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Integrated Conceptual Ecosystem Model Development for the Southwest Florida Shelf Coastal Marine Ecosystem

MARine Estuarine goal Setting (MARES) for South Florida

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Preface

In a very real sense, the MARine and Estuarine goal Setting (MARES) project is an ambitious sociological experiment. Its overall goal is to "identify the defining characteristics and fundamental regulating processes of a South Florida coastal marine ecosystem that is both sustainable and capable of providing diverse ecosystem services." The approach taken in pursuing this goal is based on the hypothesis that scientists participating in a systematic process of reaching consensus can more directly and effectively contribute to critical decisions being made by policy makers and by natural resource and environmental management agencies. This report is an intermediate product of this consensus-building process.

South Florida is the site of the world's largest and most expensive ecosystem restoration effort: the Comprehensive Everglades Restoration Plan (CERP). While a great many natural system scientists have participated in CERP, it is difficult or impossible to determine whether their contributions have made any difference. Human dimension scientists (economists, sociologists, cultural anthropologists, etc.) have been given only limited opportunity to participate. Moreover, CERP has focused upon the South Florida peninsula itself, not upon the surrounding coastal marine ecosystem. This is despite significant, well documented, deleterious environmental changes occurring in the surrounding coastal ecosystem.

The MARES project is an attempt to make science more relevant to the ecosystem restoration effort in South Florida and to facilitate Ecosystem-Based Management (EBM) in the region's coastal marine ecosystem. The project is funded by the Center for Sponsored Coastal Ocean Research, a program of NOAA's National Ocean Service.

The first step in the MARES process is to convene experts (both natural system and human dimension scientists), stakeholders, and agency representatives for the three subregions of the South Florida coastal marine ecosystem. Each group of experts is charged with drawing their shared understanding of the fundamental characteristics and processes that regulate and shape the ecosystem into a conceptual diagram (MARES infographic).

The second step is to build upon these diagrams to articulate conceptual ecosystem models that reference the existing scientific knowledge. Development of the conceptual models employs a framework (DPSER: Drivers/Pressures/State/Ecosystem Services/Responses) that explicitly incorporates information about the effects that people have upon and the benefits they gain from the ecosystem. We refer to the conceptual models developed with this approach as Integrated Conceptual Ecosystem Models (ICEMs) because people are treated as an integral part of the ecosystem, in contrast to the conceptual models developed previously for CERP.

The third step in the MARES process is to identify subregional indicators that characterize conditions in the ecosystem, both societal and ecological, and the gaps in our existing knowledge. Identification of these indicators builds on the consensus understanding contained in the ICEMs, which synthesize existing information on the ecosystem.

The indicators being developed by the MARES project are combined into a set of regional indices that can be incorporated into coastal ecosystem score cards. Implementing a score card process, such as has been done for the freshwater wetlands in CERP based upon such a set of indices, would rigorously document trajectories towards (or away from) a sustainable and satisfactory condition. Where specific seemingly critical indices cannot be calculated due to a lack of data, the information gaps identified thereby can be used by science agencies (e.g., NOAA, the National Science Foundation, or U.S. Geological Survey) to prioritize their external and internal allocation of research resources. The ICEMs and indicators organize scientific information about the relationship between people and the environment and the trade-offs that managers face in their decisions.

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Acronyms

CERP	Comprehensive Everglades Restoration Plan
CHNEP	Charlotte Harbor National Estuary Program
DPSER	Drivers-Pressures-State-Ecosystem Services-Response
EBM	Ecosystem-based Management
EI	Ecosystem Index
FKNMS	Florida Keys National Marine Sanctuary
FK/DT	Florida Keys/Dry Tortugas
ICEM	Integrated Conceptual Ecosystem Model
MARES	MARine and Estuarine goal Setting project
NPS	National Park Service
NSP	Neurotoxic shellfish poisoning
QEI	Quantitative Ecosystem Indicator
RNA	Research Natural Area
SAV	Submerged aquatic vegetation
SEFC	Southeast Florida Coast
SFCME	South Florida coastal marine ecosystem
SWFS	Southwest Florida Shelf
SWIM	Surface Water Improvement and Management

Abstract

The overall goal of the MARine and Estuarine goal Setting (MARES) project for South Florida is "to reach a science-based consensus about the defining characteristics and fundamental regulating processes of a South Florida coastal marine ecosystem that is both sustainable and capable of providing the diverse ecosystem services upon which our society depends." Through participation in a systematic process of reaching such a consensus, science can contribute more directly and effectively to the critical decisions being made by both policy makers and by natural resource and environmental management agencies. The document that follows briefly describes the MARES project and this systematic process. It then describes in considerable detail the resulting output from the first two steps in the process, the development of conceptual diagrams and an Integrated Conceptual Ecosystem Model (ICEM) for the second subregion to be addressed by MARES, the Southwest Florida Shelf (SWFS). What follows with regard to the SWFS is the input received from more than 60 scientists, agency resource managers, and representatives of environmental organizations beginning with a workshop held August 19-20, 2010 at Florida Gulf Coast University in Fort Myers, Florida.

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Introduction

The South Florida coastal marine ecosystem (SFCME) comprises the estuaries and coastal waters extending from Charlotte Harbor and the Caloosahatchee Estuary on the west coast, through the Florida Keys, and up the east coast to St. Lucie Inlet. For many who live in the region or visit here, the SFCME defines South Florida. The SFCME is a valuable natural resource that supports a significant portion of the South Florida economy through the goods and services provided by the ecosystem.

The MARine and Estuarine goal Setting (MARES) project develops three types of information that will be useful for managers and stakeholders working to sustain the SFCME and the goods and services it provides. First, conceptual diagrams draw together, in graphical form, the fundamental characteristics and processes that shape and regulate the ecosystem. Second, Integrated Conceptual Ecosystem Models (ICEMs) describe in detail the key ecosystem components and processes and how these are affected by human activities. Third, Quantitative Ecosystem Indicators (QEIs) inform managers and stakeholders on the condition of the SFCME relative to those conditions needed to sustain the ecosystem.

This, the second report of the MARES project, documents the development of a conceptual ecosystem model for the coastal marine waters surrounding the Southwest Florida Shelf (SWFS). The report begins with an overview of the SFCME and an introduction to the key concepts and terminology of the framework used to guide development of the conceptual models, the MARES Drivers-Pressures-State-Ecosystem Services-Response (DPSER) model. Companion reports will document the conceptual models developed to describe the other regions within the SFCME.

