that can not be effectively managed at a local scale, but that does not preclude taking action on stressors that can be controlled through sound, **local management strategies**.



- Establish **nutrient thresholds** and biocriteria to provide a scientific base for water quality standards.
- Quantify the effects of **nutrient and freshwater loading** on the species composition of phytoplankton and the effects of changes in species composition on the food web.
- Investigate distribution, concentration, and effects of **pharmaceuticals** discharged in wastewater on aquatic organisms.
- Assess the role of **human viruses and bacteria** on water quality, public health, and ecosystem functions.



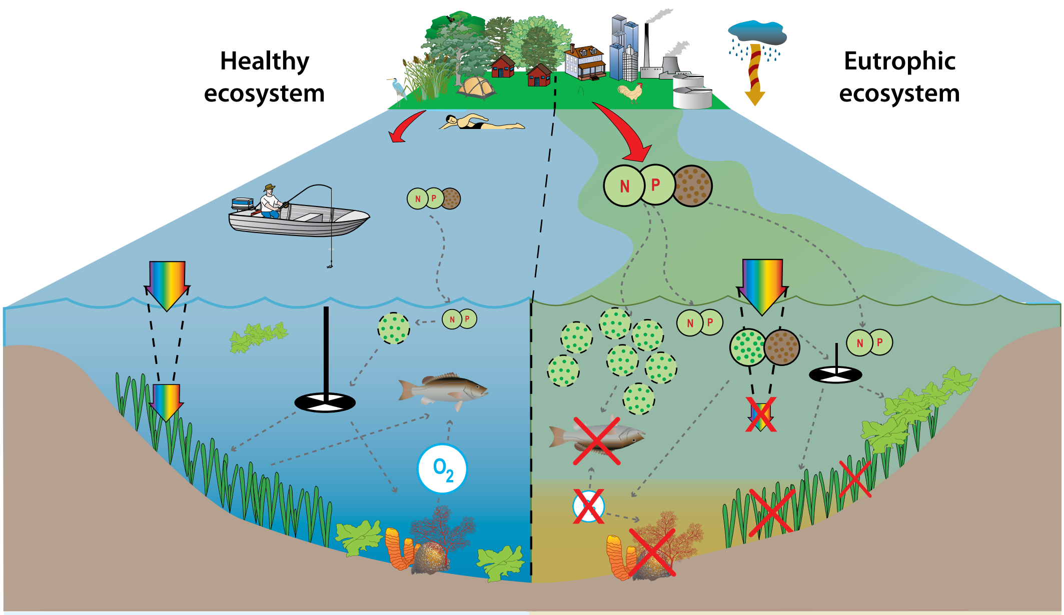
- Continue to conduct current **broad-scale water quality monitoring** to provide information on the status and trends of the ecosystem and long-term correlative data for physical and biological observations, and to help pinpoint sources of degradation to the water quality of south Florida.
- Implement monitoring programs on a sufficient scale to assess the effects of **improvements due to wastewater and stormwater infrastructure**.
- Advance tools for broad-scale monitoring to provide early warning of pollutants or **harmful algal blooms**.
- Integrate *in situ* and remote monitoring to allow rapid response to events, such as accidents, storms, or other **episodic events**.

Chapter title page: Water reflections. M. Stone, Mac Stone Photography.

Introduction

What is water quality?

"Water quality" is a term that summarizes the physical, chemical, and biological characteristics of a body of water.[1] The concept of what constitutes "good" water quality is based on several interrelated parameters, including how the water will be used (e.g., drinking, swimming, fishing); concentrations of materials in the water above natural background levels that could be deleterious to humans, plants, or animals (pollution); and the presence of compounds not usually found in the water (contaminants).[2] Section 304(a)(1) of the Clean Water Act requires the United States Environmental Protection Agency (EPA) to develop criteria for water quality that accurately reflect the latest scientific knowledge and protect the designated use.[3] The Clean Water Act and the Water Quality Standards



In healthy aquatic ecosystems, input of nutrients including nitrogen and phosphorus allow for the balanced growth of seagrasses and macroalgae (submerged aquatic vegetation), and phytoplankton (chlorophyll *a*). A low level of chlorophyll *a* in the water column helps keep water clarity high , allowing light to penetrate deep enough to reach submerged aquatic vegetation. Primary productivity by submerged aquatic vegetation and phytoplankton results in dissolved oxygen levels suitable for healthy fish and benthic communities and allows humans to enjoy the benefits of a healthy coastal environment.

In an eutrophic aquatic ecosystem, increased nutrient and sediment loads from land-based sources , including wastewater , agriculture, and stormwater, as well as nutrients dissolved in rainwater , can trigger blooms of phytoplankton and macroalgae . These blooms can result in decreased water clarity , decreased light penetration , decreased dissolved oxygen , loss of seagrasses , nuisance/toxic algal blooms, and the contamination or die-off of fish and benthic communities .

Adapted from Bricker et al. 2007.

Handbook (EPA-823-B-94-005) (epa.gov/waterscience/standards/handbook/) provide guidance to states and tribes in adopting water quality standards that must be reviewed and approved by the EPA.[4] There are three components to the water quality standards: 1) the designated use; 2) the criteria to protect that use; and 3) an antidegradation policy. Water quality criteria establish acceptable limits for materials found in water. The State of Florida water quality standards are found in Chapter 62-302 of the Florida Administrative Code.

Definitions of environmental water quality standards are based on conditions that may result in a change in the quantity or health of organisms that live in the water. However, because even pristine natural ecosystems undergo changes in response to natural variations and ecosystems gradually change over time (i.e., ecological succession), it is difficult to determine the exact point (i.e., threshold) that changes in water quality parameters begin to cause degradation of the ecosystem. In response to that problem, some states have adopted nonnumeric or narrative water quality criteria that use changes in biological communities to assess whether pollutants have reached concentrations that result in unacceptable changes to the natural ecosystem.[5] Two numeric water quality criteria are currently in place for marine waters of south Florida: a dissolved oxygen criterion and a fecal coliform bacteria criterion. Currently, the State of Florida is pursuing the development of numeric nutrient water quality criteria for all surface waters.

The state waters surrounding the Florida Keys have been designated as Outstanding Florida Waters (State of Florida Rule 62-302.700). By regulation, it is the policy of the Florida Department of Environmental Protection to afford the highest protection to Outstanding Florida Waters and to limit their degradation.[6] This designation of waters surrounding the Keys has resulted in the elimination of all direct surface water discharges of pollutants.

Eutrophication

Eutrophication has been defined as an increase in the rate of the supply of organic matter to an ecosystem. Eutrophication often progresses through a sequence of stages:

1. Enhanced primary production;
2. Changes in plant species composition;
3. Dense blooms of phytoplankton;
4. Death of cells causing the bloom;
5. Anoxic (no oxygen) conditions as organisms die;
6. Adverse effects on fish and invertebrates; and
7. Changes in the benthic community.[7]

Nutrients affect water quality

Too many nutrients

Nutrients, such as nitrogen and phosphorus, are essential for all living matter. Growth of plants is generally limited by the lack of one or more nutrients, and new plant growth depends on recycling of nutrients or receiving new nutrients from external sources. If new nutrients get into surface waters, they become available for use by the marine ecosystem. Small additions may cause inconsequential changes, but if continued or increased, they become pollutants as they disrupt the natural nutrient balance and cause unacceptable changes in community structure (e.g., algal blooms).

Generally, it is the total amount of nutrients entering a waterbody, not necessarily the absolute concentration, that can overload the ecosystem and cause changes. When the system can no longer absorb increased amounts of additional nutrients without significantly changing the structure and function of the ecosystem, the threshold of nutrient assimilative capacity is reached. The Total Maximum Daily Load for a waterbody is the total pollutant load that can be added and/or discharged to those waters without exceeding the ability of the waterbody to assimilate that load and still be in compliance with water quality standards.

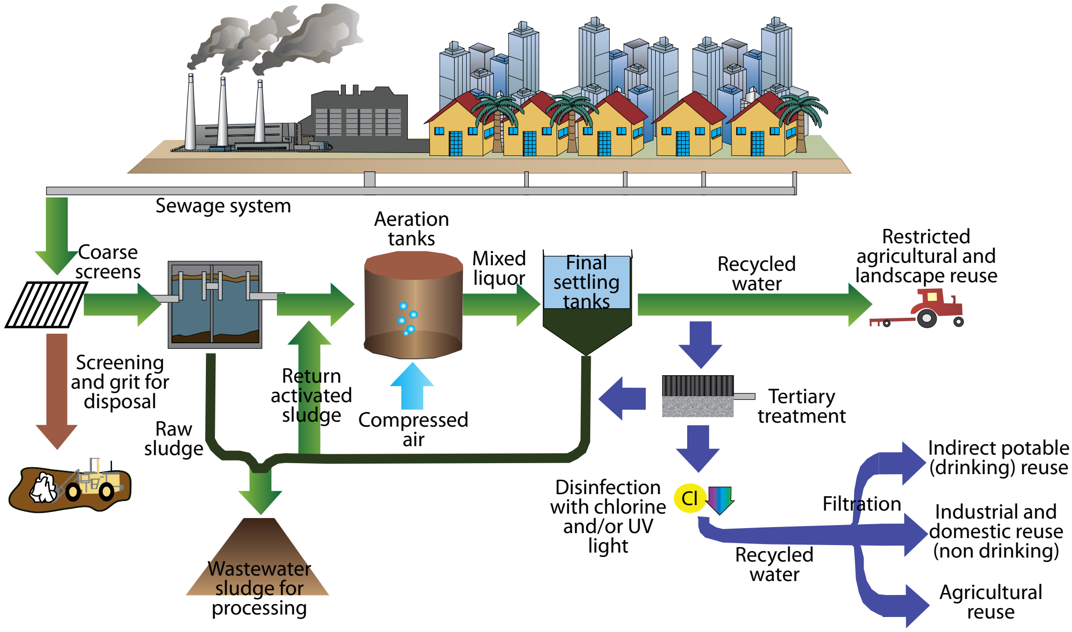
Nutrients may be limiting

Plants stop growing when they do not receive the required nutrients. The nutrient in least supply is called the "limiting nutrient." Florida Bay exhibits a gradient in limiting nutrients. To the west, phosphorus is plentiful from the waters of the Southwest Florida Shelf, and nitrogen is limiting. To the east, nitrogen is plentiful from water flowing from tidal creeks and through the mangrove fringe, mostly as dissolved organic nitrogen, and phosphorus is bound by the carbonate sediments and is not readily available.

Phytoplankton blooms in Florida Bay historically have developed in the central regions of the Bay when light, nutrients, or dissolved organic matter are not limiting. Diatoms dominate phytoplankton blooms in the western portion of the Bay where relatively high amounts of silicate from freshwater discharges occur. Phytoplankton dominated by diatoms support relatively healthy populations of large fish. Since the early 1990s, phytoplankton blooms in central Florida Bay are dominated by cyanobacteria that support a food chain consisting of smaller species of fish.

During road construction on U.S. Highway 1 entering the Florida Keys (18-Mile Stretch), water held in soils as well as freshwater runoff during Hurricane Rita (2005) resulted in large amounts of phosphorus being delivered to Barnes Sound and Blackwater Sound in the eastern portion of Florida Bay, an area normally limited by phosphorus. The results were a large and persistent phytoplankton bloom and seagrass mortality, probably from shading by dense phytoplankton concentrations.

In 2002, a plankton bloom, called a "blackwater event" because of its color in aerial photographs, formed on the Southwest Florida Shelf. Monitoring and remote sensing data revealed that it occurred as a result of a declining red tide event that moved south along the Southwest Florida Shelf at the same time that a seasonally occurring diatom bloom was triggered in western Florida Bay due to a normal, seasonal discharge from Shark River. This resulted in a large bloom consisting of a mix of toxic dinoflagellates (*Karenia brevis*, the red tide organism) and



Adapted from sewagetreatment.us

A modern central collection and wastewater treatment plant can remove nutrients from wastewater to very low levels (i.e., tertiary treatment) and provide recycled water for agricultural and landscape uses. Many older treatment plants do not provide this level of treatment.

diatoms and lead to the death of sponges and other benthic fauna over a large area.

Water column monitoring has shown that waters immediately adjacent to the Keys have significantly greater amounts of nitrate nitrogen than water farther offshore. There are two potential explanations for this. One is an excess supply of nitrate relative to phosphate. Another is nutrients from land-based sources.

Sources of pollution in south Florida waters

More than half of the coastal waters in the nation are moderately to severely degraded by nutrient pollution.[8] Nutrient pollution by nitrogen and phosphorus is the main cause of many coastal problems, including eutrophication, harmful algal blooms, dead zones, fish kills, some shellfish poisonings, and alteration of benthic community structure.

Nutrients and other pollutants can enter south Florida waters from nearfield and farfield sources. Nearfield sources include disposal of sewage (wastewater) and runoff from land (stormwater). Farfield sources include rainwater, air deposition, ocean upwelling events, and deliveries from remote waterbodies (e.g., Gulf of Mexico). Discharges of pollutants can also be classified as point sources and nonpoint sources. Point sources are discharges that occur out the end of a pipe or other fixed conveyance, such as an ocean outfall from a sewage treatment plant. Nonpoint sources occur as diffuse sources, such as stormwater washed off parking lots, highways, and lawns.[9]

J. Stamates - NOAA

Land-bases sources of pollution may enter coastal waters through navigation inlets, such as the water flowing out of Boynton Inlet on an ebbing tide.

A primary source of pollutants to coastal waters is from sewage. Septic tanks are wastewater systems for individual households (on-site systems) that can only remove a small amount of nutrients, even when properly installed with drainfields that consist of adequate soil to bind nutrients and keep them from entering surface or groundwater. However, septic tanks do not work well in rocky soils (e.g., Florida Keys) or areas with a high groundwater table (e.g., coastal areas), and they are a significant source of nutrient pollution in many locations. Cesspools are unlined holes in the ground into which wastewater is discharged; they are illegal and provide no nutrient removal. Neither septic tanks nor cesspools remove bacteria or viruses from their effluent.

Sewage treatment plants can be classified as package plants and regional plants. All sewage treatment plants are required to provide basic disinfection of their effluent before discharge. Historically, package plants provided treatment of sewage for facilities such as motels, condominiums, and restaurants throughout south Florida. In general, most package plants and small municipal plants settle and remove solids from wastewater but do not provide significant removal of dissolved nutrients from their effluent (i.e., secondary treatment). Advanced Wastewater Treatment plants do remove particulate and dissolved nutrients to very low levels (i.e., tertiary treatment). Some large municipal treatment plants in south Florida provide Advanced Wastewater Treatment.

Wastewater from septic tank systems and cesspools is disposed into the groundwater. Proximity of septic tanks and cesspools near open waters results in rapid movement of wastewater into surface waters, such as residential canals or other nearshore waters. Disposal from sewage treatment plants is permitted by the State of Florida and can be discharged directly into surface waters (open water

W. L. Kruczynski - EPA

Marathon Marina, Florida Keys, is a member of the Florida Clean Marina Program and provides pump-out services at each slip and for transient vessels. The Florida Clean Marina Program brings awareness to marine facilities and boaters regarding environmentally friendly practices intended to protect and preserve natural environment of Florida. Marinas, boat yards, and marine retailers qualify for the Clean Marina Program by demonstrating a commitment to implementing and maintaining best management practices.

discharge) or into shallow or deep injection wells.

Several large municipal treatment plants in southeast Florida have permitted open water discharges into the Atlantic Ocean and collectively have been discharging an average of about 1.4 billion liters (360 million gallons) per day of treated wastewater for decades. The outfall pipes discharge from 1.6 – 4.8 kilometers (1 – 3 miles) offshore within the zone of coral growth and the flow direction of the discharges is to the north, except when short-lived counter currents develop off the Florida Current. The ocean outfall at Delray Beach was eliminated in 2009; however, ocean outfalls remain at Miami-Dade Central, Miami-Dade North, City of Hollywood, Broward County, and Boca Raton. Significantly, the Governor of Florida signed a bill in 2008 that became the Leah Schad Memorial Ocean Outfall Program (Chapter 2008-323, Laws of Florida) that prohibits construction of new ocean outfalls and sets a timeline for elimination of existing wastewater outfalls by 2025. It also requires that wastewater previously discharged be beneficially reused. Implementation of this law will decrease potential harmful impacts to marine life and benefit onshore freshwater systems. The South Florida Coral Reef Initiative and the Florida Area Coastal Environment Program are monitoring to assess impacts of land-based sources of pollution to coastal waters of southeast Florida.

Injection wells provide a conduit for wastewater to the underlying deep groundwater. The groundwater in the Florida Keys flows toward the Atlantic Ocean. Nutrients in effluent injected into groundwater are diluted approximately one million to one before they reach surface waters.[10]

Disposal of wastewater from live-aboard and transient vessels is a localized problem in marinas or anchorages. Most marine sanitation devices on boats provide low levels of treatment (e.g., basic disinfection) and discharges may contain relatively high concentrations of nutrients as well as bacteria and viruses. Because of public health and eutrophication problems associated with these discharges, all state waters in the Florida Keys were declared a no-discharge zone in 2002, requiring that holding tanks on live-aboard vessels be pumped out and the effluent disposed at authorized facilities. Pumped out wastes are transported to land-based, permitted wastewater treatment facilities

S. Spring - Palm Beach County Reef Rescue

The Delray Beach ocean outfall discharged sewage wastewater into nearshore ocean waters for 45 years before it was retired in 2009.

for treatment and disposal. The National Oceanic and Atmospheric Administration has banned discharge from marine sanitation devices in federal waters of the Florida Keys National Marine Sanctuary.[11]

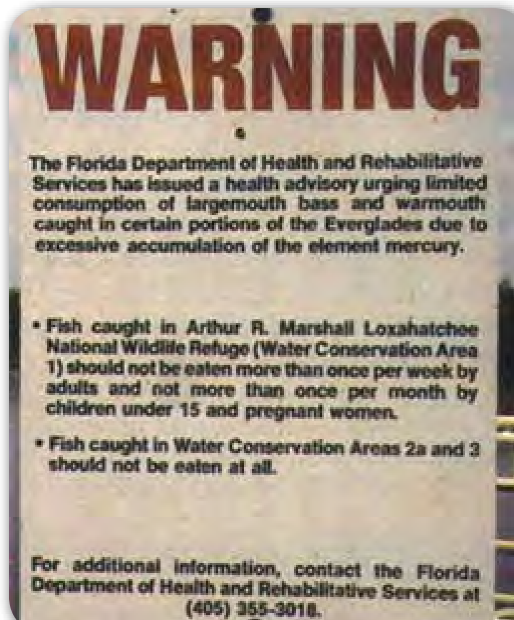
Stormwater is a major source of pollutants to surface waters nationally. Nonpoint source runoff typically contains substances such as pesticides, herbicides, organic debris, silt, nutrients, metals, and oils. The amount of pollutants entering surface waters from stormwater is largely a function of rainfall quantity, imperviousness of the substrate, and land use. In south Florida, the main pollutants include oil, greases, and heavy metals from roads, bridges, parking lots, and other paved areas and fertilizers, pesticides, and herbicides from developed and agricultural areas.

Weed wrack consists primarily of detached blades of seagrasses that are wind driven into floating mats. These mats can become trapped along shorelines and in canal systems and basins along the windward side of coastlines. Decomposition of weed wrack removes oxygen from the water, releases nutrients, and can form toxic hydrogen sulfide gas. Nutrient loading from weed wrack into canals and other nearshore waters has not been quantified.

Waters of south Florida are connected to other geographic areas by ocean currents. Total nutrient loads from farfield sources, such as the Gulf of Mexico and oceanic upwellings, may be greater than loadings from wastewater and stormwater. However, external nutrient inputs are usually more diffuse than land-based, human-induced sources. Currents can also deliver toxic contaminants, including pesticides, heavy metals, and oil from remote locations. There are few data documenting that threat, but vigilance and cooperation within the region are required to identify and minimize sources.

W.L. Kruczynski - EPA

Seagrass shed some of their leaves annually. Floating leaves (weed wrack) can accumulate in boat basins, residential canals, and along shorelines and are a source of organic loading to nearshore waters.



Florida Department of Health

Florida Department of Health issues warnings to limit the consumption of fish from areas contaminated with mercury.

Mercury is a toxic contaminant that is globally dispersed. Atmospheric deposition is the main source of mercury to marine waters in south Florida. Solid waste incinerators and coal-fired power plants are the main sources. Mercury is biomagnified through food webs and 12 states, including Florida, have statewide advisories for mercury contamination of fish in their coastal waters.[12]

Other heavy metals have not been a concern in south Florida waters. Pesticides, including chemicals used in mosquito control, are known to be toxic to aquatic organisms. However, there is little information on the amount and effects of residual pesticides that reach marine waters.

Water pollution problems and solutions for south Florida

There are three main problems with wastewater pollution of surface waters: fecal contamination (e.g., health risk); nutrient enrichment and organic loading (e.g., eutrophication, low dissolved oxygen); and presence of pharmaceuticals and personal care products, including endocrine disruptors. Presence of total fecal coliform bacteria above the State of Florida standard (200 colonies per 100 milliliters [3.4 fluid ounces] of water, monthly average; sample maximum 800 colonies/100 ml) is indicative of contamination by untreated or inadequately treated sewage and is a public health concern.[13] However, the fecal coliform standard was developed for freshwater, and its use for marine waters is less than ideal. Several states have adopted an *Enterococcus* bacteria standard that may be a better indicator of fecal contamination in marine waters.[14] Recent results suggest that replacement of a total coliform standard with an enterococci standard would be more protective of public health.[15] Normally, when fecal coliform bacteria are present

M. White - FKNMS

Tropical marine coral communities have evolved and thrive in clear waters with relatively low concentrations of nutrients.

in marine waters, it is an indicator of very recent fecal contamination. Low concentrations of fecal coliform bacteria should not necessarily be equated to low abundance of bacterial or viral pathogens.

Fecal bacteria are found in residential canals and marinas. Because animals (e.g., dogs, raccoons, birds) have coliform bacteria in their feces, analyses of chemical "fingerprints" of the bacteria are required to determine their sources. Because most viruses are species specific, use of human intestinal viruses is a more reliable indicator of human fecal contamination. Eighteen of 19 nearshore and canal locations sampled in the Keys and groundwater samples at the bank reef off Key Largo were found to contain human pathogenic viruses.[16]

Based on evidence that poor water quality in the nearshore waters of the Florida Keys is related to poor wastewater management, the Florida Legislature passed 99-395 Laws of Florida, requiring that all sewage facilities in Monroe County, including septic tanks and cesspools, upgrade and comply with promulgated treatment and disposal standards by July 1, 2010. The treatment and disposal standards conform to readily available, cost effective technologies that are used elsewhere in Florida, including Tampa Bay and the Indian River Lagoon. Although progress is being made, many municipal facilities in Monroe County remain incomplete, and the deadline has been extended until 2015.[17]

Tropical marine coral, hardbottom, and seagrass communities have evolved and thrive in relatively low nutrient (i.e., oligotrophic) conditions. Integral species in these communities efficiently absorb low concentrations of nutrients and outcompete other less adapted species. It has been argued that nutrient overenrichment is a major cause of the worldwide coral reef decline because of observations that degraded coral reefs exhibit a shift from high coral cover with low algal cover to low coral cover with high algal cover. But are the algae causing the coral decline? The extent to which nutrients are related to coral decline is the subject of much debate. Overenrichment can be the cause of localized reef degradation. Other factors such as decreased abundance of grazing fish and sea urchins and temperature stress (e.g., bleaching) may create more open substrate for algal colonization. Sedimentation can weaken corals and prevent recruitment. Coral diseases can affect corals weakened by bleaching or other stresses. Impacts that lead to coral death as well as those that reduce herbivory leave substrate open to colonization by algae and/or make effects of low level enrichment more severe.[18] Because the uptake of nutrients in an oligotrophic system is rapid and turnover of nutrients is very efficient, nutrient concentrations in the water over reefs receiving enrichment can be quite low and may not be detectable using traditional water quality analyses.

C. Kelble - NOAA

Researchers sampling water quality in Florida Bay.

Several different scientific studies have been performed in the Florida Keys to determine whether nutrient enrichment from land-based sources is impacting the bank reef. Water quality monitoring has provided ample evidence demonstrating that canals and other nearshore waters have high nutrient, chlorophyll, and bacteria concentrations that are the result of poor wastewater and stormwater treatment practices on land. Evidence is mounting that seagrasses at some nearshore locations in the Keys are experiencing nutrient enrichment, and as a result, benthic macroalgae are increasing in some locations. Analysis of surface water quality data in the Florida Keys demonstrates that inorganic nitrogen is greatest nearshore and decreases toward the outer reef tract, suggesting a land-based source.

However, results of other methods suggest that sewage from the Keys is reaching offshore reefs. Studies investigating the distribution of human pathogenic viruses have demonstrated that groundwater at the bank reef off Key Largo contains human viruses.[19] It is believed that the viruses found can come only from human sewage through the groundwater. Thus, groundwater containing diluted nutrients may reach the bank reef. This observation is supported by finding human viruses in the mucus of corals growing on the bank reef.[20] Coral mucus acts as a culture medium for bacteria and viruses. Thus, it appears that there may be conduits of rapid transport of groundwater from shore to the Florida Keys Reef Tract, but nutrients from wastewater are very diluted and may be rapidly taken up when they reach surface waters.

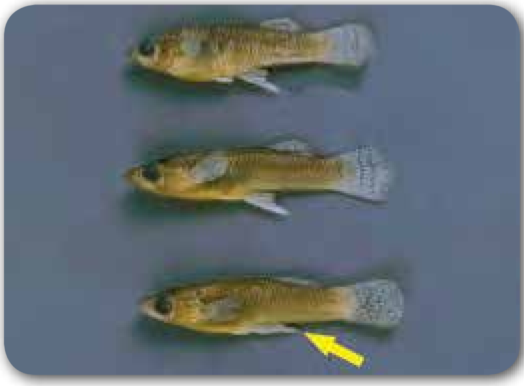
Recognizing the importance of reefs in southeast Florida, the South Florida Coral Reef Initiative formed a Land-Based Sources of Pollution Focus Team to addresses impacts to corals resulting from both point and nonpoint land-based pollution sources, and a Local Action Strategy was developed.[21] Projects in the Local Action Strategy focus on characterizing the extent and condition of the coral reef community, and quantifying, characterizing, and prioritizing the land-based pollution sources. Results will lead to the development of strategies that will reduce the impacts of land-based sources of pollution. Increased public awareness and understanding of the effects of these sources of pollution on water quality and coral reefs are essential to successful implementation of the strategies.

There is a widespread occurrence of low concentrations of pharmaceuticals, hormones and their metabolites, and other chemicals in the aquatic environment. Their source is from human usage, discharges, and excretions. Over-the-counter and prescription medications are present in human sewage and can contaminate receiving waters. Fungicides, disinfectants, and veterinary products are also common.[22]

Pharmaceuticals, steroids, and personal care products were found to be common in the Miami River and a canal system in the Florida Keys. Caffeine and cholesterol were particularly ubiquitous, and higher concentrations of caffeine were linked to locations with documented water quality problems. Thus, caffeine may be a particularly good indicator of sewage contamination.[23]

Some compounds found in water are known or suspected endocrine-disrupting chemicals. Endocrine disruptors are chemicals that may interfere with the endocrine (i.e., hormonal) system and produce adverse developmental, reproductive, neurological, and immune effects in both humans and wildlife. A wide range of substances, both natural and humanmade, can cause endocrine disruption. Endocrine disruptors may be found in many everyday products, including plastic bottles, metal food cans, detergents, flame retardants, food, toys, cosmetics, and pesticides. Endocrine disruptors may result in human health effects, including lowered fertility. Their effects on aquatic organisms include disruption of breeding cycles and changes in sex.[24, 25,26]

Other changes in water quality can result in dramatic changes to an ecosystem, such as changes in temperature, salinity, and turbidity. Turbidity decreases with distance from shore. Channels and passes throughout the Florida Keys had higher nutrient concentrations, phytoplankton, and turbidity than areas located off land.



S. A. Bortone - GCMFC

A dramatic effect of endocrine disruptors that occur in water is their ability to disrupt endocrine-mediated processes, such as reproduction, including sex determination and development of sexual characteristics. The three female mosquito fish (*Gambusia affinis*) have been "masculinized" and have developed an elongated anal fin (i.e., gonopodium) (yellow arrow) that is an organ normally used by male fish for sperm transfer. Masculinized female mosquito fish were first observed in a coastal stream receiving paper mill effluent. The effluent contained steroid analogs and precursors that adversely affected hormonal pathways.

Florida Bay has been a source of nutrient-rich and turbid waters to the Florida Keys for the last few thousand years.

Prior to the construction of the extensive drainage canal network in south Florida, offshore springs discharged large quantities of fresh groundwater into Biscayne Bay as either spring flow or the continuous seepage of fresh groundwater along the coast. When drainage canals were constructed to reduce flooding in the area, the mechanism for transporting water to the Bay was significantly altered, and rather than receiving a continuous supply of fresh groundwater, Biscayne Bay now receives wet season pulses of canal discharge. The change in timing and location of freshwater flow to the Bay has harmed the Biscayne Bay ecosystem. Organisms that live there have either adapted to wide fluctuations in salinity, flee when conditions become unfavorable, or die.[27] It is hoped that completion of the Comprehensive Everglades Restoration Plan will restore the quantity, quality, timing, and distribution of freshwater flows to downstream sources, including Florida Bay and Biscayne Bay.

Water quality is monitored to assess environmental conditions

Christopher Kelble, Cynthia Heil, and Patricia M. Glibert

All living things on Earth need water to survive. Our bodies are made up of more than 60% water, and we need clean water to drink, grow crops, swim, surf, fish, and sail. Water quality measurements provide an indicator of the nature and health of an ecosystem. Monitoring water quality characteristics allow scientists and managers to keep their "finger on the pulse" of the ecosystem and are determined by measuring a variety of water quality parameters. Measurements allow ecosystem managers to take action prior to ecosystem collapse.

Why we measure water quality

- Establish baseline conditions;
- Detect long-term trends;
- Determine suitability for uses;
- Check compliance with standards; and
- Ensure public health safety.

Most people recognize degraded water quality by characteristics such as discolored water, algal scums, and odors. But degraded water quality may not be easily recognized. For example, contamination by pathogenic bacteria and viruses may make water dangerous for swimming, but the risk is not recognizable without laboratory testing.

Water quality is also a measurement of the ability of the aquatic system to support beneficial uses. Because many systems differ greatly in their use, what constitutes good water quality is site specific, and water quality is judged by the particular purpose for which the system is being used. In fact, the United States Environmental Protection Agency identifies designated uses (e.g., fishable, drinkable, swimmable) when setting targeted levels for individual water quality parameters. If the water is to be used

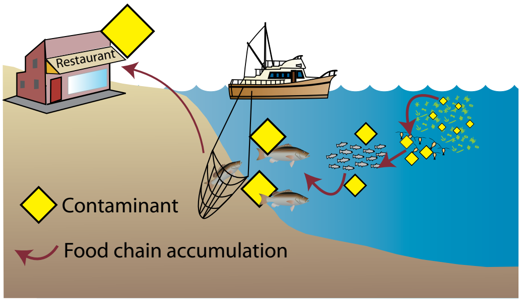
Commonly measured water quality parameters

- Temperature
- Salinity
- pH
- Turbidity
- Light attenuation
- Dissolved oxygen
- Chlorophyll *a*
- Total organic carbon
- Total organic nitrogen
- Total nitrogen
- Total phosphorus
- Nitrate
- Nitrite
- Ammonium
- Silicate
- Fecal coliform bacteria

for drinking, a specific set of chemical parameters are well defined. Waters used by fishing or shellfishing industries are characterized by parameters required to maintain healthy fisheries. For recreational purposes, such as boating, good water quality enhances the aesthetic experience.

Factors that contribute to degraded water quality can be related to both natural processes and influences of human activities. Many lakes naturally go through a life cycle in which the lakes slowly fill in over geological time. However, that process may be accelerated by human activities, such as those that result in the delivery of increased nutrients to the lake.

In coastal marine systems, human activities, such as population growth and development, often have a detrimental impact on coastal water quality. Increased or changing nutrient delivery can result in algal blooms that discolor the water and decrease light penetration, in turn affecting benthic communities, including seagrasses.



Water quality monitoring can detect contaminants, such as mercury, that can become biomagnified through food webs and is toxic to consumers.

Poor water quality conditions can affect humans in many ways. For example, bathing in waters containing harmful bacteria or consumption of seafood from areas with poor water quality can cause sickness and disease. Contaminants such as heavy metals can be concentrated in seafood through a process called biomagnification.

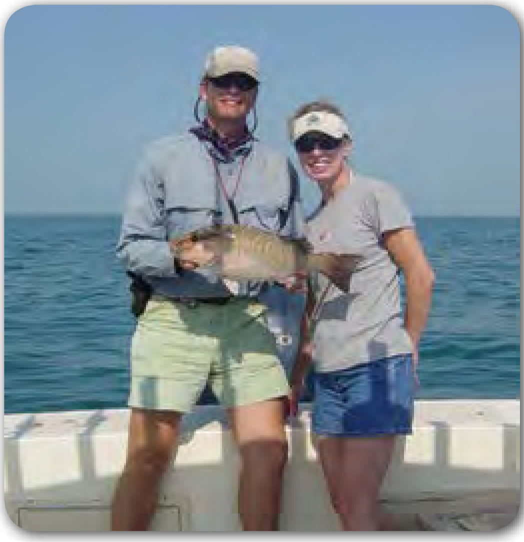
Different ecosystems have different characteristic water quality regimes. In south Florida, the coastal marine ecosystem is primarily oligotrophic, with low nutrient and chlorophyll concentrations. As such, this ecosystem responds rapidly and significantly to nutrient loads that would be considered small in many other regions. Water quality in the south Florida marine ecosystem is directly influenced by runoff from natural areas, such as creeks and streams, the nearby Everglades ecosystem, and from surrounding urban areas (land-based sources). A comprehensive water quality monitoring program is required to identify and track, and ultimately control, sources of nutrients and other contaminants that enter these waters.

Water quality in south Florida is generally good compared with other areas of the Atlantic coast, even with the major landscape changes that have occurred in south Florida. Recently, seagrass die-off and algal blooms have resulted in degraded water quality in Florida Bay. Given the landscape changes to the watershed, returning Florida Bay to nondegraded conditions is a major challenge of the Comprehensive Everglades Restoration Plan. Completion of the plan is likely to alter the south Florida marine ecosystem. The United States Commission on Ocean Policy concluded that long-term water quality monitoring is the best measure to provide accountability for management actions. Water quality monitoring in the south Florida marine ecosystem must be used to adaptively manage the restoration process to ensure that the most beneficial outcomes are achieved.

Water Quality

R. Butler

Poor water quality conditions can result in fish kills.

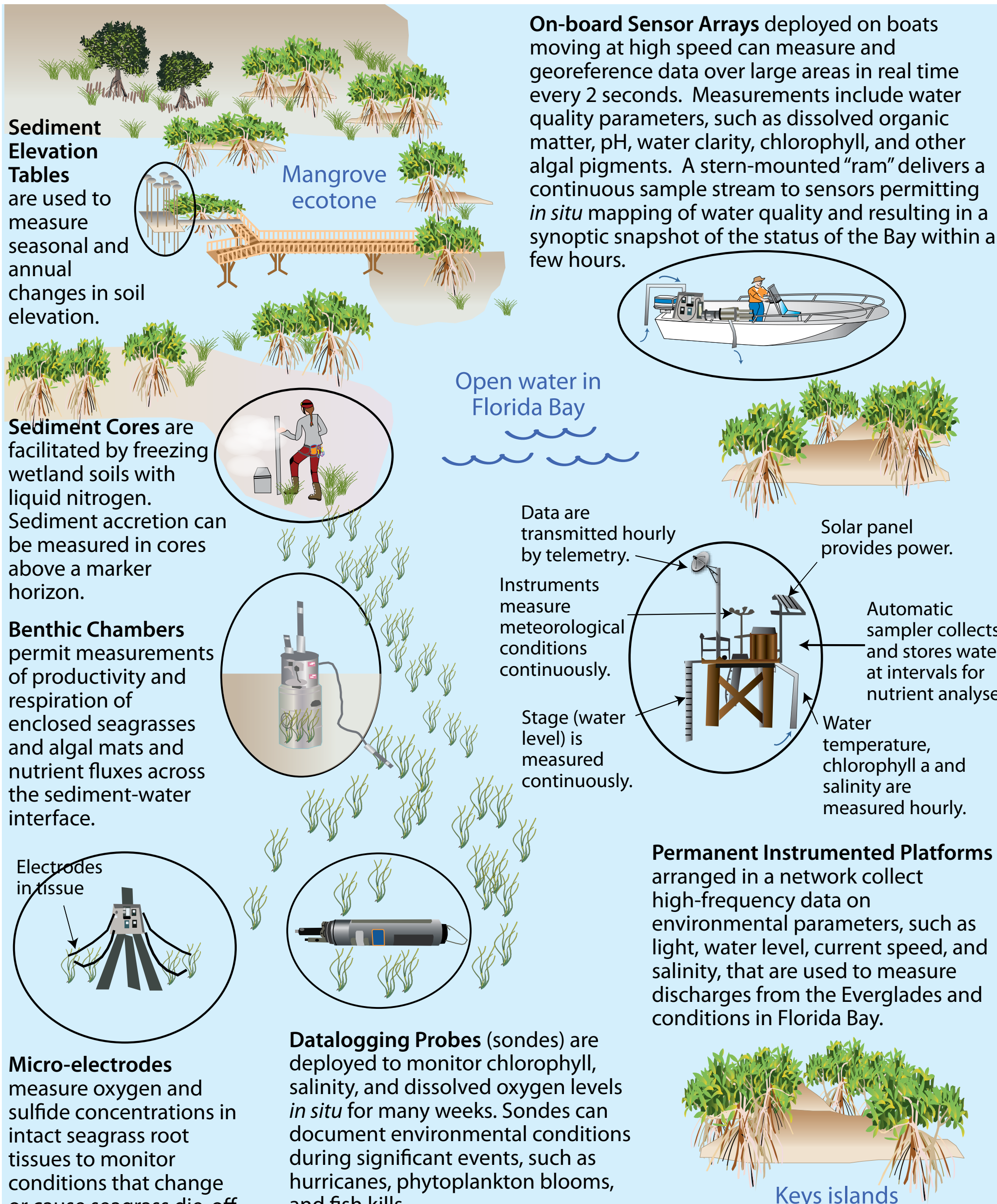


J. Teague - Finatic Charters

Good water quality is required to meet the standards of fishable, drinkable, and swimmable waters.

Field measurements are collected to assess water quality and environmental conditions

Christopher J. Madden and Kevin M. Cunniff



A number of technology tools are used to collect data on various aspects of Florida Bay, including real-time mapping, short-term measurement of ecological processes, and mid- and long-term instrument deployments to capture ecosystem metabolism, rate processes, and episodic events. A network of instrumented platforms monitors long-term water quality, environmental conditions, and system status.

Nutrients are important water quality parameters

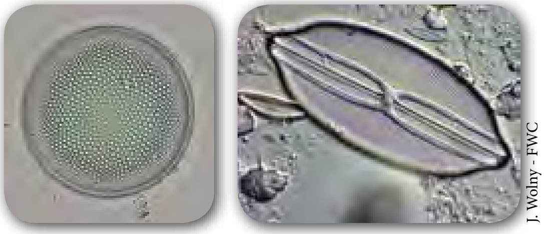
Patricia M. Glibert and Cynthia Heil

Nutrients are essential elements for life. Both plants and animals require a variety of chemical elements and vitamins to grow, maintain their metabolism, and reproduce. Animals ingest their required nutrients; plants absorb them through their cell walls, roots, and leaves. The major nutrients are nitrogen, phosphorus, and carbon as well as sulfur, silicon (for some plants), calcium, magnesium, iron, and potassium, among others. When these nutrients are not sufficiently available to meet the needs of plants or animals, they are considered to be limiting for growth or production of new biomass. The nutrients of major concern for water quality are nitrogen and phosphorus.

Liebig's Law of the Minimum (1840)

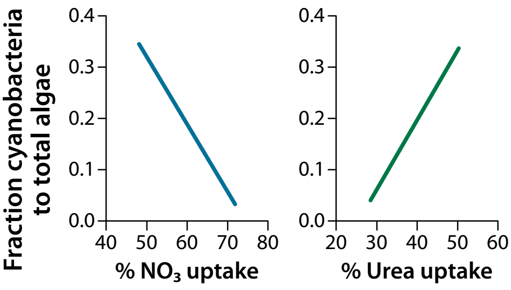
This law states that the nutrient available in the least quantity relative to the needs of the organism is the growth-limiting nutrient.

Nitrogen and phosphorus are nutrients that are present in the environment in a variety of forms. The atmosphere is comprised of about 78% nitrogen in the form of nitrogen gas (N_2), but this form is only available to organisms that have the unique capability to "fix" this gas (e.g., legumes, some bacteria) into more chemically active forms. The most common available form of nitrogen is nitrate (NO_3^-), but nitrite (NO_2^-) or ammonium (NH_4^+) are also common biologically available forms. Nitrogen can be found complexed to other elements, forming large molecules that may or may not be biologically available. Such complex molecules include urea, amino acids, proteins, pigments, and humic acids. Unlike nitrogen, phosphorus is not available as a gas. Phosphate (PO_4^{3-}) is the most common biologically and chemically available form, and phosphate can be complexed by other molecules.



Diatoms are common unicellular planktonic plants in south Florida waters. The cells are encased with unique cell walls (frustules) made of silicate (silicic acid).

Different plants and animals have different requirements for nutrients as well as different nutrient preferences. Furthermore, the proportion in which they are available is important to their growth. By way of analogy, when fertilizers (i.e., nutrients) are applied in gardens, it is common to use different formulations, depending on whether one is growing grass, tomatoes, or roses. Preferences also exist even within the microbial plants. Some, such as diatoms, have an absolute requirement for silicon, whereas other microscopic plants, such as dinoflagellates, do not. Some diatoms also tend to prefer nitrogen in the form of NO_3^- whereas dinoflagellates typically prefer nitrogen as NH_4^+ or urea.



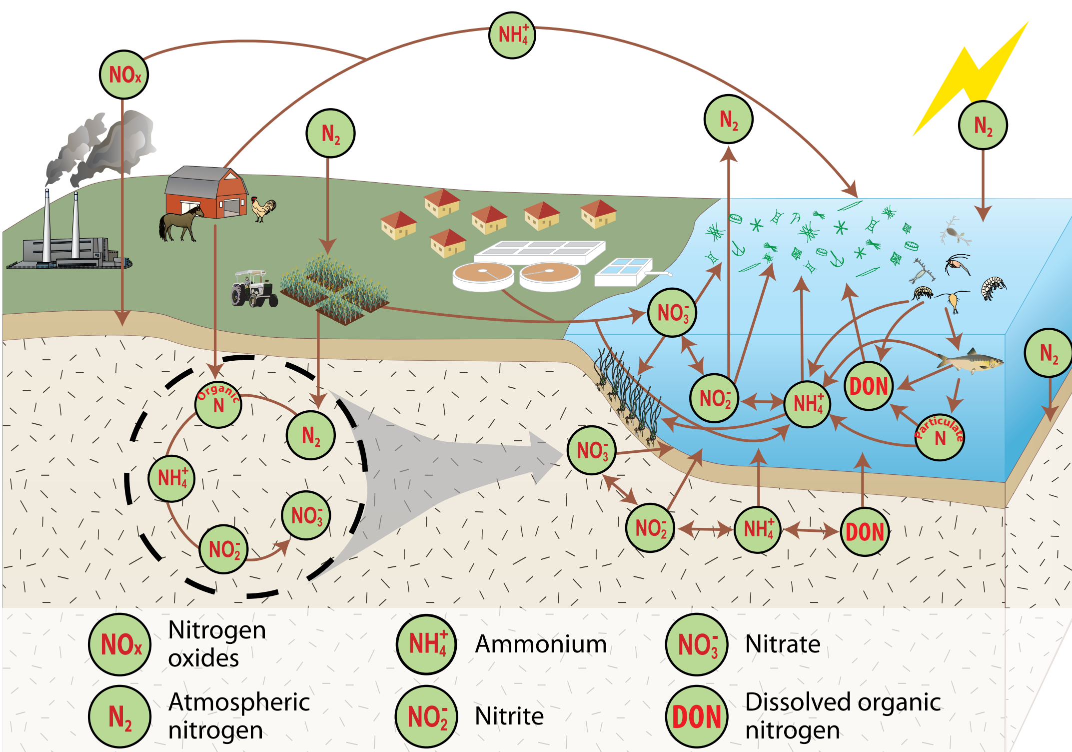
Cyanobacteria, such as *Synechococcus*, have a preference for urea over nitrate (NO_3^-). These data from eastern Florida Bay show that NO_3^- uptake is high when the fraction of cyanobacteria is low, but that urea uptake is proportionately high when cyanobacteria make up a higher proportion of the total algal community.

Nutrients cycle through the environment

Patricia M. Glibert and Cynthia Heil

Nutrients cycle through the air, land, and water in various forms. Most transformations are mediated by biological activity, particularly by microbes. Nitrogen and phosphorus are two nutrients that are important in biological processes and ecosystem structure and function.

Nitrogen gas (N_2) makes up approximately 78% of the atmosphere on Earth. It is converted by some plants (e.g., legumes) and nitrogen-fixing bacteria into ammonium (NH_4^+). Ammonium may be taken up directly by plants, including phytoplankton, but a large fraction is nitrified by bacteria to nitrite (NO_2^-) and eventually nitrate (NO_3^-). Both forms of nitrogen also may be used directly by plants. Once in plants, nitrogen is used to manufacture proteins, DNA, and other molecules needed to sustain life. Plant nitrogen is consumed by animals, and eventually excreted or released as organisms die and decay. Some of the released nitrogen may be in the form of fairly complex molecules; some molecules can be broken down and taken up directly by plants, and some cannot. Some of NO_3^- also may be denitrified by microbial activity and released to the atmosphere as N_2. The process of denitrification, however, yields many intermediate nitrogen



Nitrogen cycle: Nitrogen gas in the atmosphere is fixed by some plants and nitrogen-fixing bacteria into ammonium. Ammonium can be taken up by some plants or converted to nitrate and taken up. Some nitrate is denitrified and released back to the atmosphere as nitrogen gas. Animals excrete nitrogen in waste products and as plants and animals die and decompose, ammonium and other nitrogen compounds can enter the cycle. Too much nitrogen can cause eutrophication of waters.

compounds during the conversion from NO_3^- to N_2. Nitrous oxide (N_2O) is one such compound and is a greenhouse gas.

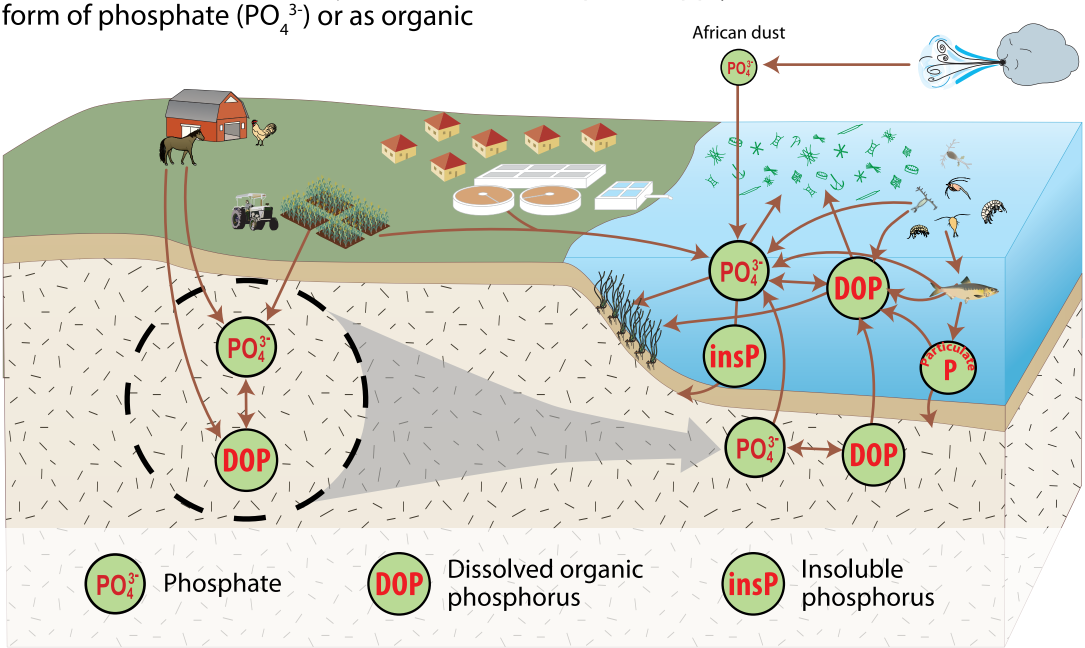
Nitrate accumulates in deep ocean waters over long periods of time. When that water reaches the surface through upwelling, it is taken up by algae and other plants and represents a new form of nitrogen to the surface waters. In contrast, ammonium generally is considered to be a regenerated form of nitrogen because it is continually recycled in water by microbial grazing and release of nitrogen by consumers.

Unlike nitrogen, there is no gaseous form of phosphorus. The major phosphorus reservoirs are in guano deposits (i.e., bird droppings) and in rocks. Phosphorus can be released from rocks through weathering and leaching and may be carried by runoff to waters. Mining of phosphorus for fertilizer has increased its availability in the environment. Phosphate like nitrate also accumulates in the deep ocean over time.

Phosphorus is taken up by plants in the form of phosphate (PO_4^{3-}) or as organic phosphorus, passed through the food chain, and released by excretion and decomposition. When plants and animals die, bacteria decompose their bodies, releasing some of the phosphorus back into the soil or water.

Human activities are causing changes to the nitrogen and phosphorus cycles and the amount of nutrients that are stored in different reservoirs. The industrial manufacture of fertilizer converts N_2 to ammonia (NH_3). The rate of industrial production of fertilizers has escalated in recent decades, and this pathway now exceeds natural fixation as the major path by which N_2 is removed from the atmosphere. Additionally, humans are altering the nitrogen cycle by burning fossil fuels and forests, which releases N_2O and other forms of nitrogen to the atmosphere.