Three Distinct Subregions within the South Florida Coastal Marine Ecosystem

South Florida coastal waters extend around the southern tip of the Florida peninsula from Charlotte Harbor on the west coast to the St. Lucie Inlet on the east coast and contain three distinct, but highly connected coastal regions (Figure 1). The oceanography of these regions varies considerably due to geomorphology and to local and regional oceanographic processes. From west to east, the three coastal subregions

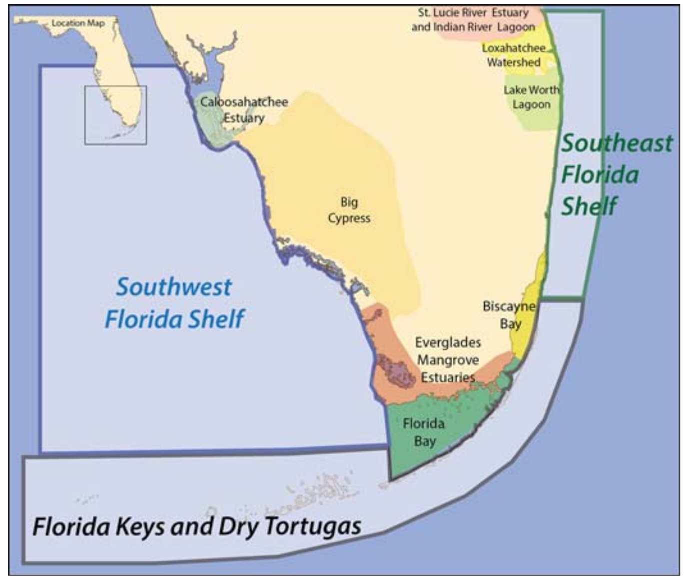

Figure 1. Map of the South Florida coastal marine ecosystem and three MARES subregions.

are the Southwest Florida Shelf (SWFS), the Florida Keys/ Dry Tortugas (FK/DT), and the Southeast Florida Coast (SEFC). The SFCME also includes two large estuarine embayments—Florida Bay and Biscayne Bay—and several smaller estuarine systems, such as the Caloosahatchee Estuary.

Each subregion exhibits distinct geomorphic and oceanographic characteristics. The SWFS encompasses the broad, shallow Florida Shelf. Oceanographic conditions here, characterized by long residence time (waters remain in a general location for a period of time) and susceptibility to stratification (waters become arranged in a layered configuration, e.g., hot at the top, cool at the bottom), favor the development of phytoplankton blooms. The FK/DT subregion encompasses the shallow, subtropical waters surrounding the Florida Keys and sits between the SWFS and Gulf of Mexico, to the north, and the energetic Florida Current system offshore to the south. The SEFC subregion is characterized by a relatively narrow shelf formed by the northern extent of the Florida Reef Tract. Eddies carried along the seaward edge of the SEFC subregion by the Florida Current influence conditions over the reef, driving the exchange with surface waters of the Florida Current and with waters upwelled from deeper depths along the shelf edge.

Currently, coastal management programs are administered on scales that are, in general, smaller than these subregions, rather than at the scale of the total SFCME. Issues of interest for ecosystem management are defined both at the scale of the SFCME in its entirety, essentially surrounding and overlapping with the geographic scope of the South Florida Ecosystem Restoration Task Force, and at smaller legal or jurisdictional boundaries (cities and counties). To support these diverse interests, descriptions of the coastal marine ecosystem occur first at the subregional scale, which recognizes the distinctive character of the ecosystem along the SWFS, surrounding the Florida Keys, and along the SEFC. It is recognized that the MARES DPSER model must encompass a variety of spatial scales to capture the total SFCME.

The MARES project uses the terms "local," "regional," and "global" to distinguish different spatial scales at which drivers and pressures act on the ecosystem, as well as the scope of management actions. With respect to management, the local scale corresponds to the smallest scale at which management occurs, i.e., at the county level: Monroe, Miami-Dade, Broward, Palm Beach, Martin, Collier, and Lee. The regional scale corresponds to the area that contains the entire SFCME, while the global scale refers to factors arising from causes outside South Florida.

Oceanographic Processes Connect Subregions

South Florida coastal regions benefit from a regional-scale recirculation pattern formed by the interplay of currents that connect the MARES subregions (Figure 2). The recirculation system has significant influence on maintaining the health,

Adapted from Kruczynski and Fletcher (2012).

Figure 2. Oceanographic processes in the South Florida coastal marine ecosystem.

diversity, and abundance of South Florida's valuable coastal marine ecosystems, including seagrass, fish and shellfish, and benthic habitats. The overall pattern of water flow is south along the west Florida coast in the Gulf of Mexico, east through the Florida Straits, and then north along the Southeast Florida Shelf. The recirculation is provided by the combination and merger of four distinct current systems: (1) downstream flow of the the Loop Current and Florida Current offshore of the SWFS and Florida Keys; (2) returning countercurrent flows in the Lower Keys and Dry Tortugas from prevailing westward winds; (3) enhancement of the countercurrent in the Florida Keys from passage of Florida Current cyclonic frontal eddies, which also act to retain particles within interior eddy recirculations; and (4) net southward flow through the SWFS that can return waters to the Florida Keys Atlantic Coastal Zone following northward excursions onto the SWFS from transient wind or eddy-driven transports.

Eddies are particularly important to the health and well-being of the marine life and coastal waters of Florida due to the state's location, peninsular shape, and the movement of the Gulf Stream. Ocean eddies are rotating bodies of water that form along the boundaries of major ocean currents. 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 kilometers across to small-scale turbulent vortices that mix fluids across the current boundary.

A continuous stream of eddies move downstream, northward, along the shoreward boundary of the Gulf Stream from the Gulf of Mexico, through the Straits of Florida, and along the southeast U.S. coast up to Cape Hatteras (Lee *et al*., 1991). These eddies are visible from space as cold, cyclonic rotating water masses interacting with the coastal waters of Florida and the states in the southeastern portion of the U.S. The eddies develop from growing disturbances of the Gulf Stream frontal boundary and are hence termed "frontal eddies."

The cold interior water of the eddies stems from upwelling of deeper, nutrient-rich strata of the Gulf Stream, which provides a basic food supply to support ecosystem development 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. For example, larvae spawned in the Dry Tortugas can be spread all along the Florida Keys by the movement and evolution of frontal eddies. The passage of frontal eddies also acts to increase the exchange of coastal waters with offshore waters of the Florida Current and, thereby, helps to maintain the natural water quality of the coastal ecosystems (Lee *et al.,* 2002; Sponaugle *et al.,* 2005; Hitchcock *et al.,* 2005).

The SWFS is the southern domain of the wide, shallow West Florida Shelf. It receives moderate freshwater from small rivers and estuaries and undergoes seasonal stratification in the spring and summer (Weisberg *et al.,* 1996). Currents over the mid to inner shelf are due primarily to wind and tidal forcing that align with the shelf's smooth north-south oriented topography (Mitchum and Sturges, 1982). Outer shelf flows are controlled by the Loop Current and eddies that move downstream along its shoreward boundary and vary considerably on day-to-month time scales. Warm eddies can separate from the Loop Current and move along the Dry Tortugas and Florida Keys Reef Tract. These separations cause instabilities that result in cold (upwelling), cyclonic frontal eddies that can be carried around the Loop Current and into the Straits of Florida and strongly interact with outer shelf waters (Paluszkiewicz *et al.,* 1983; Fratantoni *et al.,* 1998; Hamilton and Lee, 2005; Lee *et al.,* 2002).

Loop Current penetrations into the eastern Gulf of Mexico extend northward, sometimes reaching to the outer shelf off the Mississippi River delta and entraining river water for transport to the Florida Keys (Ortner *et al*., 1995). Eventually, an extended Loop Current becomes unstable and separates into a large (200-300 km), clockwise rotating warm eddy that leaves a young Loop Current to the south where it turns directly into the Straits of Florida and parallels the Florida Keys. Mean flows over the SWFS appear to be related to the Loop Current and are toward the south, connecting the southwest shelf to the Florida Keys Reef Tract through the passages in the keys island chain.

The FK/DT coastal region has a narrow shelf with a complex shallow reef topography that parallels the north-south (Upper Keys) to east-west (Middle and Lower Keys) curving chain of islands. Coastal waters tend to remain well mixed throughout the year, and there are no significant freshwater sources. Mid- to inner-shelf currents are primarily toward the west in the Lower Keys, due to prevailing westward (downwelling) winds, and shift to northward currents in the Upper Keys due to winds from the southeast that have a northward component and the close proximity of the northward flowing Florida Current (Lee and Williams, 1999; Lee *et al.,* 2002).

Waters of the SEFC are highly connected to the upstream regions of the FK/DT and SWFS by the strong northward flow along the edge of the Florida Current. The SEFC region consists of a narrow coastal zone stretching north-south 176 km from Biscayne Bay to the St. Lucie Inlet. The portion of the shelf between Miami and Palm Beach counties is unusual in that it is extremely narrow and shallow, varying in width from 1-3 km, with only 30 m water depth at the shelf break. Coastal waters here are bounded by the highly developed shoreline of southeast Florida and the strong northward flowing Florida Current at the shelf break.

The interaction of coastal and inshore waters takes place through seven tidal inlets, plus the wide and shallow “safety valve” opening to Biscayne Bay. Ocean currents play a major role in the transport and exchange of physical, chemical, and biological properties both along and across the shelf. Changes in the water column in the mid- to outer-shelf region are a direct result of the proximity to the powerful, northward flowing Florida Current with its continually evolving stream of onshore/offshore frontal meanders and small (10-30 km), cyclonic, cold-core eddies (Lee, 1975; Lee and Mayer, 1977). Upwelling in the eddy cores causes uplifting of the nutrient supply in the upper mixed layer of the ocean (nutricline) along the continental slope that can penetrate the upper layers of the water column (euphotic zone) and stimulate primary production (Lee *et al*., 1991).

The proximity of the Florida Current to the shelf break results in strong northward mean flows over the outer shelf ranging from 25-50 cm/sec. Currents near the coast are primarily in the alongshore direction (south-north) and controlled by tides and winds. Mean flows are weak and follow seasonally-averaged winds. Downstream movement of eddies along the outer shelf results in strong interactions between the Florida Current and adjacent shelf waters. Flow and temperature variability within the mid- to outer-shelf regions are dominated by the northward passage of these frontal eddies, which occur at an average frequency of once per week throughout the year with little seasonal change. Eddy passages normally take one to two days and result in considerable exchange between resident shelf waters that remain on the shelf for a period of time and new Florida Current waters within the eddy. Displacement of shelf waters by eddies at an average weekly interval represents a flushing mechanism and a mean residence time of shelf waters of approximately one week. Nearshore waters lack any significant river discharge and tend to be well mixed throughout the year.

Building a Foundation for Ecosystem-Based Management

Ecosystem-based management (EBM) is an adaptive, holistic approach to dealing with the complexity of environmental challenges. Since 2010, implementing EBM has become a guiding directive in the federal management of U.S. coastal resources (Lubchenco and Sutley, 2010). Forging a vision of the ecosystem shared by all, managers and stakeholders, is an essential initial step. The overall goal of the MARES project, to reach a science-based consensus about the defining characteristics and fundamental regulating processes of a sustainable SFCME, addresses this need directly.

The MARES project builds on previous efforts to implement EBM in connection with the hydrological restoration of the Everglades, the vast freshwater wetlands that occupy the central portion of the South Florida peninsula. Work on the Comprehensive Everglades Restoration Plan (CERP) was authorized in 2000, but planning and preparation began in the 1990s. Ogden *et al.* (2005) developed a set of conceptual ecological models for the ecosystems in the region that are directly affected by CERP. The CERP models have proven instrumental in (1) selection of performance measures and indicators, (2) implementation of regional monitoring plans, and (3) identification of critical research gaps. However, coverage by CERP conceptual models did not include the regional coastal marine ecosystem (i.e., Florida Bay, Biscayne Bay), nor did they specifically include human society and its complex relationship with the environment.

The conceptual models developed by the MARES project extend these efforts geographically, by moving offshore into the coastal marine ecosystem, and conceptually, by explicitly including human society as an integral component of the ecosystem. From an EBM perspective, it is essential to consider social, cultural, and economic factors, in both the research and management context, along with ecological variables (Weinstein, 2009; Cheong, 2008; Turner, 2000; Lubchenco, 1999; Visser, 1999). Few people live in the remaining natural area of the Everglades, and the conceptual models developed for CERP do not explicitly include human activities, such as hunting, fishing, sightseeing, etc., as part of the ecosystem, except as drivers of change in the natural ecosystem. By contrast, most of the 6.5 million people residing in South Florida live near the coast, and many residents and visitors receive benefits from the SFCME resources and services.