The use of fertilizers can cause nutrient loading as they wash into nearby waterbodies. The increased nutrient levels cause plants to grow rapidly until they use up the supply of nutrients.



Phosphorus cycle: Main reservoirs are rocks and bird guano deposits. Phosphate can be dissolved by water and be available for uptake by terrestrial or aquatic plants. Plants are eaten by animals and release particulate organic phosphorus that can be recycled or deposited in sediments and become incorporated into sedimentary rock.

Too many nutrients result in eutrophication

Patricia M. Glibert and Cynthia Heil

Eutrophication means an increase in the rate of supply of organic matter to an ecosystem. The term is used in ecology to describe the natural aging of ecosystems, such as lakes. The natural fate of a deep, nutrient-poor (i.e., oligotrophic) lake is to accumulate organic matter and become nutrient-rich (i.e., eutrophic), which over geological time scales leads to the development of a pond and eventually a marsh ecosystem. The term eutrophication is also used to describe the process of nutrient pollution by humankind (i.e., when excess nutrients are added to an ecosystem, resulting in an increase in primary productivity or algal biomass). An overgrowth of plant material, including phytoplankton, can detrimentally alter an ecosystem in multiple ways. Excess phytoplankton (i.e., blooms) may die and decompose, leading to the loss of oxygen in the water (i.e., hypoxia), and smother and kill corals, sponges, and other organisms, resulting in an alteration of the entire structure and function of the ecosystem. Eutrophication is a process, not an endpoint.

Human activities can accelerate the rate at which nutrients enter ecosystems, and there are many sources of nutrients that can lead to eutrophication. Runoff from agriculture and development, pollution from septic systems and sewers, and other human-related activities increase the inputs of both inorganic nutrients and organic substances into terrestrial and aquatic ecosystems.

Eutrophication

"The numbers and kinds of plants in the Bay are controlled, principally, by the abundance of the several kinds of nutrients and, to a lesser extent, by the forms in which they are present. Fertilizer is good, more fertilizer is better, but only up to a point. Once the 'broth' becomes too rich, the composition of species alters. The balance is delicate, and changes can be rapid…More is no longer better. Enrichment has become eutrophication." (J.R. Schubel, 1981)

W. L. Kruczynski - EPA

Excessive fertilization can disrupt the structure and function of aquatic ecosystems by causing excess primary productivity as evidenced by this eutrophic pond.

Eutrophication of waterbodies can be caused by both nonpoint (e.g., land runoff) and point sources of pollution containing phosphorus and nitrogen. Humankind has increased the rate of phosphorus loading to coastal waters by 4 times, and that of nitrogen by about 20 times, mainly due to agricultural fertilizer production and application. From 1950 – 1995, 544 million metric tons (600 million tons) of phosphorus were applied to the Earth surface, primarily on croplands. Nearly half of the nitrogen fertilizer in the world has been produced since 1985. Much of the excess fertilizer finds its way into groundwater and surface waters and causes eutrophication of receiving waters. Elevated atmospheric compounds of nitrogen from burning fossil fuels can increase nitrogen availability.

Stringent regulatory controls of point and nonpoint sources are required to minimize excess nutrient pollutants from entering waters. The goal of these regulations is to improve the water quality so that the waters remain or become fishable, swimmable, and drinkable resources for future generations.

Florida Bay receives nutrients from many sources

David T. Rudnick, Stephen P. Kelly, and Robin Bennett

Nutrient availability for primary producers and nutrient dynamics in Florida Bay are driven by the exchange of nutrients with adjacent regions and internal nutrient cycling. Nutrients enter the Bay from the south Florida peninsula via freshwater flow through the Everglades and adjacent canals, the Gulf of Mexico, the Atlantic Ocean, the Florida Keys, groundwater, and the atmosphere (via rainfall). Nitrogen and phosphorus are key nutrients that typically limit estuarine productivity and can determine the ecological condition (i.e., health) of the Bay. Excess phosphorus and/or nitrogen can fuel phytoplankton (i.e., microalgae) blooms and can cause the Bay to shift from a seagrass-dominated system to a system where algae in the shallow water column dominates visually and ecologically. In much of Florida Bay, productivity is limited by phosphorus availability, but nitrogen also can be an important determinant of Bay condition.

Very little phosphorus enters Florida Bay from the Everglades; the overwhelming source of phosphorus is derived from the inflow of Gulf of Mexico waters. The amount of phosphorus from the Gulf has been estimated using computer models of water exchange, and concentrations decrease in Florida Bay from west to east, consistent with the estimated importance of the Gulf source.

Nitrogen inputs can be from many sources. Nitrogen inputs from the Everglades can be significant, with estimated values roughly similar to those from the atmosphere and Gulf of Mexico. However, most nitrogen from the Everglades is in a dissolved organic form and not readily available for uptake by algae or seagrass. Within the Bay, dissolved organic nitrogen can be transformed by biotic and abiotic processes, making it available for uptake.

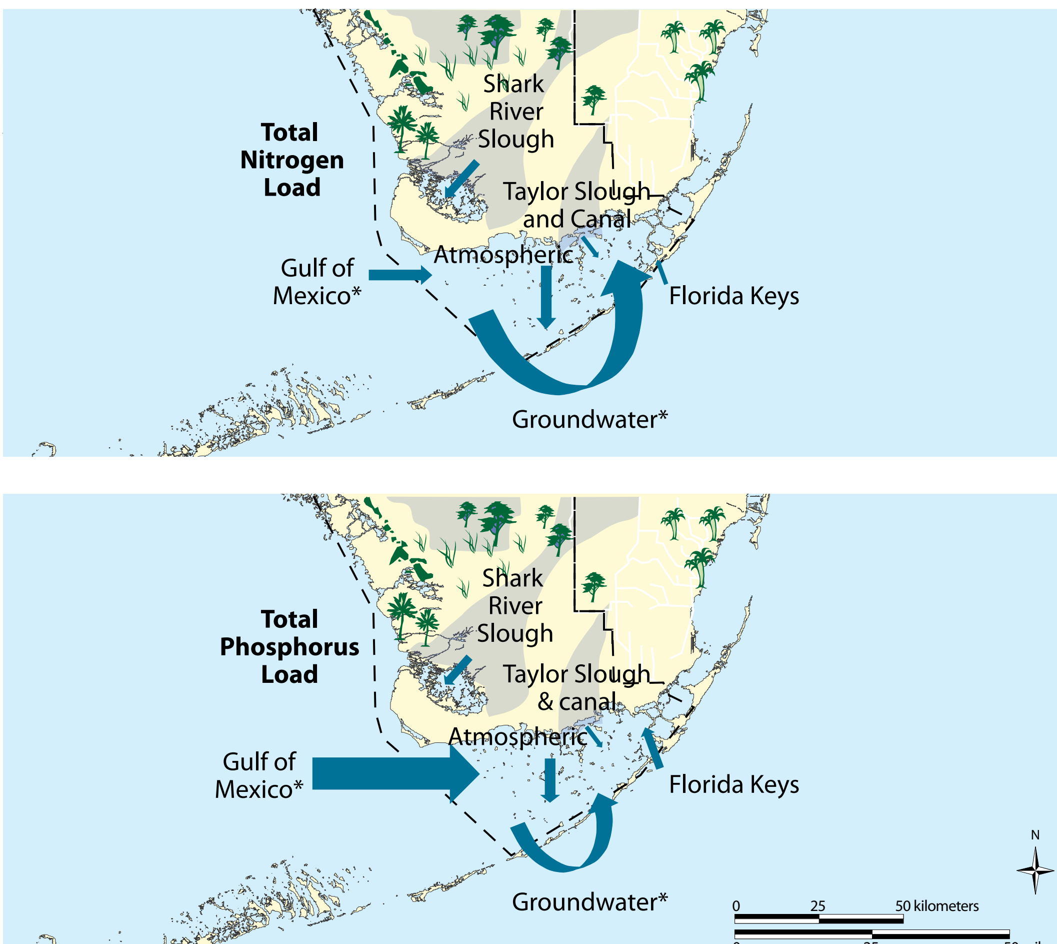
NASA

Florida Bay can be divided into zones based on similar water quality characteristics.

Water Quality

In contrast, nitrogen inputs from the atmosphere are mostly in the form of dissolved inorganic nitrogen and are readily available for uptake. The input of saline groundwater from beneath the Bay also may be an important nutrient source (especially for nitrogen), but the amount of this input is very difficult to measure, and the estimates are highly uncertain.

Nutrient inputs to the Bay are affected by both natural and anthropogenic events, including water management activities. Periods of drought decrease the amount of freshwater inputs from the Everglades and the atmosphere. Drought can result in high salinity stress and drying of wetlands that inhibit plant productivity and increase the decomposition of organic matter. With the first substantial rainfall events after a drought, nutrient inputs from the freshwater and saline coastal wetlands can be elevated. Tropical storm or hurricane events can be particularly important drivers of nutrient inputs to Florida Bay. Heavy rainfall associated with these storms increases runoff from the Everglades and stormwater releases from canals. Large amounts of leaf litter from wetland and estuarine plants and nutrients from sediments and groundwater are also mobilized during storms.



Estimates of the annual exchange of and total nitrogen (top) and total phosphorus (bottom) at the boundaries of Florida Bay. The width of the arrow indicates the relative contribution of each input. Estimates for groundwater and the Gulf of Mexico inflows (*) are more uncertain than other estimates. Groundwater inputs may include recycled Bay nutrients.

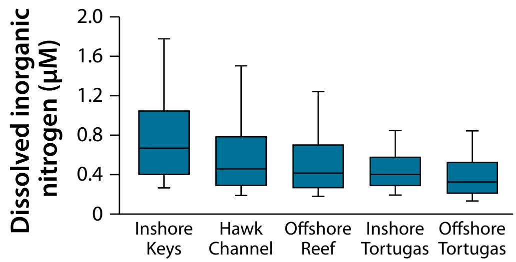
Spatial patterns of water quality in the Florida Keys National Marine Sanctuary

Joseph N. Boyer and Henry O. Briceño

Water quality has been measured at 155 fixed stations in the Florida Keys National Marine Sanctuary since 1995. Stations in the Sanctuary are part of a network of other fixed sampling sites (175 additional stations) distributed throughout the estuarine and coastal ecosystem of south Florida. The purpose of the sampling program is to address concerns in regional water quality that cross and overlap political boundaries. Biscayne Bay, Florida Bay, Whitewater Bay, and Ten Thousand Islands are sampled monthly, whereas the Sanctuary and the Southwest Florida Shelf are sampled quarterly. One of the products of this combined effort is a comprehensive evaluation of nutrient and phytoplankton biomass distributions throughout south Florida coastal waters.

Variables currently being measured include temperature, salinity, dissolved oxygen, dissolved inorganic nitrogen (including ammonium, nitrate, nitrite), total organic nitrogen, soluble reactive phosphorus, total phosphorus, total organic carbon, chlorophyll *a*, turbidity, and light extinction.

One important finding from this monitoring project is documentation of elevated nitrate in the inshore waters of the Keys. This result was evident from the first sampling event in 1995 and continues to be a characteristic of the ecosystem. Interestingly, this gradient was not observed in a comparison transect in the Tortugas (i.e., no human impact). This type of distribution implies an inshore source of nitrate that is diluted by low nutrient Atlantic Ocean waters. There were no trends in chlorophyll *a* in relation to distance from land.



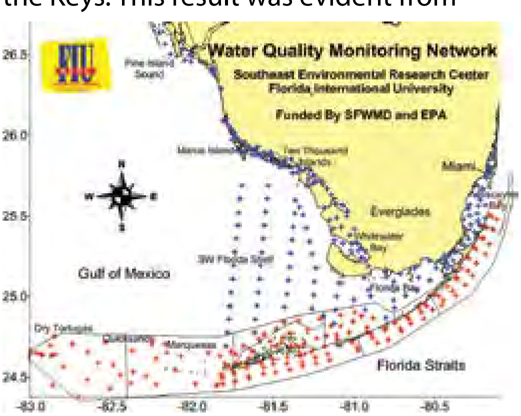
FIU

Dissolved inorganic nitrogen is highest in waters near the Keys, which is consistent with a nearshore or land-based source.

Declining nearshore-to-offshore trends were observed for dissolved inorganic nitrogen, total organic carbon, total organic nitrogen, and turbidity at all oceanside transects. Total phosphorus concentrations in the Lower Keys transects decreased with distance offshore but increased along transects in the Upper Keys.

Another observation is that elevated nitrate is a regular feature of waters on the Gulf side of the Florida Keys (Backcountry). Some of the highest concentrations are observed in this sparsely populated area. These levels are most probably indicative of waters from the Southwest Florida Shelf moving through this area and because of inputs of nutrients from sediments in this very shallow water column. The fact that phosphorus is limiting to heavy seagrass growth in that area may also result in a buildup of nitrogen in the water column.

Water quality monitoring stations can be grouped as occurring off island landmasses or opposite channels



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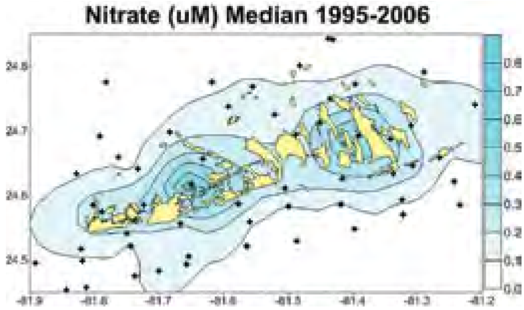
Locations of fixed water quality monitoring stations in south Florida. Stations in the Sanctuary (red) have been sampled quarterly since 1995.



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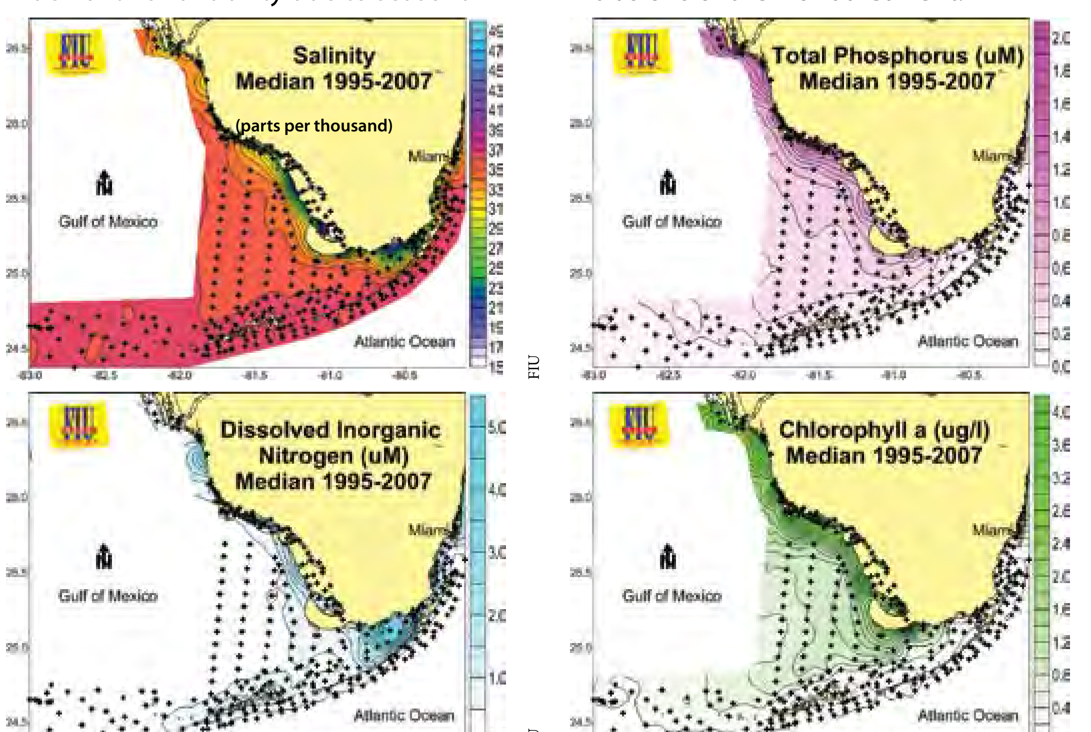
Median concentration (µM) of nitrate nitrogen (1995 – 2006) is highest (darker blue) in shallow waters on the Gulf side of the Lower Keys.

and passes. Stations located opposite channels and passes throughout the Keys had higher nutrient concentrations, phytoplankton biomass, and turbidity than those stations off islands. The area offshore Marquesas Keys exhibited the highest phytoplankton biomass (i.e., chlorophyll *a*) for any segment of the Sanctuary.

Sanctuary waters are characterized by complex water circulation patterns over both spatial and temporal scales, with much of this variability due to seasonal influence in regional circulation regimes. The Sanctuary is directly influenced by the Florida Current, the Gulf of Mexico Loop Current, inshore currents of the Southwest Florida Shelf, and tidal exchange with both Florida Bay and Biscayne Bay. Advection from these external sources has significant effects on the physical, chemical, and biological composition of waters within the Sanctuary, as does internal nutrient loading and freshwater runoff from the Keys themselves.

When the water quality of the Sanctuary is compared with data from the 175 stations sampled in the Southwest Florida Shelf, Florida Bay, Whitewater Bay, Ten Thousand Islands, and Biscayne Bay, it is apparent that the sources of water quality among the regions differ: ambient water quality in the Lower Keys and Marquesas is most strongly influenced by waters coming from the Southwest Florida Shelf; the Middle Keys by the Southwest Florida Shelf and waters from Florida Bay; the Backcountry by internal nutrient sources; and the Upper Keys by intrusions of the Florida Current.



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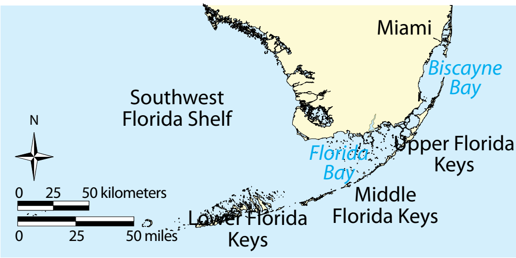
Spatial distribution of some water quality parameters (1995 – 2007).

Water residence time is a significant driver of ecosystem structure and function in estuaries

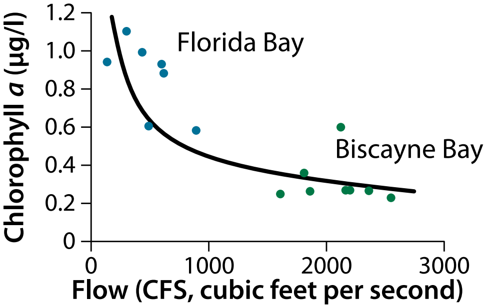
Joseph N. Boyer and Henry O. Briceño

Florida Bay is an estuary that lies between the southern tip of the Florida mainland and the Florida Keys. It covers approximately 2850 km^2 (1100 mi^2) and consists of many shallow interconnected basins, called "lakes," with an average depth of approximately 1.5 meters (5 feet). Florida Bay receives freshwater from sheet flow and creeks draining the Everglades. However, over the past century, construction of drainage canals has drastically altered the historical flow of freshwater. Because of poor flushing and high evaporation rates, portions of the Bay often become hypersaline, with salinities reaching over 40 parts per thousand (ppt). Recently, portions of Florida Bay have experienced widespread death of seagrass beds, turbid water, sustained algal blooms, and death of the sponge community.



Florida Bay and Biscayne Bay are two large estuaries in south Florida with different ecological conditions.

Biscayne Bay is the largest estuary on the southeast coast of Florida, encompassing approximately 700 km^2 (270 mi^2). It is separated from the Atlantic Ocean by a chain of islands and receives freshwater input from the Miami River and a series of smaller creeks and drainage canals along its western margin. The average freshwater flow to Biscayne Bay (121 cubic meters per second) is about 100 times the average freshwater flow to Florida Bay (1.5 m^3/s) and the rivers, creeks, and drainage canals discharging to Biscayne Bay deliver a relatively high load of nitrogen and phosphorus from adjacent urban and agricultural areas. However, even though nutrient loading into Biscayne Bay (10,203 metric tons [11,247 tons] per year total nitrogen and 24.9 metric tons [27.5 tons] per year total phosphorus) is significantly higher than loading to Florida Bay (331.7 metric tons [365.6 tons] per year total nitrogen and 3.4 metric tons [3.8 tons] per year total phosphorus), chlorophyll *a* values (plankton blooms) in Biscayne Bay are significantly lower than in Florida Bay.



Even though freshwater flow (cubic feet per second [cfs]) and nutrient loading are much higher in Biscayne Bay (green) than Florida Bay (blue), chlorophyll *a* concentration is higher in Florida Bay because of longer residence time of water (slower flushing).

FIU

Biscayne Bay has not experienced the sustained algal blooms and other dramatic ecological degradations observed in Florida Bay in recent years despite its location adjacent to a large urban area. One important reason is the difference in residence time of the water in the two estuaries. The average residence time of water in Biscayne Bay is 1 month, whereas the average in Florida Bay is 3 – 6 months. Poor internal circulation within Florida Bay due to mud banks and mangrove islands as well as reduced freshwater input result in slow turnover times of water in Florida Bay. The poor exchange of water allows increased exposure to nutrients, pollutants, and deleterious conditions that may partly explain the current conditions in Florida Bay.

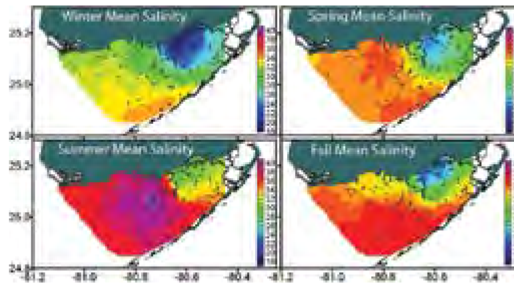
Salinity is an important variable in Florida Bay

Christopher Kelble

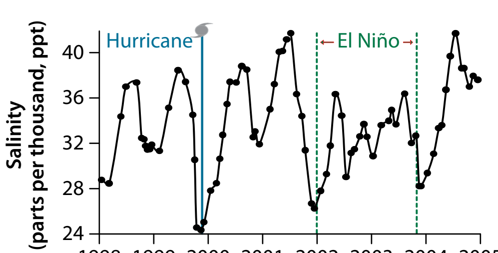
Salinity is a measurement of the concentration of salts dissolved in water. Normal seawater has a concentration of about 36 parts per thousand (ppt) total salts. When freshwater (i.e., 0 ppt) mixes with seawater in estuaries, salinity is reduced (i.e., estuarine conditions). Salinity can be used as a conservative tracer of freshwater runoff because unlike nutrients and other water quality parameters, salinity is not affected by biological processes. When evaporation exceeds rainfall or freshwater inflow, salinity can reach very high levels (i.e., more than 40 ppt), termed "hypersalinity events".

In south Florida, there is marked seasonal variation in rainfall and evaporation. When rainfall and runoff is less than evaporation, the salinity increases and reaches a maximum in early summer (June – July). Salinity decreases rapidly during the rainy months (September – December). Meteorological phenomenon, such as El Niño and tropical cyclones (i.e., hurricanes), dampen or increase, respectively, the typical annual variation in salinities.

Because of restricted circulation in Florida Bay, salinity variation is very pronounced. Florida Bay becomes hypersaline in early summer and estuarine in early winter. It is not uncommon to observe both hypersaline and estuarine conditions at different locations at the same time during intervals between those two extremes. The large salinity variations are ecologically damaging. Organisms that live in salty environments must actively regulate their interior body chemistry (i.e., osmoregulation) and have a physiological optimum of salinity, as well as minimums and maximums beyond which the organism will struggle to survive. Organisms that live in such areas either adapt to the wide fluctuations of salinity, flee when conditions become unfavorable, or die. Effects of salinity are mediated by the mobility of an organism. Sessile organisms, such as sponges, corals, and seagrasses, cannot move and are susceptible to stress and death due to unfavorable salinity conditions. Mobile organisms, such as fish, turtles, and marine mammals, can avoid localized harmful salinity conditions but may be susceptible to more widespread detrimental salinity conditions.



Mean seasonal salinities in Florida Bay, 1998 – 2005 (red indicates higher salinities, blue lower salinities).



Mean seasonal salinity distribution in Florida Bay, 1998 – 2005.

Historical water manipulation activities in south Florida have severely reduced the flow of freshwater into Florida Bay and changed the ecosystem from a predominantly estuarine condition, with a diverse seagrass community, to a more marine system, dominated almost exclusively by turtle grass. Managing water flows to reduce the severity and frequency of hypersalinity events in Florida Bay is one of the primary goals of the Comprehensive Everglades Restoration Plan.

The ecological character of Florida Bay responds to both changing climate and human activities

William L. Kruczynski, Michael B. Robblee, and James W. Fourqurean

Florida Bay is a coastal embayment found at the southern tip of Florida, downstream of the greater Everglades ecosystem. The Bay covers approximately 2850 km^2 (1100 mi^2) and is bounded on the east by the Florida Keys and open to the Gulf of Mexico along its western margin. The current ecological conditions in Florida Bay are a relatively recent development. On a geological time scale, the Earth has experienced alternating cold and warm periods. In what is now south Florida, the coral reefs that shaped the Florida Keys formed about 125,000 years ago during a warm period of elevated sea level. The last Ice Age that occurred about 28,000 years ago caused a large drop in sea level, and dry land emerged many kilometers

SFWMD

Aerial view of Florida Bay.

beyond the current Bay shoreline. At that time, the area that is presently Florida Bay was vegetated by forests, freshwater marshes, and mangroves. As sea level rose over the past 5000 years, marine and estuarine waters pushed inland, flooding modern Florida Bay as recently as 1500 years ago. Changes in climate led to the development of Florida Bay, and this very young ecosystem continues to be influenced by climate and, more recently, by human activities.

Florida Bay is a large and variable system, with mud banks enclosing shallow seagrass-covered basins or lakes in central and eastern parts of the Bay and large open water expanses in the southwestern portion of the Bay. Salinity can vary across the waterbody, with the northeastern part of the Bay influenced by

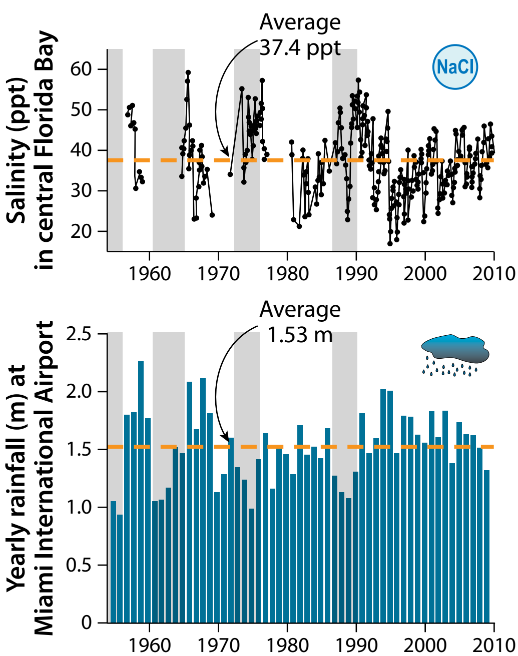
T. Scott - FGS

A mud bank in central Florida Bay vegetated by mangroves and mangrove seedlings. Mud banks restrict the flow of water between adjacent basins. Plant and animal remains found in sediment cores collected from mud banks and basins provide information of historical salinity of the Bay.

freshwater runoff from the Everglades and the salinity in southwestern and western portions of the Bay maintained near that of the adjacent Atlantic Ocean and Gulf of Mexico. Since 1950, the salinity of central Florida Bay has averaged 37.4 parts per thousand (ppt). For reference, freshwater has a salinity of near 0 ppt, and open ocean water has a salinity of around 36 ppt. More water evaporates out of Florida Bay than flows into it or falls as rain, so on average, the Bay is slightly more salty than adjacent ocean waters. However, changes to inflows of freshwater can drastically alter salinity in Florida Bay. Local rainfall varies from year to year, and the salinity in Florida Bay can get much higher after a series of below average rain years and can be fresher after a series of wetter than average rain years.

Water Quality

Paleoecological investigations of the animal life and pollen buried in the muds in Florida Bay provide a glimpse into the more recent past and demonstrate that significant changes have occurred during the past 200 years. By knowing how animals and plants are currently distributed with respect to salinity, sea level, and other environmental factors, scientists can infer what the past environment was like at any point in Florida Bay by examining how the assemblage of plants and animals changes with sediment depth; plant and animal remains are older with depth. These analyses demonstrate that Florida Bay historically had variable salinities responding to natural climate conditions that affected flows of freshwater through the Everglades into the Bay. During the late 1700s and early 1800s, salinities in Florida Bay were relatively stable and estuarine (between 20 – 30 ppt), and there were moderate amounts of submerged vegetation. From 1810 – 1892, salinities varied between 15 – 25 ppt, and the sparse aquatic vegetation present was a diverse mix of estuarine species. By the 1960s, paleoecological studies suggest that Florida Bay was dominated by plants and animals better adapted to the higher salinities of marine environments.



Salinity in central Florida Bay is highly correlated with rainfall at Miami International Airport (MIA). Periods of low rainfall (shaded areas) correspond to times of high salinities in the bay.

Available observed salinities generally support the paleoecological studies; salinities today are greater than those observed at the turn of the past century. Records from 1908 show the Bay as an estuary with salinities in the 20 ppt range and that by the late 1930s and early 1940s higher marine salinity conditions occurred. As early as 1955, extreme hypersaline conditions (i.e., 72 ppt, twice the salinity in the Gulf of Mexico) occurred in central Florida Bay and were again observed in 1991. In recent decades, hypersaline conditions (greater than 40 ppt) regularly have been present in the Bay and the end of the dry season.

Against this natural historical state of variability in salinity and ecological condition of Florida Bay, the clear connections between human alteration of the ecosystem of south Florida and conditions in Florida Bay are sometimes difficult to ascertain. The Everglades has been increasingly managed for agriculture, flood control, and water supply, with subsequent impacts to salinity conditions downstream in Florida Bay. Construction of drainage canals beginning in the 1880s, with the purpose of draining the Everglades, diverted freshwater flow to the east and west coasts of Florida and reduced flows southward into Florida Bay. The building of the Flagler Railroad (1905 – 1912) through the Florida Keys reduced the exchange of water between the Atlantic Ocean and Gulf of Mexico and increased the impact of evaporation on salinity in the interior of Florida Bay.

The shift in Florida Bay from an estuary to a marine lagoon characterized by relatively stable marine salinities but occasionally hypersaline conditions

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The diversion of freshwater flow to the Everglades (left) and the construction of Flagler's Railroad in the Florida Keys (right) changed the historical flow and salinity patterns in Florida Bay.

and clear water has had biological consequences. Most notably, the seagrass community changed from a diverse mix of seagrass species to near monotypic stands of dense turtle grass (*Thalassia testudinum*). In the late 1980s, extremely high density and biomass of turtle grass, in combination with unusually high temperature and salinity conditions, precipitated the die-off of large expanses of dense seagrass in western Florida Bay. In 1991, turbidity and phytoplankton abundance increased dramatically in the Bay as nutrients were released from dead seagrasses and exposed bottom sediments. Persistent algal blooms not associated with wind events, a phenomenon not observed before seagrass die-off, characterized the previously clear Bay waters.

Concurrent declines in the shrimp harvest in the offshore Dry Tortugas fishery, for which Florida Bay functions as a principle nursery, suggest that changes in the Bay have had regional effects. Since about 1995, the region has experienced a period of stable annual average rainfall and moderate salinities, the rich seagrass beds of western Florida Bay are recovering, and the frequency of algal blooms and high turbidity events are declining.

Efforts are being made to restore the Everglade ecosystem, including Florida Bay, to a more natural state. Resource managers must be cognizant that Florida Bay varies both spatially and temporally and responds to both natural and human-caused changes in environmental conditions. Restoration planning must take into account a clear understanding of the history of Florida Bay and set defensible goals, such as reducing the frequency and magnitude of hypersaline events in central Florida Bay. Successful restoration may result in more estuarine and variable conditions, such as those that occurred in Florida Bay before the turn of the 20th century.

FDEP

The reduction of freshwater flow to Florida Bay resulted in a shift from estuarine to marine conditions and a dense, monotypic stand of turtle grass. The high density of the grass coupled with high temperature and salinity conditions resulted in seagrass die-off over large areas of Florida Bay.

There is a gradient of nutrient limitation across Florida Bay

Patricia M. Glibert and Cynthia Heil

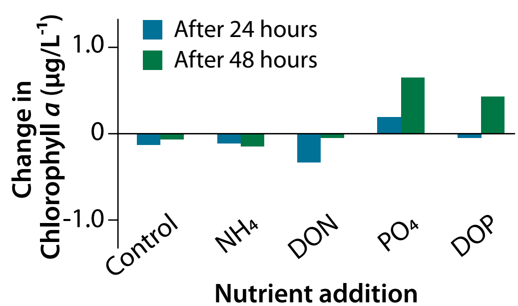
When plants do not receive the nutrients that they require, they stop growing. The nutrient in least supply, relative to the needs of the organism, is termed the "limiting nutrient." This concept was first described by Carl Sprengel and Justus von Liebig and is known as Liebig's Law of the Minimum (1840). Plants may be limited by a single nutrient, such as nitrogen, or they may be co-limited by more than one nutrient. Phytoplankton, which are free-floating microscopic plants, display nutrient limitations and, like all plants, can regulate their metabolism to improve their acquisition of the limiting nutrients.

WHOI

Alfred C. Redfield (1890 – 1983) was an ecologist before the term "ecology" was coined. He discovered that the elemental composition of planktonic organisms was consistent in ocean waters (Redfield Ratio).

All organic matter is comprised of protein, carbohydrate, lipid, and nucleic acids, which in turn are made up of the elements carbon, nitrogen, hydrogen, and phosphorus. The consistency of the relationship between elements within the plankton was first observed by Alfred C. Redfield in 1934, who found the ratio of carbon, nitrogen, and phosphorus was 106:16:1 (Redfield Ratio). Deviations in this ratio can result from the development of plankton blooms, the rapid decay, and the change from one species assemblage to another. These deviations can be used to identify potential limiting nutrients.

Florida Bay exhibits a gradient of limiting nutrients. Toward the western edge, nitrogen is the common limiting nutrient, whereas in the eastern region, phosphorus is the limiting nutrient. Nutrient limitation may develop from the depletion of the nutrient itself, as is the case for nitrogen in the western region, or from overenrichment of other elements, leading to a significant imbalance in the proportions of nitrogen and phosphorus. Phytoplankton blooms have most commonly developed in the central region of the Bay, when neither nitrogen nor phosphorus are limiting.



Typical response of algal populations in eastern Florida Bay to different nutrient additions in bioassays as measured in chlorophyll concentrations. Phosphorus limitation is indicated by the positive results of the algae to additions of phosphate (PO_4^{3-}) and dissolved organic phosphorus (DOP) additions.

There are several scientific methods to test which nutrient is limiting. One approach is called a "bioassay," where water with planktonic organisms is placed in experimental bottles and enriched with different nutrients either alone or in combination. The added nutrient that yields the greatest growth of phytoplankton in the bottles is the limiting nutrient. Using this approach, the response by the algae in eastern Bay has been found to be as much as several hundred percent after a 48-hour exposure to phosphate, whereas in western Bay, the response is also typically large to nitrogen additions.

Plankton type affects food webs

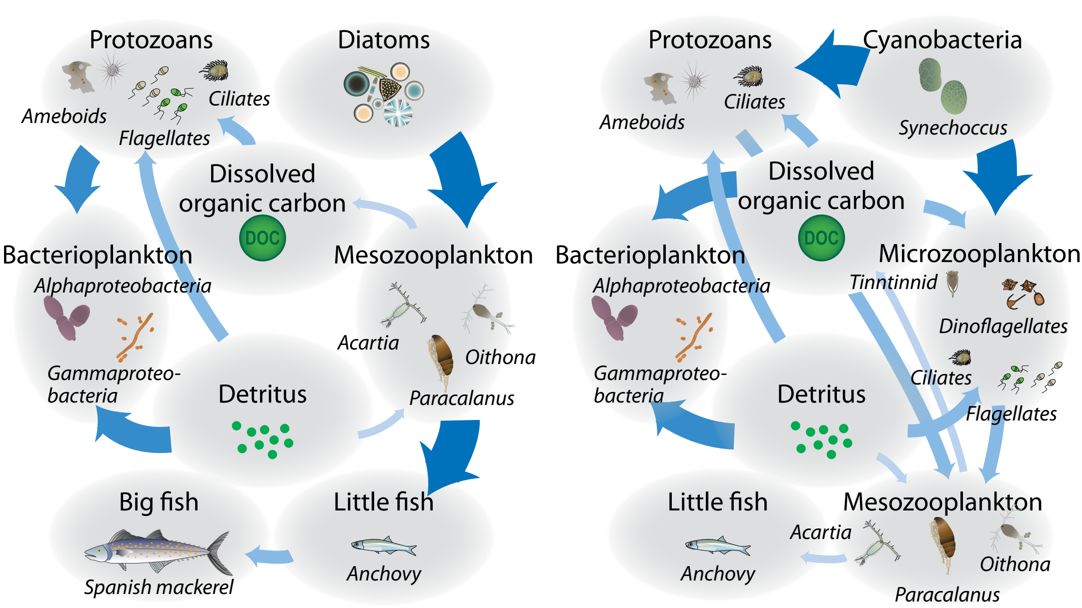
Christopher Kelble

Plants are primary producers, capturing energy from the sun and converting that energy into biological materials. Thus, plants form the base of food webs. In coastal systems, free-floating microalgae (i.e., phytoplankton) and benthic vegetation (i.e., seagrasses and macroalgae) are the primary bases of food webs, and most other organisms in the ecosystem ultimately depend on them for energy.

The planktonic food web is greatly influenced by the size, chemistry, and physical characteristics of the dominant phytoplankton species. Therefore, the type of microalgae in an area can influence the type and quantity of higher level organisms, such as fish, that are found there. In general, smaller sized phytoplankton are eaten by smaller grazers (i.e., microzooplankton) and result in smaller top level predators. The nutrient quality of the phytoplankton is also important. In large, structurally complex food webs there must be adequate quality of food in sufficient quantities.

In an ecosystem with "good" quality phytoplankton, the food web is generally less complex. The grazing community consists of larger zooplankton (i.e., mesozooplankton), sponges, and other filter feeding organisms that are then eaten by other organisms, which in turn may be eaten by larger fish. Such a "healthy" system supports larger and more diverse fish populations.

In south Florida, the dominant phytoplankton species in blooms, excluding harmful algal blooms, such as toxic red tides (*Karenia brevis*), are either small sized cyanobacteria, such as *Synechococcus*, or large diatoms. These two phytoplankton groups support significantly different food webs: the larger diatoms support healthy, large fish populations, and the cyanobacteria support a low quantity of smaller fish.



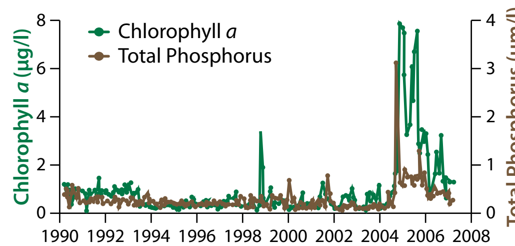
A healthy aquatic ecosystem (left) is based on a diverse mix of large phytoplankton that results in a healthy fish community. An aquatic ecosystem based on a single, overabundant species of smaller phytoplankton (right) results in a less diverse fish community dominated by smaller fish species.

An unprecedented phytoplankton bloom occurred in eastern Florida Bay from 2005 – 2008

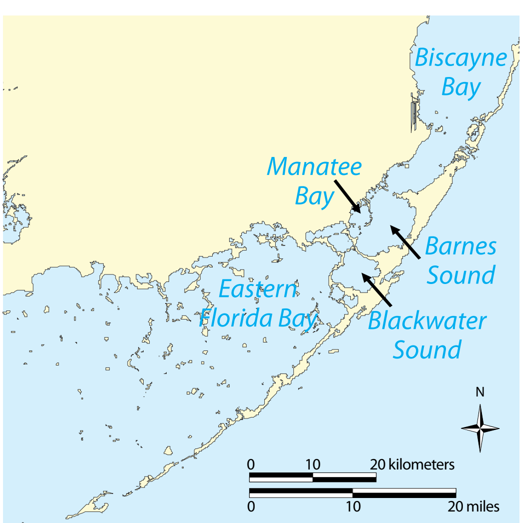
David T. Rudnick, Stephen P. Kelly, Christopher J. Madden, Kevin M. Cunniff, Joseph N. Boyer, and Stephen Blair

Eastern Florida Bay is an unusual region in an unusual estuary. The majority of estuaries receive most of their nutrients from their terrestrial watersheds, and this nutrient delivery, combined with light availability, largely determines the amount of phytoplankton (microalgae in the water) in the estuary. However, in Florida Bay, most freshwater runoff from the Everglades watershed flows into the eastern bay, and this runoff has very low concentrations of the nutrient most limiting productivity, phosphorus. This low nutrient input, combined with the presence of seagrasses that compete for phosphorus and sediments that chemically bind phosphorus, inhibits the growth of phytoplankton in the eastern Bay.

These shallow waters typically have phytoplankton abundance more similar to the open ocean than estuaries – the waters are a low nutrient "desert." More than 15 years of water quality monitoring in eastern Florida Bay documented that concentrations of chlorophyll *a*, an indicator of phytoplankton biomass, and total phosphorus were lower than almost anywhere else in coastal south Florida. That changed in the fall of 2005.



Time series of water column phosphorus (brown) and chlorophyll *a* (green), an indicator of algal biomass, in Barnes Sound located south of Biscayne Bay. The phytoplankton bloom was preceded by a large increase of phosphorus in the water column.



Map of eastern Florida Bay and southern Biscayne Bay, where a microalgal bloom occurred from 2005 – 2008.

An unprecedented bloom of cyanobacteria (a high abundance of microalgae) occurred over much of eastern Florida Bay and southern Biscayne Bay beginning in November 2005, 1 month after regional phosphorus concentrations were more than 10 times higher than typical concentrations. This exceptionally large amount of phosphorus almost certainly caused the initiation of the regional cyanobacteria bloom. What is uncertain is the source of this phosphorus and, to a lesser extent, how the bloom could persist for 3 years (2005 – 2008) in this low nutrient environment. Two hypotheses have been developed to explain the initiation of the bloom: phosphorus inputs from stormwater from hurricanes and phosphorus inputs from road construction activities.

The timing and spatial distribution of the cyanobacteria bloom provide clues about the source of the phosphorus and the cause of the bloom. The bloom first occurred at a relatively small scale in two basins east of U.S. Highway 1 (Manatee Bay and Barnes Sound) in September 2005, immediately after the passing of

NOAA

In September 2005, Hurricane Rita passed over south Florida and provided substantial amounts of rainfall to the region that may have contributed to the release of phosphorus to surface waters of eastern Florida Bay.

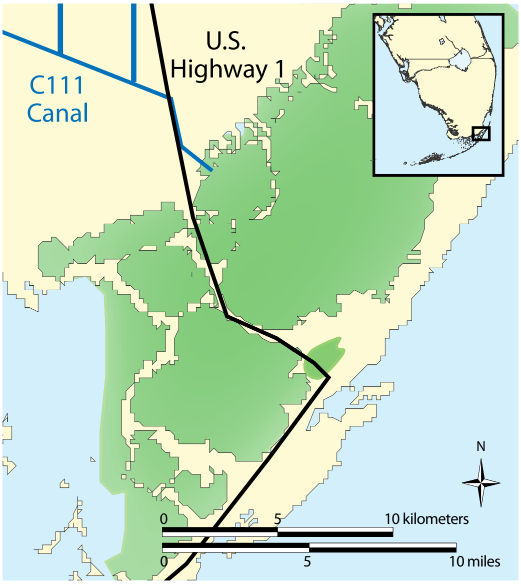
Hurricane Katrina in late August. The bloom then expanded to a regional scale in November, after the passing of two more hurricanes, Rita in late September and Wilma in late October 2005.

The timing of the bloom is consistent with the hypothesis that these three successive hurricanes initiated the bloom. A spatial clue about the cause of the bloom was that the highest chlorophyll *a* concentrations consistently occurred adjacent to U.S. Highway 1. For about 3 years, the bloom occurred on both sides of the highway, especially near Key Largo. This spatial distribution points to the possibility that a large highway construction project that started in the spring of 2005, widening the road from the Florida mainland to Key Largo, was also a cause of the bloom.

H. Carman - SFWMD

Construction along U.S. Highway 1 from the Florida mainland to Key Largo in 2005 disturbed organic soils that may have resulted in the release of phosphorus to adjacent waters.

Nutrient inputs occurred in association with both U.S. Highway 1 construction and the fall 2005 hurricanes, but the amount from every potential source cannot be estimated reliably. To widen the road bed, adjacent dense stands of mangrove trees were cut, mulched, and mixed into the peat soil along with cement to stabilize the road base. Mulching and burial of this fresh organic matter, including roots, along with disturbance of the soil organic material likely resulted in a release of nutrients



A large phytoplankton bloom persisted in eastern Florida Bay and southern Biscayne Bay from 2005 – 2008. The extent of the bloom shown is for 2006 – 2007.

through microbial decomposition processes to the surrounding waters. The amount of phosphorus released by construction activity is difficult to estimate but was likely a small component of the approximately 19 metric tons (21 tons) of phosphorus required to account for the regionally elevated phosphorus observed in October 2005. The leaves and wood of mulched mangroves probably only contained about 1 metric ton (1.1 ton) of phosphorus, whereas the soils and roots contained an unknown amount of phosphorus.

Hurricanes cause broad and strong disturbances of ecosystems, and release and transport of nutrients are part of this disturbance. One major nutrient source affected strongly by Hurricane Katrina was nutrients stored in soils and waters of the developed portion of the adjacent south Florida watershed. With Katrina, heavy rainfall (15 – 30 centimeters [6 – 12 inches]) fell in the region, and in the process of protecting residential and farming areas from flooding, stormwater was released into Manatee Bay via the C-111 Canal. With this stormwater, approximately 2.6 metric tons of phosphorus was transported toward Manatee Bay and Barnes Sound.

However, the phosphorus observed in late August does not account for the regionally elevated phosphorus found in October, nor does it come close to the estimated 19 metric tons (21 tons) required to account for the regionally elevated levels of phosphorus. Other sources of phosphorus that could have been mobilized and transported by high winds, waves, and storm surge due to hurricanes were nutrients from the Everglades, the Florida Keys, and the Bay itself. This includes releases of nutrients from wetland leaves and soils, seagrass leaves, Bay sediments, and groundwater. The exact quantity of these potential nutrient inputs in the fall of 2005 is unknown.

Neither of the hypothesized causes of the initiation of the cyanobacteria bloom (hurricanes and road construction releases) is fully consistent with the timing and characteristics of the bloom. Road construction and mangrove mulching began months before the bloom started. Many hurricanes had passed over or near Florida Bay during previous decades without the occurrence of phytoplankton blooms in this location. This includes releases of stormwater from the C-111 Canal that were similar to the quantity of water and phosphorus released with Katrina. Yet, no previous water releases were followed by blooms in the region.

H. Carman - SFWMD

The phytoplankton bloom is visible on the Manatee Bay side of the C-111 Canal terminal water control structure, S-197. This structure is opened to provide flood control during periods of high rainfall. There was a large release of water during Hurricane Katrina, which may have initiated the plankton bloom.

It is likely that both hypothesized causes contributed to the initiation of the cyanobacteria bloom and, furthermore, may have been interactive. One such interaction may have been the movement of materials from the construction site by the rain, wind, and waves of the hurricanes. Another possibility is more complex: that dissolved organic material leaching from the construction area had been decomposing in adjacent waters, with elevated demand for dissolved oxygen, at the time of the hurricanes. Large areas with low dissolved oxygen concentrations were measured following Hurricane Katrina, likely in association with dissolved oxygen uptake as well as with stratification of the water column after heavy rainfall and runoff. Such a low dissolved oxygen scenario following Hurricane Rita, another wet storm, could have spurred chemical and biological releases of phosphorus from the sediments.

Regardless of its cause, the cyanobacteria bloom spurred a chain of events, including seagrass mortality, that helped to sustain the bloom for 3 years. The occurrence of this exceptional phytoplankton bloom demonstrated the extreme sensitivity of eastern Florida Bay to phosphorus availability and how rapidly the structure and function of an ecosystem can change.

Phytoplankton blooms can be self-sustaining and alter benthic communities

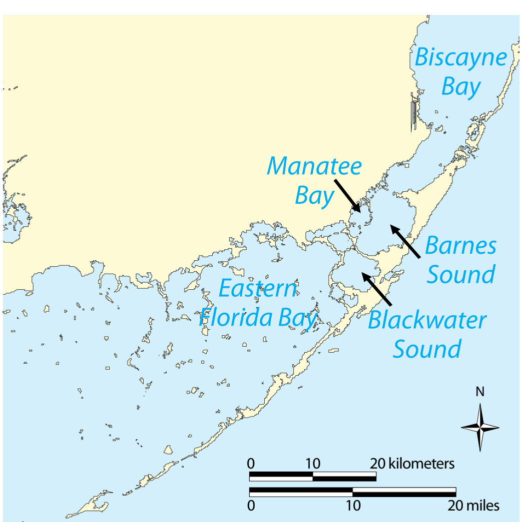
David T. Rudnick, Stephen P. Kelly, Amanda A. McDonald, and Christian L. Avila

An unprecedented phytoplankton (i.e., water column microalgae) bloom began in eastern Florida Bay and southern Biscayne Bay in the fall of 2005 and was sustained over a 3-year period. Bloom initiation was likely the result of disturbance from three consecutive hurricanes combined with road construction along U.S. Highway 1 that began in early 2005. Increased phosphorus availability was likely the key factor that initiated the bloom. Both the occurrence and the longevity of the bloom were surprising, given that this region of Florida Bay previously had very low nutrients and no recorded history of phytoplankton blooms.

To sustain such a phytoplankton bloom, cell population losses (to grazing, sinking to sediments, and export via currents) must be less than or equal to cell population gains (through growth and reproduction as well as through the import of cells via currents). A key factor enabling cell gains is the continuing supply of nutrients (both phosphorus and nitrogen). In the case of the bloom in eastern Florida Bay and southern Biscayne Bay, once the bloom began, little phosphorus was supplied from external sources; the bloom appeared to be supplied from local, internal sources of nutrients. Furthermore, the existence of the bloom created a set of circumstances that resulted in enhanced nutrient availability.

C. Avila - Miami-Dade County DERM

Cyanobacteria bloom in Barnes Sound on December 21, 2005. The cells of such blooms absorb light, greatly decrease light penetration to the bay bottom, and decrease productivity of submerged aquatic vegetation.



Map of eastern Florida Bay to southern Biscayne Bay, where a persistent phytoplankton bloom occurred from 2005 – 2008.

This scenario of a self-sustaining phytoplankton bloom involved the loss of two major ecosystem components: submerged aquatic vegetation and sponges. The loss of submerged aquatic vegetation and sponges affected the entire food web of the ecosystem because they provide habitat for a diversity of fish and invertebrates. Another effect of sponge mortality in the region of this bloom was probably a decrease in sponge grazing on bloom organisms. These effects of the phytoplankton bloom, and the associated cycle by which the bloom was sustained, are not unique to this bloom and has been observed in other estuaries.

The loss of submerged aquatic vegetation is a critical part of the cycle sustaining the phytoplankton bloom. A decrease in submerged aquatic vegetation cover in the region was measured after bloom initiation in the fall

A.V. Uhrin - NOAA

C. Avila - Miami-Dade County DERM

Clear water is required for healthy growth and productivity of submerged aquatic vegetation (left). Submerged aquatic vegetation cannot be sustained and dies when not enough light reaches the bottom, such as during prolonged phytoplankton blooms (right).

of 2005. This loss was most pronounced in Barnes Sound and Blackwater Sound: the basins where the bloom was most intense and persistent. Furthermore, the loss was greatest in the deepest waters of these basins. A likely mechanism responsible for the mortality of submerged aquatic vegetation was a decrease in light penetration through the water column to the bay bottom, decreasing submerged aquatic vegetation photosynthesis. Such shading of the bottom by phytoplankton blooms, with consequent mortality of submerged aquatic vegetation, commonly has been observed in shallow estuaries worldwide. In the case of this

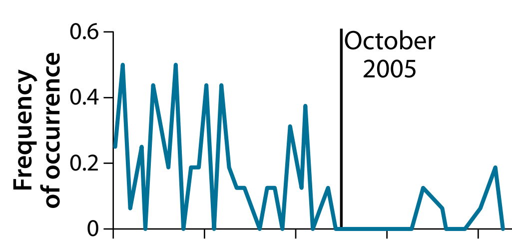
FWC

In 2005 – 2006, sponges found throughout the bloom area probably died as a result of high cyanobacteria concentrations and low dissolved oxygen.

region of Florida Bay and Biscayne Bay, other factors may also have affected submerged aquatic vegetation, including decreases in salinity and low dissolved oxygen concentrations causing lethal hydrogen sulfide toxicity following Hurricanes Katrina and Rita.

Regardless of the exact cause, once submerged aquatic vegetation mortality began, a cycle (i.e., feedback loop) began that increased nutrient availability, sustaining the bloom and further harming surviving submerged aquatic vegetation. Available nutrients in the water column increased from several processes: the decomposition of dead submerged aquatic vegetation, a decrease in benthic nutrient uptake (with the loss of submerged aquatic vegetation), and the nutrient releases associated with the destabilization of sediments due to the loss of sediment binding by seagrass roots. Sediment destabilization also increased the amount of sediment suspended in the water column, decreasing light penetration and further propagating this destructive cycle.

Another contributing factor regarding the maintenance of the phytoplankton bloom is the physical nature of the estuaries and the efficiency of nutrient cycling. Although water can flow rapidly through typical riverine estuaries, Florida Bay and the southern portion of Biscayne Bay have diffuse inputs of freshwater flow that are small relative to the volume of the systems. Consequently, water in the bloom region has a very long residence



Miami-Dade County DERM

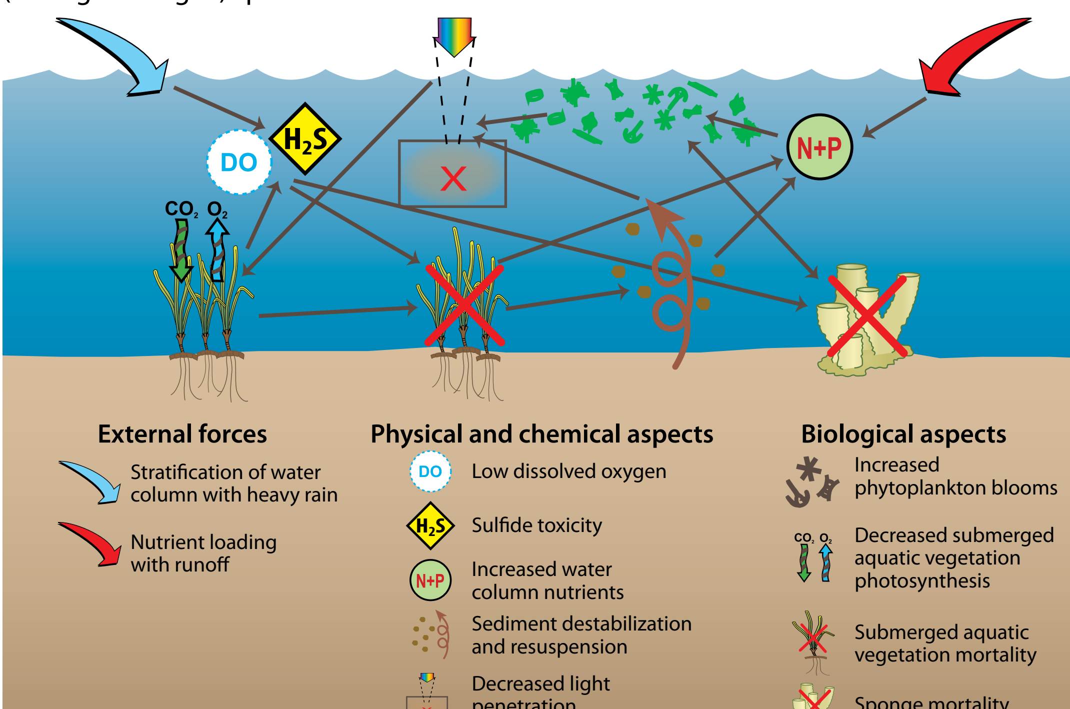
Sponge occurrence in Blackwater Sound decreased significantly in October 2005 (marked by vertical line) following the initiation of the phytoplankton bloom.

time that results in the retention of phytoplankton cells and phosphorus. This, combined with highly efficient phosphorus cycling, enabled the bloom to thrive on an initial input of phosphorus and nutrients released with the death of submerged aquatic vegetation.

The loss of sponges may also have been a factor in sustaining the bloom. Although sponges were not as common in this area of Florida Bay as in the Middle Florida Keys, they became extremely rare by 2005. The loss of sponges may have been caused by multiple factors, including decreased salinity following rainfall and runoff from hurricanes and low dissolved oxygen observed after Hurricane Katrina. It is also possible that sponge mortality was caused by the bloom itself. Sponges feed by filtering small organisms from the water column, including the dominant bloom organism, a cyanobacteria (blue-green algae) species. At low cell abundance, such filtration can slow the population growth of the cyanobacteria (a top-down control of bloom). However, at the high cell abundance of a bloom, sponge growth can be inhibited, and sponges can die, likely from clogging of their internal flow channels. With sponge mortality, grazing on bloom organisms decreased, helping to sustain the bloom.

The most likely reason why the bloom observed in eastern Florida Bay and southern Biscayne Bay lasted longer than blooms observed in other portions of Florida Bay may be the relatively low flushing characteristics in these regions.

A lesson learned from the dynamics of this bloom is that an ecosystem can quickly and readily reach a tipping point, where it changes state from one dominated by seagrass with clear water to one dominated by a sustained phytoplankton bloom with opaque, green water.



Conceptual model showing how phytoplankton blooms in eastern Florida Bay and southern Biscayne Bay were sustained through feedback loops among ecosystem components. Water column stratification due to heavy rains during hurricanes and nutrient loading from runoff are external forces affecting the ecosystem. Heavy phytoplankton growth decreases light penetration to seagrasses and clogs sponge filter mechanisms. Low dissolved oxygen due to water column stratification results in sulfide toxicity that can kill seagrasses and sponges. Death of seagrasses destabilizes sediments, which increases turbidity, and results in the release of nutrients from sediments and decomposing seagrasses.

Blackwater events can occur when unusual environmental conditions exist

Cynthia Heil

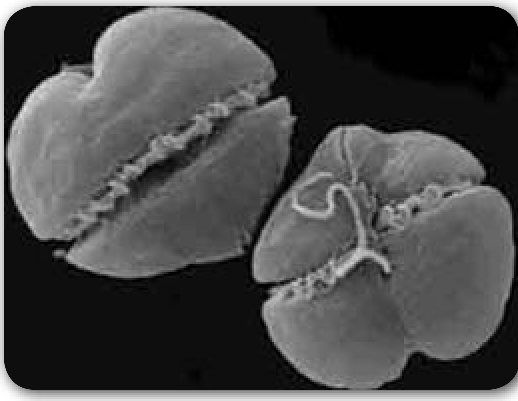
In January 2002, fishermen and pilots of small aircraft observed an area of dark colored water on the Southwest Florida Shelf, west of the Everglades, that they called "blackwater." They reported to the media that the waters were devoid of life. This shallow water area to the northwest of Florida Bay is characterized by extensive seagrass beds and a productive stone crab fishery. It receives freshwater inputs from both the Shark River in the Everglades and larger rivers to the north, including the Caloosahatchee. Much publicized in the popular press at the time, the 2002 blackwater event was not the first report of this type of event; a similar event was reported in 1898.

NASA

A 2002 blackwater event northwest of Florida Bay.

Investigations revealed that the blackwater area was not lifeless; in fact, a large algal bloom was present, consisting of a mix of nonharmful diatoms and a toxic dinoflagellate, *Karenia brevis*. *Karenia brevis* is responsible for Florida red tides. Also present in the bloom were high concentrations of comb jellyfish (i.e., ctenophores). Scientists believe that the blackwater event was caused when several different biological, chemical, and physical events co-occurred. A declining red tide event that occurred on the Southwest Florida Shelf was carried south at the same time that a seasonally occurring diatom bloom was shifted to the northwest. Using satellite imagery, scientists were able to trace the water mass containing this bloom back to an area to the north, where river waters containing both nutrients and high concentrations of dissolved tannic material supported the bloom and caused the dark colors of the water. The presence of high concentrations of comb jellyfish indicates that normal food chains were disrupted within the bloom. The mass of water containing the bloom was caught in a local area of stagnant circulation (i.e., an eddy), which kept it from being dispersed for a 3-month period. Also, unusual climate extremes were occurring in southwest Florida, including a severe drought followed by fewer and less severe winter fronts that could have dissipated the eddy.

The 2002 blackwater event had a large impact on corals, sea fans, and sponges as it passed the Lower Keys. Two coral reefs north of Key West experienced a 70% decrease in stony coral cover, a 40% reduction in coral species, and the near elimination of sponges.



FWC

Karina brevis is a toxic dinoflagellate that causes red tides in the Gulf of Mexico from Texas to Florida and along the Atlantic coast as far north as North Carolina. Red tides are characterized by discolored water, dead fish, and toxic aerosols that cause respiratory irritations. Cell size is approximately 30μm (0.001 in).

Algal blooms vary in type, size, and effect

Nancy Diersing

What organisms cause algal blooms?

Algal blooms are caused by photosynthetically-active organisms (phytoplankton) that are suspended in the upper sunlit layer of waterbodies. Phytoplankton is commonly composed of microalgae, which are microscopic plants, or a type of bacteria (cyanobacteria) that is commonly called "blue-green algae." Bloom organisms often discolor the water because of the pigments found in their cells.

What causes a bloom?

Under the right conditions of sunlight and nutrients, phytoplankton cells can grow and reproduce faster than losses due to grazing, death, sinking, or advection out of the region. Sometimes blooms are composed of one dominant species, while at other times they are comprised by many species. Cell concentrations in blooms may reach millions of cells per milliliter.

What nutrients are important?

Phytoplankton obtain nutrients needed for growth and reproduction from the water. Macronutrients, including nitrogen and phosphorus, promote growth. Vitamins and trace metals (e.g., iron, zinc, manganese) are also needed in small amounts. Excessive nutrient loads promote excessive growth.

Why are some blooms more serious than others?

Blooms may be "harmful" through direct or indirect impacts and can become long-term events that can affect the entire ecosystem. Blooms produce oxygen during the day but use oxygen during the night. The result can be lower oxygen levels in the water, harming other organisms and even leading to fish kills. Some bloom organisms contain toxins. People who eat shellfish from waters experiencing a toxic bloom can become very ill, and the toxins can affect a variety of marine organisms. Harmful algal blooms have economic and cultural implications, especially in coastal communities that depend on tourism and harvesting of seafood.

How do blooms affect the ecosystem?

Phytoplankton form the base of many food webs and are fed upon by small grazers. Any significant change in the base of a food web that affects these small grazers also affects the fish, birds, and other animals in that food web. In addition, bloom organisms can become so dense that they physically block the pores and channels of some filter feeders, such as sponges, leading to their death. Dense blooms can also block the transmittance of light to benthic macroalgae and to seagrasses, causing their decline.

How do cyanobacterial blooms differ from other algal blooms?

Many of the impacts of cyanobacterial blooms are similar to those of other algal blooms. They can disrupt ecosystem food webs, and some are toxic. One of the most common cyanobacterial bloom species in Florida Bay is *Synechococcus elongatus*.

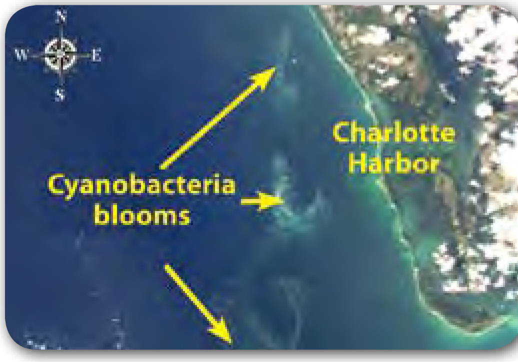
What caused the blooms in central and northern Florida Bay in the early 1990s?

A complex series of factors that are still not completely understood were responsible for blooms. It is believed that the blooms were sustained by nutrients that were released to the water column from the death and decomposition of many hectares of turtle grass and from the sediments that were no longer stabilized by seagrass roots. The resulting nutrient and light conditions, in conjunction with low flushing rates, favored the growth of *Synechococcus*.

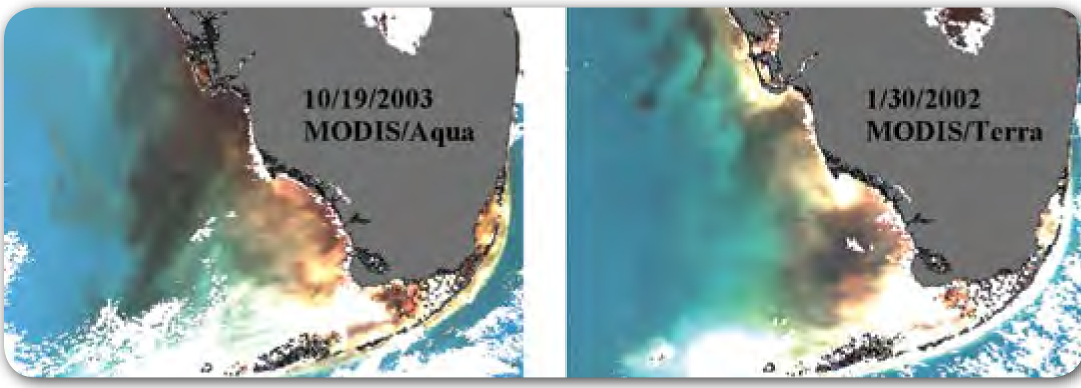
South Florida marine environments can be assessed with satellite remote sensing

Chuanmin Hu

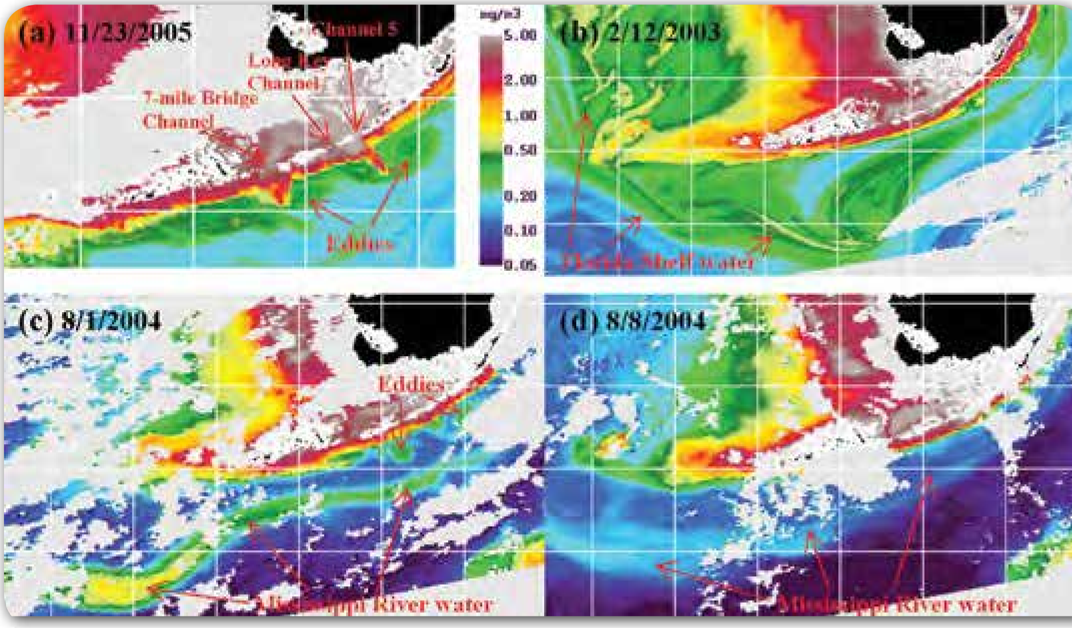
Compared with other means to collect oceanographic data, remote sensing from operational satellite instruments, such as Advanced Very High Resolution Radiometer, SeaWiFS (Sea-viewing Wide Field-of-view Sensor), and Moderate Resolution Imaging Spectroradiometer (MODIS), provides frequent (daily) and synoptic (same time) measurements of the ocean surface properties in near real time. These properties include sea surface temperature and ocean color (reflected solar light) as well as other properties derived from ocean color, including water clarity and turbidity, abundance of algae suspended in the water column, and concentrations of other suspended and dissolved materials. In some areas, these remote measurements may not be as accurate as shipboard measurements. However, they provide critical and timely information to study water quality events, monitor pollutants, help guide ship surveys, reveal connectivity between different ecosystems, validate numerical circulation models, and to assess the long-term coastal changes to help manage the coastal ecosystem. Indeed, satellite remote sensing is an indispensable component in any ocean observing system around the world because of the wide coverage and near real-time data availability. A few examples are shown here to illustrate how satellite remote sensing can be used to study and monitor the south Florida coastal ecosystem.



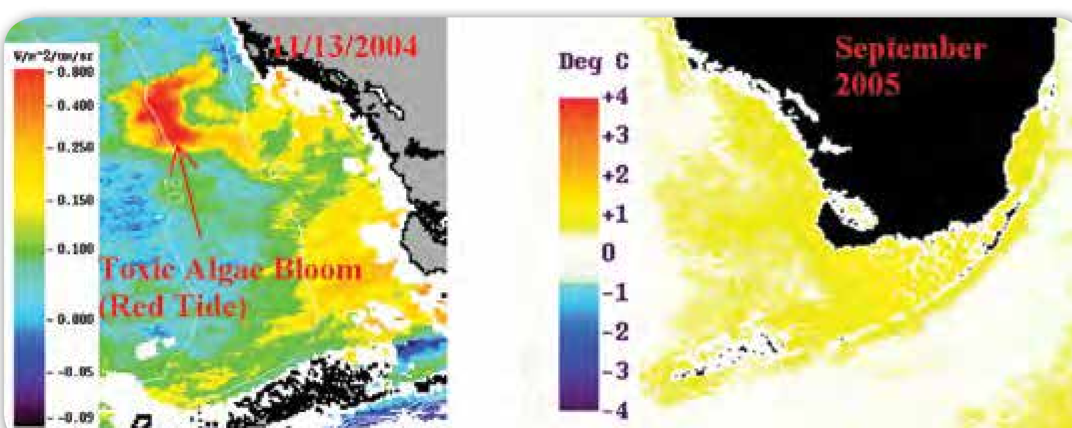
Red-Green-Blue MODIS image on May 23, 2004, showing blooms of the blue-green algae *Trichodesmium* spp. off Charlotte Harbor. The algae can fix nitrogen from the air, providing nutrients to other organisms, including the red tide algae (*Karenia brevis*).



Enhanced Red-Green-Blue MODIS images showing two examples of how the south Florida ecosystem is connected. The darkish colors resulted from light absorption by high concentrations of phytoplankton and/or dissolved materials in the water. White colors represent clouds, shallow water, or high turbidity. The "blackwater" patch on January 30, 2002 (left) is a result of earlier red tides drifting south, emanating from the north and runoff from rivers draining the Everglades. The timely detection of the blackwater event by satellite remote sensing helped coordinate ship surveys, which found toxic and nontoxic algae in the dark waters. This is the longest blackwater event in history (more than 3 months) and it resulted in significant benthic decline (die-offs of sponges and corals) in the Lower Keys. The dark water plume on October 19, 2003 (right) is due to excessive rainfall that led to higher than normal river discharge from the Caloosahatchee and Peace Rivers into Charlotte Harbor.



MODIS images showing how the south Florida marine ecosystem is affected by water from various sources. The images are color coded to show the phytoplankton abundance (through chlorophyll *a* concentrations in milligrams per cubic meter). Because of the difficulty of sensors separating the reflectance from the water column and benthic communities in shallow waters, the values for Florida Bay and other shallow waters may not be as accurate as for deeper areas; however, the emphasis here is on the spatial patterns. Image a, Intrusion of Florida Bay waters through the narrow tidal pass channels to the Atlantic side of the Florida Keys. Image b, Waters from the Southwest Florida Shelf entering the Florida Straits. Image c, Mississippi River water in the Florida Straits. Also shown are the 12-mile wide eddies near the Keys. These eddies play important roles in fish larvae transport and survival as well as in nutrient supplies. Image d, Mississippi River water diluted in the Florida Straits. It was estimated that about 23% of the entire Mississippi discharge between July – September 2004 entered the Florida Straits, equivalent to 4 times the volume of Lake Okeechobee.



Two examples of how satellite images are used to monitor the environmental health of the Southwest Florida Shelf. Left, MODIS image showing a toxic red tide bloom. The bloom is revealed by the solar-stimulated fluorescence (glow) of the algae under sunlight. Red color shows high algae concentrations. Red tides are known to kill fish and marine mammals. Right, Sea surface temperature anomaly. Portions of the Southwest Florida Shelf, Biscayne Bay, Florida Bay, and the Florida Keys were 1.0°C warmer than usual between August – September 2005, after which some degree of coral bleaching occurred at several reef sites in the Florida Keys.

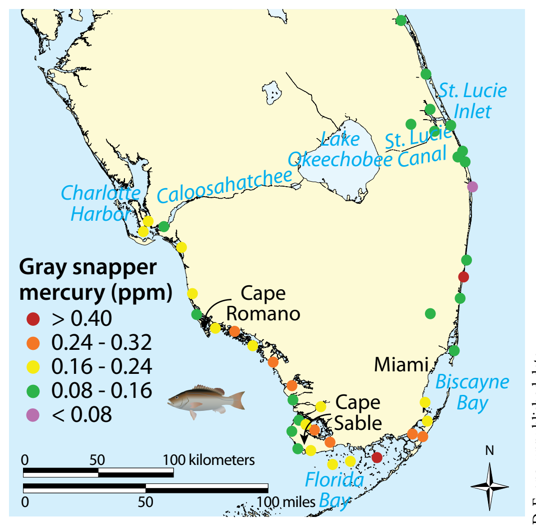
Mercury is a global contaminant with local impacts

Darren G. Rumbold and David W. Evans

Mercury is a globally dispersed contaminant and, thus, a global problem; however, localized "hot spots" can develop where local conditions favor accumulation through food webs (i.e., biomagnification). The Florida Department of Health has issued guidance advising the public to limit consumption of 59 species of commercially and recreationally valued fish from coastal waters off Florida because of the amount of toxic mercury contained in the fish flesh. Ongoing monitoring in the south Florida coastal marine environment has identified several hot spots or local regions where fish have higher mercury concentrations than surrounding areas. Fish consumption advisories are not unique to Florida. According to the United States Environmental Protection Agency (2007), 48 states, one territory, and two tribes have issued mercury advisories; 12 states, including Florida, have statewide advisories for mercury in coastal waters.

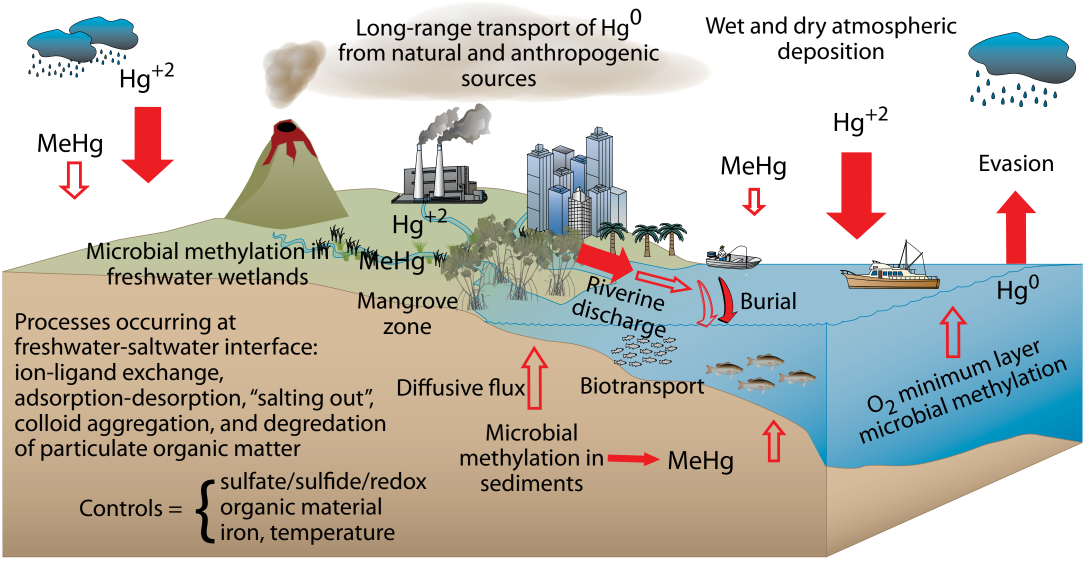
Mercury is a naturally occurring metal mobilized through various geologic processes, such as volcanic activity and the weathering of rock. Mercury mining and industrial processes, such as metal smelting and coal combustion, augment the amount available through natural processes. Although wastes from mining and chemical processing are no longer major direct sources to waterways in the United States, deposition of mercury released to the atmosphere, both in the United States and elsewhere, provides a continuing source. Mercury deposited on the landscape from past human activities also provides an ongoing source to fish.

Mercury cannot be destroyed or biodegraded. Instead it cycles among the different environmental media—air, water, soil, and biota—often taking on different chemical forms as it cycles. This determines the amount of time mercury resides in each medium and the concentration it achieves in each. Elemental mercury (symbolized as Hg0) can remain in the atmosphere for up to a year and can be globally dispersed before falling back to Earth. By comparison, the mercuric ion (Hg^{2+}) is more reactive, spending only hours or days in the atmosphere. It often deposits closer to its emission source. Hence, local deposition depends on both global and local emission sources.



Map showing mercury levels in gray snappers collected from coastal waters of south Florida.

In south Florida, atmospheric deposition is the leading source of mercury. During the 1980s and early 1990s, emissions from local municipal solid waste incinerators were believed to dominate over global background sources. These emissions have declined, but medical waste incinerators may be a new local source. Equally important, the omnipresent mercury deposition from the global atmospheric pool continues and may increase in the future. Currently, 12% of the emissions to the global pool are believed to originate from a single province in China (Guizhou), where mercury and coal, which always



General conceptual model showing sources, transport, and cycling of inorganic mercury (solid red arrow) (e.g., Hg0, Hg^{2+}) and methylmercury (open red arrow) (MeHg) to the marine environment.

contains some mercury (more so if found near mercury deposits), are mined and processed near each other. This source may increase as China uses more coal. Thus, efforts to reduce local mercury deposition through local emission controls have limited effects.

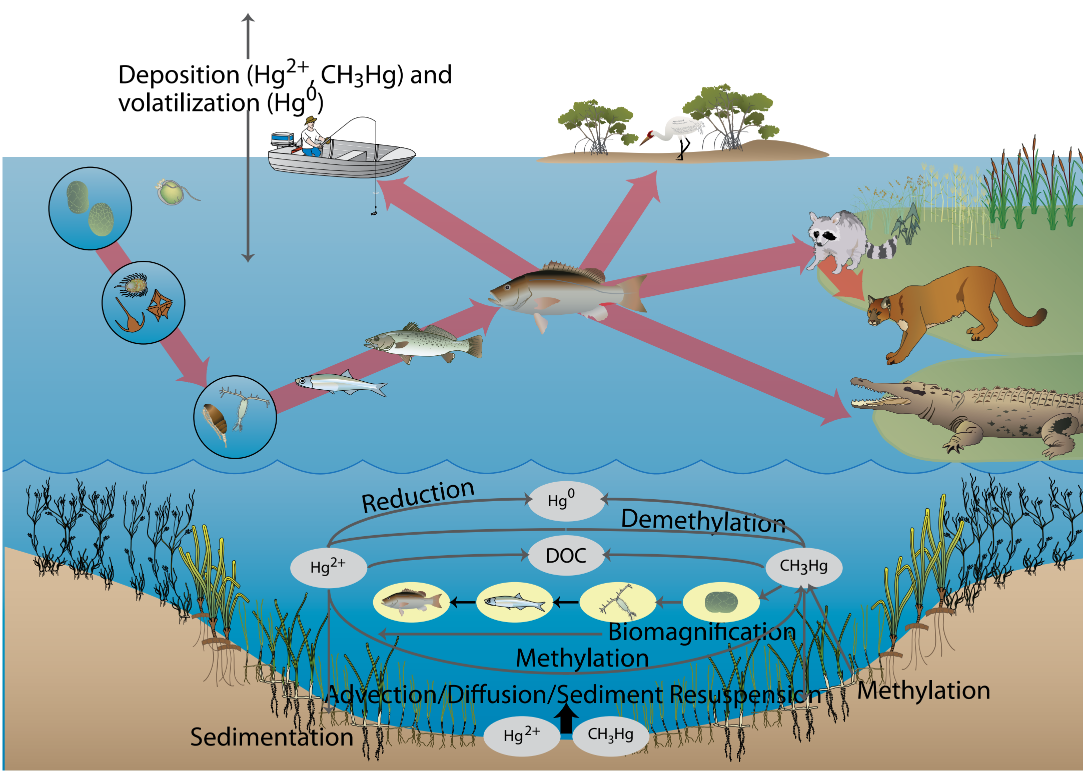
The form of mercury that is globally dispersed is of limited toxicological risk. However, if after deposition it is taken up by bacteria, in particular sulfate-reducing bacteria, this inorganic mercury (e.g., Hg^{2+}) can be transformed by the addition of a methyl group (i.e., methylation) as an incidental byproduct of the normal metabolism for the microbe. It is the amount of mercury present in this methylated form in sediment and water, not the total amount of mercury present, that is the critical factor in determining whether a given system will have a mercury problem. The trace amounts of both inorganic mercury and methylmercury in water (usually less than one part per trillion in the case of methylmercury) are not toxic if the water is ingested. Yet, methylmercury can reach harmful levels in the living biota due to its accumulation in food webs. Biomagnification is the stepwise increase in concentration in each successive level of the food web (e.g., plants < herbivores < predators) as each feeds on and accumulates the mercury accumulated in the trophic level below.

Methylmercury exposure can produce an array of toxic effects. Its most insidious effect is neurotoxicity to fetuses exposed while in the womb (i.e., in humans and other mammals). Children exposed while in the womb may show signs of mild cognitive dysfunction, and the development of cerebral palsy-like symptoms may develop. Fish-eating wildlife suffering even a mild dysfunction have reduced survival fitness through reduced competitive abilities and a greater risk of predation.

Much has been learned about the biogeochemical cycling and fate of mercury in freshwater systems, especially from research conducted in the Florida Everglades. In marine systems, much less is known about mercury cycling and its fate despite the knowledge that marine fish are the main source of methylmercury exposure in humans. There is a need to determine where methylation is occurring and what are the dominant sources of inorganic mercury that are being transformed into methylmercury.

The mangrove ecotone, which in south Florida often serves as the transition between terrestrial-freshwater and marine systems, can be an important site for methylation. Yet, a lingering downstream impact from the freshwater system is suggested in the pattern of spatial variability observed in the mercury levels in fish collected from bays along the south Florida coast. Fish from mangrove-fringed bays associated with large, wetland-containing watersheds often show higher mercury levels, suggesting that some of the methylmercury produced in the freshwater system is transported across the landscape. In Florida Bay, this was confirmed by measuring methylmercury in the water flowing down creeks into northeast Florida Bay. However, methylation of inorganic mercury also occurs in sediments of the outer bay that have nearly full strength seawater. Hence, there is a need to continue to monitor fluxes of inorganic mercury to the marine environment in order to determine the relative importance of various sources. Targeted source control is one means of reducing the toxicological impact of mercury.

In addition to inorganic mercury loading, many complicated and numerous geochemical and biological factors play a role in controlling the rate of net methylation in the receiving system. The carbon and sulfur cycles are always at the center of these biogeochemical reactions. In freshwater systems with abundant carbon, sulfur typically is limiting. In marine systems with abundant sulfur, organic matter can be limiting. Untangling these different processes and fluxes to determine which drives methylation and biomagnification is difficult in the estuaries because all are greatly influenced by hydrodynamics. Each estuary differs in its hydrodynamics with both temporal and spatial variability that comes with daily tides and seasonal changes in rainfall and runoff.



Mercury is a toxic contaminant that is globally dispersed and can be biomagnified in aquatic food chains.

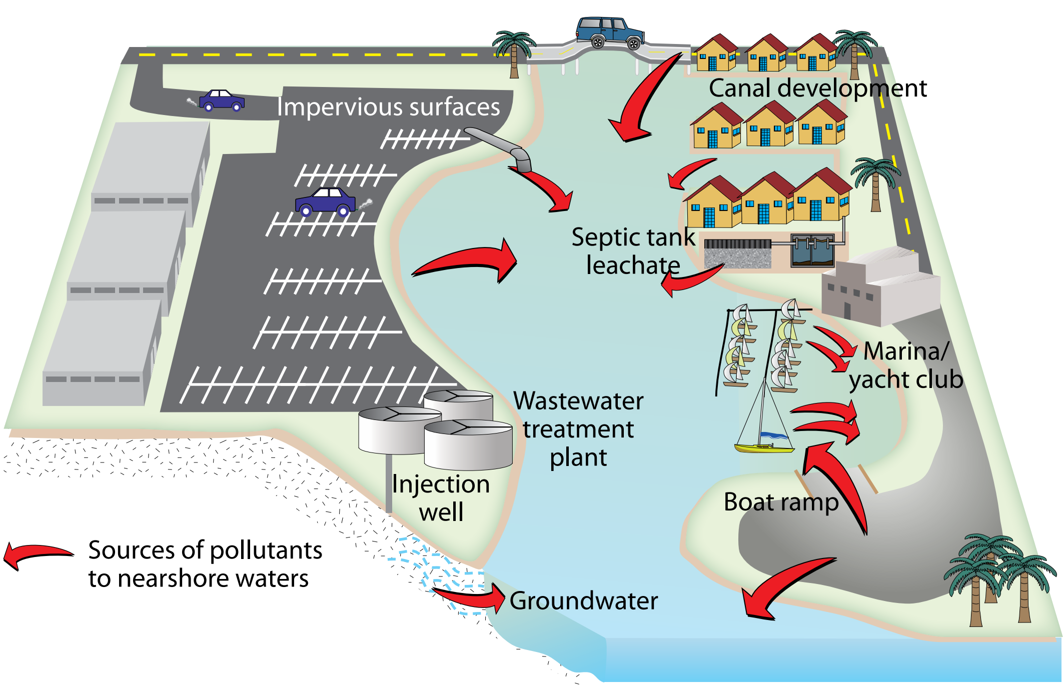
Water pollution in the Florida Keys comes from many different sources

Gus Rios, William L. Kruczynski, and George Garrett

The economy of the Florida Keys is directly linked to clean water and a healthy ecosystem. Because of the increasing population and developmental pressures experienced during recent decades, the water quality in the Keys is being degraded by human activities. In 1992, the Water Quality Protection Program identified inadequately treated wastewater and stormwater as primary sources of pollution to confined and nearshore waters of the Keys. Poorly treated wastewater and stormwater contain elevated concentrations of nutrients (e.g., nitrogen, phosphorus), that can cause algal blooms and degraded water quality. Discharges may also contain harmful bacteria and other pathogens that can pose a public health risk and can result in beach closings. Although the quality of offshore waters in the Florida Keys and Florida Bay can be influenced by external sources, such as the Loop Current and urban stormwater and runoff from the Florida mainland, evidence suggests that the quality of the Keys nearshore waters is strongly influenced by local anthropogenic sources.

On-site sewage treatment disposal systems and wastewater treatment plants

The groundwater and the nearshore waters in the Keys are closely connected. Wastewater effluent from on-site sewage treatment and disposal systems seeps into the surrounding porous limestone rock and can pollute the groundwater. Studies have shown that contaminated groundwater rapidly migrates to adjacent canals and basins, eventually discharging into and polluting nearshore waters. In 2000, the Monroe County Sanitary Wastewater Master Plan identified approximately 23,000 on-site sewage



There are many sources of pollution to nearshore waters in the Florida Keys.

treatment and disposal systems operating in the Florida Keys. The on-site systems consist mostly of septic tanks and at least 2800 illegal cesspools. There are also several hundred aerobic treatment units and approximately 250 permitted secondary treatment plants. Both aerobic treatment units and secondary treatment plants use shallow injection wells for effluent disposal. Septic tanks and cesspools provide little or no treatment because of the porous nature of the Keys limestone combined with the lack of soil and high groundwater. The permitted aerobic treatment units and the secondary treatment plants are designed to meet, at a minimum, secondary treatment and effluent disinfection, but they do little to remove nutrients.

W.L. Kruczynski - EPA

All long bridges in the Florida Keys have scuppers that discharge rainwater from roadways directly into surface waters.

Stormwater

Runoff from roads, residential areas, and businesses, including marinas and boat yards, can be a significant source of nutrient loading to surface waters. Untreated stormwater can also contain other harmful contaminants, such as bacteria, petroleum hydrocarbons, and toxic substances, such as lead and pesticides. Uncontrolled runoff can cause excessive turbidity in the water column that can be harmful to marine resources, such as seagrass beds and coral reefs. Because island settings have limited space, innovative methods to treat and dispose of stormwater are being investigated.

Discharges from vessels

Discharges from vessels account for a small percentage of the total nutrient loading to surface waters when compared with the nutrient input from land-based sources, such as septic tanks and stormwater runoff. However, sewage discharges from vessels can be a significant source of pollution in confined waters, such as anchorages and boat basins, where most vessels congregate. Petroleum discharges from vessels, such as fuel spills, can also cause significant harm to the Keys marine environment. Designation of all state waters in the Florida Keys National Marine Sanctuary as a no-discharge zone has resulted in a significant reduction of vessel discharges.

W.L. Kruczynski - EPA

Boats discharged their wastewater directly into surface waters before the advent of no-discharge zones.

Nutrients and pollutants from residential canals in the Florida Keys contaminate nearshore coastal waters

William L. Kruczynski, Gus Rios, and George Garrett

Canals were excavated to increase the area of waterfront development by dredging and filling mangrove shorelines. There are 481 canals in the Florida Keys, with a total length of 169 kilometers (111 miles). Differences in length, slope, depth, geometry, and underlying geology, as well as the population density, affect nutrient loading, flushing rates, and water quality within the canals and in nearshore coastal waters. All of the canal systems in the Keys have been inventoried and categorized by Monroe County. The inventory includes recommendations on how canal water quality and flushing rates can be improved.

Adapted from MACTEC (2003)

Port Largo Canal is a long, dead-end canal system with poor flushing. Canals were created by dredging and filling mangrove shorelines to create "fastland" for residential development.

Canals with poor water quality are listed in the Monroe County Sanitary Wastewater Master Plan. High nutrient concentrations are the result of sewage contamination, stormwater runoff, disposal of fish and yard wastes, and accumulation of floating dead seagrass and other organic debris.

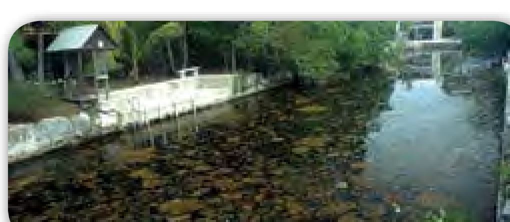
In 1987, the Florida Department of Environmental Protection measured water quality at canal and nearshore sites in Marathon for 1 year to monitor leachate from poorly functioning on-site sewage systems. Coprostanol, a degradation product of cholesterol, is indicative of solids contamination (e.g., feces) and was found in high concentrations in the sediments of canals. Coprostanol levels were highest near the head of canals and decreased toward the canal mouth due to dilution from tidal flushing.

	Open Water	Eden Pines Canal
Total Nitrogen	0.1 – 10 µM	40.5 µM
Total Phosphorus	0.1 – 0.2 µM	1.04 µM
Chlorophyll *a*	0.2 – 0.5 µM	2.78 µM

Adapted from Florida Bay Watch

Nutrient and chlorophyll concentrations are much higher in many residential canals than in open water. Micromolar (µM) is a unit of concentration.

Dissolved oxygen is generally at or close to zero near the bottoms of most canal systems. Lack of oxygen is caused by poor mixing in the water column and breakdown of organic materials in the bottom of canals. Marine life in canals is restricted to organisms that live near the surface or can withstand low oxygen levels. Many residential canals violate State Water Quality Standards for minimum dissolved oxygen concentration (i.e., 4.0 milligrams per liter). All waters surrounding the Keys are designated as Outstanding Florida Waters, where any increase of pollutants above background levels is a violation of State Water Quality Standards. Thus, canal systems that discharge degraded water to coastal waters are sources of pollution.



W.L. Kruczynski - EPA

High nutrients result in algal blooms and low dissolved oxygen in canals.

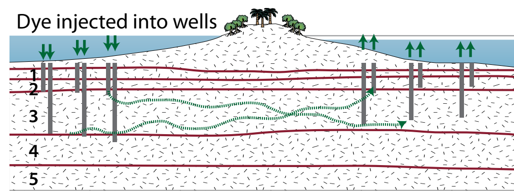
Groundwater moves through the Florida Keys from the Gulf of Mexico to the Atlantic Ocean

Eugene A. Shinn

The limestone under the Florida Keys is porous but not uniformly so. It was formed during the Pleistocene Epoch, a time when glaciers waxed and waned and sea level fluctuated many times. Coral reefs grew along the shallow Florida shelf each time the sea level was high. Each time the sea receded, the reefs and sands were laid bare and became cemented into limestone. A dense red-brown limestone crust called "calcrete" capped the rock each time the sea receded. The red-brown color is due to iron in dust that is periodically transported from Africa across the Atlantic Ocean on trade winds. Calcrete is a very impermeable layer, and there are five layers of calcrete in the upper 30.5 meters (100 feet) of limestone beneath the Keys. Because it is impermeable, it forces groundwater to flow sideways both between and across these layers. The layers of calcrete are numbered one to five and are referred to as Q Units for the Quaternary Period, the most recent period in geological history. The Q3 Unit is especially thick and extends throughout the region about 9.1 m (30 ft) below the surface.

To determine movement of water, a circular array of monitoring wells was drilled on both sides of Key Largo. Each well was constructed to allow sampling of water from above and below the impervious Q3 Unit. In the central well, one kind of tracer dye was injected above the Q3 and another dye below. By monitoring the peripheral wells, the direction and speed of movement of the dye was measured. Results showed that saline groundwater moved from the Gulf side of the Florida Keys toward the Atlantic Ocean underneath the entire width of Key Largo at a rate of about 1.8 m (6 ft) per day. Water above the Q3 moved more rapidly than water below that layer.

Water levels in Florida Bay (Gulf side) fluctuate mostly because of wind; there are very small lunar tides in Florida Bay. Lunar tide fluctuation on the Atlantic side of the Keys is about 0.9 m (3 ft) and occurs twice a day (diurnal). Measurements show that the average water level on the Bay side is several inches higher than on the Atlantic side. This creates a hydraulic head, and water runs downhill. When the Atlantic tide is low, there can be 0.9 m (3 ft) of difference in water level, and the rate of water moving toward the Atlantic is fast. When the Atlantic tide is high, the direction of flow reverses for awhile. This back-and-forth sloshing causes tidal pumping. During low tide, not only does the water move faster from the bay toward the ocean, but also the hydraulic head pushes groundwater about 0.3 m (1 ft) above sea level. At those times, water boils out of the rock where there are cracks and crevices. Even though the groundwater sloshes back and forth like water in a bathtub, the net flow is toward the Atlantic.



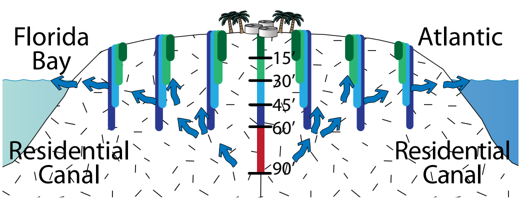
Bay to ocean groundwater flow model representing net direction of groundwater movement during normal conditions based on dye studies. The left margin of the diagram shows the relative depths of Q1 – Q5 Unit layers.

Any contaminants entering the groundwater of the islands from sewage or stormwater injection wells, septic tanks, or lawn fertilization become mixed with the flow and move toward the Atlantic. When the Atlantic tide is low, the hydraulic head diffuses upward under pressure. Studies using bacterial and viral tracers have found that the groundwater from the Keys may reach the surface water near the bank reef.

Nitrogen and phosphorus from wastewater disposed into injection wells enters surface waters

Kevin Dillon

Conventional, secondary wastewater treatment plants produce an effluent that is rich in nitrogen (nitrate) and phosphorus (phosphate) nutrients. In the Florida Keys, the effluent is injected into Class V (shallow) injection wells. Class V wells are drilled into the limestone to a depth of 27 meters (90 feet) and are cased with an impermeable lining to 18 m (60 ft), so the zone of discharge is between 18 – 27 m (60 – 90 ft) below the surface.

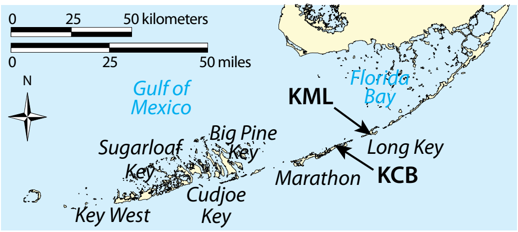


Cross section of an array of sampling wells surrounding a Class V injection well to determine rate and direction of wastewater plume and concentration of nutrients as the plume moves through limestone.

The groundwater beneath most of the Keys is saline, whereas the wastewater effluent is relatively fresh. After injection into a well, the less dense, buoyant wastewater plume rises toward the surface. Research investigating the movement of the wastewater plumes and the fate of nutrients from Class V injection wells was conducted at two sites in the Keys. The Keys Marine Laboratory has a low volume 2650 liters (700 gallons) per day disposal well on Long Key. Key Colony Beach has a relatively high disposal volume of 946,000 L (250,000 gal) per day. Monitoring wells were installed around each injection well and were drilled to 4.6, 9.1, 13.7, and 18 m (15, 30, 45, and 60 ft). Samples were taken from monitoring wells to assess nutrient concentrations of subterranean wastewater and movement of plumes using tracers (dyes and other chemicals).

Results demonstrated that wastewater is rapidly transported upward toward the surface and laterally (up to 6.4 m [21 ft] per day), which delivers tracers placed into injection wells to nearby surface waters after several days to weeks (10 and 60 days at Keys Marine Laboratory and Key Colony Beach, respectively). As the wastewater flows through cracks and fissures in the limestone, denitrifying bacteria remove 30% – 90% of the nitrate from the underground plume and convert it to harmless nitrogen gas.

Phosphate in wastewater is initially removed from solution by chemical adsorption onto the limestone; however, this sequestration is short lived. The limestone acts as a phosphate buffer, temporarily adsorbing 50% – 100% of the phosphate from solution until an equilibrium concentration of 0.8 parts per million is achieved. Once that concentration is established, it persists even when phosphate-free water is added to the system, due to the release of bound phosphate from the saturated limestone. So with time, the limestone can get saturated with phosphate and no longer removes it from the wastewater. Although more research is needed to fully understand this process, it appears that phosphate equilibrium plumes form around injection wells and slowly expand as more phosphate is added to the system until the plumes eventually reach surface waters.