The first step in the MARES process is to convene the relevant scientific experts (both natural system and human dimensions), stakeholders, and agency representatives within each subregion and charge them with developing a visual representation of their shared understanding of the fundamental characteristics and processes regulating and shaping the ecosystem. The approach being taken in the MARES project encourages scientists to participate in a systematic, inclusive process of reaching consensus. The process of consensus building avoids the adversarial approach that often hinders the application of scientific information. Through consensus building, scientists can contribute more directly and effectively to the critical decisions being made by policy makers and by natural resource and environmental management agencies (Karl *et al.,* 2007).

The second step is to build upon these diagrams to develop ICEMs. This process is then repeated for each of the three subregions. The ICEMs serve as the basis for synthesizing our scientific knowledge. They also help complete the third and final step to identify subregional indicators, QEIs (both societal and ecological), as well as major knowledge or information gaps. The QEIs are combined into a parsimonious or smaller set of ecosystem indexes (EIs) that can be incorporated into a total system score card of overall coastal ecosystem status. A total system score card can provide information as to the trajectory of the SFCME towards (or away) from a sustainable and satisfactory condition. Individual EIs (or smaller sets of indicators and metrics) may be used by different agencies with specific mandates or responsibilities to make explicit the benefits of (but also the tradeoffs between) alternative management options.

The MARES Model Framework

MARES relies upon a specific conceptual framework derived from the economic *Driver-Pressures-State-Impacts-Responses* (DPSIR) model (Tscherning *et al.,* 2012; OECD, 1993). While DPSIR has been used to inform environmental management (Mangi *et al.,* 2007), it does not explicitly incorporate the benefits that humans derive from the ecosystem. Moreover, *Impacts* imply that the effect of human society upon *State* is primarily negative and that *Responses* are warranted only after these impacts occur. MARES concludes this is insufficient for capturing the complex human dimensions of the integrated ecosystem. Efforts have been made to integrate *Ecosystem Services* and societal benefits into DPSIR models but in a somewhat indirect manner (Atkins *et al.,* 2011). In the MARES DPSER model, human benefits from the environment are represented in the *Ecosystem Services* element (Figure 3).

Humans are integrated into every element of the DPSER framework, including the effects that people have on the environment and the values that motivate their actions to sustain the regional ecosystem. The first two elements of the model framework, *Drivers* and *Pressures*, describe factors that cause change in the condition of the SWFS marine environment. *State* describes the coastal marine environment in terms of attributes that relate to *Ecosystem Services*. The *Response* element of the DPSER model framework describes decisions and actions people take to sustain or increase the *Ecosystem Services* they value. Therefore, the *Response* element introduces the notion of feedback and control into the DPSER model's representation of the integrated ecosystem and embodies the concept of EBM.

The DPSER model provides a framework for organizing social science and natural science information in a format that brings to light the relationship between humans and the environment. The managers can use information assembled by the DPSER model to set priorities and to support management decisions by examining tradeoffs among the relationships between people and the environment. Identifying the "attributes that people care about" addresses the questions of "Who cares?" and "What do they gain or lose from changes in the state of the natural resources and environmental attributes?" "Attributes people care about" are a subset of the attributes used to characterize and define the elements of *Ecosystem Services* and *State*. They serve as a link between *Ecosystem Services* and the *State* of the marine environment. *Ecosystem Services* may be evaluated objectively and ranked using techniques developed by resource economists (Farber *et al.,* 2006).

Ecosystem Services are the benefits that people derive from the environment (Farber *et al.,* 2006; Yoskowitz *et al.,* 2010). In assembling information about a marine ecosystem subregion, the MARES project team is asked to consider two questions: "What are the attributes of the coastal marine environment that people care about?" and "Who enjoys the benefits and who suffers the costs when there are changes in ecological attributes?" These questions help avoid the necessity of setting economic benefits to people and benefits to the environment in opposition. People do depend on the *State* of the coastal marine environment and its natural resources for their well-being. People are not only a *Pressure* on the environment; they also act to enhance the environment and the benefits that it provides. Goals may compete, but recognizing the dual roles that people play in the ecosystem should assist managers in balancing competing goals by making tradeoffs explicit.

Ecosystem Services have a value that can be measured by human dimension scientists that MARES measures in both economic and non-economic terms. Knowing the values that people place upon *Ecosystem Services* informs decisions that involve tradeoffs between environmental and other societal objectives and between competing objectives. Assessing the value of *Ecosystem Services* in monetary or economic terms allows a ready comparison with other sources of benefit (Farber *et al.,* 2006). When economic value is difficult to assess or not relevant to the problem, other metrics and approaches are available (Wegner and Pascual, 2011).