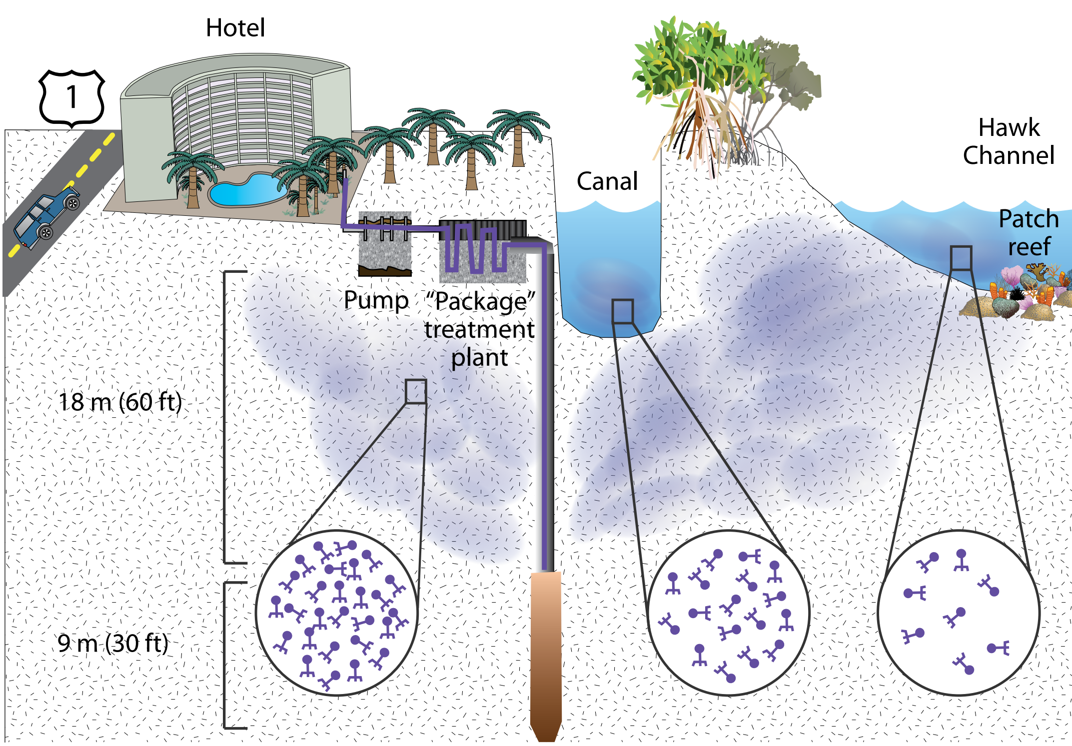
Locations of research sites: Keys Marine Laboratory (KML) on Long Key and Key Colony Beach (KCB).

Wastewater disposed into shallow injection wells can be tracked using viral tracers

John H. Paul

Class V injection wells comprise a wastewater disposal system that is commonly used by secondary treatment package plants in the Florida Keys. To determine whether such wells could result in contamination of surface waters in the Keys, viral tracer studies were performed in two Class V wells using a harmless bacteriophage. Bacteriophages are viruses that infect bacteria; they cannot infect humans. Bacteriophages not found in the Florida Keys will not multiply in the environment because their host is not found there; therefore, they make useful tools as tracers of wastewater movement.

A bacteriophage was grown to a high concentration in the laboratory and used to "seed" the injection wells over a 4-hour period. At the Saddlebunch Keys site, the rate of movement of the viral tracer away from the injection site ranged from 1.2 – 141 meters (4 – 463 feet) per hour; at Long Key the movement ranged from 0.35 – 22.5 m (1.2 – 74 ft) per hour. This means that sewage injected into the well moved away from the point of injection quickly. Thus, nutrients, microbes, or other contaminants in the sewage effluent can quickly contaminate the surface waters.



Generalized diagram showing package treatment plant, injection well, and adjacent canal and open waters (Hawk Channel). Bacteriophage tracer plume (purple cloud) spreads from point of discharge. Highest concentrations of tracer viruses were found near discharge zone, but tracer viruses were also found in the adjacent canal and surface waters (Hawk Channel). These studies demonstrate that Class V injection wells can cause contamination of surface waters in this environment because of the porous nature of the limestone substrate.

Pathogenic human viruses are present in residential canals

Dale W. Griffin

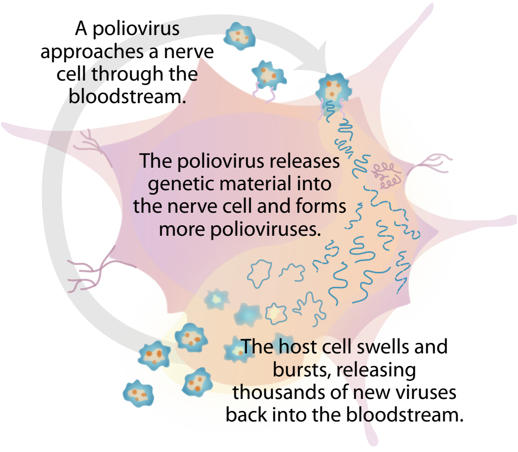
In the late 1990s, there were approximately 23,000 on-site sewage treatment and disposal systems, 2800 illegal cesspools, and 670 shallow injection wells 18 – 27 meters (60 – 90 feet) deep in the Keys. Small package sewage treatment plants disinfect wastewater to kill pathogenic and nonpathogenic microorganisms and dispose of the treated wastewater into shallow injection wells. However, they are a source of household chemicals, pharmaceuticals, and nutrients. Septic systems and cesspools not only are a source of nutrient and pharmaceutical pollution but can also be a source of pathogenic and nonpathogenic microorganisms to nearby bodies of water because those systems do not disinfect wastewater, .

Studies have been conducted using bacteriophages (viruses that infect bacteria) to trace the fate of wastewater from septic systems and shallow injection wells. Several studies performed to trace the fate of wastewater disposed into shallow injection wells in the Middle and Lower Keys demonstrated a rapid transport of wastewater to canals and nearshore surface waters. In one experiment that flushed bacteriophages into a septic tank, the organisms were detected in a nearby Key Largo canal 11 hours after they were flushed. In another experiment in Marathon, bacteriophages were found in a canal connected to Boot Key Harbor 3 hours after being flushed into a septic tank.

Are discharges from septic systems and cesspools a risk to ecosystem and human health?

Fecal microbes have the potential to displace native microbes and to disrupt essential ecosystem cycles. They have also been shown to cause a disease in marine organisms. *Serratia marcescens*, a bacterium found in the human intestinal tract and other places, such as soil, causes white-pox disease in elkhorn coral (*Acropora palmata*). Many viruses that infect people have a fecal-oral pathway of infection and typically have "shed rates" of 1 million viruses per gram of feces. Pathogenic viruses can infect people at very low doses (in some cases fewer than five viruses) and so it does not take much fecal contamination for waters to be a concern for human recreational uses.

To investigate the risk of fecal microbes to human health, 19 sites in the Florida Keys were screened for the presence of indicator bacteria (i.e., total coliforms, fecal coliforms, *Escherichia coli*, *Clostridium perfringens*, and enterococci), coliphage, and four groups of pathogenic human viruses (i.e., enteroviruses, Hepatitis A viruses, Norwalk viruses, and Norwalk-like



Adapted from Smithsonian National Museum of American History

The life cycle of a poliovirus. Enteroviruses include echoviruses, coxsackie viruses, and poliovirus. These viruses are actively shed by up to 30% of the population. In most cases, they cause asymptomatic infections (i.e., no sign of illness), but on occasion, they can cause a variety of illnesses, including flu-like symptoms, gastroenteritis, meningitis, and myocarditis, that can be lethal. Although the polio vaccine program has been very successful at preventing the disease, it is not unusual to detect the poliovirus (vaccine strain) in Florida waters affected by human feces.

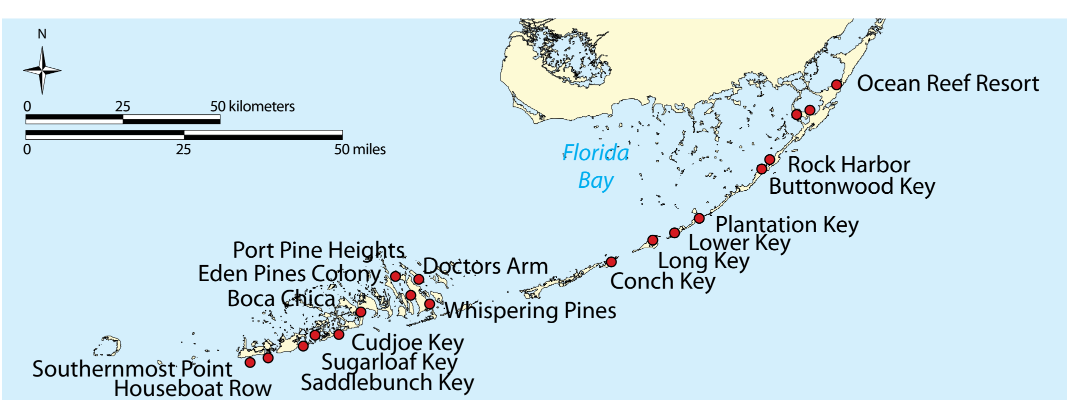
viruses). In this first study, no distinction was made between living or dead human viruses. Of the 19 sites, all but one were positive for at least one of the groups of viruses, while at the same time the bacteria data indicated good to fair water quality. The one exception was the sample taken near the Southernmost Point in Key West where the bacteria counts were also high because the city sewer system had been leaking at this site. (Key West has since upgraded its sewage collection system and now discharges into a deep well instead of an ocean outfall.)

The sites that typically had the highest counts of human viruses were canals with homes using septic systems that were part of an extensive canal network that offered no means of effective flushing (e.g., Eden Pines Canal system on Big Pine Key). The sites with the lowest counts of microbial indicators had well flushed or flow through canal systems or were connected to a central collection and treatment system.

Follow-up studies detected live and infectious enteroviruses in canals during periods when surface waters were cool. This finding emphasized the conclusion that the currently used indicator bacteria (i.e., fecal coliform and enterococci) do not accurately assess human health risk. In most cases in tropical environments, indicator bacteria are poor proxies of water quality, and pathogenic human fecal-oral microorganisms can be present when bacteria data indicate that the water is safe for recreational use. These and other studies have unequivocally demonstrated that septic tanks or cesspools, as well as leaking central collection systems, installed in porous limestone substrate in proximity to marine surface waters pose a risk to human and ecosystem health. Regulatory agencies should thoroughly evaluate hydrogeologic conditions before permitting septic tank installations in the Florida coastal environment. Conversion to central collection and sewage treatment systems will provide an increased level of protection to public health and to the unique and sensitive environments that are present in the Florida Keys.

W.L. Kruczynski - EPA

A film of scum on the surface of the water at the dead end of a multichannel canal network on Big Pine Key. Canals that are bordered by homes using septic systems should be viewed as an extension of the septic tank network, and recreational use of the canal waters should be avoided.



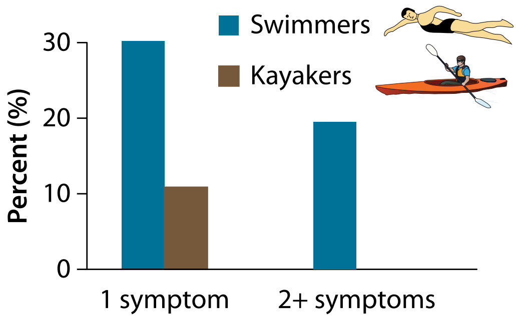
Sample site locations for bacteria and virus counts in the Florida Keys. The study showed that human viruses could be present in significant numbers when fecal bacteria counts were below State of Florida standards.

In-ground disposal of human sewage can contaminate nearshore waters and reefs with bacteria and viruses

Erin K. Lipp, Dale W. Griffin, and J. Carrie Futch

Historically, much of the sewage in the Florida Keys was disposed into on-site septic tank systems or, in some cases, cesspools. Cesspools are holes in the ground that provide no treatment of sewage. When septic tank systems function properly, the drainfield allows slow filtration and natural "treatment" of wastewater through an area of dry soil. Treatment of wastewater breaks down when the drainfield occurs in wet or saturated soils, which exist in areas with a high groundwater table, such as low-lying and coastal areas. Also, when the density of septic systems is high, the wastewater saturates the ground, and there may be insufficient area for proper filtration. Unfortunately, both of these problems arise, sometimes simultaneously, in the Florida Keys, leaving the groundwater and adjacent surface waters, including residential canals, vulnerable to contamination with bacteria and viruses found in human feces. The presence of these microbes has been used as a tracer to show that nutrients or other contaminants in human sewage are reaching coastal waters. Their presence can pose a threat to public health because many of these microbes cause a range of diseases, especially diarrhea and vomiting, when accidentally ingested while swimming.

Studies beginning in the mid-1990s show that viruses in particular can move quickly (within 11 hours in some cases) from a septic system to adjacent canal and nearshore waters. Additionally, 95% of the canals tested in 1998 contained one or more types of viruses that can infect humans. In 1999, as many as 30% of competitive swimmers in a 19 kilometer (12 mile)-race around Key West reported one or more symptoms of waterborne diseases (i.e., eye, ear, and nose problems; gastrointestinal and respiratory issues;



During the Annual Swim Around Key West in June 1999, 30% of swimmers (blue bars) reported at least one symptom of a waterborne disease, and 20% reported two or more symptoms. Only 10% of kayakers on the same route (control group, open bar) reported one symptom, and none reported multiple symptoms.

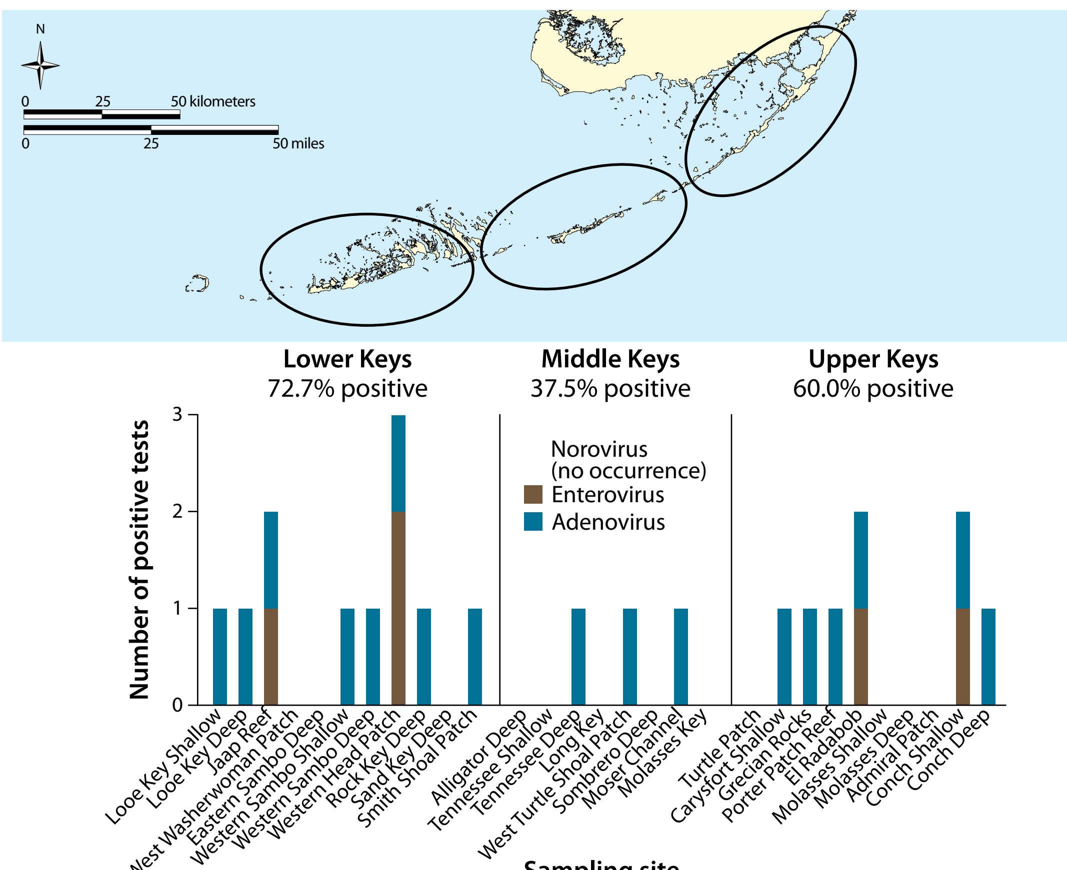
E. Lipp - UGA

Beaches in the Florida Keys are occasionally closed due to high levels of fecal indicator bacteria (Key West Citizen, July 17, 1999). Closed beaches can affect tourism and the economy.

skin rashes; and diarrhea) likely associated with swimming in contaminated water. After completion of the 1999 race, beaches in Key West were closed due to high bacterial counts.

Contamination is not restricted to nearshore waters. The genetic material of human viruses has been detected from groundwater wells and the mucus layer of corals as far as 10 km (6.2 mi) offshore. The distribution of these viruses in coral mucus corresponds with the distribution of large population centers in the Florida Keys. Highest levels were found in corals off Key West and Key Largo, and lower frequency of viral contamination occurred in corals found off the Middle Keys.

Monroe County completed its Sanitary Wastewater Master Plan in 2000, and work has begun to improve wastewater collection and treatment. Increased levels of treatment should improve water quality by reducing the levels of nutrients and human pathogens discharged into waters surrounding the Florida Keys. Key West upgraded its treatment to Advanced Wastewater Treatment, eliminated its open water discharge in 2002, and has re-sewered the city to separate stormwater from sewage. Monroe County and other municipalities are in varying stages of improving wastewater treatment to satisfy requirements of State of Florida Law 99-395.



Mucus samples from corals were collected from reefs throughout the Florida Keys and analyzed for the presence of three types of human viruses found in human sewage (noroviruses, adenoviruses, and enteroviruses). Results of the analyses are presented as number of times a reef was positive for each of the viruses. Reefs in the Upper Keys (including Key Largo with a population of approximately 26,000 people) and Lower Keys (including Key West with a population of approximately 39,000 people) had the highest percentage of reefs positive for human viruses, whereas the frequency of virus detection was considerably lower in the Middle Keys (with a human population of approximately 11,000).

Navigational inlets are conduits for land-based sources of pollution

J. Carrie Futch, Dale W. Griffin, Ken Banks, and Erin K. Lipp

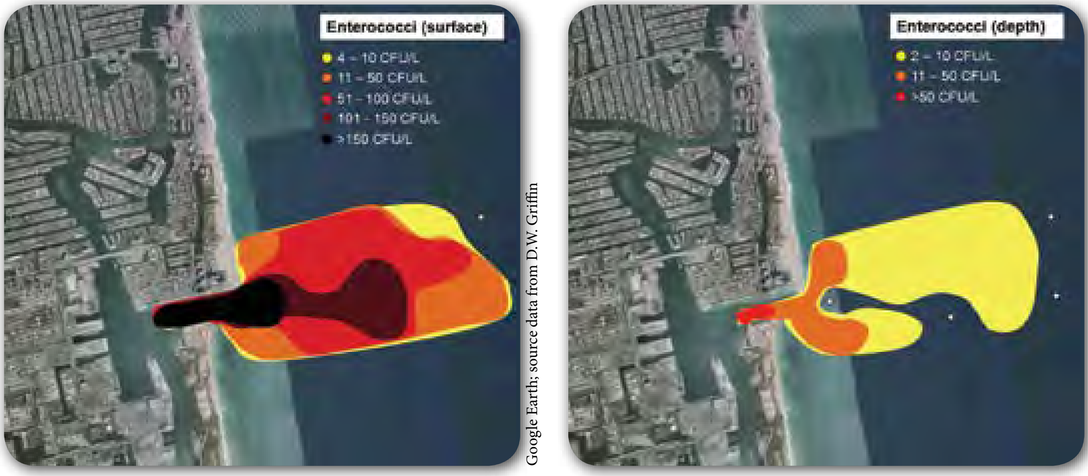
Large navigational inlets in southeast Florida can act as conduits of wastewater and stormwater pollutants from developed areas to nearshore marine waters. Pollutant constituents can affect human recreational use and ecosystem health. These discharges, in combination with regulated releases of inland waters, such as freshwater from Lake Okeechobee, can result in contamination of nearby ocean waters.

In Broward County, Port Everglades is a large commercial port that receives waters from the Middle River, New River, and the Dania Cutoff Canal as well as influxes from urban stormwater and agricultural runoff via the Intracoastal Waterway. Untreated sewage from spills or leaks from improperly functioning septic tanks can enter these waters. Contaminants that reach the Intracoastal Waterway are eventually subject to tidal mixing with ocean waters through Port Everglades Inlet.

Research conducted offshore from Port Everglades Inlet indicates that sewage and other wastewater contaminants are affecting ocean waters, coral reefs, and nearby beaches. Samples collected on an outgoing tide at the Port Everglades Inlet contained multiple types of noroviruses in addition to other microbes found in human sewage. Elevated levels of pharmaceuticals typically present in sewage were also found. Noroviruses are one of the most common causes of diarrhea in adults, and infamously known as the "cruise ship virus."

NOAA image enhanced by R. Dodge - NSU

Aerial photograph of outgoing tide at Port Everglades Inlet (circa 1981). The inlet may act as a conduit for pollution to the marine environment, introducing bacterial and viral contamination. Image has been enhanced to increase visibility of the Intracoastal Waterway and water exiting the inlet.



Google Earth; source data from D.W. Griffin

Google Earth; source data from D.W. Griffin

Colorized plots show the concentration of sewage-associated bacteria (enterococci) as it exits the Port Everglades Inlet on the surface (left) and on the bottom (right) during an outgoing tide. Black and red are the highest concentrations (CFU/L =colony forming units per liter of water); yellow is the lowest concentration.

Improving wastewater and stormwater treatment reduces nutrient loading to canals and nearshore waters

Scott McClelland and Stephen R. Lienhart

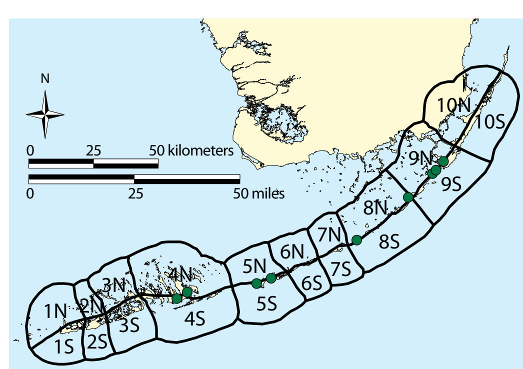
The Florida Keys is a chain of islands approximately 350 kilometers (220 miles) long, extending from the end of the Florida peninsula and curving southwest toward the Dry Tortugas. Consisting of 822 islands, of which about 30 are inhabited, the Florida Keys are traversed by U.S. Highway 1 that includes 30 km (19 mi) of bridges. Key West represents about 31% (24,630 people) of the population of the Florida Keys, which is about 78,990 people according to the Bureau of Economic and Business Research for April 1, 2007.

FDEP

Aerial view (2004) of densely populated canal developments in Key Largo. Historically, poor wastewater and stormwater treatment as well as poor circulation and flushing resulted in degraded water quality in canals.

Residential canals were excavated in the Florida Keys during the development of the inhabited islands to provide waterfront access for residents. Canal systems were designed to maximize development with little regard to water quality. Currently, water quality in canals is poor due to inadequate wastewater and stormwater treatment, as well as limited circulation and tidal flushing. In addition, weed wrack (i.e., detached seagrass blades) collects in some canals, decomposes, and forms an organic ooze in the canal bottom that consumes dissolved oxygen and releases nutrients.

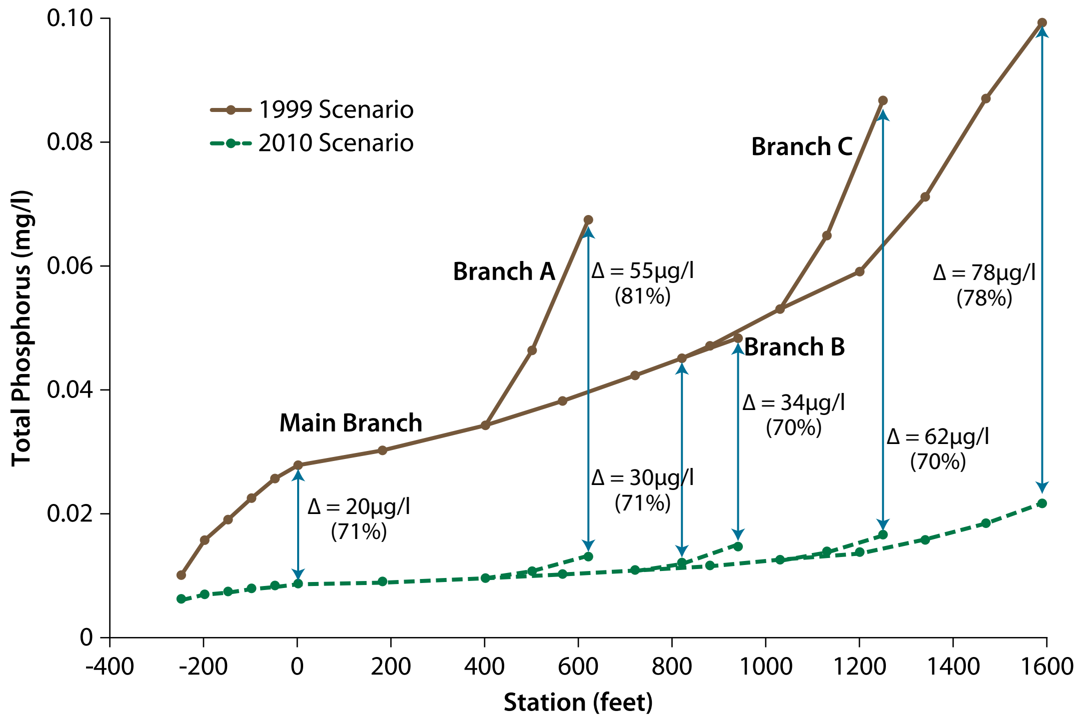
The Florida Keys Reasonable Assurance document considered the potential impacts of anthropogenic nutrient loading of the nearshore waters of the Florida Keys, including the many canals. The nearshore waters of the Keys were divided into 20 modeling areas from the shoreline to about 12.1 km (7.5 mi) offshore. Also, 10 representative canals were modeled, and nutrients from the land (i.e., wastewater, stormwater, urban and natural runoff) were loaded into the shoreline boundary of the models. The models advectively distributed the loads through mixing and tidal dynamics until steady state was reached. These models were used to test the potential nutrient concentration that may result from the significant wastewater and stormwater improvements being made in the Keys. The modeling showed that at 500 meters (1600 feet) from the shoreline, the improved anthropogenic nutrient loading would result in total nitrogen and total phosphorus concentrations less than 10 µg/l and 2 µg/l above natural background concentrations, respectively.



Location of 20 nearshore areas and 10 residential canals (green dots) that were modeled to show that improved anthropogenic nutrient loading would reduce total nitrogen and total phosphorus to near background concentrations.

Natural background concentrations were simulated by eliminating anthropogenic inputs (i.e., point sources) and changing urban land uses into natural lands. Furthermore, the nearshore nutrient concentrations are predicted to return to ambient values similar to or less than those measured during the time when the Keys were designated Outstanding Florida Waters.

Modeling of the 10 representative canals provided similar results. Canals were modeled to assess changes in total phosphorus for the 1999 baseline condition (believed to be the worst case) and the 2020 improved condition when the majority of the nutrient reduction activities are expected to be completed. Results for Canal 50 (in Key Largo) show that total phosphorus in 1999 was about 0.01 mg/l at the canal mouth and increased 10 times to 0.10 mg/l at the end of the main channel. Canal 50 has three dead-end branches: A, B, and C. The model predicts that in 2020, there would be a 71% reduction in total phosphorus in the main branch and 70% – 81% reductions in the canal branches. These results are due to decreased wastewater and septic tank inputs into the canal and improved nearshore nutrient conditions, primarily the result of a reduction of anthropogenic influences. Ancillary benefits may also be achieved with reduced septic loads, including reduced enteric bacteria (i.e., fecal coliform and enterococci) and viruses. Nutrient reduction activities will return the quality of nearshore waters to historical levels. However, even with reduced nutrient loads to canals, poor tidal flushing, limited circulation, and the presence of weed wrack will still limit the water quality in the canals.



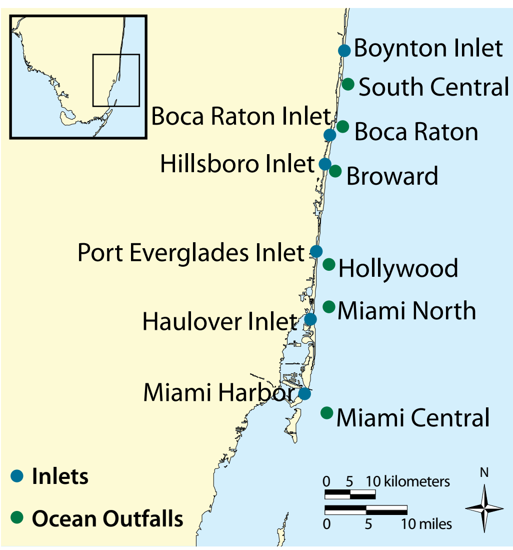
Results of modeling total phosphorus concentration in a residential canal (Canal 50) in the Florida Keys before (brown) and after (green) improvements to sewage treatments. Total phosphorus concentration is shown on the y-axis (mg/l). The figure shows a canal with a main branch and three side branches (Branch A, B, and C). The solid red line represents the 1999 time period, which assumes the worst case conditions (i.e., high phosphorus concentrations). The dotted green line shows modeled concentrations after sewage and stormwater improvements have been implemented. Total phosphorus concentration would decrease by 71% at the mouth of the canal and midway on the main branch, and 81%, 70%, and 78% in Branches A, B, and C, respectively.

The Florida Area Coastal Environment Program supports science-based water quality management

Thomas Carsey and Jack Stamates

The Florida Area Coastal Environment (FACE) Program is an ongoing research effort led by the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory since 2004. The FACE Program highlights the need to comprehensively assess the coastal zone to help understand the impacts of land-based sources of pollution on southeast Florida coral reef habitats and to formulate science-based management. The broad objectives of the program include the following:

- Quantifying the sources of nutrients and microbial contaminants;
- Quantifying the relative contributions of those sources to the nutrient budget and microbiological loads of the region; and
- Determining the likely exposure of coral reef resources to nutrient and microbiologic sources.



Study sites of the FACE Program include inlets and ocean outfalls from sewage treatment plants from Miami (Miami-Dade County) to Boynton Inlet (Palm Beach County).

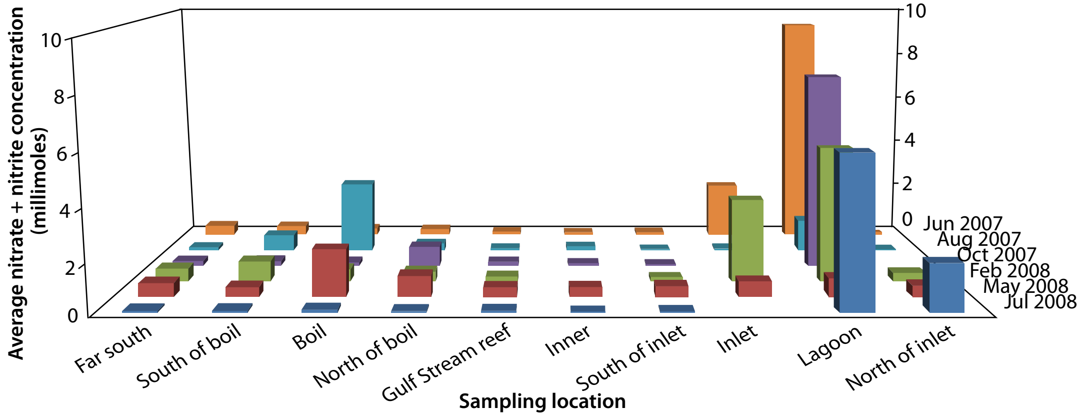
This extensive field program has performed surveys of sewage outfalls at all six existing wastewater plants in the study area (Miami Central, Miami South, Hollywood, Broward, Boca Raton, and South Central) and at several inlets and their respective receiving waters. Ultimately, FACE will undertake detailed physical, chemical, and biological studies at each inlet and outfall, including recording ocean currents, nutrient concentrations and source tracking, microbiology, and stable isotope analyses. Examples of information from some completed studies are given here.

Tracer studies

A study was conducted at the Hollywood Wastewater Treatment Plant outfall in June 2004 using sulfur hexafluoride to trace the direction of the outfall plume (i.e., boil). Sulfur hexafluoride is a humanmade compound. The plume was traced flowing north, near the coast, for 66 kilometers (41 miles). A second tracer study was performed near the outfall of the South Central Regional Wastewater Treatment Plant and in nearby Boynton Inlet in 2007. Results suggested a rapid dilution of the outfall effluent by the surroundings waters. Waters exiting Boynton Inlet were traced over 34 km (21 mi) north of the inlet.

Currents

Measurements of currents help to elucidate sources of water that can affect important coral communities. Ocean current data have been measured at several locations off Palm Beach County for extended periods of time. For example, instrumentation at the north end of Gulf Stream Reef from April 2006 – September 2007 recorded a northerly current flow 86% of the time.



Averaged concentrations of nitrate and nitrite from six bimonthly cruises from south of the South Central ocean outfall (i.e., boil) to north of Boynton Inlet. Horizontal axis names refer to sampling regions. Seasonal variation and variation by site are shown in this three-dimensional graph.

Nutrients

Nutrients (e.g., nitrite, nitrate, orthophosphate, silicate, ammonia) were measured during intensive studies at the Boynton Inlet and at all six wastewater treatment plant ocean outfalls. These results help to evaluate the relative concentration as well as the dilution of these nutrients in the receiving waters. Elevated nutrients were found near the outfall boils and at Boynton Inlet.

Inlet studies

Detailed flow, chemical, and microbiological sampling measurements were made at the Boynton Inlet during two 48-hour-long studies. These studies noted considerable, but highly variable nutrient flux. Additional inlet studies are planned.

Microbiology

A variety of microbial contaminants were measured at sewage outfalls and at several inlets and adjoining waters. High bacterial counts (*Methanobrevibacter smithii*), viral counts (*Norovirus*), and intestinal parasitic protozoans (*Cryptosporidum* and *Giardia*) were detected at sewage outfalls and during outgoing tides from inlets. A comparison of results from the six outfalls shows the highest concentrations of microbial contaminants at the Miami-North boil.

Location	*M. smithii* (GE*/100mL)	*Norovirus* (GE*/100mL)	*Cryptosporidium* oocysts	*Giardia* cysts/100L
South Central boil	700	no detection	no detection	no detection
Hollywood boil	3.0×10^5	235	55	67
Boca Raton boil	2.7×10^4	2.3	<1	<1
Broward boil	3.7×10^5	6.3	8	2
Miami-North boil	1.3×10^5	347	236	246
Miami-Central boil	3.4×10^5	11	8	120
Deep-water control	no detection	no detection		

*GE = Genome Equivalent is a measure of the abundance of microbes.

Abundances of microbes, including intestinal bacteria (*Methanobrevibacter smithii*), human viral pathogens (*Norovirus*), and intestinal parasitic protozoans (*Cryptosporidium* and *Giardia*) from surface water at wastewater ocean outfalls (i.e., boils) and a deep-water control site, February 2008.

Pharmaceuticals are present in wastewater discharges

Piero R. Gardinali

Coastal habitats are among the most productive and diverse components of the marine ecosystem but are also the most vulnerable to pollution. South Florida contains vital fresh, estuarine, and saltwater habitats that are linked by complex hydrological and biological connections. Because southeast Florida coastal habitats are adjacent to large population centers, they are adversely affected by physical abuse and through the discharge of pollutants. One type of pollutant that has only recently received attention is the discharge of personal care products and pharmaceuticals (i.e., microconstituents) into surface waters. These microconstituents include insect repellents, sunscreens, fragrances, plasticizers, human and veterinary pharmaceuticals, anti-inflammatory drugs, antibiotics, birth control hormones, and other drugs.

Some common microconstituent pollutants

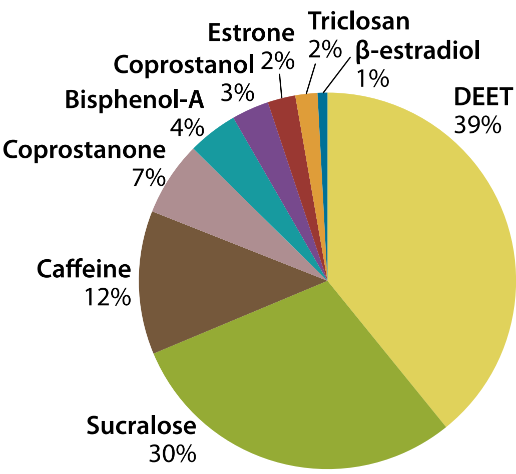
- **β-estradiol**: A main component of human estrogen hormone and an endocrine-disrupting hormone.
- **Bisphenol-A**: A chemical found in food containers and reusable plastic bottles and an endocrine-disrupting compound.
- **Caffeine**: A stimulant found in coffee, sodas, sports drinks, and drugs.
- **Coprostanol/coprostanone**: Metabolites of cholesterol used as a tracer of human fecal contamination in the environment.
- **DEET**: A chemical used in insect repellents.
- **Estrone**: A human estrogen hormone that is an endocrine-disrupting hormone in the environment.
- **Sucralose**: An artificial sweetener that is resistant to conventional wastewater practices.
- **Triclosan**: An antibacterial chemical found in soaps, detergents, and some plastics.

M. Averette

The Miami River is an urban river that receives point and nonpoint pollution from many sources.

Modern wastewater treatment facilities can remove nutrients prior to discharges to surface waters or groundwater. However, unregulated organic chemicals commonly used as personal care products have been found to survive the treatment process and have been increasingly detected in wastewater discharges from central treatment facilities, on-site systems, and surface coastal waters worldwide. The occurrence, fate, and transport of microconstituent pollutants are being studied to understand their sources and dissipation in coastal environments. However, their environmental toxicology, including the risks associated with their presence, is less well known.

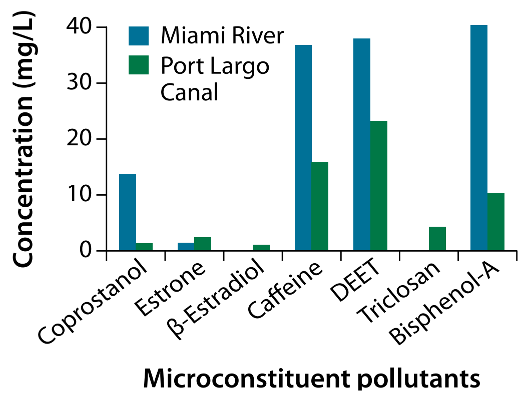
Communities are turning to water reuse, recharge, and reclamation because clean drinking water is becoming scarce. A major challenge in the use of these solutions for water conservation is the presence of microconstituents that survive traditional wastewater treatment methods. A case in point is estrone, an endocrine-disrupting hormone that can affect development and reproduction of fishes in concentrations as low as a few parts per trillion. Estrone has been found to be ubiquitous in surface waters and reclaimed wastewater. It was the most common microconstituent in Little Venice canals (Florida Keys) where most of the homes were on cesspools or poorly functional septic tanks before improved wastewater treatment became available. Other endocrine-disruptive chemicals found in south Florida waters include an estrogen derivative (β-estradiol) and a plasticizer (Bisphenol-A).



Composite of the chemical ecology of surface waters of the Miami River, Port Largo Canal (Key Largo), Little Venice canals (Marathon), and Looe Key showing all the microconstituents found and their relative percentage.

The artificial sweetener sucralose (Splenda®) is chlorinated table sugar that has a long shelf life and is very stable at high temperatures. These qualities, exceptional for food manufacturing, make it resistant to conventional wastewater treatment practices. Sucralose is very common in wastewater and in both nearshore and offshore surface waters in the Florida Keys. DEET, an active ingredient in insect repellents, and caffeine from coffee, tea, and soft drinks are also common in south Florida waters.

Microconstituent pollutants are so varied in their chemical composition, volume, and stability that detailed studies are needed on local and regional scales to assess the chemical ecology of receiving waters. For example, the Miami River has a different chemical "fingerprint" of microconstituents than Port Largo Canal (Key Largo).



The chemical "fingerprint" of microconstituents in the Miami River (blue) and Port Largo Canal (green) are very different.

Coprostanol is related to cholesterol and is commonly used as an indicator of sewage pollution. Coprostanol is found in higher concentrations in the Miami River than in Port Largo Canal, whereas triclosan, a compound commonly used in antibacterial soaps and detergents, was more prevalent in Port Largo Canal and absent from the Miami River.

At present, the best management practices and the most effective strategies to prevent chronic releases of microconstituents include development of effective wastewater treatment methods and consumer-based education programs stressing proper household disposal. Monitoring programs should include a suite of microconstituents so that risks associated with the fate and transport to marine ecosystems can be assessed and information can be used to develop science-based management actions.

Boot Key Harbor shows successful water quality improvements

William L. Kruczynski and Richard Tanner

On June 19, 2002, all State of Florida waters within the Florida Keys National Marine Sanctuary became a no-discharge zone for sewage from all vessels. The designation was made by the United States Environmental Protection Agency at the request of Monroe County and the Governor of Florida.

No-discharge zone

A no-discharge zone is a geographic area where discharge of sewage (i.e., blackwater), whether treated or not, is prohibited from all vessels. It is illegal to discharge sewage from boats into surface waters in a no-discharge zone. Discharge of gray water (galley, showers, washdown water) is not illegal in a no-discharge zone.

Why was this action taken?

The biological resources of the Florida Keys National Marine Sanctuary depend on clear, low nutrient waters. It is estimated that vessels account for about 3% – 5% of total nutrients discharged to Sanctuary waters. However, vessel discharge constitutes a significant source of water pollution in harbors, marinas, and other areas with poor circulation. Treatment provided by marine sanitation devices on vessels disinfect the waste but

P. J. Smith

Boats moored at some of the 226 mooring balls in Boot Key Harbor, Marathon, Florida.

do not remove nutrients. Excess nutrients result in water quality degradation. Prior to this designation, houseboats were required to have sewage pumped out, whereas transient vessels could discharge wastewater directly into surface waters. In a no-discharge zone, all vessels are required to store their sewage in a holding tank and have that tank pumped out at an approved facility. A list of available pump-out facilities in the Florida Keys is given at http://fl-monroecounty.civicplus.com/DocumentView.aspx?Did=313

finalized, 226 mooring balls were installed, pump-out was facilitated by available onshore facilities and mobile pump-out boats, and a dock master was hired to oversee activities in the harbor.

In 2004 – 2005, the first year of operation of the completed facilities, 6568 vessels were pumped out, removing approximately 375,000 liters (99,000 gallons) of sewage that would have been discharged into the harbor. In 2007 – 2008, approximately 591,000 L (156,000 gal) of wastewater was properly disposed

W. L. Kruczynski - EPA

Pump-out facilities removed 99,000 gallons of vessel sewage during the first year of operation in Boot Key Harbor. Before the no-discharge zone designation, sewage would have been discharged directly to surface waters.

Boot Key Harbor

In 1990, the Florida Department of Environmental Regulation conducted an intensive 1-year study in Boot Key Harbor and found low dissolved oxygen and high fecal bacteria counts in proximity to anchored vessels. Violations of the State standards for dissolved oxygen and bacteria were common. At the time of the sampling, approximately 400 vessels were anchored in the Harbor during winter months. After designation of state waters as a no-discharge zone, a harbor plan was

from vessels by City of Marathon facilities at Boot Key Harbor and private marinas in Marathon.

Through the diligence of Monroe County and the City of Marathon, Boot Key Harbor is now very well managed and has improving water quality. It is reported that porpoises, mullet, eagle rays, and other marine organisms that were not seen for many years within the harbor are now commonly sighted. Also, fecal bacteria levels have been greatly reduced in surface waters and regularly meet state standards. This is truly a success story.

Sewage treatment improvements enhance water quality in Little Venice canals, Florida Keys

Henry O. Briceño and Joseph N. Boyer

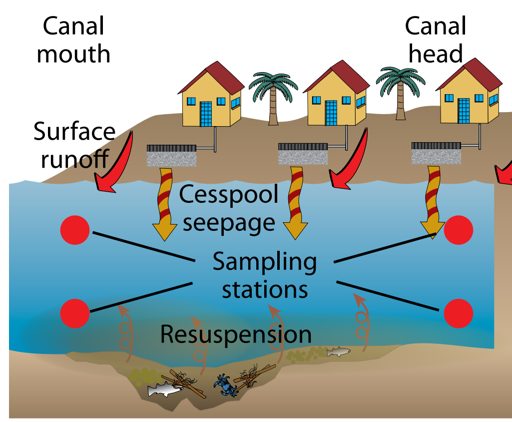
Fecal coliform bacteria and enterococci (*Enterococcus* spp.) bacteria live in human intestines, and their presence in surface waters is correlated with fecal contamination and the presence of human pathogens. Testing surface waters, beaches, and shellfish beds for the presence of these bacteria is a routine method for protecting public health.

Historically, many communities in south Florida were built with poorly functioning on-site wastewater treatment systems. Cesspools are holes in the ground that provide no treatment of wastewater, and septic tanks do not function well in areas with high water tables and/or limestone substrates. Both allow untreated wastewater to rapidly infiltrate the groundwater. Canals within residential communities intersect the groundwater and have high nutrient concentrations and elevated concentrations of fecal bacteria and human viruses.

The Little Venice neighborhood in Marathon, Florida, had high development density, a large concentration of cesspools and inadequate septic systems, and poor canal water quality. In 2004, an advanced wastewater collection system and treatment plant was constructed to serve as a demonstration project to assess the effects of central collection and treatment of wastewater on the water quality in the residential canal system of Little Venice. Phase I entailed sampling the canal water quality from 2001 – 2003, before the treatment plant was built. Monitoring was halted during construction (2004) and resumed in 2005 – 2008 (Phase II) to assess changes after improved wastewater treatment (i.e., remediation).

Google Earth

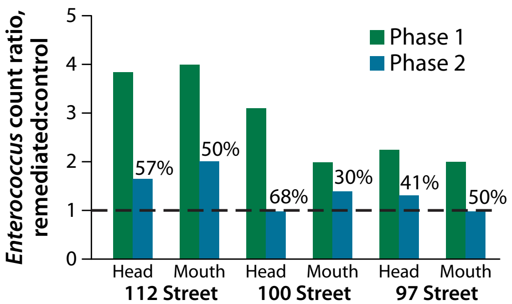
Location of water quality sampling stations (yellow dots) at head and mouth of canals in Little Venice, Marathon, Florida, and offshore control station.



A cross section of a residential canal in Little Venice. Wastewater was deposited into a cesspools beneath houses before remediation. Untreated wastewater entered the canal via groundwater. Organic excrement accumulated in the bottom of canals for many years.

Sampling occurred weekly at the head and mouth of three canals (97th St., 100th St., and 112th St.) scheduled to receive central collection and treatment (remediated), one control canal (91st St.) lacking remedial actions, and a nearshore control site. Weekly measurements included salinity, temperature, nutrients, dissolved oxygen, and fecal coliform and enterococci bacteria counts.

Water quality in the Little Venice area is the result of a dynamic interaction among water masses moving from the Gulf of Mexico to the Atlantic Ocean through Vaca Cut and alongshore, ocean waters, and stormwater runoff. Thus, changes in water quality due to improved sewage treatment practices can be difficult to separate from changes due to natural variation and the occasional influence of remote waterbodies. Additionally, water quality in the canals may be influenced by their depth and length, flushing rates, groundwater seepage, and the accumulation of organic excrement and debris that has collected in the bottom of the canals for many years.



This bar graph compares *Enterococcus* bacteria count ratios between remediated canal sites and the corresponding control site in the 91st St. canal for Phase I (green) and Phase II (blue). Ratios above 1.0 indicate worsening conditions than the control canal, and changes from Phase I to Phase II are shown as percentages of improvement. All stations sampled in the remediated canals show an improvement in bacteria counts after remediation.

Overall, this demonstration project documented that removing cesspools and nonfunctional septic tanks from a waterfront residential neighborhood resulted in a decrease in fecal coliform and enterococci bacteria in adjacent canals by 77% and 57%, respectively, 4 years after remediation. The improvement was greatest at stations that had higher bacterial counts in Phase I.

The heads of canals experience more restricted circulation (flushing) than the mouths of canals, and the heads of canals consistently had higher bacterial counts than stations at canal mouths. Before remediation, 5.2% of weekly counts of enterococci at canal mouths exceeded the recommended safe levels. Three years after houses were connected to the central wastewater collection system, the level of exceedances dropped to 4.0%, and during 2008, they dropped further to 1.6%, a sign of significant improvement.

Improvements to concentrations of bacteria may be masked by the regrowth of the bacteria in the organic-rich and nutrient-rich bottom sediments. So, in addition to comparisons of individual sites between pretreatment and posttreatment, bacteria counts were compared between remediated sites and control sites to filter out effects occurring across the region that may not be related to remediation. These analyses indicate that enterococci count ratios in Phase II decreased significantly compared with the corresponding control sites (30% – 68%), likely due to the improved sewage treatment practices in homes adjacent to the canals.

W. L. Kruczynski - EPA

Little Venice subdivision is a very dense development. Prior to connection to a central collection system and an advanced wastewater treatment plant, most homes discharged sewage into an unlined hole under the house (cesspool), which resulted in high concentrations of fecal bacteria in the canals.

The concentration of dissolved oxygen is an important water quality parameter because it controls the type and number of organisms that can live in the water and the chemistry of other compounds found there (e.g., heavy metals). Prior to remediation, the amount of dissolved oxygen in canals fell below the State Water Quality Standard for Class III marine waters (minimum 4.0 mg/l or daily average 5.0 mg/l) 57% of the time for surface samples and 67% of the time for bottom samples. After remediation, dissolved oxygen exceedances decreased to 49% and 58% for surface and bottom samples, respectively. The high concentrations of organic sediments in the canals may continue to contribute to the slow improvement in levels of oxygen until the canals are fully flushed.

You can help to improve water quality

William L. Kruczynski, Gus Rios, and George Garrett

There are many activities that homeowners, visitors, and local governments can do to improve water quality in canals and other nearshore waters.

Reduce nutrient loading

Nutrients, mainly nitrogen and phosphorus, are important for plant growth. However, too many nutrients leads to problems, such as algal blooms. Because canals, marina basins, and other confined waters have poor circulation and flushing, they are especially susceptible to impacts of excess nutrients.

The following activities will minimize nutrient loading into waters:

- Support implementation of wastewater and stormwater master plans and enforcement of state water quality regulations.
- Maintain septic tanks and drainfields to ensure nutrient uptake.
- Limit application of fertilizers and other chemicals away from canals.
- Create buffer zones adjacent to surface waters and direct drainage away from open water.
- Compost organic wastes or dispose in household garbage, not in canals.
- Replace exotic vegetation with native plants, especially on canal banks.
- Use phosphorus-free detergents.
- Discharge gray water from washing machines, sinks, and showers to approved wastewater treatment systems.
- Comply with no-discharge zone regulations.

Use water efficiently

- Install high efficiency shower heads.
- Fill bathtub with minimal amount of water needed.
- Run dishwasher and clothes washer only when full.
- Keep diapers and other trash out of toilets.
- Turn off faucets when not in use and while shaving and brushing teeth.
- Eliminate plumbing leaks.
- Install aerators in faucets.
- Replace old appliances with high efficiency models.

Increase canal circulation and flushing

Generally, measures to improve circulation and flushing of canals are beyond the means of individuals. However, individuals and homeowner associations can work with local governments to make improvements.

Water quality in dead-end canals can be improved by:

- Backfilling deep canals to shallower depths to facilitate tidal exchange and mixing;
- Aerating canal waters to assist vertical circulation;
- Removing accumulation of organic, oxygen-demanding sediments from canals;
- Installing flushing channels and culverts provided that the action will not degrade receiving waters; and
- Installing floating booms, air curtains, and other devices to prevent floating weeds and other debris from entering canals.

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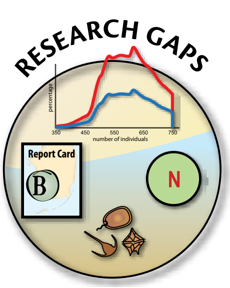
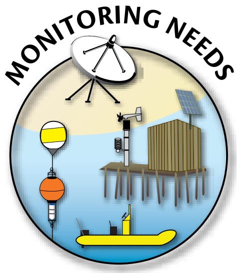
4. CORAL REEFS AND HARDBOTTOM HABITATS

Coral Reefs and Hardbottom Habitats Chapter Recommendations

- Coordinate management efforts to identify and **reduce local, regional**, and **global stressors** to corals and coral reefs.
- Develop an effective and strategic approach to inform the public of the **implications of climate change** on coral resources, garner their support in passing legislation and regulations to reduce carbon emissions, and share the responsibility of improved stewardship of reef resources.
- Promote establishment of **Marine Protected Areas** and special management zones to maximize the ability of a reef ecosystem to recover from human and natural disturbances. Because not all of the functions of all the species on a reef are fully known, it is prudent to protect them all for the benefit of the whole.
- Establish and increase **mooring buoy programs** to limit damage from anchoring on coral reefs and hardbottom habitat.
- **Secure funding support** for education and effective communication on best management practices for diving, snorkeling, and fishing around coral reefs.
- **Implement science-based fishing regulations** to allow recovery of depleted fish stocks and protect key species from overfishing.



- Identify causes and methods of transmission of **coral diseases** and the role of multiple stressors affecting reef health.
- Quantify the role of **microorganism communities** in coral health and resilience.
- Differentiate between **natural variation** in coral abundance and human-induced changes.
- Conduct controlled experiments to identify factors affecting **recruitment** rates in stony corals.
- Quantify the role of **hardbottom communities** in the structure and function of the south Florida marine ecosystem.
- Determine the role of **genetic variability** and connectivity among sites and regions related to coral recruitment, survival, and longevity.
- Identify and assess genetic components of corals **resilient to bleaching** and other diseases and culture them for use in restoration projects.
- Conduct socioeconomic studies to regularly assess the **ecosystem values** provided by natural and artificial reefs.
- Quantify the effects of **ocean acidification** on coral growth and health.



- Continue monitoring of **abundance and diversity** of coral reef organisms.
- Quantify factors controlling successful **coral recruitment** patterns.
- Monitor annual changes of **coral disease patterns** throughout the region and identify "hot spots" of occurrence.
- Monitor **artificial reefs** to evaluate whether intended objectives are being met.

Chapter title page: Sherwood Forest, Dry Tortugas. J. Luo, UM/RSMAS.

Introduction

What are corals?

Corals are bottom-dwelling marine animals that are related to sea anemones and jellyfish. Common corals are actually colonies composed of individual polyps. A polyp is a cup-shaped unit composed of a mouth located at the apex of a stalk that is surrounded by tentacles.[1] Polyps resemble sea anemones in structure. There are two main groups of corals: hard corals and soft corals.

Hard corals, or stony corals, are comprised of polyps that have six tentacles, or multiples of six.[2] Polyps of hard corals secrete a rigid skeleton made of calcium carbonate that they extract from seawater. The polyps live on the surface of the skeleton and excrete a protective mucus layer. There are two major growth forms of hard corals: branching corals and boulder corals. Branching corals in south Florida include elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*). Common boulder corals in south Florida include boulder star coral (*Montastraea annularis*) and grooved brain coral (*Colpophyllia natans*). Not all corals form coral reefs; those that do are called hermatypic hard corals. Hermatypic corals harbor symbiotic algae (zooxanthellae) within the polyp cells that give them their various colors.[3,4] Elkhorn coral, boulder star coral, and grooved brain coral are examples of reef-forming corals.


J.W. Porter - UGA

Hard (i.e., stony) corals, such as this pillar coral, consist of a colony of individual polyps that excrete a calcium carbonate skeleton. Each polyp has a multiple of six tentacles.

Soft corals are also called "octocorals" because their polyps have eight tentacles, or multiples of eight. Most soft corals secrete a flexible skeleton that consists of a core made from a protein called gorgonin and surrounded by an outer layer that contains the polyps. Soft corals are also known as "gorgonians" because of their inner core.[2]


D.S. Gilliam - NSU

Soft corals (i.e., octocorals) consist of polyps surrounding a flexible core. Each polyp has multiples of eight tentacles.

Hard corals were originally classified by Carl Linnaeus, the founder of modern taxonomy, as "Zoophyta", meaning "animal plants" because they had characteristics of both.[5] Hard corals can feed on planktonic prey that they capture by their tentacles. The tentacles contain stinging cells called nematocysts that are triggered by touch and pierce their prey; then the tentacle delivers the prey item to the polyp mouth. Most corals extend their tentacles at night for feeding.

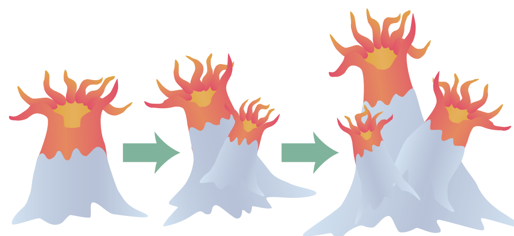
Hard coral polyps are translucent animals that get their colors from the zooxanthellae algae that live within the polyps. Zooxanthellae are microscopic, single-celled algae that contain chloroplasts and carry out photosynthesis in the presence of sunlight. Coral polyps and their zooxanthellae live in a mutualistic symbiotic relationship in which both partners benefit. This coral-algae partnership is extremely efficient, and more than 90% of the organic materials that the algae produce are used by the coral for growth and other metabolic needs.[6] The coral supplies the algae with carbon dioxide and nutrients. Corals actually control the numbers of zooxanthellae within their tissues by limiting the amount of nitrogen they supply to the algae. About one third of the sugars received from the algae is used to produce the protective mucus layer of the coral.[4,6]

Many of the shallow reef-dwelling soft corals have symbiotic algae. Soft corals also feed by capturing small prey in their mucus nets and with their harpoon-armed tentacles.

J. Luo - UM/RSMAS

Coral reefs are found in tropical and subtropical oceans where water is shallow and clear enough to allow sufficient sunlight to penetrate to the bottom.

Corals and the coral reefs that they form provide an interesting paradox: well-developed coral communities are found in the most nutrient-deficient waters of the world. Hard corals need a lot of energy to build their skeletons faster than waves or bioeroding organisms can wear them away. Coral communities are highly productive. It is the partnership between hard corals and their symbiotic algae that allows corals to live in a nutrient-poor environment where sunlight is a plentiful source of energy and planktonic food is generally limited.[4] Coral communities efficiently recycle and preserve organic matter, and that efficiency allows corals to outcompete other organisms in oligotrophic (low nutrient) waters. Efficient recycling of nutrients helps to explain how primary productivity of coral reefs can exceed productivity of areas where nutrients are more abundant.[6]



A coral polyp divides by asexual budding to create a coral colony.

Hard corals can reproduce sexually. In some (brooders), fertilization takes place within the polyp. In others (broadcast spawners), fertilization takes place in the water column. Fertilization results in an embryo and eventually a planula that is distributed by ocean currents. Planulas can attach to suitable substrate and form a polyp. The polyp then divides by asexual budding and creates a colony that acts as a single organism. The limestone skeletons produced by each polyp interconnect. Coral colonies can also propagate through a process of fragmentation when a broken piece of colony can grow a new clone. Branching corals frequently propagate by fragmentation after being broken-up by hurricanes and strong waves or other physical damage.

Coral reef formation

Some, but not all, corals have the ability to join other coral colonies to form spectacularly diverse limestone communities called coral reefs. Some coral reefs on Earth today began growing over 50 million years ago, and some fossil reefs similar to present-day reefs have existed since the age of the dinosaurs (150 million years ago).[7] Coral reefs are found in tropical and subtropical oceans where water is shallow and clear enough to allow sufficient sunlight to penetrate to the bottom and where water temperature is between 18° – 36°C (64° – 97°F); optimal reef growth occurs between 26° – 28°C (79° – 82°F).[8] The adaptation to nutrient-deficient conditions also includes a dependence on adjacent mangrove and seagrass communities to intercept nutrients and sediments from land before they reach the reef. Mangrove and seagrass communities also provide nursery and foraging areas for some animals that dwell on the reef.

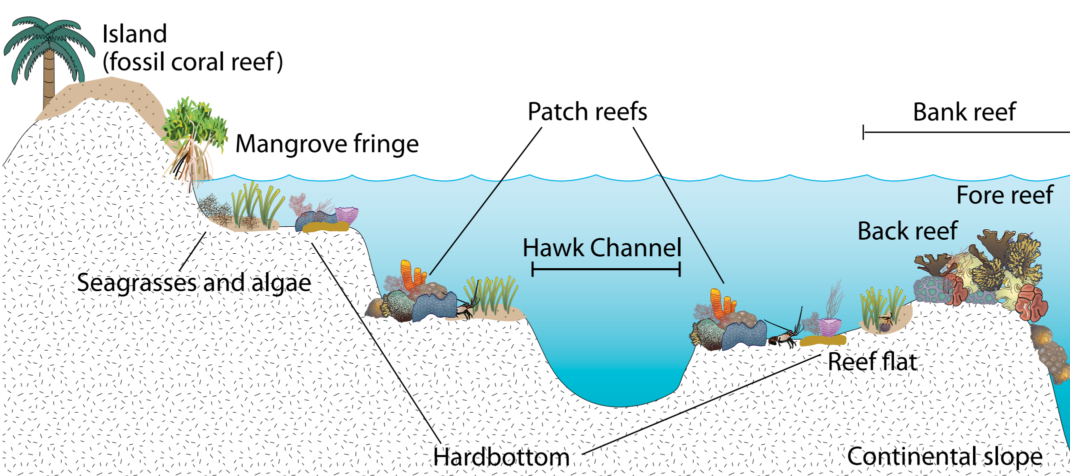
Living coral reefs in south Florida (i.e., Holocene reefs) are about 6000 – 8000 years old and formed when sea level stabilized after the last Ice Age. The two coral species most responsible for Holocene (modern-day) reef building in south Florida are elkhorn coral (*Acropora palmata*) and star coral (*Montastraea annularis*); other colonizing species add to the framework set down by those species.[9,10]

Only the outer layer of a reef is alive. As coral colonies grow and expand and new corals settle, they build their skeletons on top of dead corals from earlier generations. The growth rate of coral reefs in the Keys has been measured by coring through the reef foundation; vertical reef growth rate varies between approximately 0.65 – 4.85 meters (2 – 16 feet) per 1000 years.[9,11]

Geographic distribution of corals

Different coral formations are found throughout south Florida. From about Cape Canaveral to Fort Pierce, the ivory tree coral (*Oculina varicosa*) occurs in banks at about 70 – 100 m (230 – 328 ft) or deeper and can form pinnacles up to 30.5 m (100 ft) tall. Because light levels are low at those depths, the primary food source for the benthic community is phytoplankton and detritus. Like shallow water reef corals, *Oculina* banks provide habitat for a great diversity of fish and invertebrates, including economically important species. Because of heavy fishing pressure and impacts from trawling, the *Oculina* bank off Fort Pierce has been designated a Habitat Area of Particular Concern and is closed to snapper, grouper, and rock shrimp fishing.[10,12]

The area between St. Lucie Inlet and Cape Florida (Key Biscayne, Miami)



From Cape Florida to the Dry Tortugas, corals occur on hardbottom habitats, patch reefs, and deep and shallow bank reefs. Hardbottoms are dominated by octocorals, algae, sponges, and scattered hard corals. Patch reefs have high diversity and coverage of octocorals and hard corals and are generally circular in shape. Bank reefs occur at the edge of the continental shelf in a high-energy environment and have high relief and high hard coral coverage and diversity.

contains the Southeast Florida Reef System. From St. Lucie Inlet to Palm Beach County, elements of tropical coral reef biota occur and become more abundant toward Cape Florida. Staghorn coral (*Acropora cervicornis*) thickets have recently become common in this area. The reefs found in this area are characterized as an octocoral- and sponge-dominated community, with scattered hard corals growing on terraces of fossilized coral reefs built predominantly by elkhorn coral approximately 4000 years ago.[10] Colonies and thickets of staghorn and elkhorn corals as well as boulder corals are found in this area.

The area south and west of Cape Florida is characterized by three main types of coral habitats—hardbottoms, patch reefs, and bank reefs—that are collectively known as the Florida Keys Reef Tract.[10] It is the only shallow water coral reef habitat found on the continental shelf of North America. It is the third longest barrier reef in the world and can be seen from outer space. Hardbottom habitats generally are found close to shore and are dominated by octocorals, sponges, and algae and have low coverage of hard coral species. Patch reefs have high biodiversity of octocorals and hard corals, are generally circular in shape, and have a vertical relief of a few meters. Patch reefs are generally found in waters less than 10 m (33 ft) deep.[9] In the Florida Keys, they are found close to shore and seaward of Hawk Channel in a mosaic of habitats, including seagrasses and hardbottom communities. Patch reefs are the principal reef type between Elliott Key and Key Largo where several thousand patch reefs are found.[13]

Bank reefs occur as a discontinuous band parallel to the Florida Keys island chain and flank the edge of the continental shelf. Bank reefs can be divided into shallow and deep reef zones. The shallow portion of the bank reef occurs in a high-energy environment (wave action) and is dominated by branching corals, fire coral (*Millepora* spp.), and the colonial zoanthid *Palythoa*

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As corals have disappeared, a colonial zoanthid (*Palythoa*) has increased in dominance at bank reefs.

caribaeorum. The deep bank reefs consist mostly of large boulder corals, barrel sponges, and octocorals. Bank reefs exist in a continuous line south of Cape Florida to the Dry Tortugas.[9,10,13] Bank reefs are found 7 – 13 kilometers (4.4 – 8 miles) seaward of the Florida Keys and have a spur-and-groove structure characterized by elongated sections of reef with high vertical relief (spurs) separated by deeper sandy areas (grooves). Spurs and grooves are oriented perpendicular to shore.[14,15]

In the Upper Keys and in Miami, large islands act as barriers to waters from Biscayne Bay and Florida Bay and have supported the development of extensive offshore reefs seaward of Elliott Key and Key Largo. The Middle Keys are smaller islands that are separated by wide channels connected to Florida Bay and have limited reef development. The islands of the Lower Keys provide some protection to water transport from the Gulf side of the Keys, and the reef development is extensive. Major bank reefs in the Florida Keys include: Carysfort, The Elbow, Key Largo Dry Rocks, Grecian Rocks, French, Molasses, Alligator, Tennessee, Sombrero, Looe Key, American Shoals, Eastern, Middle, and Western Sambos, Eastern and Western Dry Rocks, Rock Key, and Sand Key.[10]

Off the west coast of south Florida, there are no three-dimensional tropical coral reefs. Ledges and outcroppings of limestone are colonized by an assemblage


NOAA


NOAA

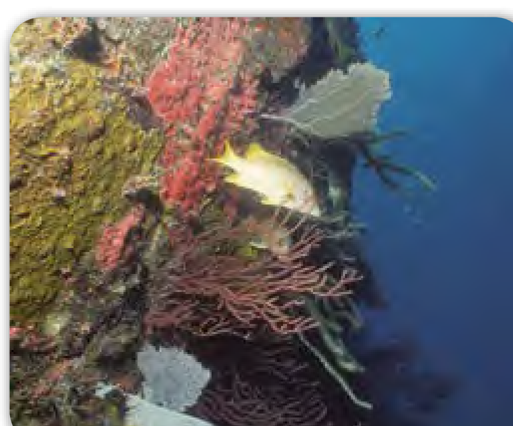
Two coral spurs separated by a light-colored groove (left). Spur-and-groove reefs are a common feature of windward shores of islands, likely because of the continued effects of erosion caused by swell and trade wind waves. The topography of these structures consists of parallel linear spurs (ridges) of active coral growth separated by grooves (depressions) of accumulated sediments and coral debris. Spurs and grooves are oriented perpendicular to shore (right).

of hardy corals, such as knobby star coral (*Solenastrea hyades*) that are capable of living in more turbid water than reef-building corals. The Florida Middle Grounds is a hardbottom community growing on a fossil reef formation located approximately 150 km (93 mi) northwest of Tampa Bay. It has relatively high coral diversity and coverage, but is not an active, three-dimensional reef comparable to those found in the Florida Keys.[10]

Artificial reefs

Artificial reefs are humanmade underwater structures that are constructed by placing materials on the seafloor. They can be made from a variety of hard materials including concrete rubble, rocks and boulders, engineered concrete artificial reef modules, carefully cleaned and prepared steel vessels, and other environmentally suitable artificial reef materials. Shipwrecks are the result of unintentional sinking or mishap resulting in unplanned humanmade marine structure. A main purpose of planned artificial reefs is to provide a hard, stable surface to which algae and other encrusting organisms, such as barnacles, oysters, and corals, can attach. The three-dimensional structure of an artificial reef and the encrusting community of marine life provide structure and food for a diverse assemblage of fish. Artificial reefs may remove some burden of divers, snorkelers, and fishermen from natural reefs. Three ships were sunk in the Florida Keys National Marine Sanctuary for that purpose, one each in the Upper (USS *Spiegel Grove*), Middle (*Adolphus Busch*), and Lower (USNS *General Hoyt S. Vandenburg*) Keys. These wrecks and the many others that exist in south Florida are popular dive spots.

Artificial reefs have also been constructed as compensatory mitigation for hardbottom or reef habitats that were lost through construction projects, including beach nourishment, and vessel groundings. The success of mitigation reefs is measured by their ability to mimic the natural hardbottom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In 1942, the merchant vessel *Benwood* ran aground in the Upper Keys near French Reef and Dixie Shoals. The steel hull of the vessel is colonized by corals, sponges, and algae. The *Benwood* is one of nine sites within the Florida Keys National Marine Sanctuary Shipwreck Trail.

environments that they are intended to replace. Quantitative monitoring at one constructed limestone boulder reef in Broward County revealed that hard and soft coral abundance, diversity, and average size were nearly equal to those found on the natural nearshore hardbottom 5 years after construction.[16] Additional monitoring is needed to conclusively demonstrate that artificial reefs constructed as mitigation provide the same habitat value as the affected natural substrates.

Coral reefs are ecologically and economically important

Coral reefs have ecological and economic values, and the Earth would likely be a less interesting place to live and play if coral reefs did not exist. The three-dimensional structures of coral reefs harbor an amazing biodiversity of plants and animals. They cover less than 1% of the ocean floor, but support about 25% of all marine creatures.[17] About one third of the marine fish (about 6000 – 8000 species) in the world are estimated to live only on coral reefs.[18,19] They provide habitat for numerous species of invertebrates, including mollusks, sponges, sea urchins, starfish, crustaceans, worms, and many other taxonomic groups. Coral reefs are known as the "tropical rain forests of the sea" because of the richness and abundance of species contained in such relatively small areas.[20]

In nature, there are no useless, superfluous life forms. Every life form plays a role in maintaining the ecological integrity of the planet. Maintenance of biodiversity is important because greater species diversity ensures natural sustainability for all life forms. Loss of biodiversity can change ecosystem form and function. Healthy ecosystems that support a full suite of species that characterize the ecosystem are better able to withstand and recover from a variety of disasters. The extirpation of even a single species can have major ecological significance.[21] For example, the loss of the long-spined sea urchin from south Florida reefs is believed to be directly responsible for increased macroalgal growth and decreased coral recruitment. Because not all of the functions of all the species on a reef are fully known, it is prudent to protect them all for the benefit of the whole.

On a global scale, the number of people using coral reefs for subsistence and pleasure has not been adequately quantified, although many small tropical countries are completely dependant on coral reef resources. A healthy coral reef community benefits society in many ways, including protection of shores from impacts of waves and storms; provision of organisms used for food, medicines, and biotechnological advances; and tourism.[21] An example of the value of coral reefs in the development of medicines is azidothymidine (AZT), a treatment for people with HIV infections that is based on chemicals found in a reef sponge.[22] Corals are also an integral part of the global carbon cycle; they remove carbon dioxide, a greenhouse gas, from ocean water and sequester it in coral skeletons and reefs.[11,23]

The economic value of reefs, both artificial and natural, in southeastern Florida (Martin, Palm Beach, Broward, Miami-Dade, and Monroe Counties) was studied in 2001.[24] Reef values were calculated two ways: 1) by assessing "use" of the reefs as person-days spent snorkeling, fishing, or diving and 2) as the expenditures, or dollars, spent to visit the reefs that may include charter boat fees, fuel, bait, tackle, ramp and marina fees, lodging, food, beverages, and equipment rental. The report concluded that 28.8 million person-days were spent using natural and artificial reefs in the five-county region during 2001. Additionally, expenditures for fishing, snorkeling, and SCUBA diving on artificial and natural reefs in the five counties totaled an estimated $3.0 billion per year.[24]

Another value of coral reefs to humankind is knowing that they, as other wild and natural areas on Earth, simply exist. Many people who have never seen a coral reef in person take solace in the fact that coral reefs exist and are teeming with diverse wildlife. They may formalize their support for the continued existence of coral reefs or other wild places by joining and supporting conservation organizations and purchasing speciality license plates, such as Florida's "Protect Our Reefs" plate. Although little empirical work exists on valuation measures of reefs by nonusers and groups distant to coral reefs, studies have suggested that nonuser and distant groups should be included in valuations because of their unflinching support for conservation of all things wild or coral reefs in particular.[25]

NPS

Snorkeling over coral reef and hardbottom habitats is a popular recreational activity in south Florida.

Factors that control the distribution and abundance of corals and coral reefs in south Florida

Different coral species have different ecological requirements. Several species of corals are able to grow and thrive in the more turbid waters of southwest Florida and in Florida Bay. However, they typically occur as isolated colonies and do not construct reefs. Among these corals are the knobby star coral (*Solenastrea hyades*), starlet coral (*Siderastrea siderea*), and robust tree coral (*Oculina robusta*). The southeast coast of Florida has a much more diverse coral community, and healthy growth depends on several interrelated environmental factors, including warm, clear tropical water; normal sea-strength salinity; adequate light penetration; low inorganic nutrients and turbidity; low sedimentation; and vigorous water movement. The role of the Florida Current in providing the proper environmental conditions for coral growth and survival in southeast Florida cannot be overemphasized. It is the influence of the Florida Current and its eddies in shallow waters that allows the temperatures, salinity, and water clarity that are required for coral growth and reef formation. It moderates winter temperatures and provides nutrients, plankton, food sources, and recruitment from remote geographic areas.[10]

South Florida is at the northern latitudinal limit of extensive reef growth in North America, and minimum winter temperature provides the main control of coral reef distribution. Coral reefs cannot form where seawater temperature falls below 18°C (64°F) for extended periods. Corals can generally withstand temperatures as high as 30°C (86°F). An extreme winter cold spell in 1977 in south Florida resulted in widespread death of staghorn corals. In January 2010, a prolonged cold spell resulted in the death of 200- to 300-year-old boulder star corals at shallow patch reefs.[26] The impacts of that cold spell on the Florida Keys Reef Tract are still being evaluated.

Most corals require a stable salinity within a range of 30 – 40 parts per thousand (ppt) salt, and that requirement restricts reef growth near shorelines because freshwater runoff can dilute ambient salinity. The stable-salinity requirement and narrow band of temperature tolerance also result in reduced growth in tidal passes between the islands of the Florida Keys because of the influence of water from Florida Bay that is variable in both temperature and salinity.[27]

Adequate light, nutrients, and turbidity are expressions of clear water. If corals receive too little light, the zooxanthellae cannot photosynthesize efficiently, and coral polyp feeding cannot make up the lost energy required for growth.[22,28] Shading by turbidity and phytoplankton blooms because of a high amount of nutrients in the water column is a cause of decreased light penetration. Reef growth in the Florida Keys can occur to about 30 m (98 ft), and hermatypic corals can survive to about 40 – 45 m (131 – 148 ft).[10] Sediments suspended in the water column decrease light penetration and can settle, smother coral colonies, and impair feeding. Energy used by coral polyps to remove sediments is energy lost from growth and reproduction.

Stressors of corals

South Florida coral reefs are affected by local (e.g., land-based sources of pollution), regional (e.g., water drainage and delivery), and global (e.g., climate change) stresses caused by humans and natural events. Hurricanes, El Niño, coral grazers and degraders, and diseases are natural threats that corals have faced for millennia. It appears that the effects of natural threats may be compounded by stresses caused by humans. Human-induced stressors include overfishing, coastal development, physical impacts by divers and snorkelers, vessel groundings, harvesting of live rock, and dredge-and-fill projects. Global climate change is a human-induced threat to coral reefs worldwide that may ultimately override impacts from other stressors.[22]

Severe hurricanes can detach, overturn, and kill corals due to high wave activity, but results of individual storms have generally been found to be localized to individual reefs. Storms can also fragment branching corals and result in their propagation and expansion in distribution.

Overfishing causes imbalances in community structure. Fishing usually results in the removal of large, predatory fish that can result in increased populations of smaller fishes. Some smaller fish (e.g., three-spot damsel fish) nibble on corals, and when populations increase without checks and balances, corals can suffer. In this case, three-spot


NPS

Given enough time and under healthy growing conditions, staghorn coral that has been broken by the wave action of hurricanes regenerates itself through a process called asexual fragmentation.

damsel fish usually feed on faster-growing elkhorn corals, but with the loss of elkhorn corals due to diseases, damsel fish now feed on slower-growing boulder corals that cannot keep up with their grazing pressure and can die.[29] Destructive fishing practices (e.g., poisoning, blasting, fish traps) are not legal in south Florida, but vigilant enforcement is required.

Trap fishing is permitted in south Florida for blue crabs, stone crabs, and spiny lobsters. Stone crab and spiny lobster traps are constructed of wood or plastic and are weighted by a poured concrete slab that keeps the trap on the seafloor. Placement of traps on seagrasses, hardbottoms, and coral reefs can result in crushing or otherwise destroying valuable benthic habitats. Once traps become lost or abandoned, they may "ghost fish", that is, continue to trap marine organisms until traps degrade enough to allow escape. Lost and abandoned traps visually pollute, damage sensitive habitats, and become hazards to navigation.[30] Traps may become abandoned for several reasons: they can move during storms, making them difficult to locate; they may be snagged by passing vessels and dragged to another area; or, they may be illegally abandoned by their owners. The Florida Fish and Wildlife Conservation Commission has two programs dedicated to removing lost and abandoned traps from state waters. The Spiny Lobster, Stone Crab, and Blue Crab Trap Retrieval Program contracts commercial fishermen to remove abandoned traps from state waters during closed seasons, and the Derelict Trap Retrieval and Debris Removal Program provides a mechanism to authorize volunteer groups to collect derelict traps and trap debris during open or closed seasons.[31]

Increases in several abiotic factors that control coral growth and abundance (salinity, light, low turbidity, and nutrients) can be affected by coastal development. Land clearing can cause increased turbidity and nutrients in surface waters. Coastal construction can result in the removal of mangroves and seagrasses that filter out nutrients and sediments before they reach reefs. When nutrients are added to receiving waters, water clarity is reduced, and faster-growing phytoplankton and benthic seaweeds can outcompete, smother corals, and eliminate settling habitat for coral larvae. Pollution from land has also been implicated in at least one coral disease, white pox.[32]

The biggest threat to corals on a global scale is increasing seawater temperature. When temperature rises above a critical threshold, zooxanthellae are expelled from corals, causing them to appear white (i.e., coral bleaching).[22,33] Bleached corals are stressed not only from the temperature, but also from the lack of food provided by their zooxanthellae partners. Prolonged bleaching can lead to other diseases and coral death.

A recent study has shown that regulating wastewater discharge from the land may help coral reefs to resist climate change. Corals living in cleaner water with fewer nutrients survived better during hot periods than corals in water with higher nutrients that became diseased and bleached.[34] In the face of climate change and ocean warming, that study gives managers hope that maintaining high water quality can improve survival of corals. However, proximity to potential sources of stressors is not always an adequate proxy for assigning risks to reef health. Coral cover, size, growth, and mortality are not always directly related to water quality gradients.[35]

NOAA

Bleached corals have a white appearance because of the loss of symbiotic algae (zooxanthellae) that give coral their color.

Global temperature is rising because of increased greenhouse gases in the upper atmosphere that form a "blanket" around the Earth. Activities such as burning fossil fuels, changes in land use, and reduction of forest cover result in increased atmospheric concentrations of CO_2 and other greenhouse gases. Increased CO_2 in the ocean can also reduce the ability of corals to secrete limestone skeletons, making them more fragile and slowing their growth.[22,36]

Management

The ecological and economic values of corals and coral reefs to south Florida have long been recognized. Important management actions are in place to help sustain and improve coral resources. The designation of the Florida Keys National Marine Sanctuary provides a management plan that promotes conservation while allowing multiple uses of the resource. A key element is the designation of Marine Protected Areas (MPAs). Setting aside areas where the coral community is left alone (i.e., no-take MPAs) has resulted in larger size and abundance of fishes (e.g., groupers, snappers) and lobsters within the MPAs at Western Sambo (Lower Keys) and Dry Tortugas, as well as in other areas around the world.[37] When allowed to recover, corals attract fish, and fish "spill over" outside the boundaries of the MPAs can improve fishing. MPAs can also provide a control of uses by multiple and often competing user groups of the resource.[38]

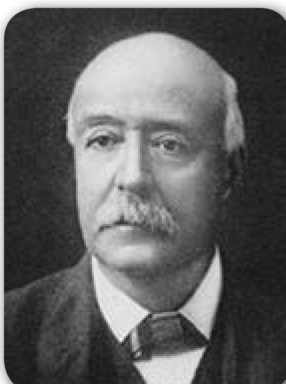
Improving defensible, sustainable fishing regulations; restoring historically lost habitats; and requiring improved wastewater and stormwater treatment and disposal practices will reduce stressors to the coral reef community. In south Florida, many agencies and academic institutions work together to promote wise stewardship of these resources, including regulatory, research, enforcement, and management agencies.

Probably the most important way to reverse damage to our coral reefs is to reduce the emission of greenhouse gases to stem global warming.[22] This may be the hardest stressor to address because it requires informed national and global cooperation. However, just because it is difficult does not mean that global warming can be ignored by governments or individuals. Understanding the importance of coral reefs to Earth and the threats that they face is the first step toward finding workable solutions.

Louis and Alexander Agassiz pioneered coral reef research

Walter C. Jaap

Louis and Alexander Agassiz, their students, and technicians pioneered marine research, particularly in taxonomy and the distribution and abundance of animals found on Florida coral reefs. The father and son were stirred by a raging argument among scientists that stemmed from the 1842 Charles Darwin book that discussed the formation and origins of coral reefs. Alexander passionately pursued an alternative explanation to Darwin's theory of seafloor subsidence to explain coral reef origins and development.



National Academy of Science Archives

Alexander Agassiz, ca. 1850.

In the 1800s, the U.S. government regarded coral reefs as an impediment to shipping and considered using explosives to destroy them in order to avoid the many shipwrecks common in Florida waters. Louis proposed that rather than destroying the reefs, a series of lighthouses be installed along the reef to warn mariners of their locations. That recommendation was adopted, thus saving an important ecosystem from wholesale destruction.

One of Alexander's greatest contributions to coral reef science was completing a comprehensive map of the Dry Tortugas, one of the earliest known maps in the world that provided estimates of coral reef habitats. He surveyed approximately 160 km^2 (100 mi^2) of seafloor in 1881 using a sextant to determine location, a glass-bottomed bucket to make observations, and a lead line to determine depth and sea bottom characteristics.

NOAA

A portion of the seafloor map surrounding Garden Key, Dry Tortugas, prepared by Alexander Agassiz in 1881. This is one of the earliest coral reef habitat maps showing distribution and abundance of corals. It was produced with simple tools: a glass-bottom bucket and a lead line.

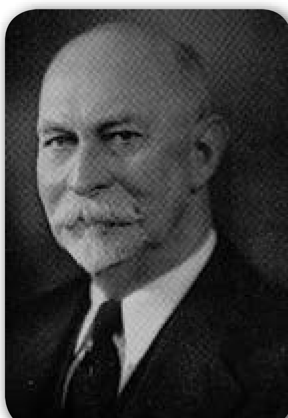
K. Anderson -www.lighthousefriends.com

Between 1833 – 1841, 324 vessels were lost on Florida Keys reefs, 63 at Carysfort Reef. Carysfort Lighthouse was constructed in 1852, one of the lighthouses constructed as a result of Agassiz's recommendation.

Alfred Mayor and Thomas Vaughan expanded coral reef research in south Florida

Walter C. Jaap

One of the most heroic and charismatic early coral reef researchers was Alfred Goldsborough Mayor. A student of Alexander Agassiz, Mayor convinced the Carnegie Institution to build and fund a marine laboratory on Loggerhead Key, Dry Tortugas. The Carnegie Laboratory was opened in 1905 and supported many disciplines of science. Virtually all of the studies were published in the Papers of the Tortugas Laboratory, and Mayor edited each article. Mayor was not only a scientist, but also a talented artist, sailor, fundraiser, and leader. His personal contributions were the taxonomy and systematics of jellyfish and physiological research on thermal tolerance of tropical marine animals (coral bleaching). In addition, Mayor was a hands-on scientist who actually put on dive gear to study coral reefs in Dry Tortugas and Samoa. He died of tuberculosis on Loggerhead Key in 1922, but the Carnegie Laboratory that he founded continued to function until 1939.



USGS

Thomas Wayland Vaughan, ca. 1900.

A. Mayor collection

Alfred Goldsborough Mayor (1868 – 1922) at the wheel of *Physalia*. Mayor changed his name from Mayer in 1918.

Mayor's colleague, geologist Thomas Wayland Vaughan, was interested in the underlying history of coral reefs. In later life, he founded Scripps Institution of Oceanography. His work at the Carnegie Laboratory included the study of fossil records and modern status of Florida and Caribbean reef systems. Vaughan conducted growth rate studies on many corals species and compiled and published seawater temperatures at lighthouses along the Florida Keys Reef Tract for a 25-year period. This is one of the best historical climate records in Florida.

A. Mayor collection courtesy of W. Jaap.

A. Mayor collection courtesy of W. C. Jaap

Loggerhead Key, Dry Tortugas, ca. 1910.

J. W. Wells courtesy of W.C. Jaap

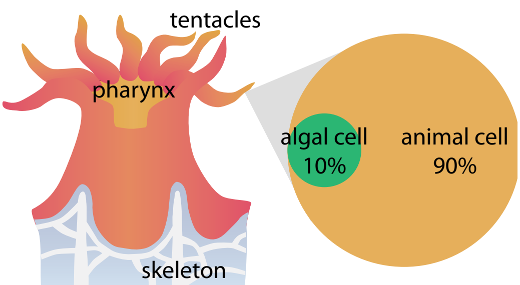
Research diver at Dry Tortugas, ca. 1930.

Corals are amazing creatures

James W. Porter

Are corals animal, vegetable, or mineral?

For all other creatures on the planet, the answer is one of these; but corals are animals that have characteristics of all three! Corals have been described as sea anemones that have a paperweight skeleton. Only 1% of the total weight of coral is living tissue, and the remainder is the skeleton. The animal tissue cells contain symbiotic algae, called zooxanthellae. Symbiosis means unlike organisms living together. The symbiotic algae are single-celled plants that give corals their color.



Corals are made up of individual polyps. They differ from their closest relatives, sea anemones, in their ability to produce a calcium carbonate (i.e., limestone) skeleton. Algal cells live within the coral cells in a mutualistic symbiotic relationship, where both partners benefit.

Did you know?

Corals were misclassifed by the founder of modern taxonomy, Carl Linnaeus, who described them as Zoophyta (animal plants) in 1742. In fact, the species name of elkhorn coral, *Acropora palmata*, comes from the palm-like shape of its branches.

Corals are vegetarians by day (relying on food produced by the symbiotic algae) but are carnivores by night. They have tentacles with small harpoon-like barbs, called nematocysts, that can eject, stab, and reel in unsuspecting prey that swim too close. Most Caribbean corals extend their tentacles only at night, but a few species, most notably pillar coral (*Dendrogyra cylindrus*), leave them out all day.

No two coral specimens are exactly alike. The myriad of shapes, both between different species and between individuals of the same species, reflect subtle differences in light, shade, and water movement in their immediate surroundings. For example, boulder corals found in deeper water are flatter, which allows them to intercept more light coming down from the water surface.

J.W. Porter - UGA

Photomicrograph of coral tentacles showing stinging nematocyst cells that appear as small white spots. When triggered, the cells release a barbed harpoon that captures prey and brings it to the polyp mouth.

Corals are among the most efficient organisms on earth

Like all plants, the symbiotic algae of corals are photosynthetic and use the energy of the sun to fix carbon dioxide from the water to produce sugars, starches, fats, and oils. The algae then "translocate" these foods directly to the animal cells. Almost nothing is lost in this transfer. Oxygen is a byproduct of photosynthesis. Most other animals on Earth are only about 10% efficient in food chain transfers. For example, when a cow eats grass, only 10% of the grass contributes to the mass of the cow.

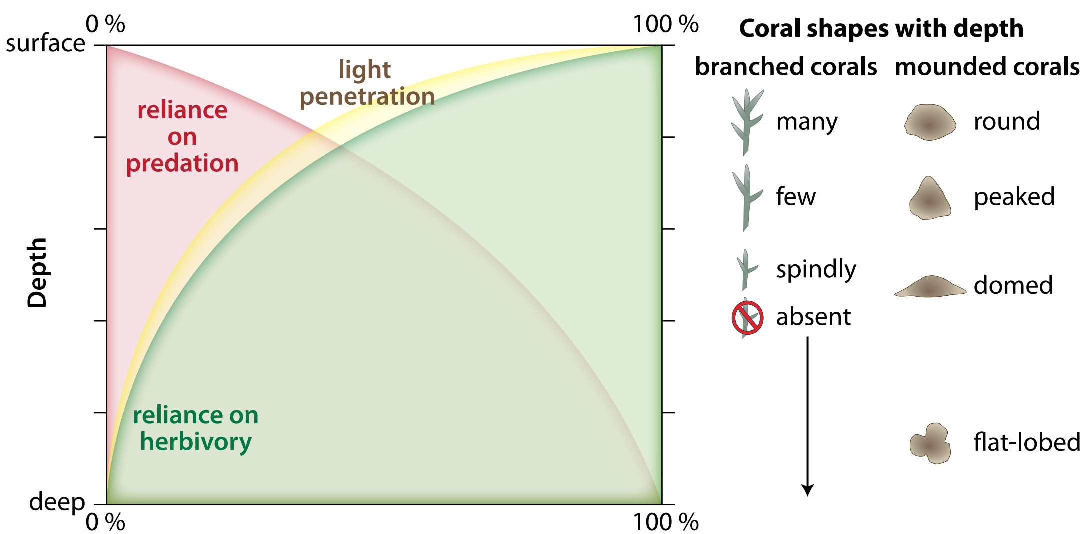
Corals are 95% efficient in transforming plant material and energy from sunlight into living coral tissue. Whenever it is sunny, corals act as plants and produce more oxygen than they consume. Corals also use energy from the sun to convert dissolved calcium in seawater into a solid calcium carbonate (i.e., limestone) coral skeleton.

Corals are very efficient at recycling materials. During the day, as algae photosynthesize, they produce oxygen and the corals consume it. In turn, corals respire carbon dioxide that the algae need for photosynthesis. However, it does not end there: the corals then excrete nitrogen and phosphorus waste, which fertilizes the plant cells.

Corals can reproduce sexually or asexually. Most release eggs and sperm into the water to produce swimming larvae called planulae. Planulae must find suitable substrate on which to settle and grow. Alternatively, corals can reproduce vegetatively when broken pieces reattach to the substrate. Vegetative reproduction is common following fragmentation of colonies after hurricanes. Regrowth by asexual reproduction produces colonies that are genetically identical to the parent stock (clones). This genetic homogeneity may put vegetative propagules at risk during disease outbreaks because they lack the genetic diversity that may favor more disease-resistant individuals.

How can the most diverse and productive of all marine communities on Earth survive and flourish in the most nutrient-poor waters on Earth?

Tropical water over coral reefs is very clear because there is so little material in it (i.e., oligotrophic). Corals flourish under these conditions because of the perfection of coral-algal symbiosis. Their reliance on solar power, energy efficiency, and material recycling has led to the long-term success and survival of coral reefs, one of the most diverse and productive environments on Earth. It is not a stretch of the imagination to suggest that corals provide a survival lesson for humankind; efficiency in the present may be a key to a sustainable future.



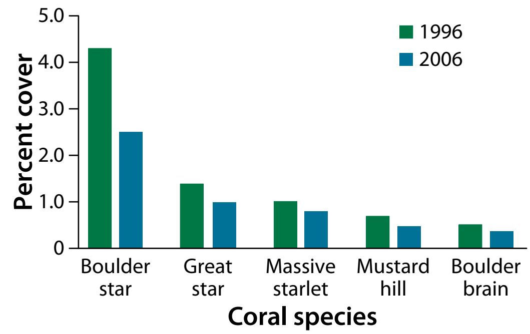
Light from the sun declines exponentially with depth on a coral reef (yellow line). As light declines with depth, reliance on photosynthesis as an energy source declines with it (green line). Corals make up for this energy loss by increasing the amount of food that they capture and eat with increasing depth (red line). As ambient light changes with depth, so do coral shapes. Branching corals usually depend more on high light intensity and disappear altogether with depth. Mounded (i.e., boulder) corals flatten with increasing depth to provide more surface area to intercept available light as the intensity of light decreases.

Thirty-two hard coral species can be found in south Florida

James W. Porter

There are 66 species of hard corals that occur in the Caribbean basin. Thirty-two of those species, including all the major reef-building (hermatypic) corals, are found in south Florida. Historically, corals were classified by 1) skeletal morphology (i.e., mounded, branching, or plating forms), 2) polyp morphology (i.e., round or elongate), and 3) polyp organization (i.e., solitary versus arranged along ridges or in valleys). Modern genetics, however, are upending this tidy classification system. For example, one Floridian species, the fused staghorn coral (*Acropora prolifera*), has recently been shown to be a genetic hybrid between elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*).

Until recently, two coral species dominated the Florida Keys Reef Tract coral reefs: elkhorn coral and boulder star coral. Elkhorn coral and closely related staghorn coral populations have declined so drastically over the past several decades that both species have been listed as Threatened Species under the United States Endangered Species Act. Hurricanes, bleaching, and disease are contributing to their loss. A major decline in the abundance of elkhorn coral in the Florida Keys occurred after two consecutive massive bleaching events in 1997 – 1998 and the species is struggling to recover. Boulder star coral (*Montastraea annularis*) is currently the most abundant coral in the Florida Keys, but its populations are also waning. From 1996 – 2006, the percent cover of *M. annularis* dropped from an average of 4.5% Keys-wide to less than 2.5%. The four other most common coral species in the Florida Keys, great star coral (*Montastraea cavernosa*), massive starlet coral (*Siderastrea siderea*), mustard hill coral (*Porites astreoides*), and boulder brain coral (*Colpophyllia natans*) have also declined in percent cover.



Mean percent coral cover loss of the five most common boulder corals in the Florida Keys National Marine Sanctuary (1996 – 2006). The most common coral, boulder star coral, experienced the greatest loss in cover.

Photographs presented on the next several pages show the diverse forms and colors of the corals found in south Florida. Some corals species have different shapes and colors than those shown here depending on the depth, available light, and other environmental conditions where they are growing. The robust ivory tree coral and the knobby star coral are commonly observed in shallow seagrass habitats because their branching morphology and superior sediment-shedding abilities allow them to flourish in soft sediments. The vast majority of the coral species pictured here can be observed on patch reefs and the outer-reef platforms of the Florida Keys Reef Tract that runs from Miami south to the Dry Tortugas. The Dry Tortugas, located 113 kilometers (70 miles) west of Key West, has the richest marine flora and fauna of the Florida Keys Reef Tract. The complex geomorphology coupled with consistently clearer water makes the Dry Tortugas a biodiversity hotspot in Florida for corals and other marine species.

J.W. Porter - UGA

Staghorn coral (*Acropora cervicornis*)

J.W. Porter - UGA

Fragile saucer coral (*Agaricia fragilis*)

J.W. Porter - UGA

Elkhorn coral (*Acropora palmata*)

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Lamarck's sheet coral (*Agaricia lamarcki*)

M. Myers - UGA

Fused staghorn coral (*Acropora prolifera*)

FWRI

Boulder brain coral (*Colpophyllia natans*)

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Lettuce coral (*Agaricia agaricites*)

FWRI

Pillar coral (*Dendrogyra cylindrus*)


J.W. Porter - UGA

Elliptical star coral (*Dichocoenia stokesi*)


C. and A. Sheppard - coralpedia.bio.warwick.ac.uk

Smooth flower coral (*Eusmilia fastigiata*)


J.W. Porter - UGA

Knobby brain coral (*Diploria clivosa*)


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Golf ball coral (*Favia fragum*)


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Grooved brain coral (*Diploria labyrinthiformis*)


J.W. Porter - UGA

Sunray lettuce coral (*Leptoseris cucullata*)


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Symmetrical brain coral (*Diploria strigosa*)


F. Charpin - reefguide.org

Rose coral (*Manicina areolata*)

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Maze coral (*Meandrina meandrites*)

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Knobby cactus coral (*Mycetophyllia aliciae*)

J.W. Porter - UGA

Boulder star coral (*Montastraea annularis*)

J.W. Porter - UGA

Ridged cactus coral (*Mycetophyllia lamarckiana*)

F. Charpin - reefguide.org

Great star coral (*Montastraea cavernosa*)

FWRI

Spiny flower coral (*Mussa angulosa*)

C. and A. Sheppard - coralpedia.bio.warwick.ac.uk

Star coral (*Montastraea faveolata*)

J. Adams - advancedaquarist.com

Robust ivory tree coral (*Oculina robusta*)

F. Charpin - reefguide.org

Mustard hill coral (*Porites astreoides*)

J.W. Porter - UGA

Massive starlet coral (*Siderastrea siderea*)

J.W. Porter - UGA

Clubbed finger coral (*Porites porites*)

F. Charpin - reefguide.org

Smooth star coral (*Solenastrea bournoni*)

F. Charpin - reefguide.org

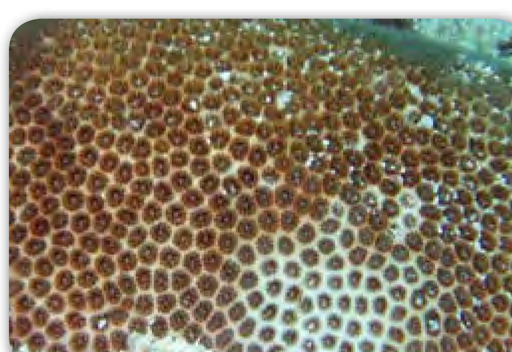
Artichoke coral (*Scolymia cubensis*)

J. Adams - advancedaquarist.com

Knobby star coral (*Solenastrea hyades*)

C. and A. Sheppard - coralpedia.bio.warwick.ac.uk

Lesser starlet coral (*Siderastrea radians*)



F. Charpin - reefguide.org

Blushing star coral *(Stephanocoenia intersepta)*

The southwest Florida coast has a unique assemblage of corals

Bryan Fluech

The diversity of stony and soft corals found off the southwest coast of Florida is very limited compared to the diversity found on the east coast of Florida. Seasonal temperature fluctuations and high turbidity are characteristics of the Gulf of Mexico that provide less than ideal conditions for most corals. Yet, several hardy species do inhabit the region.

Much of the shallow continental shelf off southwest Florida consists of unconsolidated sand and shell rubble substrates overlying a limestone base rock. Isolated tracts of natural hardbottom ledges and rock outcroppings as well as artificial reefs are interspersed throughout the region and provide suitable substrate for coral colonization. Unlike many of the corals found in the Florida Keys, corals associated with southwest Florida hardbottom communities typically occur as isolated colonies and do not construct reefs. These corals and other associated biota, including macroalgae, tunicates, sponges, hydroids, and bryozoans, contribute to the productivity of southwest Florida unique hardbottom communities. They provide structure, protection, and food sources for a variety of fish assemblages and invertebrates, including recreational and commercially important species, such as red grouper (*Epinephelus morio*), gag grouper (*Mycteroperca microlepis*), and Florida stone crab (*Menippe mercenaria*).