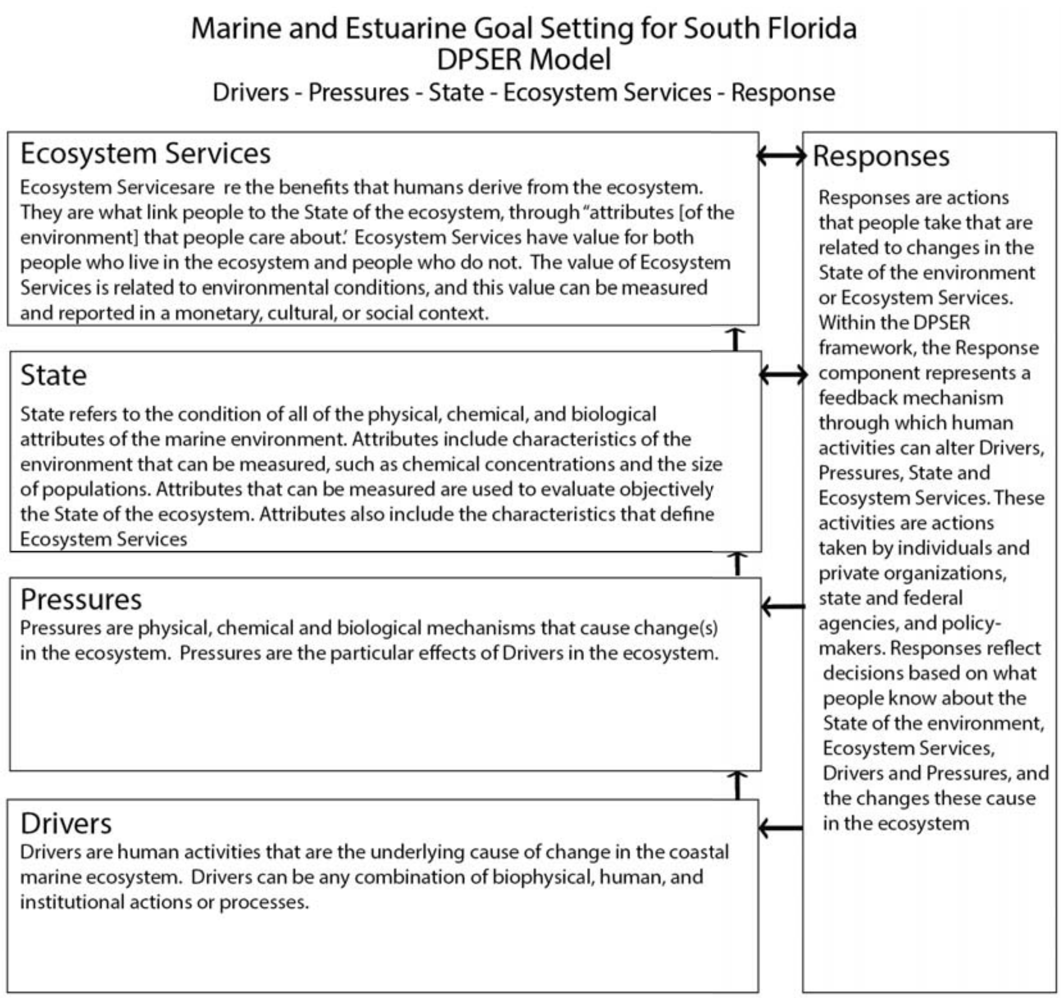

Figure 3. The MARES Drivers-Pressures-State-Ecosystem Services-Response (DPSER) model.

Economic values for recreational activities in the Florida Keys were estimated by Leeworthy and Bowker (1997) using a simple model of the economics of natural resource and environmental change. This model shows how actual and perceived changes in environmental attributes and ecosystem services can change the demand for and economic value of outdoor recreation and tourism. Economic values include market and nonmarket values received by users (those participating in recreation activities) and non-users.

Large scale natural resource projects are typically informed by benefit cost analysis in evaluating management alternatives. It is also recognized that there is a suite of values that can influence decision making, e.g., ethical, cultural, and other considerations such as equity, sustainability, and ecological stewardship (Costanza and Folke, 1997). An equity analysis of management alternatives will examine who receives the benefits and who pays the costs, and then make an assessment of whether or not it is fair. Sustainability and stewardship analyses focus on the intertemporal distribution of those services. Cultural and ethical considerations may place constraints on acceptable management decisions (Farber *et al.,* 2006).

State refers to the condition of the coastal marine environment that includes all of the physical, chemical, and biological components of the system. The *State* of the ecosystem is defined, operationally, by attributes. Attributes are a parsimonious subset of all the descriptive characteristics of an environment that represent its overall condition (Ogden *et al.,* 2005). Attributes are measurable and are used to evaluate the ecosystem, e.g., an abundance and diversity of fish found on coral reefs can illustrate the habitat is healthy.

Drivers can be any combination of biophysical, human, and institutional actions or processes. *Drivers* are human activities that are the underlying cause of change in the coastal marine ecosystem and reflect human needs. *Pressures* are the particular manifestations of *Drivers* within the ecosystem. *Pressures* are physical, chemical, and biological mechanisms that directly or proximally cause change in the ecosystem. As such, there is an inherent hierarchical scale between ultimate drivers, which are the expression of human needs and desires to direct *Pressures* on the ecosystem. For example, human population growth leads to increased energy requirements that are met through the burning of fossil fuels. The burning of fossil fuels leads to the emission of carbon dioxide (CO_2) into the atmosphere, which is transferred to the ocean, producing ocean acidification that has a direct *Pressure* on the ecosystem.

Within the DPSER framework, *Response* encompasses human actions motivated either by changes in the condition in the environment (*State*) or in the *Ecosystem Services* provided. Actions that have the effect of altering *Drivers, Pressures,* or *State* of the ecosystem introduce a mechanism for feedback into the system and, therefore, the possibility of control. *Response* includes activities for gathering information, decision making, and program implementation that are conducted by agencies charged with making policies and implementing management actions that affect the SWFS regional ecosystem. Additionally, changes in attitudes and perceptions of the environment by individuals and related changes in behavior that, while less purposeful than the activities of management agencies, can have a large effect on the *Drivers* and *Pressures* acting on the ecosystem are also included.

The Southwest Florida Shelf

Physical Setting: Dynamic Geomorphology

The southwest Florida coastal marine ecosystem lies along an expanse of low-lying coast that begins in Fort Myers and stretches south for about 125 miles (200 km) to Cape Sable, which marks the entrance to Florida Bay. Shallow coastal waters extend west for 150-180 miles (250-300 km) over the broad Florida Shelf. Geomorphic evolution of the southwest Florida coast and shelf is affected over the long term by relative rates of sea-level rise and sedimentation and over the short term by the prevailing sedimentologic processes and patterns of watershed hydrology. The present geomorphology reflects a north-to-south variation in the short-term factors during a period of relatively stable, slow sea-level rise. Four discrete geomorphologic provinces can be recognized along this section of coast. These are, from north to south: (1) Barrier Islands Province; (2) Ten Thousand Islands Province; (3) Everglades Province; and (4) Cape Sable Province (Figure 4).

The Barrier Islands Province extends south to Cape Romano, just south of Marco Island, where the longshore drift, which