B. Fluech - FSG

Red grouper on natural hardbottom ledge off the southwest coast of Florida.

Stony corals

Stony corals consist of polyps with multiples of six tentacles and produce an external calcium carbonate skeleton.

B. Fluech - FSG

Knobby star coral (*Solenastrea hyades*). This is one of the most common stony corals in southwest Florida. The colonies have lobed heads with irregular bulges on the surface and range from a few centimeters to 61 centimeters (2 feet) in size. Colors range from yellow-brown to cream and tan. The polyps often can be seen feeding during the day.

FWC

Hidden cup coral (*Phyllangia americana*). Hidden cup coral forms small colonies with polyps less than 2.5 cm (1 inch) wide. They settle and grow mostly on subvertical and overhanging features, thus avoiding sedimentation impacts associated with horizontal sufaces. They vary in color from yellow to reddish brown.

B. Fluech - FSG

Starlet corals (*Siderastrea* spp.). *Siderastrea siderea* and *Siderastrea radians* occur in the area as irregular rounded domes and mounds and vary in color from golden-brown to brown to gray. Colonies can range from a few centimeters to about 0.5 meters (20 in) in diameter.

B. Fluech - FSG

Robust ivory tree coral (*Oculina robusta*). This species is less common than knobby star and starlet corals and is known to prefer shallow turbid waters. Colonies form as large, "busy," tree-like structures with a thick base and can reach close to 1 meter (3 feet) in length. Color is generally yellowish brown and the colony appears "shaggy" when the polyps are fully extended.

FWC

Tube coral (*Cladocora arbuscula*). Tube corals form small colonies less than 10 cm (4 in) in diameter and are typically less than 5 cm (2 in) high. They range in color from tan and golden brown to dark brown. They may be attached to rocks, especially in sedimented areas, or they may be loose and free living, commonly in rubble or seagrass.

Soft corals

Soft corals do not have hard skeletons or build reefs. Common examples include sea fans, sea whips, leather corals, and tree corals. Their body tissue is supported with small carbonate skeletal elements called sclerites that are suspended in an inorganic matrix. Sclerites give the tissues support while still allowing a lot of flexibility. The sclerites come in many shapes and sizes and are important features in the identification of soft corals.

NOAA

Regal sea fan (*Leptogorgia hebes*). Regal sea fans are thickly branched and are generally aligned in a single plane (flat). They occur in a variety of colors, including red, orange, and purple.

B. Fluech - FSG

Sea whips (*Leptogorgia virgulata*). Sea whips form long, straight, stiff, and moderately branched stalks. They occur in a range of colors, including yellow, orange, and purple.

Corals are the building blocks of reefs

Steven L. Miller, Eugene A. Shinn, and Barbara H. Lidz

Corals are colonies composed of individual polyps. Each polyp has a mouth at one end that is encircled by tentacles and a base where calcium carbonate is secreted from substances the polyp extracts from seawater. Polyps in coral colonies are interconnected and cover the limestone part of the coral (i.e., skeleton) with a thin layer of living mucus-like tissue. Under the right conditions, animals with this simple biological organization can build massive three-dimensional coral reef structures, some of which in the geologic past grew hundreds of kilometers in length and tens to hundreds of meters thick. The skeleton of each coral colony is basically rock-hard limestone and depending on the species, can range in size and shape from that of a small coin, to branching thickets the size of football fields, to massive boulder-shaped colonies the size of a school bus. Geologists often have described reefs as being similar to brick buildings, where the bricks represent coral colonies and the mortar is the cemented sediment, facilitated by calcareous algae, bryozoans, and other organisms, that holds the reef structure together.

Coral reefs are built mainly by hermatypic corals. The four common reef-building corals in south Florida are: elkhorn coral (*Acropora palmata*), boulder star coral (*Montastraea annularis*), staghorn coral (*Acropora cervicornis*), and great star coral (*Montastraea cavernosa*).

Formation of coral reefs depends on the growth of coral colonies and production of calcium carbonate by the many corals and other animals found on the reef. Factors that influence the ability of corals to grow and produce their carbonate skeletons include light, depth, temperature, and the productivity of zooxanthellae that live in the coral tissues of hermatypic corals. Light is required because the zooxanthellae, which are known to enhance calcification, are photosynthetic. Water depth is important because the quality and quantity of light change with depth. Some corals respond to decreasing light intensity at depth by growing flatter, plate-like colonies, thus presenting exposure of a greater surface area to the dim sunlight compared with their more spherical shapes when growing in shallower water. Warm temperatures are required for the formation of coral reefs, and they generally do not form where temperatures fall below 18°C (64°F) for extended periods of time. Optimal temperatures are between 26° – 28°C (79° – 82°F). Optimal salinity for reef development is between 30 – 40 parts per thousand (ppt). Under favorable conditions, boulder corals can grow up to a few centimeters (1 inch) a year, whereas branching corals can exceed 10 centimeters (4 inches) per branch over the same period.

J. Luo - UM/ RSMAS

Individual coral colonies when cemented together form coral reefs.

Physical conditions affect coral reef formation

Eugene A. Shinn

The local distribution of coral reefs is controlled by the pre-existing topography, general geography (i.e., the lay of the land), fluctuating sea level, and the kind or quality of water in which they are bathed. There are two main classes of reefs in the Florida Keys: the bank reef system and patch reef system.

Bank reefs

- Found offshore in an elongated broken arc from Miami along the Florida Keys to the Dry Tortugas.
- Located farther seaward than patch reefs.
- Significantly larger than patch reefs and have spur-and-groove formations.

Patch reefs

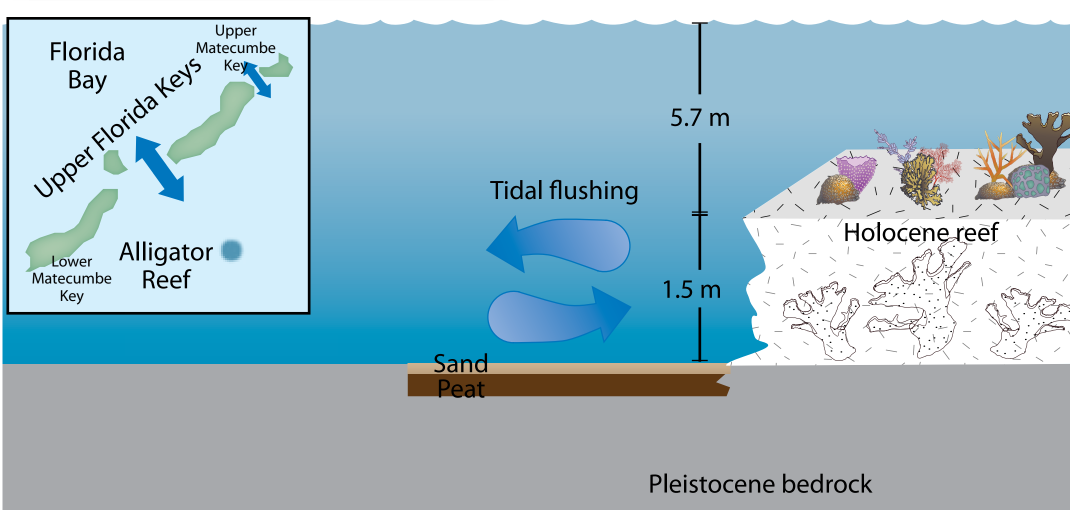
- Coral accumulations composed mainly of boulder corals.
- Singular or clustered, exist in various shapes but are generally circular to subcircular in shape.
- Commonly surrounded by bare sand, called "sand halos".

Bank reef system

Corals require a hard surface for initial settlement by their free-swimming larvae. When the sea, which is still rising today, flooded the shelf off the Florida Keys between 6000 – 7000 years ago, it submerged fossil reefs and ancient cemented beach-dune ridges. These were just the right sites for new corals to become established, and the coincident processes of rising sea level and renewed coral growth on top of elevated dune ridges and old coral skeletons continues today. But this has not happened everywhere off the Florida Keys. As sea level continues to rise, sometime in the future the present Florida Keys will be drowned once again, and more reefs will begin growing on their hard, sand-free surfaces. Again, this will not happen everywhere.

Tidal passes, the other factor

Lower Keys corals formed differently from those in the Upper and Middle Keys. This is partly due to the merging of water



Alligator Reef is limited in growth by the amount of exposed Pleistocene bedrock. The washing effect of water through the tidal pass has exposed peat and sandy sediments upon which coral reefs cannot become established.

Satellite image showing tidal passes and bank reef formations in the lee of the Florida Keys island chain.

from the Atlantic Ocean and the Gulf of Mexico and the subsequent formation of Florida Bay approximately 3000 years ago. Corals bathed in the waters from the shallow Bay became stressed by the extreme seasonal temperature fluctuations, turbidity, high salinity, and nutrients, inimical factors that limit coral growth.

So what was the result of all this change caused by a rising sea? Reefs that had begun growing off the Middle Keys and offshore from tidal passes were assaulted by outpourings of unfavorable Gulf and Bay waters. Corals either did not become established off the passes or, if present, died. The result is that there are fewer bank reef formations off the Middle Keys than elsewhere along the Florida Keys Reef Tract. The effects of rising sea level and creation of tidal passes on coral reefs are observed worldwide from the Bahamas to the Great Barrier Reef off Australia. Geologists term such a condition as reefs that were "shot in the back by their own lagoons." Any reefs that had begun growth before tidal-pass formation simply could not continue growing and are known as "give-up" reefs. All of this happened before the Keys became developed, so modern civilization cannot be blamed for poor reef growth in those areas.

The bank reef is better developed off Key Largo than in the Middle Keys because there are no natural tidal passes through Key Largo. Thus, offshore reefs there are protected from outflow of unfavorable Gulf and Bay waters. There are some areas off the oolite Keys from Big Pine Key to Key West that are somewhat protected, but there are many shallow tidal passes in the Lower Keys that funnel water toward the Atlantic. As a result, water off the Lower Keys is generally more turbid than that off the Upper Keys.

Beyond Key West and westward to the Dry Tortugas, strong north-south currents prevail. Water in that region is periodically too cold during winter months for growth of branching coral species, especially during passage of cold fronts. The temperature-sensitive branching elkhorn and staghorn corals that built reefs in the Upper Keys are for the most part absent between Key West and the Dry Tortugas. Examination of cores drilled through the reefs at Dry Tortugas shows that many species of the more temperature-resistant boulder corals, rather than those of branching corals, built the 15.2 meters (50 feet)-thick reefs at Dry Tortugas.

Patch reefs

There are thousands of patch reefs in marine waters of south Florida. Patch reefs exist primarily in wave-protected areas either in the lee of the bank reefs or in shallow, more turbid water closer to shore. A few patch reefs became established on some of the pre-existing linear reefs, but most colonized a different kind of hard surface than the linear reefs. Boulder corals recruited to the landward edges of two troughs that line the seaward side of the main, shallower, bedrock depression under Hawk Channel. There are about 3000 such patches off the Upper Keys and a few thousand closer to shore off the Lower Keys. Like the linear reefs, they are largely absent opposite the main tidal passes where they would be exposed to the full impact of Florida Bay waters.

Why do corals grow in south Florida?

William K. Fitt

Reef-building corals are restricted in their geographic distribution because the association of corals and their symbiotic algae (i.e., zooxanthellae) requires a very specific combination of temperature, salinity, and water clarity to produce the large quantities of limestone needed for coral reef formation. In light of such stringent environmental restrictions, reefs generally are confined to tropical and semitropical waters.

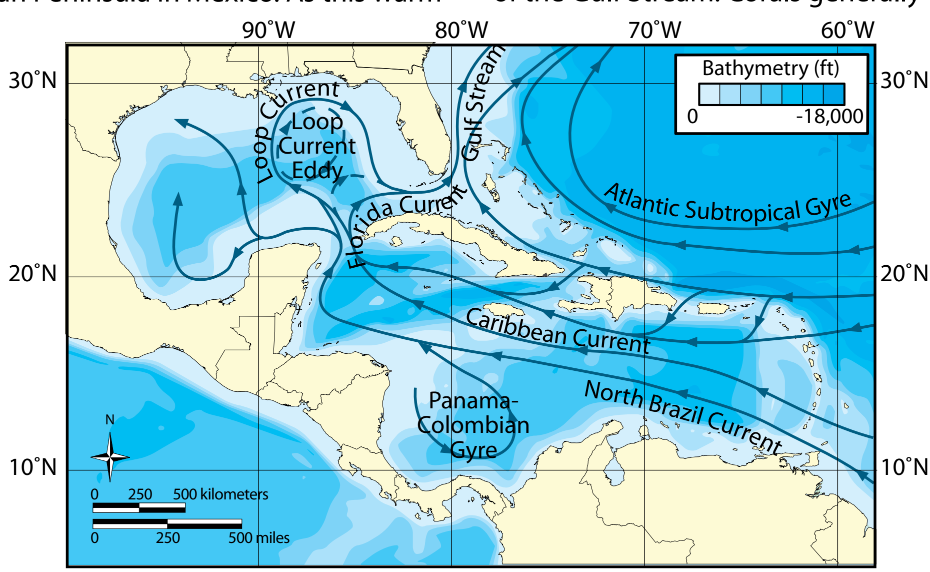
South Florida is at the northern limit of extensive reef development in North America and historically had the right mix of environmental conditions to allow hard corals to flourish and develop coral reefs.

The Gulf Stream system

Water currents circle the oceans pushed by prevailing winds. The North Equatorial Current travels west across the Atlantic Ocean. As it crosses the Equator, the waters warm up and drive the Caribbean Current that flows through the Caribbean Sea and past Central America and the Yucatán Peninsula in Mexico. As this warm water current enters the Gulf of Mexico, it forms the Loop Current in the eastern Gulf and exits the Gulf as the Florida Current. The Florida Current flows past the Dry Tortugas and up the east coast of Florida. It becomes known as the Gulf Stream as it flows past Cape Hatteras. The tropical characteristics of the Caribbean Current remain as this water mass passes around Florida and the Florida Keys. It is the influence of this current system in shallow waters that allows the temperature, salinity, and water clarity required for coral reef development in south Florida.

Temperature

The formation of highly consolidated reefs only occurs where the seawater temperature does not fall below 18°C (64°F) for extended periods of time. These conditions do not occur higher than the 30° North and 30° South latitudes. Bermuda, at 32° North latitude, is an exception to this rule because it lies directly in the path of the warm waters of the Gulf Stream. Corals generally can



The Gulf Stream current system brings warm, salty, and clear water to south Florida. This allows the development of coral reefs in areas shallow enough that adequate light reaches the bottom.

withstand temperatures as high as 30°C (86°F), depending on the species of coral, type of zooxanthellae living inside the coral tissues, and the degree on which the coral relies on the zooxanthellae to produce food (the degree of autotrophy).

The average seawater temperature in the Florida Keys is between 18°C – 20°C (64°F – 68°F), with summertime highs reaching more than 31°C (88°F). These temperatures are recorded from oceanographic recording stations located approximately 4.8 – 8.0 kilometers (3 – 5 miles) offshore and are relatively stable because of the influence of the warm Florida Current. Shallow waters experience wider variations in temperature and salinity. By comparison, temperatures recorded from Florida Bay on the west side of the Florida Keys are more correlated with air temperatures and are more variable than in deeper offshore waters.

Winter cold spells

On average, 30 – 40 cold fronts are recorded in south Florida each winter. On occasion, these cold fronts can cause water temperatures low enough to stress or kill corals. For example, during the winter of 1977, a severe cold period killed massive stands of staghorn coral (*Acropora cervicornis*) throughout the Keys and Dry Tortugas. A recent "double" cold front passed through the Florida Keys in January 2010, illustrating several mechanisms that control the growth of reef-building corals as well as the increase in environmental extremes that may be associated with climate change. The first cold front entered south Florida in early January 2010 and reduced temperatures in Hawk Channel 1.6 – 6.4 km (1– 4 mi) offshore to less than 16°C (61°F) for 1 week. This was followed immediately by a second, more severe cold front that dropped temperatures on patch reefs in Hawk Channel to less than 12°C (54°F).

Most zooxanthellate corals, octocorals, and anemones died, including 200- to 300-year-old star corals (*Montastraea* spp.). Massive starlet coral (*Siderastrea*


W.K. Fitt - UGA

Cold-stressed corals, winter 2009 – 2010.

siderea) colonies on patch reefs survived, but bleached. Some massive starlet coral colonies died when water temperatures dipped below 9°C (48°F) along the shoreline at Long Key Pass.

Salinity

Most corals require very salty water, ranging between 30 – 40 parts per thousand (ppt) salt. Average seawater salinity is about 36 ppt. Corals are isosmotic with salinity (i.e., have the same internal salinity as the water that surrounds them). Because of this, with few exceptions, they do not tolerate wide fluctuations in salinity. In general, the closer to the shore, the more potential there is for freshwater from rain and runoff to dilute salinity, particularly after hurricanes and tropical storms. Therefore, most reef-building corals are found at least a couple of kilometers from shore in south Florida where salinity is minimally affected by rain and freshwater runoff. Florida Bay experiences wide fluctuations in salinity, and only the most hardy, salinity-tolerant species of non-reef-building corals can survive there.

Heavy rains and coastal runoff can reduce salinities in Florida Bay to hyposalinity (i.e., low salinity) conditions. Hypersalinity (i.e., excessively high salinity) in Florida Bay is caused by droughts and/or low freshwater flows from the Everglades. Droughts in the 1950s – 1980s resulted in salinities of 50 ppt or greater at times in Florida Bay. Highly saline water is heavier than normal seawater, and when it exits the passes between the Keys, it can negatively affect corals found offshore.

Light

There is a delicate balance between the amount of light reaching corals and their health. Depth is crucial to the ability of corals to "harvest" light because light is rapidly depleted with increasing water depth. The clearer the water is (i.e., less turbid), the deeper light can penetrate. The number of species of corals on a reef declines rapidly with water depth because of decreasing light conditions. Essentially all reef-building corals are found in water less than 100 m (328 ft) deep because of their reliance on the light requirement of their zooxanthellae for nutrition.

If corals receive too little light, the zooxanthellae in corals cannot photosynthesize efficiently; if they receive too much light, the zooxanthellae may be expelled from the coral tissue and the coral may bleach. Shading from turbidity, including phytoplankton, may be one reason that corals on shallow patch reefs in Hawk Channel appear to be "healthier" than corals growing on the fore reef in the Keys. High incidence of ultraviolet light can trigger coral bleaching; the turbidity in Hawk Channel reduces the amount of ultraviolet light reaching the corals.

Nutrients

Water clarity is affected by nutrients. More nutrients result in more phytoplankton and less light penetration in the water column. Generally, water over coral reefs is very low in dissolved nitrogen and phosphorus nutrients. Nutrient pollution from nearfield and farfield sources has the potential to adversely affect coral reefs. Potential sources of nutrient pollution in south Florida are from land and nutrients delivered from the Southwest Florida Shelf and the Gulf Stream system. Also, occasional cold water upwelling events deliver nutrients to the fore reef.

Calcium carbonate concentration

Reef waters are typically saturated with calcium carbonate. Zooxanthellae in corals photosynthesize (fix carbon) from bicarbonate ions dissolved in seawater. Carbonate chemistry in seawater is relatively complex. The availability of the required form of dissolved carbon is primarily controlled by the temperature and pH (i.e., acidity) of the seawater. If seawater pH decreases (i.e., ocean acidification), as is predicted because of an increase in CO_2 in the atmosphere, it could result in a change in availability of carbon to the zooxanthellae and a change in calcification rates of corals, calcareous algae, and organisms that produce calcium carbonate shells (e.g., sea urchins, benthic and planktonic foraminifera, snails, clams).

Sediments

High concentrations of sediments in the water column can smother coral colonies, clog the mouths of coral polyps, and impair feeding. Suspended sediments can also decrease the depth that light can penetrate into the water column and limit coral growth and survival. Suspended sediments are generally higher on the Gulf side of the Keys compared to the Atlantic side. Reef development on the Atlantic side of the Keys has historically been reduced opposite large tidal passes between the Florida Keys because of the sediment-laden and seasonally cold Gulf waters from the Southwest Florida Shelf and from Florida Bay that are inimical to coral growth and reef development.

Conclusion

Coral reefs can be stressed by local, regional, and global stressors that can be caused by humans or natural events. South Florida coral reefs are degrading, reflecting a worldwide trend in coral decline. Reasons for the decline in coral cover in south Florida are attributed to multiple stressors, including nutrient pollution from nearfield and farfield sources, variations in temperature, salinity, sediments, light availability, and carbonate chemistry of seawater.

Stony corals exhibit several reproductive strategies

Steven L. Miller, William F. Precht, and Struan R. Smith

Some corals reproduce asexually when pieces break (i.e., fragment), reattach to the bottom, and grow into new colonies. Fragmented corals are genetically identical to their parent colony. Most corals can reproduce sexually, and some species are hermaphroditic, meaning that both sexes are found in the same individual.

There are two main forms of sexual reproduction in corals. Some are broadcast spawners and release eggs and sperm into the water where fertilization occurs. Fertilization results in a larva (i.e., planula) that is transported by currents for days or longer before settling to the bottom, attaching to a suitable substrate, and growing into a polyp that eventually becomes a coral colony. Other coral species are brooding corals where fertilization is internal. Larvae are released from brooding corals into the water, and they settle and attach to the bottom within hours after being released.

New corals have to establish themselves (i.e., coral recruitment) in order for degraded reefs to recover and for healthy coral populations to sustain themselves. Lack of sufficient numbers of adults to produce a suitable number of larvae (i.e., sexual) or coral fragments (i.e., asexual) may limit recruitment of new colonies.

P. Gillette - UM/RSMAS

A broadcast spawning coral (*Montastraea*) in the Florida Keys releasing gamete bundles (pink spheres) during a spawning event. Broadcast spawners release eggs and sperm into the water column where fertilization takes place. Fertilized eggs develop into larvae (i.e., planulae) that are transported by ocean currents before settling on suitable bottom habitat and forming a coral colony.

Coral larval attachment may be limited by the presence of benthic algae or sediments. In addition, micropredators, such as brittle stars, may consume newly settled larvae. Recruitment can also be influenced by geography. For example, larval settlement in the Middle Keys may be affected by discharges from Florida Bay, whereas the coastal waters of the Upper Keys are protected from those discharges.

Massive starlet coral (*Siderastrea siderea*), a broadcast spawner, has the highest number of new recruits at most sampling stations in the Florida Keys. However, in general, smaller brooding corals, such as species of *Porites* and *Agaricia*, are more successful with recruitment and have a higher density than broadcast spawners at most sampling sites. Brooding species reproduce throughout the year, grow fast, and do not live as long as more massive broadcast spawners. For these reasons, they are called "weedy" coral species. The massive species, such as the star corals (*Montastraea* spp.) and brain corals (*Diploria* spp.) are broadcast spawners that reproduce only once or twice a year. They are long-lived on the order of decades or longer, and they only need to reproduce successfully once during their long lifetimes to successfully replace themselves.

Recruitment of corals in the Florida Keys is similar to that found in the Caribbean in terms of absolute numbers and patterns among species groups. Recruitment of many broadcast spawning coral species has always been an infrequent event, even when the species were very abundant on Caribbean and Atlantic reefs. Thus, low recruitment of these long-lived species may be sufficient to maintain current population numbers but seriously inhibits the recovery of populations devastated by diseases and bleaching events.

Geologic tools are used to decipher the history of reef formation

Steven L. Miller, Eugene A. Shinn, and Barbara H. Lidz

Our knowledge of how and when reefs accrete is based on data obtained with several different technologies. A complete picture emerges when data sets are combined.

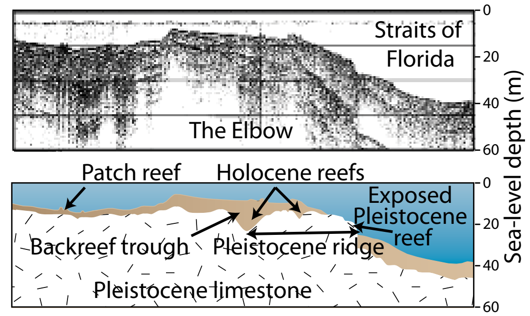
Cores

Cylindrical cores can be cut out of a coral reef with a lightweight diver-operated drilling system. The hard cores are sliced in the laboratory with a rock saw. The core slices provide a cross section of the reef that represents growth over long periods of time. Core material can be dated, and the growth of individual corals and of the reef as a whole can be measured. Rates vary but are generally in the range of millimeters to centimeters per year for healthy reefs. Cores from reef interiors show that reefs consist of everything from sections dominated by species of stony corals growing on top of one another to a mix of coral fragments, carbonate shells, debris, sediment, and even open spaces.

Scientists use a pneumatic coring device to obtain coral cores.

Seismic profiling

Graphic cross sections of reefs can be viewed using seismic profiling instruments, which are essentially high-powered fish finders that penetrate the seafloor with sound waves. The profiles comprise characteristic lines produced when sound is reflected back from the rock surfaces below. The lines mimic those surfaces. These profiles help geologists to evaluate reef formation, structure, thickness, and geometry.



Top: seismic profile of The Elbow reef (Upper Keys). Bottom: interpreted line drawing of the above seismic profile.

Exposed fossil reefs

Actual cross sections of coral limestone reefs can be viewed in areas where reefs are exposed naturally or where they have been exposed by human activities, such as canal excavation and mining. The Windley Key Fossil Reef Geological State Park in the Middle Florida Keys is a limestone quarry excavated in an emergent coral reef. The quarry once supplied building stone for many public buildings in Miami. The emergent reef, which grew during a time of higher sea level about 125,000 years ago, now forms all islands of the Upper and Middle Keys.

The history of reef formation is exposed in Key Largo Limestone at Windley Key Fossil Reef Geological State Park.

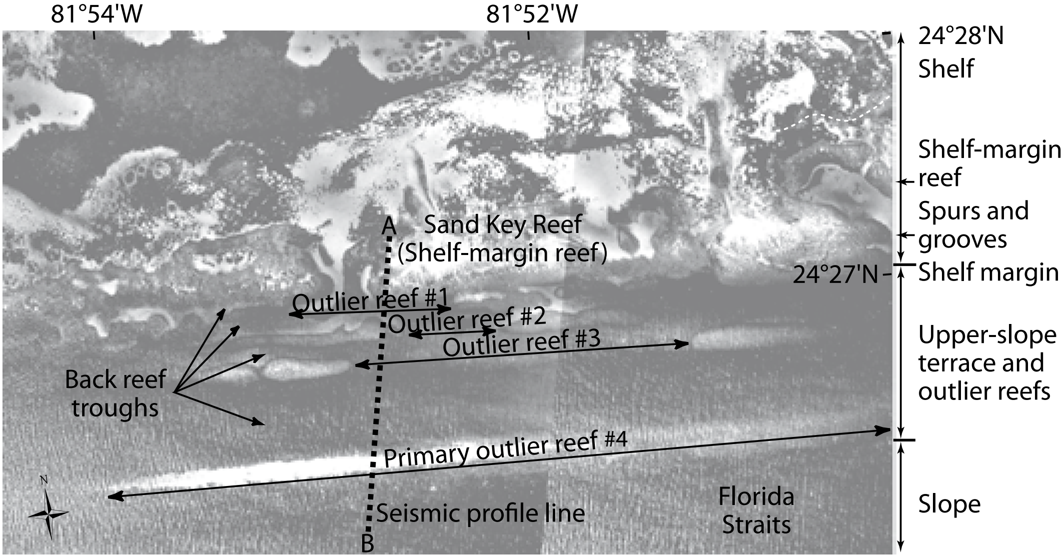
Outlier reefs are found off the Florida Keys

Barbara H. Lidz

Research into how, where, when, and why modern coral reefs grow led to an investigation of a series of immense linear rock ridges that are found beyond the present shelf margin (bank) reef off the Lower Keys. Aerial photomosaics show that the ridges are discontinuous and parallel to the shelf margin. Seismic profiles indicate that they developed on a 40 meter (130 feet)-deep terrace seaward of the shelf edge. The outermost ridge is the largest (primary outlier reef) and is nearly 30 m (100 ft) high, 1.6 km (1 mi) wide, and 56 kilometers (35 miles) long. Navigation charts of the area depict the ridges. Seismic profiles along the same terrace off Key Largo (Upper Keys) show four similar linear structures, but they are much smaller, only a meter or so high, narrower, and are buried by sediments.

Scientists drilled a core in the outermost ridge off the Lower Keys and found that the ridge consists of corals. The other parallel formations are also reefs. By using radiometric dating methods, researchers determined that the fossil reefs were alive about 80,000 years ago during a global high stand of sea level, one of several that occurred in a period of geologic time called the Pleistocene. These reefs are named outlier reefs because they are seaward of the shelf-margin reef that harbors modern coral and hardbottom communities.

The terrace upon which the outlier reefs grew represents a previous shoreline that may be as recent as 190,000 years old. Its 3.2 km (2 mi) width indicates that the shoreline existed for a long time and that sea level may have remained near that position for thousands of years. While exposed, it is likely that winds formed sand dunes along the shoreline and that sand grains in the dunes became cemented with time. As a rising sea surface flooded the terrace, the hardened dunes were also submerged and corals colonized their surfaces. For unknown



Photograph courtesy of J. Pitts - FDOT

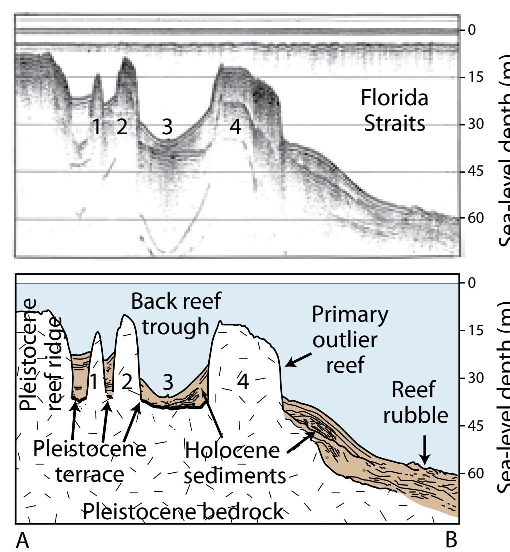
Aerial photo of the region seaward of Sand Key Reef shows the four discontinuous tracts of outlier reefs seaward of the shelf-margin reef. The seawardmost outlier reef (#4) is the largest. The seismic profile was taken along transect A – B.

reasons, corals did not survive on the northern dune ridges (Upper Keys) but they thrived off Key West, and organisms typically associated with a healthy coral reef ecosystem were probably abundant. As the sea continued rising, those corals flourished, keeping up with the rise, and over thousands of years, they constructed the huge outlier reefs.

All scientific information available indicates that during the period of outlier-reef formation, sea level remained below elevation of the Florida shelf. Florida Bay did not exist, and the growing outliers were thus sheltered from shallow coastal and Bay waters that would have been deleterious to their survival. A broad continuous spit of land that included all of what are now Florida Bay, the Florida Keys and shallow shelf, and the Marquesas-Quicksands Ridge, jutted into the Gulf of Mexico and protected the growing reefs from cold Gulf waters as well. Then, around 77,800 years ago, a time that corresponds to the age of the youngest cored and dated Pleistocene coral, sea level fell well below the Florida shelf and remained below until about 8000 years ago. During those thousands of years, corals remained exposed to air and could not grow. When sea level rose once again, it flooded the outlier reefs and shelf. Corals again grew briefly on the Lower Keys outlier reefs, from about 8900 – 6900 years ago, but then coral growth stopped.

What caused the abrupt demise of the outlier-reef builders shortly after 6900 years ago is not known. One theory is that as water became deeper across the shelf, it eventually linked turbid, cold Gulf waters with the clear, warm Atlantic Ocean waters needed by the corals. This exposure to cold temperatures weakened the corals, and reef building ceased.

Today, the surface of the largest outlier reef (primary outlier reef) in the Lower Keys lies about 9 m (30 ft) below sea level and harbors only a very few widely scattered heads of live coral. Storm waves remove and push loose coral and sand from the reef crests into the deep troughs behind the coral-rock ridges. Eventually, given enough time, the broad troughs will fill, as is known to have occurred in the Upper Keys where Holocene sands pushed by onshore winds and waves have filled sections of the much shallower 80,000-year-old back reef trough behind the shelf-margin reef. The infilling was rapid, relative to geologic time, having taken place within the most recent 8000 years of shelf flooding. Given their greater breadth and depth and the alongshore direction of winds and waves in the Lower Keys, a considerably longer amount of geologic time will be needed to fill the outlier reef troughs.



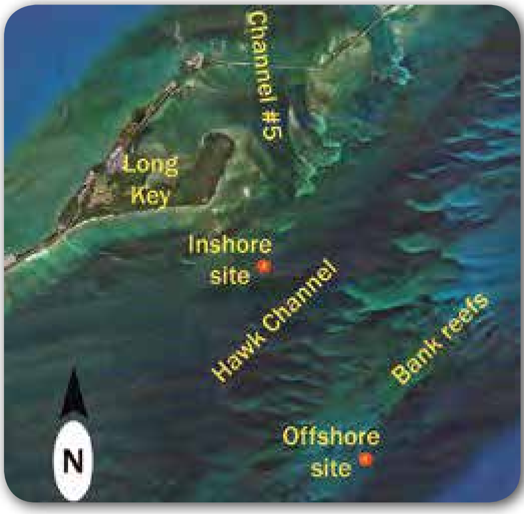
From Lidz et al. (1991)

Seismic profiles (A – B) present a sound wave "picture" through rock and sediment. Sound waves pass through the ground and echo or reflect back different types of sediment and rock surfaces. A machine records the echoes and draws a picture of the reflections. Top: a seismic profile across the shelf margin and outlier reefs seaward of Sand Key Reef, southwest of Key West, Florida. Currents flowing essentially westward, toward the reader and parallel to the rock ridges, prevent the troughs between the margin and outlier reefs from rapidly filling with layers of sand and coral debris. The troughs are known as "back reef troughs." Note the reflection (heavy line) that marks the hard rock surface of the old (Pleistocene) terrace floor. The primary outlier reef (#4) grew at the seaward edge of the terrace. Bottom: interpreted line drawing of the seismic profile shows an outline of the cross section of the four parallel tracts of outlier reefs. The tracts are discontinuous. The seismic profile just clipped the end of a reef in tract #3. Note that the terrace cannot be traced below the outlier reefs because coral reefs and coral debris characteristically block transmission of sound waves. Depth below sea level is in meters.

Discharges from Florida Bay influence growth of corals

Clayton B. Cook, Erich M. Mueller, Eric R. Annis, and M. Drew Ferrier

There are many differences in water quality between Florida Bay and the Florida Keys Reef Tract. The shallow Bay has greater temperature extremes, more variation in salinity, and finer sediments than the bank reefs. Bay waters also have elevated nutrients (i.e., nitrogen and phosphorus), and are much more turbid than water at the Reef Tract. These differences are reflected in the corals found in the two environments. Depending on location, the Florida Keys Reef Tract has 32 (Biscayne National Park) – 47 (Dry Tortugas) species of hard corals that form the structural framework of the reef system. In contrast, only four species of stony coral (rose coral [*Manicina areolata*], finger coral [*Porites porites*], lesser starlet coral [*Siderastrea radians*], smooth star coral [*Solenastrea bournoni*]) are commonly found in Florida Bay. These are hardy corals that can withstand the environmental challenges presented by Florida Bay waters.



Google Earth

Turbid (lighter-colored) waters flow out of Florida Bay through Channel 5 and toward the reef tract. Inshore is the location of the coral transplantation study site in the tidal flow from Channel 5. Offshore is the location of the transplantation study site on the eastern edge of the bank reef.

Water is exchanged between Florida Bay and the Atlantic Ocean through tidal passes between the Keys, flowing from the Bay to the ocean during ebbing tides and reversing during flood tides. However, there is an overall net flow from Florida Bay to the Atlantic. An alongshore counter current flowing to the southwest in Hawk

E.M. Mueller - MML

Stainless steel coral maintenance structure used to deploy coral cores at the two sites. Each coral core was about 51 millimeters (2 inches) in diameter and was mounted in a PVC collar screwed into the structure.

Channel intercepts some of this flow. Reef growth is greatest in areas that are not exposed to direct flow from Florida Bay.

An experiment was performed in 1996 – 1997 to assess how Florida Bay waters actually affect reef corals. Cores of the same size were cut from large colonies of the large star coral (*Montastraea faveolata*) and were transplanted to two sites south of Long Key. Both sites were at equivalent depths (3.6 – 4.6 meters [12 – 15 feet]). The inshore site was located in the tidal flow from Channel 5, whereas the offshore site was located across Hawk Channel on the eastern edge of Tennessee Reef. Transplanted corals were sampled and structures were cleaned every 3 months for 15 months.

The corals from the inshore site were typically darker in coloration than those at the offshore site at every sampling period because of an increased amount of chlorophyll. Reef-building corals contain symbiotic algae (i.e., zooxanthellae) in their tissues. These algae are responsible both for the productivity of reef corals and for the accelerated rate of calcium carbonate deposition (i.e., coral skeleton formation) that results in growth and formation of coral reefs. Inshore corals had increased chlorophyll content of these algae due to the elevated turbidity (i.e., decreased light transmission) of the Florida Bay water. It is common to see an elevated chlorophyll content in shaded corals; the algae synthesize more photosynthetic pigments to trap more light under reduced illumination, and appear darker in color.

C.B. Cook - HBOI

Coral cores collected 9 months after deployment. The difference in pigmentation between corals placed inshore (two darker corals on left) and offshore (two lighter corals on right) is due to increased photosynthetic pigments in corals growing in inshore turbid (shaded) water.

At the beginning of the experiment, each coral core had the same area of living coral tissue. After 15 months, the corals growing offshore appeared healthy, whereas coral cores growing at the inshore site were smaller, and in some, part of the core was missing. Inshore corals had less live tissue and a smaller number of coral polyps than offshore corals.

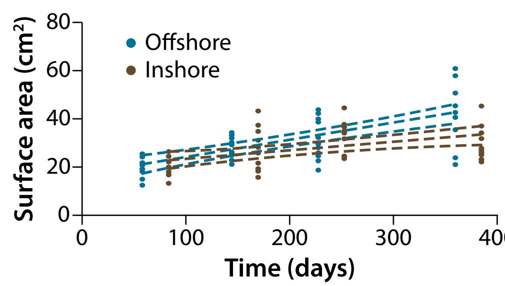
The loss of skeleton in some of the inshore corals may be related to the less dense skeletons that these corals

C.B. Cook - HBOI

Coral cores collected 15 months after deployment. Left: inshore coral. Right: offshore coral. Some corals growing inshore had areas devoid of coral tissue and places where the skeleton was broken.

produced. The linear extension (increase in diameter) was similar between the two study sites, but the actual amount of calcium carbonate that each unit deposited during the experiment was always greater at the offshore reef site. This indicates that the inshore corals were making less dense skeletons that were potentially weaker and more prone to the activities of boring organisms, such as sponges and bivalves, that bio-erode coral skeletons.

One model of coral growth states that linear extension is not light limited, but bulk calcification is light limited. It appears that turbidity results in reduced coral calcification by reducing the amount of light available to the zooxanthellae for photosynthesis. The increased chlorophyll content of the algae seems to be insufficient to compensate for this.



After 15 months, the coral transplants growing offshore (blue) had significantly higher surface areas than inshore transplants (brown).

The most likely explanation for the growth patterns observed is that light limitation of bulk $CaCO_3$ deposition was greater at the inshore site. Similar patterns of coral growth, resulting from turbid water, have been observed in Mexico and on the Great Barrier Reef in Australia.

This research demonstrates that turbidity is one of the major inimical factors of Florida Bay waters that inhibit the growth of reef corals and, thus, coral reefs, but it certainly is not the only one. High turbidity operates in concert with the other factors (e.g., nutrient loading, temperature and salinity fluctuations) in reducing the ability of most reef corals to be competitive in this environment.

Long-term monitoring documents the decline of corals in the Florida Keys and Dry Tortugas

Rob Ruzicka

The Florida Keys Coral Reef Evaluation and Monitoring Project (CREMP) was initiated to monitor the status and trends of coral reef resources in the Florida Keys National Marine Sanctuary (FKNMS) and Dry Tortugas. The program is a cooperative effort between the United States Environmental Protection Agency, the National Oceanic and Atmospheric Administration, and the Florida Fish and Wildlife Conservation Commission. CREMP is one component of the FKNMS Water Quality Protection Program, which includes monitoring projects for seagrasses, coral reefs, and water quality. CREMP began annual sampling in 1996 in the FKNMS, and in 1999, additional sites were installed and sampled in the Dry Tortugas.

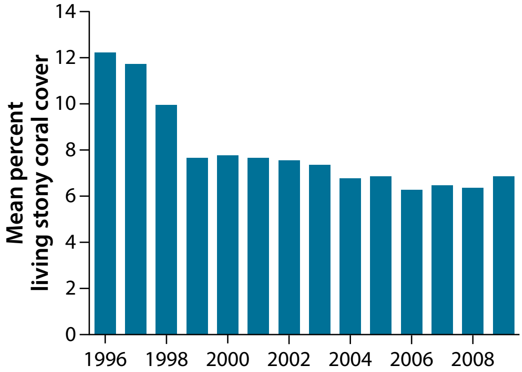
R. Ruzicka - FWRI

The Coral Reef Evaluation and Monitoring Project monitors 34 sites in the FKNMS and three sites in the Dry Tortugas annually.

Each sampling site consists of two to four monitoring stations delineated by permanent markers. Stations are approximately 2 meters (6.5 feet) wide by 22 m (72 ft) long and generally run perpendicular to the reef crest. Within each station, CREMP records stony coral species richness, coral disease presence and absence, and the number of *Diadema* sea urchins and uses three video transects to measure the spatial coverage of stony corals, octocorals, macroalgae, sponges, and other coral reef flora and fauna. Results are analyzed Sanctuary-wide and by region for the Upper Keys, Middle Keys, Lower Keys, and Dry Tortugas. Currently, CREMP monitors 109 stations at 34 sites in the Florida Keys and three sites in the Dry Tortugas.

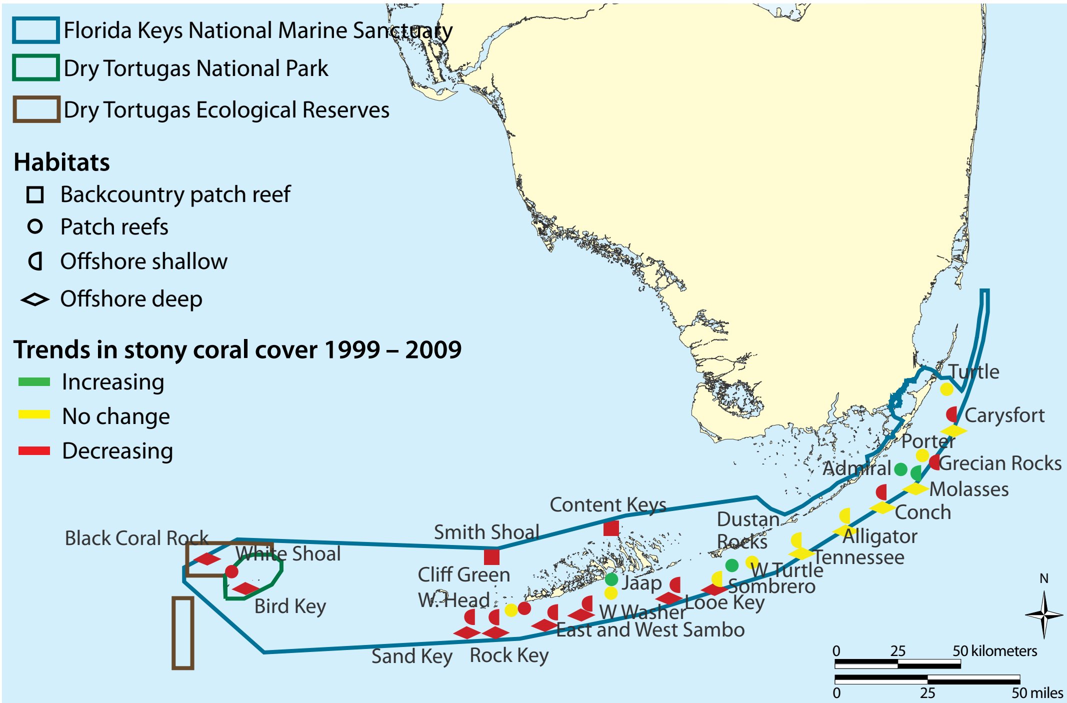
Stony coral cover

Over the duration of the project (1996 – 2009), living coral cover declined from 12.7% to 7.3% Sanctuary-wide. Coral cover reached its lowest level (6.4%) in 2006. Several factors have contributed to the major losses in coral cover.



Mean percent living stony coral cover decreased santuary-wide from 12.7% in 1996 to 7.3% in 2009. Coral cover reached its lowest level (6.4%) in 2006. A large decline in coral cover occurred in 1998 and 1999 following two consecutive years of extensive coral bleaching. There was a small increase in stony coral cover between 2008 – 2009.

Successive and severe declines in coral cover took place in 1998 and 1999 due to a prolonged El Niño weather pattern that caused extensive coral bleaching and mortality throughout the Caribbean and Western Atlantic. Also, Hurricane Georges struck the Keys in September of 1998 and caused widespread coral damage. The decline in stony coral cover between 2005 – 2006 can be attributed to the 2005 Atlantic hurricane season, the most active hurricane season on record, in which several storms passed through or were



Location of CREMP sampling locations throughout the Florida Keys and Dry Tortugas. Different colors show the proportional changes in stony coral cover over the past 10 years of monitoring (1999 – 2009). The different symbols indicate the type of coral reef habitat monitored. Significant declines in coral cover were observed in offshore shallow and deep reef sites in the Lower Keys and Dry Tortugas and Backcountry (red). No significant change in coral coverage was observed in most Atlantic patch reefs (yellow circles). Three patch reef sites, Jaap Reef, Dustan Rocks, and Admiral Reef (green circles), and one offshore shallow reef site, Molasses Reef (green half circle), had a significant increase in coral cover.

adjacent to the Keys. Although hurricanes and coral bleaching events have had a major impact on corals in the Florida Keys and Dry Tortugas, other acute and chronic stressors, such as coral diseases, periodic algal blooms, and decreasing water quality may also contribute to decreased coral cover.

Over the past 10 years of monitoring, coral cover decreased at 20 of 37 (54%) sites, remained similar at 13 (35%) sites, and increased at 4 of 37 (11%) sites. There were significant differences in coral cover between regions and type of reef habitat. Two thirds of all deep and shallow fore reef sites have declined in coral cover. In contrast, 80% of patch reef sites had no change or an increase in coral cover. Regional differences in declines were stark, especially in the Dry Tortugas and the Lower Keys where 16 of 19 sites (84% combined for both regions) showed a declining trend in coral cover, whereas most Middle and Upper Keys sites had no significant change in coral cover over the past 10 years.

The five coral species with the highest mean percent cover in 2009 were boulder star coral (*Montastraea annularis*), great star coral (*Montastraea cavernosa*), massive starlet coral (*Siderastrea siderea*), mustard hill coral (*Porites astreoides*), and boulder brain coral (*Colpophyllia natans*). Since 1996, each of these species has had a percent cover greater than 0.5%. In many cases, the overall decline of stony coral cover throughout the Florida Keys and Dry Tortugas is largely due to the decreased cover of boulder star coral. Coral cover for the other species aforementioned has been steadily declining as well, except for massive starlet coral, which has increased slightly in percent cover.

Cover of elkhorn coral, now listed as threatened under the U.S. Endangered Species Act, contributed greater than 1% coral cover during the first 2 years of the project but declined significantly when it was decimated by disease in 1999. In 2 years, elkhorn coral cover was reduced from greater than 1% to less than 0.2% and has not recovered.

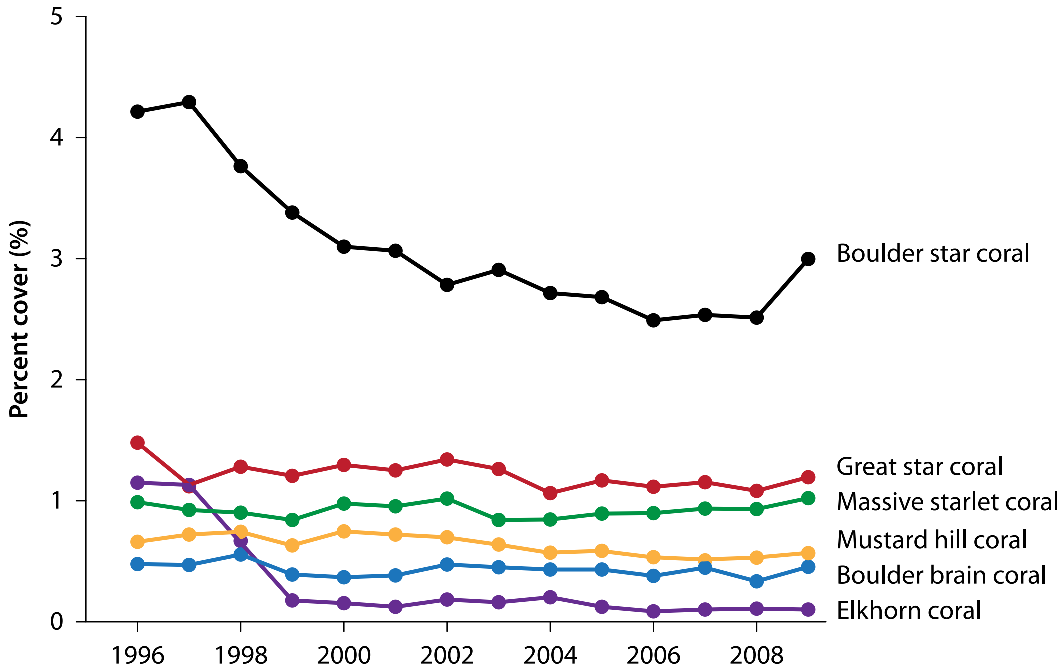
Species richness

Species richness is the number of species found at a location. The maximum number of hard coral species found in a single year was 46 in 1999 when all sites in the Florida Keys and Dry Tortugas were combined. Seventy-six percent of all monitoring stations showed a decrease in number of species over the sampling period. On average, the number of species occurring at each station declined by three species during the past 14 years.

F. Charpin - reefguide.org

Coral cover for massive starlet coral has been increasing slightly since 2003.

When presence and absence of species are compared for all stations sampled during the 14-year sampling period, 29 species are present at fewer stations than when they were previously observed. Only 9 coral species are now found at more stations than were observed in 1996. The occurrence of two species has not changed since 1996.

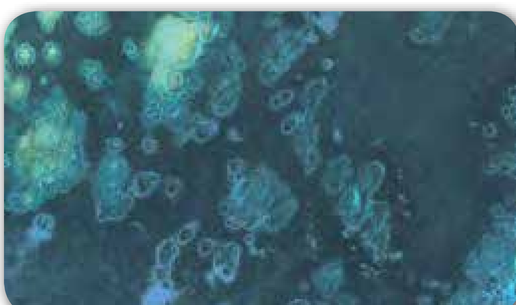


Changes in mean percent stony coral cover for the six most spatially dominant species from all sites. Boulder star coral (black) declined the most over the 14-year sampling period. Note that coverage of elkhorn coral (purple) declined precipitously from 1997 – 1998 and has not recovered.

Patch reefs are healthy reef habitats

Diego Lirman

Patch reefs are found in shallow water (1.8 – 9 meters [6 – 30 feet] deep) between the shoreline and the outer-bank reefs. They are a unique and defining characteristic of the coral reef ecosystem of southeast Florida. More than 6000 individual or aggregated patch reefs have been mapped from Miami to the Dry Tortugas. Patch reefs usually are circular or elliptical in shape and commonly are surrounded by sand or seagrass. They range in size from a few meters up to about 730 m (2395 ft) in diameter and can have 1 – 3 m (3 – 10 ft) of vertical relief.



NPS

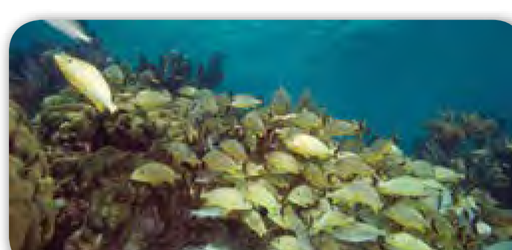
Aerial photograph of a portion of the northern Florida Keys Reef Tract showing a large number of lagoonal patch reefs.

The main corals found on patch reefs include star corals (*Montastraea* spp.), massive starlet coral (*Siderastrea siderea*), and brain corals (*Diploria* spp.). Patch reefs, especially those found fewer than 5 kilometers (3 miles) from shore, are among the healthiest reef communities of the Florida Keys Reef Tract, based on their high percentage of live coral cover (maximum coral cover is greater than 50%; mean coral cover is 17%). Also, the coral colonies found at patch reefs have little partial mortality (i.e., most of the coral colony is alive), and there is a high abundance of reef fishes.

A prominent feature of patch reef habitats is an abundance of large colonies of star corals (*Montastraea* spp.) that often exceed 1.8 m (6 ft) in diameter. Large, healthy star corals are increasingly rare in other reef habitats of the Florida Keys. Aggregations of these colonies often are described as clusters and provide essential habitat for many reef fishes and hard substrate for other benthic organisms. In addition, the reproduction by these large, old-growth corals can provide larvae to help to replenish depleted offshore reef habitats.

Many animals are residents of patch reefs as adults, such as spiny lobster and red grouper. Patch reefs also provide important habitat "pit stops" in the life history migration of commercially important fish and invertebrate species because of their location between bank reefs and the coastal wetlands and seagrass beds. Many species that spawn offshore have larvae that migrate into nursery habitats in Biscayne Bay and Florida Bay and can be found at patch reefs during their migration and development.

Many of the larger patch reefs in the Florida Keys National Marine Sanctuary are protected as Special Protected Areas (SPAs), including Hens and Chickens, Cheeca Rocks, and Newfound Harbor reefs. In SPAs, only nonconsumptive recreational activities are allowed, such as snorkeling, SCUBA diving, and glass-bottom boat rides. The major objective of the designation of reef areas as SPAs was to resolve conflicts between consumptive and nonconsumptive users.



E. D'Alessandro - UM/RSMAS

Schools of grunts and snappers are common sights on patch reefs in southeast Florida.

Coral cover in Dry Tortugas National Park has substantially decreased from historic amounts

Douglas Morrison

Coral reefs are one of the most important natural resources in Dry Tortugas National Park, and branching (acroporid) corals are a main reef builder. There are three species of branching corals in the Park: staghorn (*Acropora cervicornis*); elkhorn (*Acropora palmata*); and a hybrid species of staghorn and elkhorn coral, fused staghorn coral (*Acropora prolifera*). Reefs in the Dry Tortugas have been monitored since 1881, and staghorn coral has historically accounted for more than half of the coral reef coverage. In 1881, Alexander Agassiz mapped 461 hectares (1140 acres) of branching coral reefs, mostly staghorn coral. In 1976, the area covered by branching corals was found to be 478 ha (1181 ac). By 2009, however, there was only 0.5 ha (less than 2 ac) of known acroporid reefs in the Park, a 99% loss.

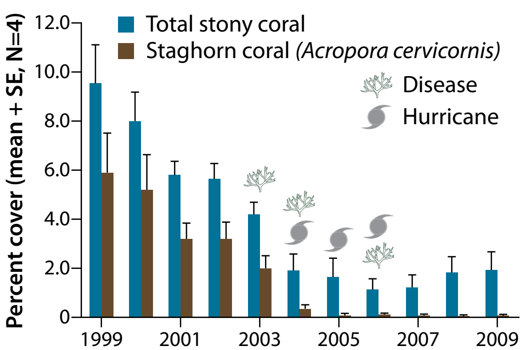
D. Morrison - NPS

Healthy (left) and diseased (right) fused staghorn coral (*Acropora prolifera*). Disease and hurricanes have resulted in recent losses of corals in Dry Tortugas National Park.

Annual detailed benthic surveys in Dry Tortugas National Park were initiated in 1999. Results show a marked decline in total percent cover of coral from 1999 – 2006, and an increase in total coral cover from 2007 – 2009. However, there has been a 99% decrease in the spatial extent of branching corals in the Dry Tortugas since 1999, with little recovery.

Causes for the decline

A cold-water event in 1977 caused nearly 90% mortality of staghorn coral in Dry Tortugas National Park. However, that species started recovering in the 1980s, but disease outbreaks caused a substantial loss of all branching corals during the 1990s and early 2000s. For example, a patch of fused staghorn coral near Garden Key experienced a 90% mass mortality in 2003 because of disease.



Percent stony coral cover at White Shoal, Dry Tortugas National Park. Total coral cover decreased 83% from 1999 to 2009 with some recovery since 2007. Staghorn coral decreased 98% over the same period and has shown no recovery.

Branching corals are very susceptible to physical damage due to hurricanes and tropical storms. Five hurricanes passed over the Dry Tortugas in 2004 – 2005, an unprecedented event, and caused additional losses of branching coral coverage. However, by 2009, live coverage of total, fused staghorn and elkhorn corals were not statistically different from 2004, suggesting recovery from the 2005 hurricanes. In contrast, staghorn coral decreased 98% at two monitoring sites from 1999 – 2009, with no recovery. The 2010, the cold-water event was found to have no effects on acroporid corals in Dry Tortugas National Park.

The National Park Service has partnered with The Nature Conservancy to grow and transplant corals to attempt to restore acroporid coral reefs in the Park.

Foraminifera are useful indicators of environmental conditions of coral reefs

Pamela Hallock

Foraminifera (i.e., forams) are a very diverse group of single-celled organisms that occur in most marine environments. They are characterized by a protective shell, usually of calcium carbonate, that can have single or multiple chambers. Multiple chambers are interconnected by openings called foramen from which they get their name. Approximately 5000 species of forams exist today. They are well preserved in the fossil record, and more than 50,000 fossil species of forams have been described. They are very abundant organisms and form carbonate sediments, "oozes" on the ocean floor, and sedimentary rocks. The most famous foram accumulations are the limestones of Egypt from which the pyramids were built.

Some forams are planktonic, but most live on the seafloor; in the bottom; or attached to a substrate, such as seagrass leaves, as epiphytes. A wide range of environmental factors influences where individual species can live. They have a relatively short life span, very specific ecological requirements, and a rapid response to environmental changes. Thus, the presence or absence of particular species or assemblages of species has been found to be very useful indicators of present or past environmental conditions.

P. Hallock - USF

Photomicrograph of three species of multichambered marine foraminifera with symbiotic algae. The largest is about 2 mm (0.8 in) in size. Such forams bleach when environmental conditions become unfavorable. Monitoring the species assemblages of forams provides a simple, noninvasive indicator of water quality.

They are also useful tools in identifying currently changing environmental conditions. Some species of forams (the Miliolida) produce calcareous shells with a chemical composition in equilibrium with seawater, and their shells are more soluble than shells of other species when exposed to reduced carbonate saturation. Thus, the abundance and diversity of such forams are good indicators of strong carbonate saturation, and they will likely be among the first to decline as rising atmospheric carbon dioxide concentrations result in progressive ocean acidification.

Many reef-dwelling forams contain algal symbionts similar to coral zooxanthellae, which give them color. Unlike corals that expel their symbionts, some forams consume their symbionts when exposed to too much sunlight. Because foram species are very specific in their ecological requirements, are relatively immobile, small, abundant, and easily sampled, scientists have developed a Foram Index that can be used to describe past and present ecological conditions of an area.

Scientists are currently studying the influence of local, regional, and global environmental changes associated with human activities to determine when foram assemblages respond in parallel with corals and when they do not. There is much hope that forams can serve as accurate predictors of environmental change.

Sand grain sources at coral reefs indicate reef health

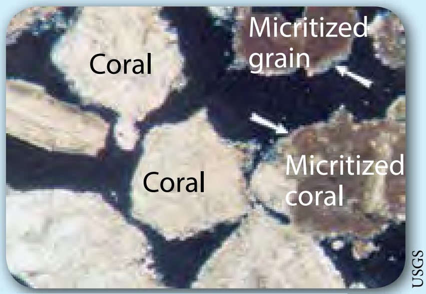
Barbara H. Lidz

The origin of sand grains gathered from along the Florida Keys Reef Tract can be used as an indicator of the overall health of the reef. The grains consist mostly of calcium carbonate that has been precipitated from seawater by reef organisms. Grain sizes range from mud and silt to gravel. Sediment grains mainly consist of broken shells, particles of calcareous algae, and coral sands. Coral-rich sands are produced from weathering and erosion of dead corals by organisms such as parrotfish, sea urchins, boring algae, barnacles, fungi, mollusks, and sponges. Wave action can redistribute the sands locally, but they generally remain near their place of origin. Percentages of grain types in a sample, except coral grains, represent the types of live organisms and their relative dominance in that local area.

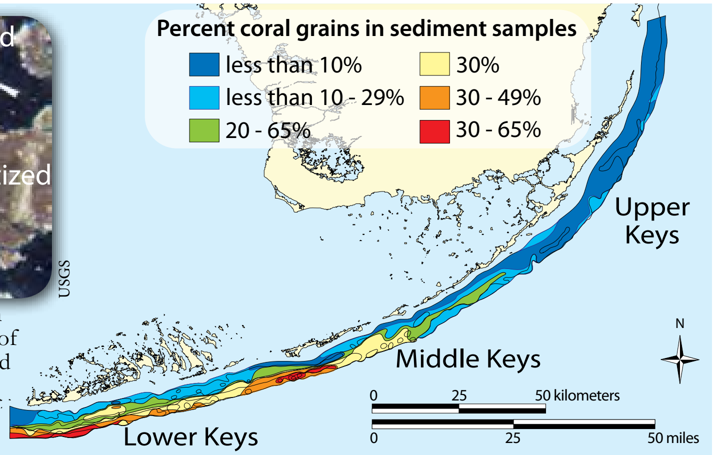
In 1989, a study examined the composition of sand grains at 143 sites off the Florida Keys. The results showed that the percentage of coral grains was correlated with the degree of observed reef decline: the higher the percentage of coral grains in the sample, the lower the frequency of live corals in that local area. Percentages of coral grains in the sands were also higher compared with earlier studies on sediment composition, indicating cumulative coral degradation.

A major finding of the study was that sediments at reefs opposite the widest tidal passes were richest in coral sands. Percentages of coral grains were highest in the Lower Keys outer shelf (65% of total sand grains), and that area had the highest percentage of observed dead corals. Off the Upper Keys, the percentages of fragmented calcareous algae and molluscan shells were greater than coral grain percentages.

Corals of the Lower Keys are topographically the most exposed to strong, cold, Gulf, and ocean currents. Also, tidal passes in the Lower and Middle Keys can deliver inimical turbid coastal bay waters that can affect the offshore reefs. Natural tidal passes are generally absent in the Upper Keys where the elongated islands shield offshore reefs from impacts of Bay and Gulf waters. Thus, reefs off the Upper Keys occupy relatively sheltered settings and are the healthiest on the reef tract, a condition that is reflected in relatively low percentages of coral sands in the sediments at those reefs.



Origin and composition of sands can be determined by viewing thin slices of grains under a microscope. Some sand grains have been chemically altered (micritized), and often their origins cannot be determined.



Percentages of coral grains in sands at reefs correlate positively with the amount of observed dead, skeletal coral.

Coral reefs provide important ecosystem services

James W. Porter

Nature's greatest architects

Corals are the master builders of nature. They build coral reefs and provide habitat for a wonderful diversity of life forms. By the simple act of depositing their calcium carbonate (i.e., limestone) skeletons, the cumulative effect is to build the largest and most topographically complex natural architectural creations in the living world. Coral reefs can be so large that they can be seen from outer space.

NASA

Image of Looe Key coral reef and a portion of the Lower Florida Keys. Coral reefs can be so large that they can be seen from outer space.

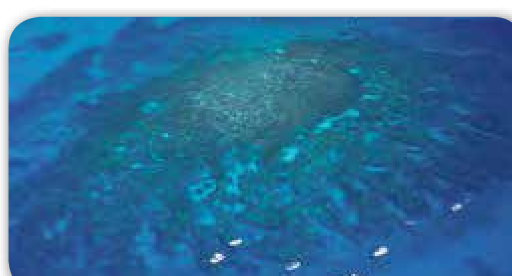
For every ounce of carbon dioxide (CO_2) fixed into organic material during coral photosynthesis, an equal weight of CO_2 is deposited as calcium carbonate into coral skeletons. Over millions of years, coral reefs have created massive fossil limestone formations found all over the world. Early civilizations depended on this "soft rock" because it could be cut into building blocks for homes, fortifications, and monuments. The Greek Acropolis, Mayan temples at Tikal, and the archaeological structures of Angkor Wat were all built from fossil coral reefs.

Nature's first line of defense

Coral reefs protect the coastline from the destructive effects of storms. During the catastrophic Indian Ocean Tsunami of 2004, towns along the coast of Sumatra behind healthy coral reefs suffered less destruction than towns with degraded offshore reefs. One of the predictions of global warming is for an increase in the intensity and, but with less statistical certainty, the number of hurricanes. Thus, protecting "nature's sea wall" may be as important a priority in hurricane preparedness in south Florida as increasing the capacity of evacuation routes.

Biodiversity hot spots

Coral reefs are extraordinarily diverse both at the species level and at higher levels of taxonomic classification. For example, of the 34 known animal phyla, 32 are found on coral reefs. Contrast that with the fact that only nine animal phyla are found in tropical rain forests. Rain forests have higher species diversity than coral reefs, but it is almost entirely based on the representation of species from one class of exclusively terrestrial organisms–the insects. Insects are by far the most diverse and most successful of all land animals. For instance, almost two



J. W. Porter - UGA

Aerial view of Looe Key, a bank reef in the Lower Florida Keys, showing topographic complexity and diversity of coral reef habitats, including spur-and-groove formations, deep reef, fore reef, reef crest, and back reef.

thirds of all described animal species on Earth are insects. However, there are no marine insects, which may be because on a comparative time scale, insects evolved relatively late in the history of the planet. Most evolutionary ecologists believe that by the time insects began to fall or crawl into the ocean, the many and already diverse denizens of the deep probably ate them before they could evolve into marine forms.

D.S. Gilliam - NSU

Coral communities, such as this one off Palm Beach County, Florida, have high biodiversity.

Drugs from the sea

Coral reefs are a pharmaceutical cornucopia. One quarter of all medicines on a drug store shelf come from the natural world, and a significant number of those come from the sea. Two of the most effective anti-cancer drugs on the market today were first extracted from Floridian reef organisms: Prostaglandin© from sea fans and Bryostatin© from bryozoa. Bryostatin© is useful in combating breast cancer, a leading cause of cancer-related mortality among women.

It is not a mystery why many pharmaceutical chemicals come from coral reefs. As the oldest and most diverse community on Earth, survival of the fittest has reached its pinnacle of expression on coral reefs. Tropical marine organisms produce more unique defense compounds than plants or animals from any other environment on Earth. These compounds protect reef organisms against attacks from other creatures. But as quickly as one chemical defense compound evolves, another potential chemical deterrent to this defense compound also evolves. This is the biological world equivalent of an evolutionary "arms race" that has been going on for millions of years on coral reefs.

An analogy between coral reefs and human societies

Although corals and humans are pretty much at opposite ends of biological organization, humans and human societies have more in common with corals and coral reefs than might initially be apparent:

- Humans and corals both evolved in the tropics.
- Corals tend zooxanthellae as a plant food source, and humans grow crops.
- Unlike many other animals, corals and humans are both herbivores and carnivores.
- Human and coral skeletons are made from calcium.
- Both corals and humans build with limestone, and both edifices are prone to damage by hurricanes.

However, among many differences, several stand out:

- The high productivity of coral reefs is due to the preservation of high species diversity. By contrast, most productive human landscapes are monocultures of rice, corn, or wheat.
- Corals farm their plants inside their cells; humans cut down the natural world to make way for their crops.
- Coral reefs have survived for at least 250 million years. Will humans make it that long?

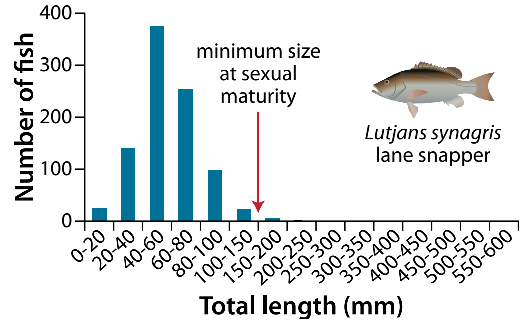
By their amazing diversity and impressive longevity, coral reefs set a high standard on how to survive on Planet Earth (or "Planet Ocean," as corals may prefer it be called). Perhaps another value that coral reefs provide is to remind humankind that the best way to create sustainable communities is to preserve the diversity of life in and around them. Earth is our shared home, and coral reefs and other natural environments depend on humans to "get it right."

The nearshore hardbottom community provides critical habitat for juvenile fishes in the Florida Keys

Marie-Agnès Tellier

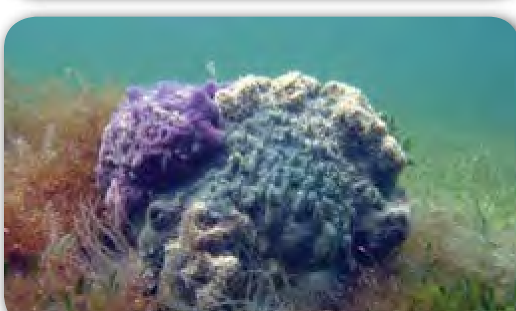
Hardbottom habitat is one of the most common marine communities in south Florida. It is characterized by a solid substrate (i.e., rock) that is colonized by an epibiotic (attached) community consisting of algae, sponges, octocorals, stony corals, and other animal groups. Hardbottom habitat can be found from subtidal areas to the edge of the continental shelf.

Nearshore areas in the Florida Keys are partially characterized by a combination of hardbottom and hardbottom mixed with seagrass habitats that cover approximately 67,000 hectares (165,560 acres) or approximately 29% of nearshore habitats. Within 2 kilometers (1.2 miles) from shore, the nearshore hardbottom habitat is characterized by a solid, low-relief limestone platform, supporting a diverse assemblage of sponges, corals, octocorals, and solution holes that provide varying degrees of structural complexity favorable to fish and motile invertebrates. These biological and physical structures provide both shelter and foraging habitat.



Size-class distribution of lane snapper collected from nearshore hardbottom habitat in the Florida Keys. Approximately 99% of the lane snappers collected on hardbottom habitats were juveniles that were smaller than minimum size at sexual maturity.

R.D. Bertelsen - FWC



R.D. Bertelsen - FWC

Nearshore hardbottom (top) and hardbottom mixed with seagrass (bottom) habitats are critical for juvenile fishes in the Florida Keys.

During a recent survey of hardbottom habitats in the Florida Keys, more than 32,000 fish were observed among 186 species. Eighty-nine percent of the fish collected were smaller than 150 millimeters (6 inches) total length, and approximately 75% of the fish were less than 25% of their adult maximum size. More than 90% of reef fish species observed were juveniles, including white grunts (*Haemulon plumierii*), gray snappers (*Lutjanus griseus*), lane snappers (*Lutjanus synagris*), yellowtail snappers (*Ocyurus chrysurus*), red groupers (*Epinephelus morio*), and gag groupers (*Mycteroperca microlepis*).

The nearshore hardbottom habitat is susceptible to impacts from fishing, diving, and snorkeling activities; climatic events, such as hurricanes; and pollutants from land-based sources. An understanding of the importance of the nearshore hardbottom habitats in the life history of commercially and ecologically important fish species is essential for informed management of the Florida Keys marine ecosystem.

Corals have inspired major biotechnological advances

Max Teplitski

In aquaria as well as in natural environments, corals can emit a fluorescent glow under the right illumination. This occurs because corals contain fluorescent proteins that absorb certain wavelengths of light and then glow at a different hue. Corals make fluorescent proteins in every color of the rainbow, and their discovery has revolutionized biotechnology. For example, scientists are using the coral genes that encode a fluorescent protein as a marker to track gene expression in plants, animals, and even bacteria.

M. Matz - UT

Corals emit a fluorescent glow under the right illumination as seen in this elkhorn coral. Scientists are using the ability of coral pigments to change colors to make exquisitely sensitive detectors of toxins, drugs, and explosives. Fluorescent coral pigments are being used to track regulation of genes required for disease resistance, organ development, and physiological changes that result in cancer or other diseases.

Use of such easily traceable fluorescent markers is especially important in learning how diseases develop in order to then specifically block or disrupt the disease progression. Fluorescent reporters are also used in the battlefield. For example, fluorescent protein markers were engineered into a gene that responds to explosives. That gene was then placed into a short-lived weedy relative of the mustard plant and the seeds of that plant were scattered over minefields. When the seedlings sprout, they emit a fluorescent glow only when growing next to an explosive landmine, making landmines easy to detect and ultimately disarm.

Even though corals lack simple physical deterrents, such as spines or shells, they are not defenseless. They have evolved a sophisticated biochemical arsenal that they use as a shield against predators and pathogens. Scientists have begun to recognize the unique pharmaceutical potential of chemicals produced by corals and other marine invertebrates. A collection of tens of thousands of purified compounds and mixtures from sea creatures is maintained by the National Cancer Institute. Researchers have identified many novel anti-inflammatory, cancer-fighting, and antibiotic compounds using chemicals contained in that collection. Further research will identify additional chemical scaffolds upon which new classes of pharmaceuticals will be built.

Corals produce a skeleton that is made of a calcium carbonate mineral called aragonite. Properties of aragonite are attractive to both medical and material scientists. Tiny granules of aragonite embedded into a titanium mesh are being tested for their ability to induce regeneration of bones. Corals make aragonite using only seawater and dissolved calcium and carbon dioxide. Factory synthesis of aragonite, on the other hand, currently requires a step with temperatures as high as 900°C (1650°F) as part of the development process. Because aragonite can be used as an additive to cement, engineers are investigating its production by mimicking what corals do, using seawater and sequestering CO_2, a greenhouse gas, from fossil-fueled power plants.

Unlocking the mysteries of corals has already resulted in progress in several fields of science. Responsible bioprospecting of corals will surely continue to open new scientific horizons.

Coral reefs provide economic value

Grace M. Johns

Coral reefs have many values, including value in recreation, commercial seafood harvest, and the value people place on knowing that coral reefs are healthy for future generations to enjoy. An economic study of the value of south Florida coral reefs was conducted in 2001 – 2003. For simplicity, all values are for 2001.

J. Luo - UM/RSMAS

SCUBA diving is a popular activity at coral reefs.

Residents and visitors spent 18.7 million person-days on southeast Florida coral reefs in 2001. A person-day is one person participating in a reef-related activity for all or part of 1 day. Approximately 9.8 million person-days were spent by residents and 8.9 million person-days were spent by visitors. The most used coral reefs are in Miami-Dade County, with 6.2 million person-days annually.

County	Residents	Visitors	Total
Martin	210,000	59,000	269,000
Palm Beach	1,901,000	930,000	2,831,000
Broward	2,437,000	3,030,000	5,467,000
Miami-Dade	2,965,000	3,250,000	6,215,000
Monroe	2,277,000	1,600,000	3,877,000
Total	9,790,000	8,869,000	18,659,000

Number of person-days spent recreating on coral reefs in southeast Florida by county in 2001.

About one half of these person-days was spent recreational fishing, and about one quarter each was spent snorkeling and SCUBA diving. Recreators in the five counties spent 9.7 million person-days fishing on coral reefs, 4.2 million person-days snorkeling, and 4.6 million person-days SCUBA diving in 2001.

County	Fishing	Snorkeling	SCUBA	Total
Martin	213,000	31,000	25,000	269,000
Palm Beach	1,148,000	418,000	1,266,000	2,832,000
Broward	2,582,000	838,000	2,007,000	5,427,000
Miami-Dade	3,965,000	1,484,000	753,000	6,202,000
Monroe	1,825,000	1,469,000	510,000	3,804,000
Total	9,733,000	4,240,000	4,561,000	18,534,000

Number of person-days spent recreating on coral reefs by activity and county in 2001.

People who fish, snorkel, and SCUBA dive on coral reefs receive value from that experience that can be measured in dollars by their expenditures to use the reefs and their willingness to pay an additional amount to be assured that coral reefs will be maintained in their existing condition. The expenditures made by these recreators in 2001 totaled an estimated $1.9 billion and included charter boat fees, fuel, bait, tackle, ramp fees, marina fees, lodging, food, beverages, and equipment rental. The annual willingness to pay to protect coral reefs in their existing condition totaled an estimated $233 million. Thus, the total value of coral reefs in southeast Florida to recreators who used the reefs in 2001 was $2.1 billion.

County	Dollars spent	Pay to protect	Total value
Martin	$10	$4	$14
Palm Beach	262	42	304
Broward	708	83	791
Miami-Dade	571	47	618
Monroe	342	57	401
Total	$1,894	$233	$2,127

Annual value of coral reefs in southeast Florida in millions of dollars in 2001.

Corals are a potential tool in measuring climate change

Eugene A. Shinn

Will climate change cause corals to go extinct, or will they begin colonizing cooler waters? No one can give a definitive answer to that question today, but some simple experiments and observations have contributed to our understanding of this topic. Above all, these observations demonstrate that corals are hardy, but temperature sensitive, and may serve as indicators of climate change. Because the geographic ranges and abundance of corals have varied significantly over geologic time, there is a need for close collaboration among biologists and geologists in studying factors influencing the long-term and short-term population changes in corals.

Temperature tolerances of some coral species

In 1914, Alfred Mayer (Mayor) measured temperature tolerances of some hard coral species. Some 50 years later, a simple *in situ* experiment confirmed Mayor's results for staghorn coral (*Acropora cervicornis*) and demonstrated why that species does not grow nearshore in the Florida Keys. Staghorn coral was transplanted to a nearshore area, and seasonal water temperatures were found to fluctuate more than in offshore waters. The nearshore transplants grew at the same rate as corals found offshore until summer when nearshore corals bleached, expelling their zooxanthellae and retarding their growth rate. They survived summer temperatures of 33.8°C (93°F) for 2 months.

Coral species	Low survival temperature		High survival temperature	
	°C	°F	°C	°F
Staghorn coral	14.1	57.4	36.8	98.2
Elkhorn coral	no data		35.7	96.3
Symmetrical brain coral	15.3	59.5	37.7	99.9
Boulder star coral	16.0	60.8	36.2	97.2
Mustard hill coral	no data		36.7	98.1
Thin finger coral	10.2	50.4	38.2	100.8
Lesser starlet coral	1.8 – 6.7	35.4 – 44.0	38.2	100.8
Massive starlet coral	11.5	52.7	37.8	100.0

Mayer (Mayor) (1914, 1915, and 1918)

Survival temperatures of some common coral species.

Coral species	Temperature	
	°C	°F
Elkhorn coral	17.4 – 17.8	63.3 – 64.0
Thin finger coral	14.5 – 14.7	58.1 – 58.5
Lesser starlet coral	10.5 – 17.3	50.9 – 63.1
Rose coral	16.3 – 18.6	61.3 – 65.5

Mayer (Mayor) (1915)

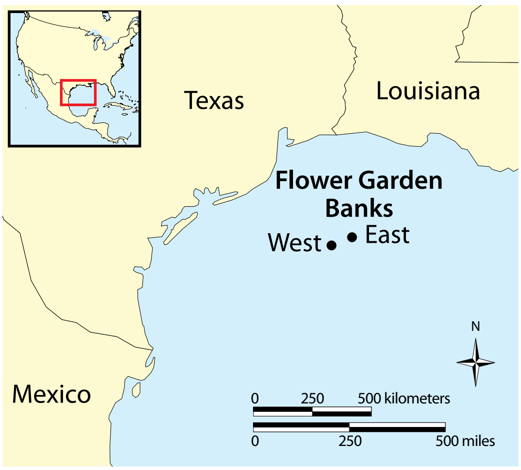
Temperatures at which corals lost their ability to capture food.

W.C. Jaap - FWRI

W.C. Jaap - FWRI

Top: Staghorn coral thicket at Loggerhead Key, 1965.
Right: Dead staghorn rubble after 1977 cold-water event.

However, after the transplants regained their zooxanthellae, a winter cold front lowered nearshore water temperature to 13.3°C (56°F), and the nearshore corals died. In addition, the study found that the growth rate of offshore staghorn corals increased during summer months (30°C [86°F] maximum) and slowed during winter months when temperatures reached 27.7°C (82°F). Thus, staghorn coral is a relatively sensitive indicator of temperature, which is a main factor controlling its local distribution.



Location of Flower Garden Banks National Marine Sanctuary.

Several other coral transplant studies have been performed that help to define temperature tolerance and the future survival of several species of corals. In the late 1960s, elkhorn coral (*Acropora palmata*) was transplanted from Florida to Bermuda where the species is naturally absent. That experimental transplantation was conducted twice, and in both cases low water temperatures in winter killed the transplants. It is possible that with warming seas, *Acropora* species could colonize Bermuda if coral larvae can live long enough to make the oceanic journey.

In the mid-1970s, boulder corals (*Montastraea annularis*), were transplanted to nearshore locations in the Florida Keys. The transplants closest to shore died during a severe cold period in 1977. During that period, water temperatures dropped to 8.8°C (48°F), and snow fell in Miami. The growth rate of offshore corals that survived was retarded. This cold period killed massive stands of staghorn coral, such as those at Loggerhead Key, where it has yet to recover.

Elkhorn coral was also transplanted to an experimental reef site at Flower Garden Banks National Marine Sanctuary in the northwestern Gulf of Mexico. The corals survived the transplantation, but researchers removed them because they were not part of the local ecosystem as it exists today. More recent research discovered that elkhorn and staghorn grew at the Flower Garden Banks about 6000 years ago during the Holocene thermal maximum, a time when global temperature is believed to have been higher than today. Recently, two living elkhorn colonies have been found at the Flower Gardens. These observations support the theory that global warming may result in the return of large numbers of acroporid corals to the Flower Garden Banks.

In addition to transplant studies, geological observations of fossil corals give clues to their environmental tolerances. A large shelf edge *Acropora* reef flourished off Fort Lauderdale until about 7000 years ago. This extinct reef is at a depth of between 14.9 – 17.9 meters

W.F. Precht - FKNMS

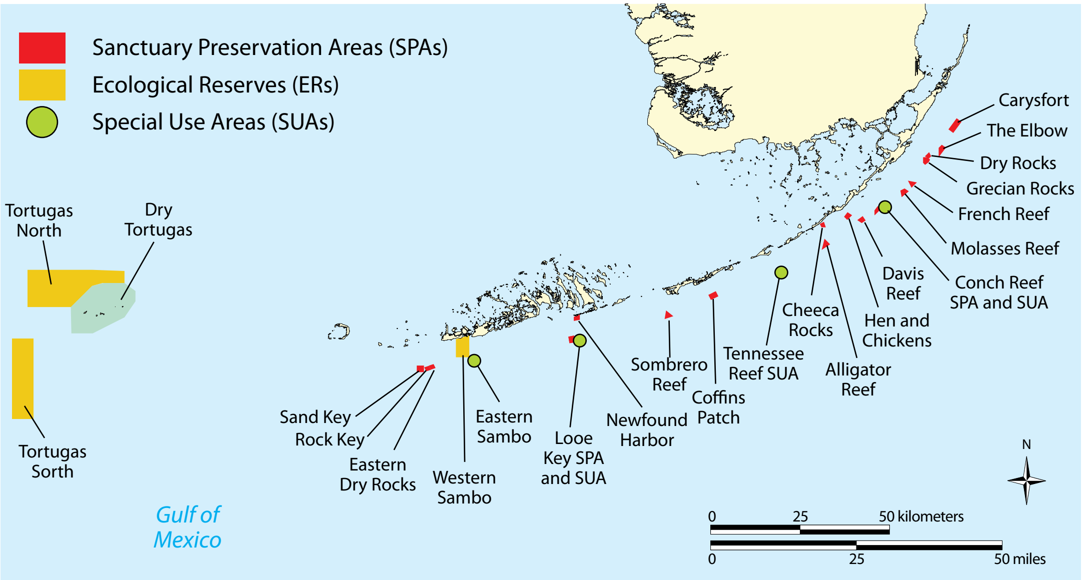
Living elkhorn coral colony recently discovered at Flower Garden Banks National Marine Sanctuary.

(49 – 59 feet). Dating of a fossil elkhorn coral at Cobblers Reef off Barbados revealed that the reef was alive from 4500 years ago to about 350 years ago. Both the Fort Lauderdale and the Barbados reefs disappeared long before impacts by human populations. Research suggests that the situation in Barbados may have been due to a period of intense hurricanes. Did climate change, sea-level rise, or both play a role? We do not know and must attempt to learn from these geological observations in order to understand recent coral demise.

Further evidence of periodic declines in coral cover was provided by a study where 39 fossil staghorn coral pieces from 19 sites along the Florida Keys Reef Tract were dated. The results revealed two periods where staghorn coral was absent, each lasting approximately 500 years. One gap occurred approximately 3000 years ago, and a more pronounced gap occurred 4500 years ago. What caused the mortality of this species? Are we now seeing a repeat of former die-offs?

Present-day coral reefs

The present-day reefs that are found along the Florida shelf margin facing the Florida Straits consist of coralline spurs built primarily by elkhorn corals that grew directly on the underlying Pleistocene limestone. Many of these true Holocene reefs are marked with lighthouses in the Florida Keys. The scattered distribution of all Holocene reefs (less than 1% of the area of the Florida Keys Reef Tract) and extensive skeletal veneers along the platform margin of reefs that did not reach sea level indicate periodic interruptions of Holocene coral growth. Given uninterrupted growth, even the slowest-growing coral species should have kept pace with sea-level rise during the past 6000 years. The faster-growing branching corals could have easily outpaced the rise, but they have not, and we do not know why. Dating has revealed that most Holocene reef spurs ceased growing about 2000 years ago, and their composition has become overgrown by fire corals, sponges, and gorgonians. The thickest Holocene reefs are those that have kept pace with rising sea level and occur in discontinuous rows landward of the platform margin in places like Grecian Rocks and Key Largo Dry Rocks in the Upper Keys. Reefs there are up to 14.9 m (49 ft) thick.



Location of well-known Holocene reefs in the Florida Keys.

Coral reefs throughout the wider Caribbean basin are in decline

Margaret W. Miller

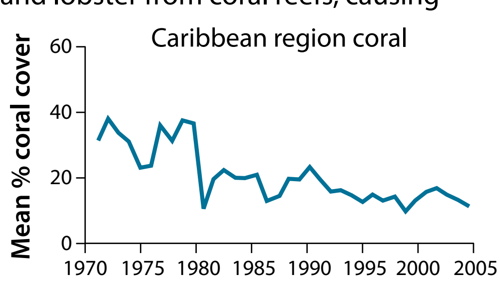
> **Stresses to Florida coral reefs**
>
> Florida reef communities are growing at the northern temperature limits of reef development, subjecting them to high levels of naturally occurring stresses, such as cold winters. Additional stresses are imposed by large human populations living, recreating, and using the coastal environment.

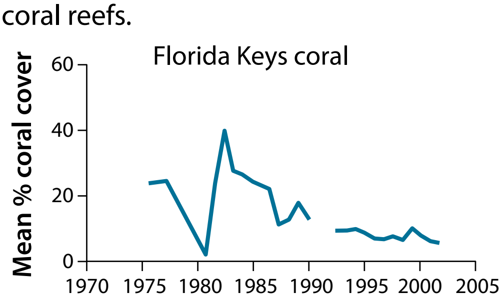
Imagine that four out of every five trees in all the forests of an entire continent died and did not appear to be regrowing. Coral reef decline is occurring similarly to such a hypothetical scenario throughout the Atlantic and Caribbean basins, including south Florida. Coral cover throughout the Caribbean region has decreased from an overall average of more than 35% live coral cover in the 1970s to around 10% in 2000s. The overall average live coral cover throughout the Florida Keys Reef Tract was only 6.1% in 2006.

Declines in branching corals occurred in the Dry Tortugas prior to 1977, likely from natural stresses such as storm damage and cold winters. Although precise data on Keys reef status are not abundant prior to the mid-1990s, it is clear from studies at a few individual sites that rates of decline in live coral cover for Florida Keys reefs continue at high levels through the present. Similar loss of live coral has even been observed in some areas that are remote from land-based human impacts, suggesting that large-scale environmental changes, such as global warming and local human activities are degrading reefs.

Corals are not the only component of the reef ecosystem that is in trouble. Humans have removed fishes, conch, and lobster from coral reefs, causing a cascading effect on the ecosystem. Although it is difficult to know how reefs looked before modern times, it is likely that large animals that are rare or extinct today, such as green turtles, manatees, large sharks, and monk seals, played important roles in Caribbean coral reefs of the past.

Long-spined sea urchins (*Diadema antillarum*) are crucial reef grazers that maintain clean substrate for corals and other reef invertebrates to recruit and grow. Over 90% of these urchins died between 1982 – 1983 throughout the entire Caribbean region and have not recovered in the Florida Keys. The loss of large populations of important grazing animals to the reef ecosystem is one of the primary impacts that has resulted in declines in Caribbean and south Florida coral reefs.





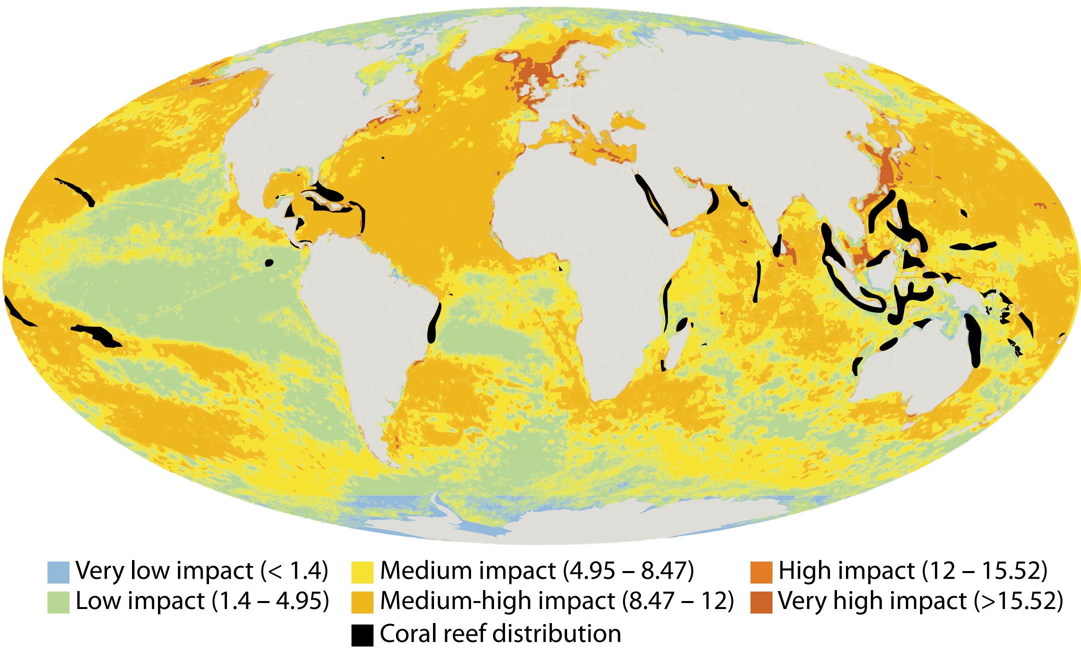
From Schutte et al. (2010)

Summary of measurements of live coral cover from combined studies on Caribbean (left) and Florida Keys (right) reefs. Coral cover, averaged throughout the Caribbean region, declined from a mean of more than 35% in the 1970s to about 10% in the 2000s. Overall coral cover in the Florida Keys probably started around 25% in the 1970s and has declined to around 5%. Although the trend averaged across many sites shown here appears fairly stable since about 1995, individual reefs have continued to show precipitous declines from intermittent catastrophic events.

Global stressors are impacting coral reefs

Andrew C. Baker

Coral reef ecosystems are severely threatened by the impact of human activities. Although some of these threats are local, affecting relatively small reef areas or regions, some threats are global and are having large-scale effects on reefs around the world. These global threats include overfishing, climate change, ocean acidification, and disease.



From Halpern et al. (2008)

Coral reef distribution and the severity of human impacts to the worldwide oceans. Measures of the impact of human activities range from very low (<1.4) to very high (>15.52).

Overfishing and overharvesting are perhaps the oldest threats to coral reefs. Historically, their impacts were confined to local reef areas close to human populations, but in recent decades, overfishing has become a truly global problem, with significant impacts on reefs worldwide. Large consumer species, such as turtles, sharks, and other large carnivorous and herbivorous fish, are now significantly reduced both in size and in numbers on virtually all coral reefs. Today, over a billion people worldwide rely on fish that grow and live on coral reefs as a significant source of food. Only a few reef areas, such as the Line Islands in the Pacific Ocean and the Chagos Islands in the Indian Ocean, have escaped the worst effects of overfishing principally because of their remote location and small number of human inhabitants. Unless large-scale efforts are undertaken to protect these areas from fishing, as was announced for the Chagos Islands in April 2010, it is likely that even these relatively pristine reef communities will be affected as global commercial fisheries expand their ranges.

Climate change is a more recent and even more severe global threat to reefs. The emission of greenhouse gases, principally carbon dioxide from the burning of fossil fuels, is resulting in warmer oceans. Warming is a threat to corals because the fragile partnership that exists between corals and their symbiotic algae (i.e., zooxanthellae) breaks down when corals are exposed to temperatures only a degree or two above the normal summertime maximum. This disruption of coral-algal symbiosis results in coral reef bleaching, in which corals lose their zooxanthellae and turn pale or white.

A.C. Baker - UM/RSMAS

When corals are stressed by warm temperatures, they can loose the symbiotic algae that give corals their color. If bleaching is severe or prolonged, bleached corals will eventually die. However, if conditions quickly return to normal, bleached corals can recover, usually within a few weeks.

Episodes of mass coral reef bleaching have occurred in one or more of the coral reef regions in the world almost annually for the past 30 years, with particularly strong events resulting in widespread death of corals in the eastern Pacific in 1982 – 1983, the western Indian Ocean in 1997 – 1998, the Great Barrier Reef in 2002, and the eastern Caribbean in 2005. With global warming scenarios indicating further warming of 2° – 4°C (3.6° – 7.2°F) by 2100, it is likely that coral reefs will be devastated by the impact of repeat episodes of severe coral bleaching unless significant adaptation or other response mechanisms allow them to accommodate warming temperatures.

In addition to global warming, increases in atmospheric carbon dioxide also lead to ocean acidification because carbon dioxide dissolves in seawater and lowers its pH. The acidification of the oceans makes it more difficult for corals (and other calcifying marine organisms) to build their calcium carbonate (i.e., aragonite) skeletons. Weaker skeletons that grow more slowly are believed to hinder the ability of corals to compete with other reef organisms and build reef structures that provide ecosystem habitat.

It is anticipated that the oceans will become increasingly acidic in the future as carbon dioxide emissions continue. Although the tropical shallow waters where coral reef ecosystems are found will be the slowest to respond to acidification, it is nevertheless clear that without dramatic reductions in emissions, ocean acidification will make it more difficult for corals to bounce back from disturbance as a result of other global and local stressors, including coral bleaching.

NOAA

Corals weakened by bleaching or other stressors may be more susceptible to other diseases, such as black-band disease shown here. In addition, pathogen development and transmission may be accelerated at higher temperatures.

A further global threat to reefs that may be driven by greenhouse gases is the emergence and spread of marine diseases, which seem to be linked to the warming of the worldwide oceans as a result of climate change. Corals weakened by bleaching and other stressors may play a part in explaining this trend, but it is also possible that pathogen development and transmission rate is increased at higher temperatures, leading to disease outbreaks.

Coral reefs are being affected worldwide as a result of these threats. These threats make it even more important for us to reduce local stresses to coral reefs, such as poor water quality and habitat destruction, so that these ecosystems have a fighting chance of surviving through this century.

Fifty years of coral boom-and-bust at Grecian Rocks shows changes in the coral reef

Eugene A. Shinn

E.A. Shinn - USGS

E.A. Shinn - USGS

E.A. Shinn - USGS

E.A. Shinn - USGS

E.A. Shinn - USGS

The images shown are selected from a 50-year time series (1960 – 2010), taken at Grecian Rocks reef off Key Largo. The images document the drastic demise of staghorn coral (*Acropora cervicornis*) that began in 1979 and peaked in 1983 – 1984.

Coverage of staghorn coral at this site expanded rapidly following the passage of Hurricane Donna (1960) and continued in spite of Hurricane Betsy (1965). Rapid growth continued until 1978 when staghorn coral almost covered the boulder coral (*Montastraea* spp.) shown in all of the photographs.

A study conducted at this site in 1960 revealed that staghorn grew at an average rate of 10 centimeters (4 inches) per year, and that growth rate was affected by annual temperature fluctuation. An average of three new branches formed from the terminal polyp each February and grew 10 cm (4 in) before repeating the branching process the following winter. At that rate, a clump of 10 branches could potentially proliferate into 56 kilometers (35 miles) of branches in only 10 years!

Branches that grew to within a centimeter of the *Montastraea* coral were attacked and killed by the *Montastraea* head, demonstrating the ability of *Montastraea* to fend off faster-growing branching corals by attacking with defensive mechanisms.

By 1979, acroporids everywhere in Florida were beginning to show signs of stress and disease. There were no living branching corals at this site on Grecian Rocks by 1988. Similar observations were photographically documented at Carysfort Reef, and synchronous demise of acroporids occurred in 1983 at San Salvador, eastern Bahamas. The *Montastraea* head shown in these photographs is only partially alive in 2010 and its morphology has changed radically.

Is nutrient pollution killing Florida coral reefs?

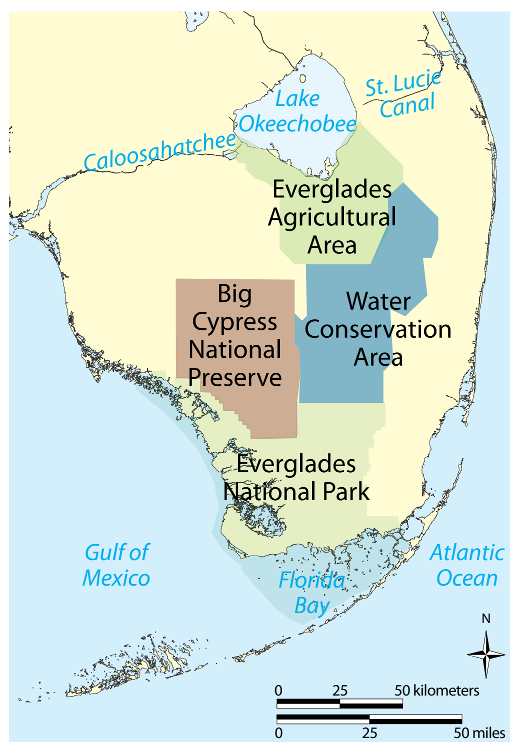
Steven L. Miller and William F. Precht

Declining water quality often is cited as the primary cause of stress to south Florida coral reefs. Indeed, coral reefs can grow and thrive only in areas that are not limited by degraded water quality. Increases in the abundance of benthic macroalgae observed on some bank reefs in the Florida Keys support an assumption that nutrient pollution from land-based sources may be the cause of increased algal growth. However, it is more complicated than that, and no studies have conclusively linked increased algal growth on reefs in the Keys with discharges from land-based sources of nutrients.

The reduction in grazing due to the loss of a major herbivore on south Florida reefs, the long-spined sea urchin, has undoubtedly resulted in growth of benthic macroalgae on some reefs that is unrelated to nutrient influxes.

Some recent evidence using viral tracers shows that it is probable that nutrients may be delivered to offshore reefs in the Keys with groundwater. However, surface water samples fail to detect increased nutrient concentrations. Studies on injection wells in the Keys have shown that wastewater nutrients are diluted by more than a million to one by groundwater close to the injection point. Much more dilution must result with the transfer of groundwater offshore. Long-term water quality data taken at bank reefs show that, in general, water quality is good and has not decreased over the past 15 years, which bolsters the argument for other reasons for observed increases in algal cover.