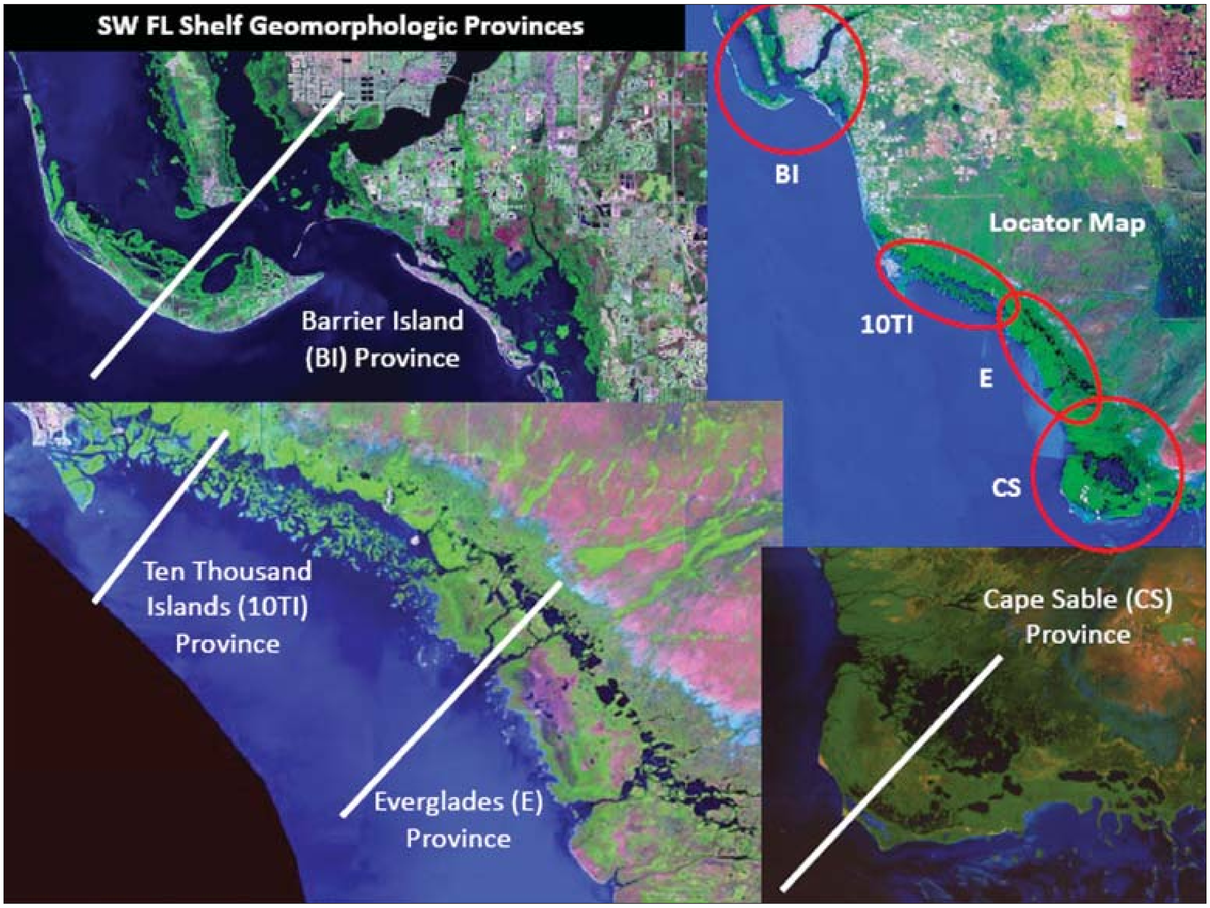

Figure 4. Four geomorphologic provinces of the Southwest Florida Shelf region: (1) Barrier Islands Province (upper left); (2) Ten Thousand Islands Province (lower left); (3) Everglades Province (lower left); and (4) Cape Sable Province (lower right).

carries quartz-dominated sand southward, separates from the shore. Shoreface sediments in this province are a mix of quartz sands and carbonate shell gravel; shell gravels become progressively richer relative to quartz sands toward the south or down-drift direction as longshore sediment supplies wane (Scholl, 1963). Environments associated with barrier islands include back-barrier mangrove forests and, occasionally, salt marshes, tidal flats, and flood tidal deltas landward of between-barrier inlets. The inner shelf's energy is focused on the seaward side of the barrier islands to create wave-influenced beaches and bars. Barrier islands serve to increase the residence time of freshwater in the back-barrier bays and wetlands and, by reducing wave and storm energy in their lee, create a suite of back-barrier environments not otherwise realized in an open coastal setting.

Coastal geomorphology of the Ten Thousand Island Province is a product of oyster reef development. These mangrove-forested islands assume a thin, irregular, anastomosing geometry because they mimic the shape of the precursor oyster reefs upon which they are established. These islands are a product of the last 3200 years of late Holocene history when sea-level rise was less than 10 cm per century (Wanless *et al.*, 1994). These islands have caused the coast to prograde through this 3200-year history. The islands located more seaward (i.e., outer islands) are older and, consequently, more robust than those located closer to the inner bay margins (Parkinson, 1989). The existence of these islands serves to trap freshwater in a fashion similar to barrier islands, and a productive estuarine environment thrives landward of the Gullivan Bay margin. Current rates of sea-level rise average 34 cm per century globally (Church and White, 2006). Accelerated sea-level rise, however, will ultimately lead to Ten Thousand Island instability and eventual loss, creating a more open coast.

The Everglades Province begins abruptly just southeast of Everglades City. The geomorphology is characterized by numerous large islands separated from the mainland by inner bays. Several tidal rivers (e.g., Chatham, Lostman's, Harney, and Broad rivers) connect the inner bays to the coast. Hoye (2009) has demonstrated that the Everglades Province's inner bays are degradational features, formed through the loss and deflation of peatlands. This contrasts greatly with the origin of the Ten Thousand Islands' inner bays which are constructional, rather than degradational features. The structure of the Everglades Province generates a unique mosaic of habitats, compared with the Ten Thousand Islands Province. Tidal mixing with marine water in the inner bays is more restricted, and these bays receive greater volumes of freshwater from slough-way sheet flow. Oyster reefs are absent or rare within the inner bays, yet can be prolific on the outer coast adjacent to river mouths. Seaward of the outer margin, expansive mud and sand flats exist. These are attributed to storm ebb-flow deposition following hurricane passage (Perlmutter, 1982; Risi *et al*., 1995; Tedesco *et al*., 1995).

The southernmost geomorphic region is the Cape Sable Province. Overall, Cape Sable Province's origin is similar to the Everglades Province, but here wetland degradation inshore of the coastal margin has progressed further to generate the larger bays. Oyster reef to mangrove-island progradation is absent here; even the river mouths lack prolific oyster reef development, presumably due to the greater influx of freshwater. Whitewater and Oyster bays are the two largest features that define the inshore geomorphology. Whitewater Bay's scalloped perimeter suggests a wetland peat degradational origin similar to what has been proposed for the inner bays in the Everglades Province. The mosaic of habitats in the Cape Sable Province is similar to what is seen in the Everglades Province. The inner bays are more expansive and generally lack oyster reef development. A lagoon (i.e., marine waters trapped behind the coastal ridge) sits between the inner bay and the outer coastal margin.

Connectivity

Circulation patterns within South Florida coastal waters maintain the vitality and variety of the ecosystem, but they also provide a conduit for the input of pollutants from remote upstream regions (see Figure 2). The SWFS subregion includes the southern extreme of the West Florida Shelf as it merges with the Florida Keys. Thus, this region is highly influenced by the processes occurring on the West Florida Shelf, such as strong synoptic wind forcing, seasonal changes in wind forcing, Loop Current excursions into the northeast Gulf of Mexico, and river discharge and stratification. The importance of the connection between this region and remote sources of pollutants was reiterated during the Deepwater Horizon oil spill in 2010.