The amount of nutrients delivered to offshore reefs must be evaluated relative to other nutrient influxes, such as the Gulf Stream flow, tidal flushing, and upwelling. Frequent cold-water upwelling events regularly deliver high volumes of nutrient-rich water to the fore reef in the Florida Keys. These events deliver water with 10- to 40-fold higher nutrient concentrations than published estimates of influxes to nearshore waters from wastewater and stormwater. Thus,



Most water discharged from the Everglades Agricultural Area flows through Everglades Conservation Areas and Everglades National Park before reaching marine waters. There is little chance that nutrient pollution from the Everglades Agricultural Area is adversely affecting coral reefs of south Florida.

Nutrient-enriched water discharged from agricultural areas into Everglades wetlands results in a conversion of the native sawgrass communities to cattails. Most water discharged from the Everglades Agricultural Area flows through Everglades Conservation Areas and Everglades National Park before reaching marine waters.

the Florida Keys Reef Tract has been historically and periodically subjected to high concentrations of nonanthropogenic nitrogen and phosphorus. Currently, pollution from remote sources via the Gulf Stream system is not considered a major problem but remains an issue that must be carefully watched. Oil spills and floodwaters carrying pollutants to the Gulf of Mexico are a potential threat to downstream ecosystems, including the coral reefs of south Florida.

In the past few thousand years, coral reef development in the Florida Keys has been greatest seaward of the islands compared to seaward of the tidal passes. It is believed that water exiting the broad shallow expanses of Florida Bay through the tidal passes between the Keys was hot enough in the summer and cold enough in the winter to stress or kill reef-building corals. One would expect a similar effect today, with coral assemblages being healthier and more robust where the Keys block the flow of water out of Florida Bay. However, this is not the case; essentially all reef communities of the Keys, even those blocked from Florida Bay, have been in decline. It is most probable that the main causes of the widespread regional decline are from global stressors, including climate change.

Nutrient pollution from the Everglades Agricultural Area south of Lake Okeechobee has been cited by some as a primary factor of coral reef decline in south Florida, including the Florida Keys. Although nutrients discharged from the Everglades Agricultural Area have significant local effects on the Everglades, they have no or minimal impacts on the southern reaches of Everglades National Park and Florida Bay. Therefore, impacts of agricultural runoff on offshore reefs, located even farther away from the source, are highly unlikely. Significant management attention is being focused on restoring the quality, quantity, timing, and distribution of water from upstream sources to the Everglades. If done correctly, these efforts can only improve water quality filtered through the Everglades and discharged to Florida Bay and beyond.

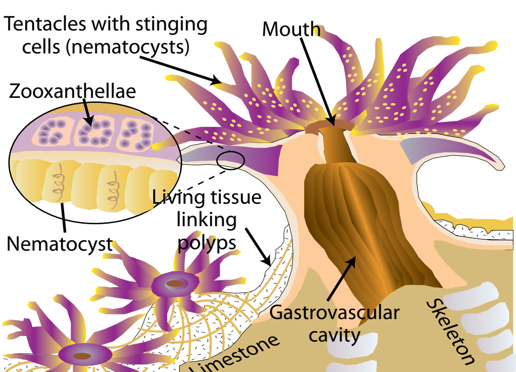
Microbial communities are important to corals

Kim B. Ritchie

Although it has been known for some time that microbes can cause coral diseases, scientists are beginning to realize that many microbes, including bacteria, form beneficial associations with corals and are important for coral health.

Bacteria were the first living organisms on Earth, and fossil records show their presence for at least 3.5 billion years, that is about 2 billion years before higher organisms emerged. Bacteria are responsible for the accumulation of oxygen in our atmosphere, the evolution of higher organisms, and many processes on earth that make life as we know it possible. Because the majority of evolution took place in the oceans, where life first began, there has been ample time for the evolution of beneficial associations between bacteria and marine invertebrates.

Corals produce mucus that coats the outsides of their polyps. This mucus is used for protection, much like the mucosal linings of human membranes. When corals become covered in sediments, they produce mucus in sheets so that foreign material can be sloughed away. Coral mucus also protects the coral from sun damage and from drying out if exposed to air at low tides. Coral mucus even contains antibiotic properties to help prevent infections to corals.



Structure of a coral polyp.

K.B. Ritchie - MML

Corals, such as this healthy elkhorn coral at Carysfort Reef in 2008, harbor beneficial bacteria that may provide resistance to invasion by foreign microbes, including those that cause coral diseases.

Nutrients in the slimy mucus attract a large number of bacteria that find food and shelter there.

Different coral species produce a specific composition of mucus that is believed to attract specific groups of beneficial bacteria. These bacteria are believed to provide important protective, metabolic, and nutritional functions. Resident bacteria are believed to help corals resist invasion by pathogens by preventing attachment and entry into coral cells or by competing for nutrient availability, thereby maintaining the optimal microbial balance. Also, it is now known that some of these bacteria produce antibiotics that may help corals to resist diseases.

When corals are stressed by an increase in ultraviolet light, temperature change, or other factors, they become more susceptible to illnesses, including attack by opportunistic pathogens. It has been shown that some of the more sensitive corals, such as elkhorn coral (*Acropora palmata*), lose immunity when temperatures increase. A rise in the abundance of potentially pathogenic coral bacteria (*Vibrio*) has also been documented during times of increased temperatures. Coral stress and loss of immunity, together with an increase in opportunistic coral pathogens during times of greatest stress, may explain why corals are much more sensitive to disease and decline during times of heat stress.

Coral diseases are a major cause of coral death

Deborah L. Santavy and Esther C. Peters

Corals are susceptible to diseases

Some coral diseases are associated with pathogenic bacteria; however, the causes of most coral diseases remain unknown. Some diseases trigger rapid and extensive mortality, whereas others slowly cause localized color changes or injure coral tissue, but recovery can occur. Several coral diseases involve the symbiotic algae harbored in the coral tissue. Although causes vary, all diseases occur in response to biotic stresses, such as bacteria or fungi, or abiotic stresses, such as changes in sea temperature, pollutants, or terrestrial runoff. Most probably result from multiple stresses that can reduce coral immunity and promote increased disease-causing microorganisms.

The increase of coral disease in recent decades caused widespread mortality of many coral reefs in the Florida Keys and Caribbean, leading some scientists to predict their ecological extinction in this century if the trend persists. Widespread mortality can eliminate entire coral species and replace them with more tolerant ones, resulting in loss of habitat for many reef fish and invertebrates. Often, replacement species are not major reef-building corals.

A 1998 – 2006 study that assessed coral health from Biscayne Bay to the Dry Tortugas concluded that low incidences of coral diseases were widespread, with only 15% of the area containing no disease. White-pox outbreaks at Looe Key in 1998 affected almost half of the elkhorn corals (*Acropora palmata*) and coincided with the worst coral bleaching in Florida. Both of those events caused extensive coral mortality in the Keys, with significant declines of elkhorn, staghorn (*Acropora cervicornis*), and boulder corals (*Montastraea* spp.). The dominant coral diseases found were white pox, dark spot, white band, and white plague. Most coral diseases have been aptly named based on the color or pattern of the affected coral tissue.

D.L. Santavy - EPA

D.L. Santavy - EPA

Black-band disease. Black-band disease was the first coral disease described and was found during the 1970s in the Florida Keys. Infected stony corals and sea fans have a compact black band covering the margin of healthy tissue next to tissue-depleted bare white skeleton. The band is a microbial mat comprising filamentous blue-green algae (i.e., cyanobacteria) and many different types of bacteria that secrete toxins and create an anoxic (i.e., no oxygen) environment, killing coral cells. Black-band disease infects mostly boulder corals but can infect other species. Many corals at Looe Key, Florida were infected with black-band disease during the 1980s and died.

D.L. Santavy - EPA

Coral bleaching. When stressed by extreme seawater conditions, corals lose their symbiotic algae and become bleached. The photosynthetic pigments of algae give corals their characteristic colors. After corals bleach, the tissue becomes translucent, and the white coral skeleton beneath is revealed. Some corals, such as fire corals, are more susceptible to bleaching than others. Genetic and environmental factors trigger some individuals, colonies, and species to respond differently. The most severe bleaching in the Florida Keys occurred during the summers of 1997 and 1998. Bleaching often is attributed to increased seawater temperatures, ultraviolet light, and calm sea conditions and is associated with global climate change and El Niño events. Prolonged bleaching can cause partial to total colony death. If stressful conditions cease after a short time, colonies often can reacquire their symbiotic algae and survive.

D.L. Santavy - EPA

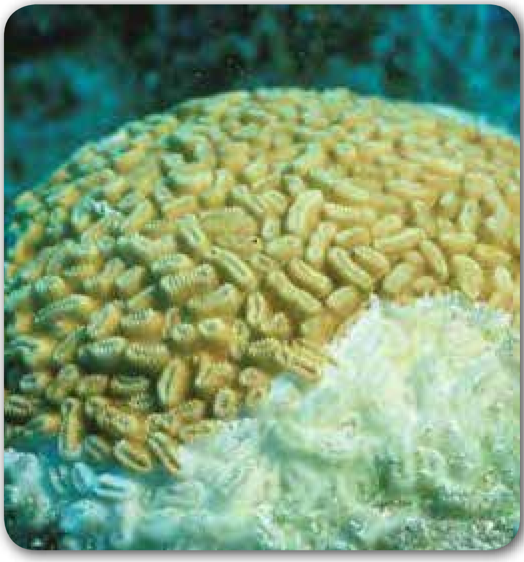
Dark-spot disease. Diseased tissues appear as purple, gray, or brown irregular lesions over the colony surface, which slowly enlarge from their centers and can cause tissue mortality. Darkened areas often are depressed and contain smaller-than-normal polyps. Dark-spot disease affects massive starlet (*Siderastrea siderea*), blushing (*Stephanocoenia intersepta*), and boulder star (*Montastraea annularis* complex: *M. annularis*, *M. faveolata*, and *M. franksii*) corals.

D.L. Santavy - EPA

Red-band disease. Red-band disease is similar to black-band disease, except the band is red to maroon in color and is caused by different cyanobacterial species. Unlike black-band disease, the band can be compact or diffuse, resembling a web-like net adjacent to healthy tissue and tissue-depleted skeleton. Red-band disease infects massive and plating corals through the Caribbean basin and is especially prevalent on sea fans in the Florida Keys.

A. Bruckner - NOAA

White-band disease. White-band disease only affects Caribbean acroporid species, staghorn (*Acropora cervicornis*) and elkhorn (*A. palmata*) corals. The tissue uniformly sloughs off the coral skeleton, usually progressing from the colony base to the branch tips. Bacterial aggregates are found at the tissue-skeletal interface and are believed to play a role in white-band disease. This disease caused extensive mortality in acroporids throughout the Caribbean and Florida in the past several decades. Decline due to white-band disease is one reason cited for listing these corals as threatened species under the federal Endangered Species Act.

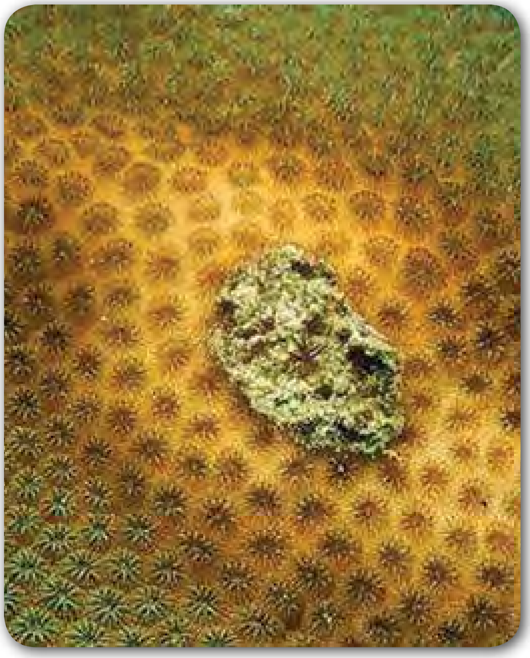


G.P. Schmahl - NOAA

White plague. White plague has similar features to white-band disease. It affects up to 45 Caribbean coral species but not the acroporids. The disease is characterized by large white areas of skeleton exposed by recent tissue mortality. The exposed skeleton usually is stark white because of recent and rapid tissue destruction, up to 2 cm (1 in) per day along the tissue loss margin. White plague lesions usually originate at the colony base and progress toward the center. The rapidly spreading disease appears to have originated in the Florida Keys. It was first reported in 1977, with another outbreak recorded in 1995.

D.L. Santavy - EPA

White-pox disease. White-pox disease, also known as white-patch disease, only affects elkhorn coral (*Acropora palmata*) in Florida and the Caribbean. It was first reported in 1996 near Key West. Irregularly shaped bare skeleton appears scattered over the colony, and the skeleton can be eroded or intact. The cause of the disease has been identified as the bacterium *Serratia marcescens*, which is common in the human intestine and the environment.



E.C. Peters - GMU

Caribbean yellow-band disease. This disease affects star corals (*Montastraea* spp.) and brain corals. It was first described in 1994 from the Lower Keys but is now known to occur throughout the Caribbean. First, the affected tissue appears as a pale-yellow patch. As the disease progresses, a yellow band of tissue forms at the outer edges of the original patch, and white skeleton is exposed in the center of the infection site. Corals can be infected for many years, and the disease can affect multiple locations on a colony. The cause of the disease is a consortium of bacteria that kills most of the symbiotic algae, resulting in paled tissue retaining a yellowish color.

Corals can have growth anomalies

Esther C. Peters and Deborah L. Santavy

Coral growth anomalies are changes in the coral cells that deposit the calcium carbonate skeleton. They usually appear as raised areas of the skeleton and tissue that are different from the surrounding normal areas on the same colony. The features include abnormal shape, size, and development or loss of the corallites (i.e., skeletal cups that protect the polyps), and either paler or darker tissue color. Because growth anomalies are well-circumscribed masses with a faster rate of skeletal accretion, they have been called tumors and compared to cancer. The causes are unknown, although recent research suggests an infectious agent, such as a virus or DNA mutations caused by ultraviolet light or toxins, might produce abnormal proliferating cells. Two kinds of growth anomalies are generally recognized.

E.C. Peters - GMU

Gigantism. These lesions appear as bulging growths and have been found on reefs throughout the Florida Keys and worldwide. Gigantism results from rapid growth and multiplication of a single polyp, and the abnormal skeletal elements can be either larger than those on the rest of the colony or can consist of corallites that are smaller than those on the rest of the colony. The skeleton produced by the abnormal polyps often is less dense than the surrounding material.

E.C. Peters - GMU

Abnormal corallites can also be smaller than those on the rest of the colony, as seen on this lesion occurring on an elliptical star coral.

Neoplasia. Cells in these lesions produce only gastrovascular canals and skeleton. The lesions proliferate and connect all polyps, which disappear from the porous, whitened protuberant masses. Neoplastic lesions are found on acroporid corals, such as the elkhorn coral (*Acropora palmata*), and appear as "bubbly" translucent coral tissue at the lesion margin. Affected tissue lacks symbiotic algae, loses its mucus-secreting protective cells, does not produce eggs and sperm for reproduction, and can die. This growth anomaly is considered to be a coral cancer.

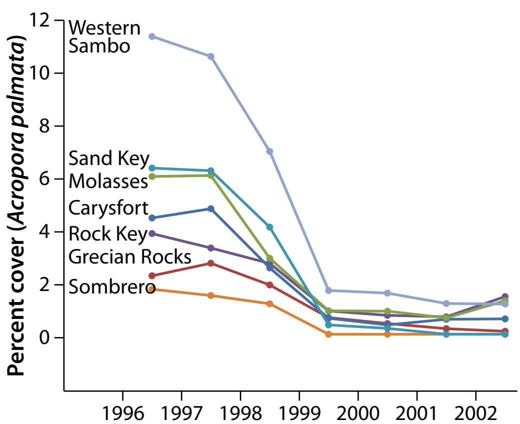
E.C. Peters - GMU

Close-up of a neoplastic lesion in elkhorn coral. Affected tissue lacks symbiotic algae and mucus-secreting cells and is protuberant. Scale is in centimeters.

Elkhorn corals are susceptible to white-pox disease

Kathryn Patterson Sutherland, Erin K. Lipp, and James W. Porter

In 1996, a new coral disease called white pox was first reported to affect elkhorn corals (*Acropora palmata*) at reefs near Key West. The disease was common on Florida reefs between 1996 – 2001, and during that time period, elkhorn coral populations declined by 87% Keys-wide. A second species of branching acroporid coral, the staghorn coral (*Acropora cervicornis*), also suffered significant declines in the mid- to late-1990s due to a similar disease called "white band."



Adapted from Sutherland and Ritchie (2004) with kind permission from Spring Science and Business Media

Percent cover of living elkhorn coral at reefs in the Florida Keys National Marine Sanctuary. Coral cover declined an average of 87% between 1996 – 2002.

White pox and white band are the most commonly reported diseases for the branching corals on Atlantic and Caribbean reefs. Between the 1970s – 1980s, white-band disease is believed to have resulted in a Caribbean-wide decline of branching corals. Although many of the populations of branching corals were lost due to a combination of white-band disease, bleaching, and hurricane damage in the Florida Keys, coverage remained at about 12% for elkhorn and staghorn corals during the mid-1990s when wide-scale observations of white-pox disease were first recorded and the percent coverage of elkhorn coral dropped to less than 2%.

Outbreaks of white-pox disease have been observed throughout the Caribbean, but the focus of the disease outbreak appeared to be in the Florida Keys. The decimation of the populations of branching corals in Florida contributed to the May 2006 listing of elkhorn and staghorn corals as threatened under the United States Endangered Species Act.

In 2002, a bacterium called *Serratia marcescens* was identified as a cause of white-pox disease. This bacterium is common in the intestines and feces of humans and other animals and in freshwater and soil. Recent studies recovered a unique strain of *S. marcescens* from diseased corals and sewage. The strain, isolated from reef and sewage sources, establishes a definitive connection between human sewage and white-pox disease of corals. These studies also demonstrate that *S. marcescens* cannot be isolated from all coral colonies apparently affected by white-pox disease. Outbreaks of white pox have waned in intensity since 2000, although the disease is still commonly reported. The current low prevalence of the disease may be due to the decimation of susceptible elkhorn populations during previous outbreaks and the loss of large colonies due to hurricanes. The observation of small recruits and isolated large colonies indicates that elkhorn corals that are resistant to white pox may exist.

J.W. Porter - UGA

Elkhorn coral affected by white-pox disease. White patches are denuded coral skeleton from which all living coral tissue has been lost.

Aspergillosis is a fungal disease that affects sea fans

Kiho Kim

In the Florida Keys, the sea fan coral, *Gorgonia ventalina*, is a common and iconic member of reef communities. The sea fan coral is made up of an intricate latticework of branches that form a large, flat fan that is usually oriented perpendicular to the dominant direction of water flow. In 1995, sea fans around the island of Saba (Netherlands Antilles) were found with unusual lesions, a sign of disease. By the summer of 1996, such lesions were also found on sea fans in the Florida Keys.

This disease, which has now spread throughout the Caribbean and affects all three species of Caribbean sea fans, leads to purpling of tissue surrounding the lesions and galls that may grow to 2 – 3 centimeters (0.8 – 1.2 inches) in diameter. The impact of aspergillosis on sea fans has been well documented in the Florida Keys. The first large-scale survey in 1997 revealed disease prevalence of nearly 43%; subsequent studies documented mortality rates ranging from 5% – 95% per year among infected sea fans. The disease tended to increase during the summer months and was the most severe among the larger sea fans. Once infected, there was near-complete reproductive failure, leading to low levels of recruitment during the outbreak. The disease began to decline in 2000, and by 2005 the disease prevalence was less than 1% throughout the Keys.

The disease is caused by the fungus *Aspergillus sydowii*. The pathogen was unexpected given it is a common soil fungus that was only occasionally isolated from aquatic environments. Moreover, although *Aspergillus* fungi in general are opportunistic pathogens, none were known previously to affect marine invertebrates. Thus, unanswered questions regarding this disease include "What triggered the outbreak in 1995?" and "How did the fungus evolve from a soil organism into a marine pathogen?" Scientists are still working on answering these questions.

Elevated temperature and nutrient pollution are likely stressors leading to the outbreak of aspergillosis in sea fans. Warmer water tends to favor the growth of the pathogen while stressing the coral. In addition, nitrogen pollution seems to increase the severity of the disease.

K. Kim - AU

Aspergillosis is a disease of sea fans caused by the common soil fungus, *Aspergillus sydowii*. Infection results in tissue necrosis surrounded by areas characterized by a deeply purple margin.

Scientists are learning that sea fans are capable of defending themselves by using a suite of chemical (e.g., anti-fungal compounds), cellular (e.g., immune response), and physical means. Activation of those defenses is marked by the purpling of disease-affected tissue. The purpling results from an increase in the proportion of purple sclerites (small carbonate skeletal elements) and indicates an attempt to fortify vulnerable coral tissue and reduce the spread of the pathogen. It should be noted that the purpling is a general response to contact with living agents, so care must be taken when diagnosing sea fans with aspergillosis.

Physical stressors affect the Southeast Florida Reef System

David S. Gilliam and Jocelyn L. Karazsia

The Florida reef system is extensive, running parallel to the coast for 500 kilometers (305 miles) from Martin County to the Dry Tortugas. The Southeast Florida Reef System extends for more than 150 km (91.5 mi) from Martin County to Miami-Dade County. There are over 30 species of stony corals living on the high-latitude reef system. They comprise 2% – 3% of the reef cover that includes a diverse assemblage of gorgonians, sponges, and fishes. The Southeast Florida Reef System includes unique areas with higher stony coral cover (greater than 10%), including significant populations of the staghorn coral (*Acropora cervicornis*).

The Southeast Florida Reef System lies within 4.5 km (3 mi) of a coast that is home to more than 6 million people. The proximity to a highly populated urban area subjects the reef system to ever-increasing physical stressors (impacts). Physical stressors are perhaps a greater threat to the Southeast Florida Reef System than they are to the rest of the Florida reef system. Physical threats include anchoring and gear impacts associated with commercial and recreational fishing and diving; sewage outfalls; marine construction activities, such as fiber optic cables; beach renourishment; channel dredging; and major shipping ports and ship groundings.

Physical stresses to the Southeast Florida Reef System have historically included damage to the reef framework (e.g., fracturing, breaking, crushing) as well as injuries to the reef community (e.g., dislodged, overturned, and fragmented sponges, octocorals, and stony coral colonies). These injuries result in a loss of biological and physical resources, which disrupts normal coral reef ecosystem function. These detrimental effects extend beyond the actual injured reef habitat to numerous reef-associated and reef-dependent species that utilize the reef for shelter and feeding.

Southeast Florida has nine inlets and three major ports: Port of Palm Beach in Palm Beach County, Port Everglades (Fort Lauderdale) in Broward County, and the Port of Miami in Miami-Dade County. At Port Everglades alone, over 5300 ships call annually. Inlets and ports require periodic maintenance dredging to keep them navigable. Generally, maintenance dredging does not directly impact reef communities but may indirectly stress

D.S. Gilliam - NSU

Fragmented and overturned brain corals from a ship grounding at a southeast Florida reef. Reconfiguration of anchorages at Port Everglades and the Port of Miami will reduce the likelihood of future groundings. Restoration activities are required to reverse physical impacts to reefs.

these communities through increased turbidity and sedimentation. Turbidity occurs when sediments are suspended in the water column and can clog fish gills, lessen feeding efficiency, and reduce the amount of light available to light-dependent organisms, such as corals. Sediment deposition can result in reef burial. Port expansion projects can have a direct impact on many hectares of coral habitat through dredging for the widening and deepening of entrance channels. The Port of Miami entrance channel has recently been approved for deepening and widening, and expansion projects are proposed for Port Everglades and Port of Palm Beach. The anchorages associated with the ports can also pose a significant threat to the Southeast Florida Reef System. Ships use anchorages while waiting for berths, travel orders, or good weather for travel. Unfortunately, these anchorages are currently located very close to or on coral habitat, and the areas adjacent to anchorages are much more likely to be affected by anchor drags and major grounding events by large ships.

Since 1994, over 10 major ship groundings have been documented near Port Everglades, damaging in total more than 5 hectares (12 acres) of reef habitat. Reattachment of fragmented and dislodged stony coral colonies was completed after many of the grounding events, but reef recovery is very slow, and full recovery, if possible, may require tens to hundreds of years.

A. Booher - FEMA

Beach nourishment is performed to replace sand lost to erosion. Sand is pumped from offshore sites to the beach. Impacts to nearshore hardbottom areas by placement of sand have been documented, and offshore reefs may be impacted by turbidity associated with sand dredging.

There is some good news. With the combined efforts of concerned local, state, and federal agencies and academia, the Port Everglades anchorage has been reconfigured by eliminating the shallower anchorage, which was located between reefs, and expanding the deeper outer anchorage (Federal Register/Vol. 73, No. 24/Tuesday, February 5, 2008/Rules and Regulations). These changes will greatly reduce the likelihood of future groundings. Efforts are underway to reconfigure the Port of Miami anchorage to reduce impacts to reefs in that area.

Beaches are important to the economy of southeast Florida, but because of changing environmental conditions, storms, and inlets that disrupt natural sand movement, many southeast Florida beaches undergo periodic beach nourishment. Generally, sand is dredged from offshore locations (borrow pits) located between the reef terraces, and pumped onto beaches. Projects are designed to minimize impacts to hardbottom areas close to the beach and avoid impacts to offshore reefs near the borrow pits. However, beach dredge-and-fill activities can bury nearshore hardbottom reef communities, and offshore reef communities may be directly affected by dredging too close to the reefs or by increased turbidity and sedimentation from the sand excavation activities. Although monitoring is conducted before, during, and after these projects, the long-term and cumulative impacts from repeated nourishment activities are unknown.

Although smaller in scale, other coastal construction activities that have physically impacted the Southeast Florida Reef System include the installation of fiber optic cables and geotechnical boring (i.e., drilling) for possible placement of natural gas pipelines. Individually, these activities generally affect small areas, but cumulative impacts associated with numerous projects along the entire southeast Florida coast can have significant effects on the reef system.

The southeast Florida population is likely to continue to grow, and the physical stressors associated with this growth are going to increase. Management agencies responsible for protecting and conserving the reef system must continue to require avoidance and minimization of physical impacts for all coastal construction activities that have the potential to harm reef communities. A better understanding of reef recovery rates will support resource management decisions that result in reduced impacts. Increased public awareness of the Southeast Florida Reef System will prompt decision makers to eliminate, or at least reduce, physical stresses on the system.

Biological stressors affect south Florida coral reefs

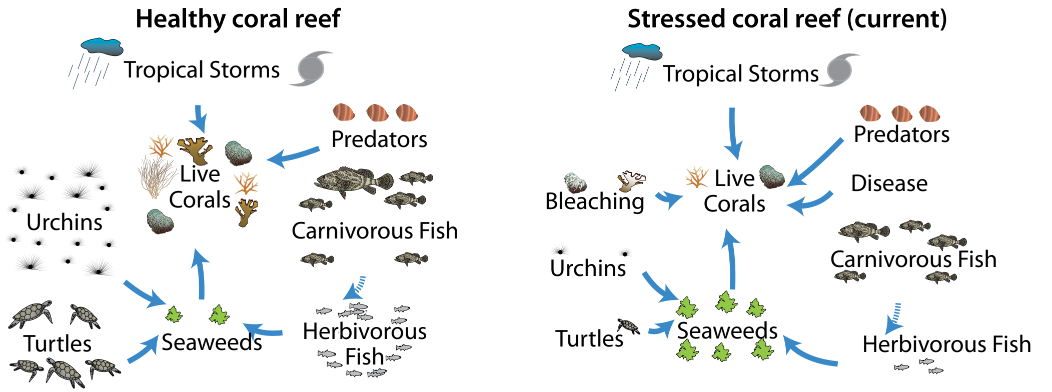
Margaret W. Miller

Coral reefs are the sum of the presence, abundance, and function of their parts. The status of a coral reef ecosystem is defined by what organisms are present, how many of them are there, and what they are doing. Also, it is important to know how reef organisms "make a living" (i.e., what they eat and what eats them).

Because reefs are diverse ecosystems, there are also lots of ways that the different players interact. Some interactions are beneficial, and some are not. For example, there are a range of reef organisms (from worms to snails to fish) that eat live coral tissue. These coral predators can have very detrimental impacts, especially when predators become abundant or corals become rare because of mortality from other stressors. These coral predators may themselves be preyed upon by higher predators, and so reduction in the numbers of higher predators may result in higher predation on corals.

Fishing has radically changed south Florida reef communities. Most targeted fish populations, such as large grouper and snapper species and lobster and queen conch, have been reduced to very low population levels. Most of these targeted species are predators, and it is likely that removing such a large volume of predators affects the entire ecosystem by allowing their prey to proliferate. Because the coral reef ecosystem is so complex, the exact nature and extent of these effects are difficult to quantify.

Coral reefs are somewhat different from many ecosystems in that they normally contain a relatively low abundance of living plant matter (relative to forests, grasslands, seagrass meadows, or kelp beds). This is largely because almost all of the plant growth is immediately eaten by reef grazers. Indeed, one of the major changes observed throughout the world when coral reefs are degraded is a proliferation of reef seaweeds. This can result from increased resources for the plants (e.g., influx of nutrients from human sources such as sewage or fertilizer runoff), which allow them to grow faster, or from a reduction in the grazing level that slows their removal, such as the Caribbean-wide die-off of grazing sea urchins. When seaweeds proliferate on reefs, they occupy space that then is not available to corals or other benthic animals for recolonization. Also, some seaweeds may exude chemicals or trap sediments that are harmful to adult and, especially, juvenile corals.



A healthy coral reef ecosystem (left) and a biologically stressed coral reef ecosystem (right). Arrows indicate consumption or other negative impact to live corals. Urchins and turtles have been drastically reduced on present-day reefs. Loss of herbivory resulted in increased amounts of seaweeds that compete with corals for space.

Reefs of the past: Key Largo Limestone lacks branching coral species

William F. Precht , Lindsey L. Precht, and Steven L. Miller

Key Largo Limestone forms the present-day islands of the Upper and Middle Florida Keys. These coral-rich limestones were formed during the last interglacial high sea-level stand that occurred in the Pleistocene Epoch between 120,000 – 135,000 years ago. Key Largo Limestone has been well studied, and it has been noted that all the coral species identified in the Key Largo Limestone are living today in the waters of the Florida Keys Reef Tract. However, not all of the corals living today have been found in the Key Largo Limestone. All descriptions of Key Largo Limestone note the presence of a coral assemblage dominated by massive boulder corals, an almost complete absence of elkhorn coral (*Acropora palmata*), a reef crest species, and a paucity of staghorn coral (*Acropora cervicornis*). What precluded the growth of these branching acroporid corals in south Florida during the Pleistocene Epoch?

The fact that coral reefs of south Florida are at the latitudinal extreme of reef development in the western Atlantic is one explanation for the lack of elkhorn coral in the Key Largo Limestone. The geographic range of a species contracts and expands in response to changing environmental conditions through time and space. At the apex of the last major interglacial period, the entire south Florida peninsula was flooded, creating a broad, shallow carbonate platform that allowed unimpeded flow from a much-enlarged Gulf of Mexico over a broad, shallow carbonate bank in the west to the Florida Straits and the open Atlantic in the east. Reef communities forming at the interface between the two waterbodies would have been bathed by waters of variable quality, temperature, salinity, and sediments. With no exposed islands (Keys) to protect the reefs during the winter months, chilled and sediment-laden Gulf waters would have periodically poured

Elkhorn corals presently grow in the Florida Keys, but are rarely found in Key Largo Limestone fossils from the Pleistocene Epoch (120,000 – 135,000 years before present).

onto these shelf-margin reefs. Under this scenario, the resulting coral community would have been essentially devoid of shallow, warm water-loving, reef crest species, such as elkhorn coral.

At slightly deeper depths on the fore reef, ephemeral thickets of fast-growing staghorn coral may have existed in sheltered pockets in an assemblage of boulder corals. This explanation is supported by an examination of growth bands in the fossilized coral skeletons of these species. Fossilized coral found in Key Largo Limestone had significantly reduced growth rates compared to growth under ideal conditions. This indicates that corals grew under fluctuating and hostile environmental conditions that were unfavorable to all but the hardiest reef-building coral species in Florida during the last major interglacial period. This same condition occurs today on a smaller scale, resulting in poorer coral reef growth conditions opposite tidal passes in the Middle Keys compared with areas in the lee of the island landmasses.

The last interglacial period has been proposed as a possible analog for future climate change and rapidly changing sea levels. Thus, understanding the presence and absence of individual species of reef corals in the Key Largo Limestone as a result of the changing environmental conditions during the Pleistocene Epoch, may hold the key to predicting the future of corals and coral reefs in the rapidly changing world.

Reefs of the future: a look into a crystal ball

Steven L. Miller and William F. Precht

The long-term implications of coral reef decline experienced in Florida today are not known for certain, but it is likely that the current dramatic loss of corals could persist for decades or longer. Against the background of previous coral loss and the likelihood of continued decline, what would be required for natural coral reef recovery to occur in the Florida Keys? What will reefs of the future look like?

W.F. Precht - FKNMS

Elkhorn coral was prominent on reef crests in the recent past but was absent in reefs that formed the Florida Keys during the Pleistocene Epoch. It is possible that elkhorn and staghorn corals could repopulate reefs in the near future because they are fast-growing species, and remnant populations still exist. However, they are susceptible to epidemic coral diseases that could keep population numbers low unless disease-resistant strains prosper. In the long-term, sea-level rise could connect the Gulf of Mexico and Atlantic and result in conditions unfavorable for branching corals.

The most likely scenario in the short-term would be the recovery of populations of two ecologically and geologically important fast-growing species, elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*). Individual branches of both of these species can grow as fast as 10 centimeters (4 inches) per year, and with repeated branching that occurs annually, growth becomes geometric, which is sufficient to substantially repopulate all of the habitats previously occupied in Florida in a matter of decades. This is not an unreasonable expectation considering a recent estimate of over 10 million individual colonies of branching corals that are presently scattered across reefs and hardbottoms in the Keys. However, prolific and expansive thickets would be expected to grow only in the lee of large islands or seaward of the mainland of the Florida peninsula in areas protected from inimical waters of Florida Bay. If climate change is realized as predicted, a northward expansion of the branching corals and the reef tract could also be possible, mimicking conditions of the mid-Holocene warm period approximately 6000 years ago when coral reef growth was prolific as far north as Broward County.

C. Kendall - SEPM

F. Charpin - reefguide.org

Suitable lack of substrate, including proliferation of fleshy algae, may limit larval recruitment to reefs of the future (top). If conditions are not right for branching corals, "weedy" and brooding corals, such as mustard hill coral, may dominate reefs of the future (bottom).

What could prevent recovery of reefs dominated by branching corals? Disease pathogens are still present, cold weather fronts still occur, global warming and bleaching events are increasing in frequency and intensity, hurricanes can set back reef development, and predators are continuing to take their toll on remnant populations. The lack of suitable substrate may also limit larval recruitment of corals in areas where algal populations remain high. If one or both of the *Acropora* species do not recover, the continued high abundance of fleshy macroalgae and an increasingly important role for "weedy" and brooding corals, such as *Porites* and *Agaricia*, is likely. At longer time scales (decades to centuries), slower-growing, disturbance-tolerant, boulder coral species will most likely prevail.

Sea-level rise and the future of coral reefs in Florida

A challenge posed by global climate change is anticipating the potential response of the Florida Keys Reef Tract to the predicted levels of sea-level rise over the next few centuries. No matter what the ultimate rate or maximum level of sea-level rise may be, one thing is certain: the progressive flooding of the south Florida Platform will have serious consequences for reef development in the future. Specifically, predictions of future sea level superimposed on topographic charts for the Florida Keys has revealed that tidal passes will get larger between the Keys, and eventually, the entire island tract will be submerged. Most of the Florida Keys will flood with a rise of as little as 1 – 2 meters (3.3 – 6.6 feet) and would become totally submerged with a rise of little more than 5 m (16.4 ft). The result of this flooding would be unimpeded water flow between the Gulf of Mexico and the Atlantic that would continuously expose remaining reefs to waters of extreme variability in temperature, nutrients, salinity, and turbidity. These conditions would be especially hostile to temperature-sensitive species and would likely result in a coral community devoid of branching corals. In short, the present reef tract would drown, but in time, a new reef system would backstep and colonize the topographic highs on the platform. Using the past as a key to predicting the future, under optimum conditions, the resulting coral reefs and species would probably resemble the fossil coral reefs found in the Key Largo Limestone that lacks branching corals.

C. Kendall - SEPM

It is possible that reefs of the future may resemble the coral reefs formed in the Pleistocene Epoch and fossilized in the Key Largo Limestone. Elkhorn coral was almost completely absent from Pleistocene reefs probably because water quality conditions were not conducive to its growth or survival. This cross section of Key Largo Limestone shows a fossilized boulder coral.

Corals can be cultured and used for research and reef restoration projects

Diego Lirman

The recent patterns of widespread decline in coral abundance and condition have highlighted the need to promote localized activities to protect and recover surviving coral populations. In southeast Florida, the need for reef restoration is being addressed through the development of several coral nursery programs designed to salvage and propagate corals as well as through transplanting colonies to depleted or damaged habitats. Coral reef restoration using nursery corals has the potential to diminish or reverse population declines and accelerate the regrowth of a reef after chronic or acute disturbances. These programs, consisting of both in-water and land-based coral nurseries, are designed to provide a mechanism for salvaging corals that have been damaged by physical impacts such as ship groundings, or those that would be destroyed due to construction or dredging projects. After collection and transportation to the nurseries, parent colonies are propagated through controlled fragmentation, thus continuously increasing the available stock.

With funding from The Nature Conservancy and the National Oceanic and Atmospheric Administration Coral Reef Conservation Program, in-water coral nurseries dedicated mainly to the study and propagation of the branching corals staghorn (*Acropora cervicornis*) and elkhorn (*Acropora palmata*) have been established in southeast Florida. In-water coral nurseries are presently located in Broward County (managed by Nova Southeastern University), Biscayne National Park (managed by the National Park Service and the University of Miami), the Upper Florida Keys (managed by Ken Nedimyer), and the Lower Florida Keys (managed by Mote Marine Laboratory). Land-based nurseries are found at the University of Miami and Mote Marine Laboratory. Additional coral nurseries are planned in the near future for both the Florida Keys and the Dry Tortugas.

D. Lirman - UM RSMAS

Platform used to grow staghorn fragments in Florida nurseries prior to transplantation back to the reef.

The goals of this program are to develop effective coral fragmentation and propagation methodologies and to evaluate the role of genetics on coral resilience. The fast growth of staghorn and elkhorn corals, up to 10 centimeters (4 inches) per year, makes them ideal candidates for propagation and restoration programs. Once among the most abundant, elkhorn and staghorn corals have experienced a drastic decline mainly due to hurricane impacts, elevated temperatures, and coral diseases. This regionwide decline has resulted in losses of up to 95% of colonies at many locations. It is expected that the staghorn and elkhorn coral fragments kept in the Florida nurseries will provide an expanding coral stock to be used in future reef restoration and scientific experiments.

Nursery-grown corals provide reef scientists with coral microcolonies of known genetic makeup. Scientists can use these corals in controlled laboratory experiments on coral physiology and other topics, such as coral diseases and the impacts of global climate change on coral calcification and growth.

Coral propagation can produce large numbers of coral transplants

David Vaughan and Erich Bartels

Historically, coral reef restoration programs were initiated primarily in response to physical impacts from vessel groundings and anchor damage. Restoration efforts generally included stabilization of the substrate and reattachment of damaged corals. More recently, the widespread loss of stony corals due to increasing sea surface temperatures, coral bleaching and diseases, and other stressors and disturbances has increased at such an alarming rate that other restoration techniques are being explored. One such alternative is the cultivation and propagation of live corals in coral nurseries.

E. Bartels - MML

Newly mounted staghorn coral fragment epoxied onto cement culture base. Coral fragment is about 2.5 centimeter (1 inch) long.

Establishing and maintaining a coral nursery, either land-based in large tanks or field-based (*in situ*), entails propagating corals through the use of small pieces called fragments that are attached to artificial substrate. In order to establish a brood-stock population, small coral fragments are acquired from nearby stocks of healthy corals or from colonies fragmented by storms or other impacts. Various methods have been used for stabilizing and growing these small fragments, including mounting to concrete disks, suspending them from frames or racks secured to the bottom, and hanging them from lines suspended off the seafloor.

E. Bartels - MML

Nursery-grown staghorn coral colony.

After 1 – 2 months, coral polyps begin to overgrow the material they are attached to, and after 6 – 12 months, a fragment of staghorn coral (*Acropora cervicornis*) can more than double in size and produce three or more branching sections. This brood stock coral can then be further fragmented to produce multiple replicate fragments for continued culture in the nursery, or the cultured coral can be outplanted at a restoration site by attaching the entire coral to the substrate. Using these methods, coral nurseries can produce large numbers of coral transplants in a relatively short period of time using a minimal amount of natural material as brood stock. As a result, nursery-based cultivation of corals is likely to become an important resource for the restoration and stabilization of coral populations on south Florida reefs.

E. Bartels - MML

In situ staghorn coral nursery. Corals are grown on concrete blocks and suspended on lines in the water column.

The Coral Rescue and Nursery Program benefits restoration, research, aquaculture, and aquaria

Lauri MacLaughlin

The Florida Keys National Marine Sanctuary (FKNMS) Coral Rescue and Nursery Program relocates coral colonies that are threatened by unavoidable coastal development activities and maintains the rescued corals for use in restoration and science projects. Examples of threats to corals rescued by this program include seawall construction and repairs, marina and dock development, and shoreline stabilization projects.

L. MacLaughlin - FKNMS

Typical encrusting coral at Truman Mole Pier, Key West being removed using hand tools.

Corals are carefully removed from their substrate using hand tools. The rescue program began during the repairs of the Key West Truman Harbor Mole Pier in 2003 when thousands of healthy corals attached to the existing pier walls were in peril. FKNMS staff have developed protocols for coral risk assessment, rescue, and transplantation, and provides training for private contractors, agency personnel, and volunteers working on such projects within the Sanctuary. The Sanctuary partners with public and private aquaria, universities, research laboratories, state and national parks, local residents, and students to help salvage threatened corals.

Rescued corals are maintained in a coral nursery located at the Nancy Foster Florida Keys Environmental Complex in Key West, Florida. Corals are kept until they can be placed in FKNMS-approved beneficial use projects.

Currently, approximately 350 individual pieces of stony corals, representing 14 genera, are being cared for and are awaiting relocation. Rescued corals are transferred to appropriate education, research, aquaculture, and restoration projects. Use of rescued corals for projects relieves collecting pressure from natural habitats by providing scientists with an alternate and viable source of coral samples. Results of research with rescued corals provides a scientific basis for effective management to help protect coral reefs, including identifying factors contributing to reef resilience to bleaching and other diseases.

L. MacLaughlin - FKNMS

Rescued corals are maintained in baskets in Truman Harbor, Key West.

Florida has an active artificial reef program

Jon Dodrill and Pamela J. Fletcher

Artificial reefs are materials intentionally placed on the seafloor by humans to accomplish specific biological and/or socioeconomic objectives. In south Florida, artificial reefs consist of humanmade materials, such as "clean" designed or precast concrete structures, building rubble, and steel vessels and barges, as well as natural substances, such as limestone. Artificial reefs may be used to mitigate losses or damage to natural reef systems caused by vessel groundings or other impacts. They may also be used as habitat enhancements to provide substrate for shellfish, corals, and other benthic organisms and as shelter for dozens of fish species that use the reefs in the course of their individual life cycles for shelter, feeding, or breeding.

K. Millie - FWC

South Florida has an active artificial reef program that includes the deployment of steel vessels, such as the Governor's Reef located in Palm Beach County.

Florida has one of the most active artificial reef programs in the nation. There are approximately 705 artificial reefs along the south Florida coastline from Martin County to Lee County. These are placed at nearshore or estuarine bay or lagoonal sites (i.e., Lake Worth Lagoon, Palm Beach County) at depths as shallow as 3.6 meters (12 feet) and at offshore locations as deep as 91.4 m (300 ft). Each artificial reef is strategically placed on the ocean floor within approved reef sites permitted by the U.S. Army Corps of Engineers and the Florida Department of Environmental Protection. In south Florida, there are no private reef deployments, and projects are overseen by local government resource managers. Projects must comply with permit conditions and adhere to guidelines established by the Florida Fish and Wildlife Conservation Commission. The site and the materials deployed must be inspected to ensure the reefs remain where placed, do not harm the marine environment, and do not become an obstruction to navigation.

Why construct artificial reefs?

Artificial reefs have been constructed with one or more of the following intended objectives:

1. Enhance private recreational and charter fishing and diving opportunities;
2. Provide a socioeconomic benefit to local coastal communities;
3. Increase reef fish habitat;
4. Reduce user conflict;
5. Facilitate reef-related research;
6. Provide for mitigation or restoration of damaged hardbottom; and
7. While accomplishing objectives 1– 6, do no harm to benthic communities, fishery resources, Essential Fish Habitat, or human health.

Structures placed on the seafloor for engineering purposes to manipulate shoreline processes (e.g., wave attenuation devices, jetties, erosion control structures), as well as accidental shipwrecks or other materials lost at sea, are not classified as artificial reefs under the Florida Fish and Wildlife Conservation Commission definition of artificial reefs.

Artificial reefs have economic value

Grace M. Johns

Artificial reefs are humanmade habitats built from various materials, including rock, old ships, concrete, and prefabricated modules. They are placed in areas away from natural reefs, creating new marine life communities.

D.S. Gilliam - NSU

Tetrahedrons are commercial modules that are used to create artificial reefs. Tetrahedrons stack in a stable configuration and offer multiple-size interstices for reef dwellers.

Over the past several decades, both nearshore and offshore habitats for many fish and shellfish have been significantly reduced or heavily impacted by coastal development, accidents, and severe storms. The reduction of these habitats, along with increased pressures on our remaining coastal resources, has led to declines in many marine life populations.

County	Residents	Visitors	Total
Martin	143,000	117,000	260,000
Palm Beach	1,075,000	330,000	1,405,000
Broward	1,281,000	2,690,000	3,971,000
Miami-Dade	1,540,000	1,410,000	2,950,000
Monroe	1,102,000	480,000	1,582,000
Total	5,141,000	5,027,000	10,168,000

Approximately 10.2 million person-days were spent recreating on artificial reefs in southeast Florida in 2001. This is about one half as many days as are spent recreating on natural coral reefs.

County	Fishing	Snorkeling	SCUBA	Total
Martin	241,000	6,000	13,000	260,000
Palm Beach	613,000	327,000	465,000	1,405,000
Broward	1,866,000	249,000	1,845,000	3,960,000
Miami-Dade	1,939,000	625,000	385,000	2,949,000
Monroe	800,000	398,000	379,000	1,577,000
Total	5,459,000	1,605,000	3,087,000	10,151,000

Number of person-days spent recreating on southeast Florida artificial reefs in 2001. Overall, fishing and SCUBA diving are the predominant activities on artificial reefs. (Data do not include glass-bottom boat tours.)

Artificial reefs provide food, shelter, protection, and spawning areas for hundreds of species of fish and other marine organisms. They also provide alternate areas for use by SCUBA divers and anglers, reducing the user pressures on natural reefs. Palm Beach County and Broward County have a significant number of artificial reefs, and more are constructed every year. However, they are not a panacea, and additional research is required to quantify their use in fisheries management. They have been used to offset losses of nearshore reefs to beach nourishment projects, but the value of replacement of inshore fish refuges with artificial structures requires more research.

County	Dollars spent	Pay to protect	Total value
Martin	$10	$4	$14
Palm Beach	117	9	126
Broward	587	56	643
Miami-Dade	277	10	288
Monroe	123	10	132
Total	$1,114	$89	$1,203

Recreators spent $1.1 billion to use artificial reefs in 2001 and were willing to pay an estimated additional $89 million to protect them. Thus, their total annual value to recreators is $1.2 billion. (Data are in millions of dollars.)

You can help to protect Florida coral reefs

Brian D. Keller

Even if you do not live near a coral reef, you can help to protect them. Effects of global warming and physical damage by careless actions are major threats to coral reefs of the world.

Things you can do to combat climate change:

- Reduce the amount of fossil fuels that you consume by improving the energy efficiency of your home and business.
- Reduce driving by selecting energy-efficient vehicles, carpooling, walking, and bicycling.
- Support efforts of local, state, and national governments and private industries to reduce the amount of fossil fuel consumption.

NOAA

Anchoring on coral reefs causes physical damage to corals and other reef organisms. Please use mooring buoys.

Actions you can take to avoid direct impacts to coral reef resource:

- Do not anchor on reefs. Use mooring buoys when available.
- Do not touch corals when diving or snorkeling. Keep fins, gear, and hands away from the reef to avoid damage to delicate corals.
- Stay off the bottom because disturbed sediments can smother corals.
- Use approved marine sanitation devices and onshore pump-out facilities to dispose of wastewater.
- Do not throw trash into the water.

Other things you can do to conserve coral reef resources for the enjoyment of future generations:

- Educate yourself and others about coral reefs and the creatures that they support.
- Support organizations that protect coral reefs.
- Volunteer for a reef cleanup activity
- Participate in the Great Annual Fish Count.
- Be an informed consumer. Buy marine fish and other organisms that have been collected in an ecologically sound manner.
- Buy products that are coral inspired rather than coral derived.
- Support reef-friendly businesses, including dive shops, marinas, hotels, and other coastal businesses.
- Hire local guides when visiting coral reefs.
- Recycle trash to keep it out of oceans and landfills.
- Conserve water so there is less runoff and wastewater that can get back into marine environments.
- Report dumping or other illegal activities to enforcement agencies. Be the eyes and ears of the reef!
- Support local efforts to improve wastewater and stormwater treatment and disposal methods.

NOAA

Coral reefs and their organisms, such as these gray snappers, are susceptable to impacts of climate change. Do your part to reduce greenhouse gases.

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