Recirculating current systems link the different subregions of the South Florida coastal ecosystem and form an effective retention zone for locally-spawned larvae. Retention in countercurrents and eddies provide the larval pathways and opportunities for recruitment from local, regional, and Gulf-wide sources. Trajectories of near-surface drifters deployed in the Shark River discharge plume show that there are three common pathways that connect the entire South Florida coastal system (Figure 5).

The two primary pathways are either to the southeast and through the passages of the Middle Keys, which is most common during winter and spring, or southwest to the Dry Tortugas, which is most common during the fall. Advective time scales to reach the Keys coastal zone are one to two months for these routes. The third pathway is to the northwest in the summer and eventual entrainment by the Loop Current, followed by transport to the Dry Tortugas. This exchange route takes place over a three- to six-month time period. After drifters reach the Keys coastal zone, they tend to either recirculate in coastal eddies and wind-driven countercurrents for periods of one to three months, or become entrained in the Florida Current and removed from the coastal system.

The southeastward mean flow connecting the two shelf regions provides the source water for western Florida Bay and entrains the freshwater outflows from the Everglades and through the Ten Thousand Islands. The magnitude of this mean southeast flow is about 100-200 times larger than the freshwater outflow from the Everglades, which results in a low-salinity band that is trapped along the coast of the Ten Thousand Islands and extends to the southeast into western Florida Bay. Thus, the sustainability of ecosystems in South Florida waters is dependent on water management policies of the entire region, as well as those of upstream regions in the eastern Gulf of Mexico.

Low-salinity intrusions into South Florida coastal regions from southward transport down the SWFS and entrainment along the Florida Current front show the region to be significantly linked to remote regions of the eastern Gulf of Mexico. Although the physical mechanisms providing the linkages are not well understood, the most likely causes are the Loop Current and its influence on shelf circulation (Hetland *et al.*, 1999).

The variability of local circulation patterns is highly dependent on synoptic-scale winds. The strongest subtidal currents are in the alongshore (north-south) direction and are a direct barotropic response to alongshore winds. Seasonal changes in wind forcing also produce seasonal differences in the strength and variability of the currents, with greater current amplitudes in winter following cold front passages and weaker currents in summer. 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 with a shift of summer winds to the southeast. The lower layer currents are more persistent toward the south throughout the year.

Human Population

South Florida experienced a rapid change in economic and demographic factors within the last century. Florida was the only U.S. state to grow from a population of less than one million at the start of the 20th century to a population of over 10 million by the century's end (Hobbs and Stoops, 2002). Most of this population growth occurred in the five southern counties adjacent to coral reefs (Palm Beach, Broward, Miami-Dade, Monroe, and Collier). In 2030, southeast Florida is anticipated to have a population of 8.5 million, 2.4 million more than today (South Florida

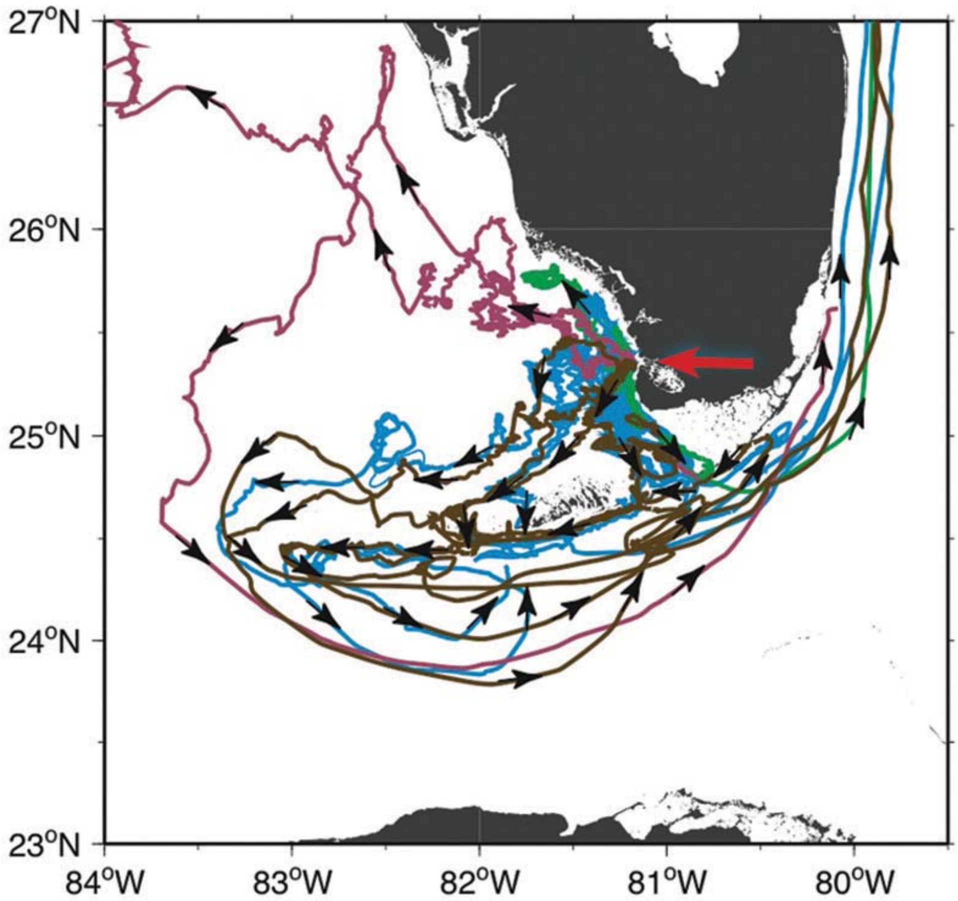

Figure 5. Circulation patterns link the Southwest Florida Shelf to local and regional waters. Shown here are the pathways of satellite-tracked surface drifters deployed in the Shark River discharge plume (red arrow) from September 1994-February 2000. The lines show seasonal pathways of flow: winter is blue; spring is green; summer is lavender; and fall is brown.

Economic Forecasting Partnership, 2006). The population size of South Florida influences many regional- and local-scale drivers like coastal development, agriculture, wastewater, fishing, and boating.

Human population and development along the SWFS coast is restricted to the the coastal zones of Collier and Lee counties, which are in the northern half of the subregion, i.e., in the area described previously as the Barrier Islands Province (Figure 6). Southwest Florida was sparsely populated until completion of the Tamiami Trail (U.S. Route 41) in 1928, which provided reliable road access from Tampa Bay to Miami. Retirement income is the single largest component of the region's economic base. Tourism is the next largest component of the economy; the population increases by 30 percent during the winter. Agriculture is the third largest component of the economy. Until the recent economic downturn, this was one of the fastest growing areas in Florida.

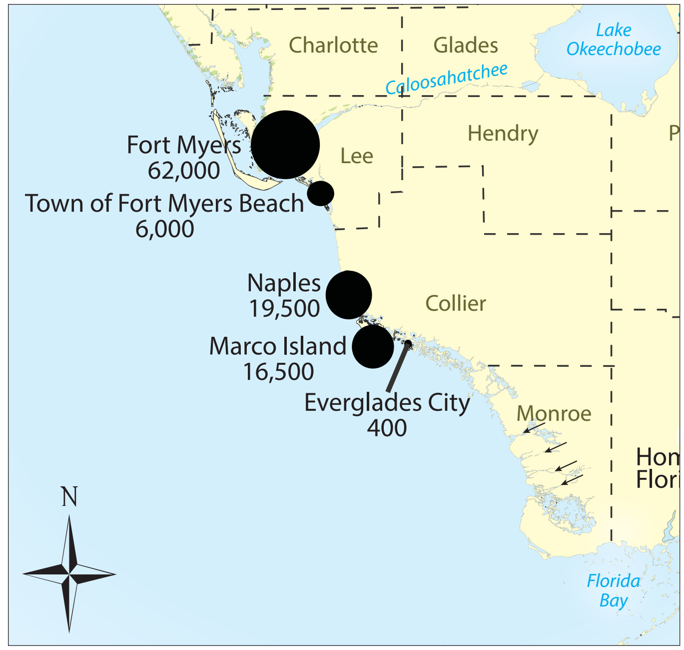

Figure 6. Population centers in southwest Florida (Bureau of Census, 2010).

Collier County

Collier County is on the southwest coast of Florida, bordering the Gulf of Mexico with Naples as its largest city. In 2010, the county had 321,520 residents. Eleven percent of county residents live in the three incorporated municipalities: Everglades City, Marco Island, and Naples. Over the last ten years, the population in this county grew by 28 percent. The University of Florida, Bureau of Economic Research projects the county's population will reach 330,700 by 2015.

Lee County

Lee County is on the southwest coast of Florida, bordering the Gulf of Mexico with Cape Coral as it largest city. In 2010, the county had 618,754 residents. Forty-four percent of county residents live in the five incorporated municipalities: Bonita Springs, Cape Coral, Fort Myers, Fort Myers Beach, and Sanibel. Over the last ten years, the population in this county grew by 40 percent. The University of Florida, Bureau of Economic Research projects the county's population will reach 625,500 by 2015.

The Southwest Florida Shelf Integrated Conceptual Ecosystem Model

Conceptual Diagram: Picturing the Ecosystem

The first step in the systematic MARES process is to develop conceptual diagrams (here a series of cross-section infographics) of the geographic provinces, the processes operating upon them, and the factors affecting their condition (Figures 7-10). The SWFS ecosystem consists of benthic offshore habitats, inshore flats, coastal wetlands, oyster reefs, and submerged aquatic vegetation (SAV), as well as the overlying water column and the fish and shellfish that move among these habitats (see appendices for more information). Degradation of habitats is a major concern in the SWFS because it reduces ecosystem services that residents rely upon, including recreational and commercial fishing and tourism. Local factors that affect the ecosystem and its services are altered freshwater flows, fishing, tourism, and land-use changes that alter sediment and toxin loading. Regional factors that affect the ecosystem include nutrient

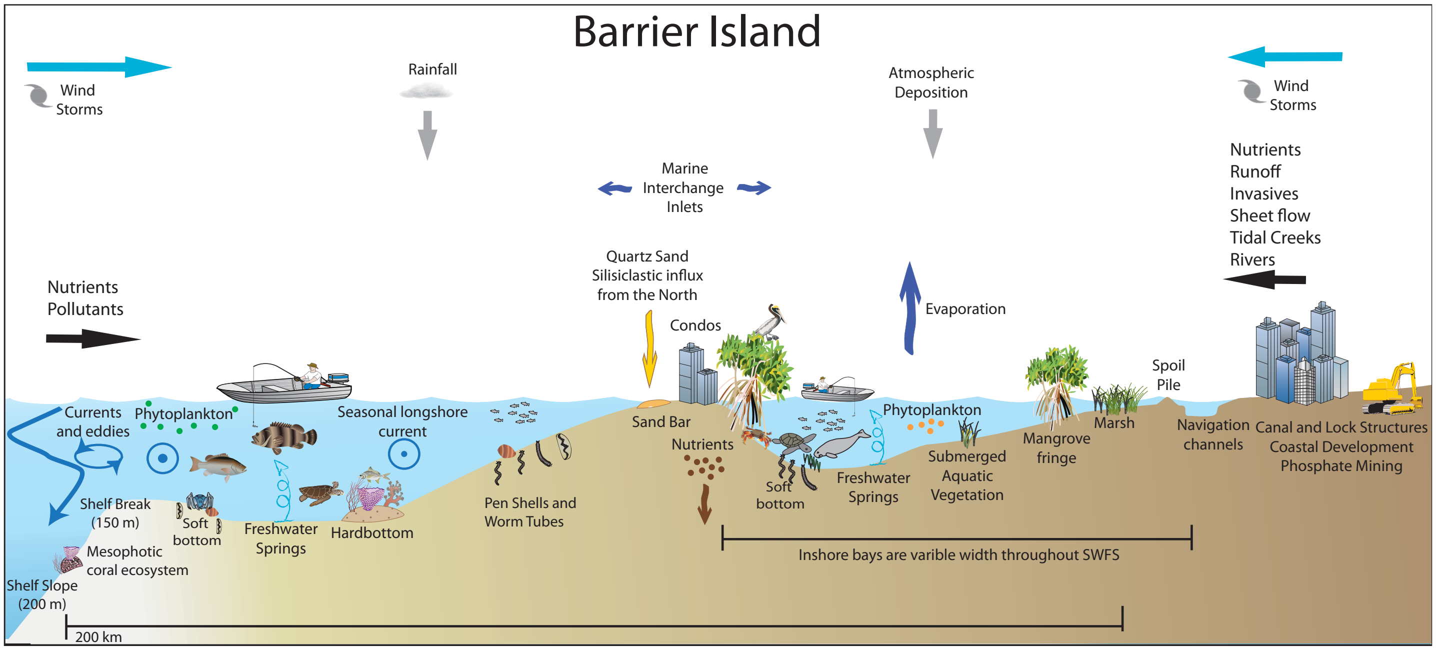

Figure 7. Conceptual diagram of the Southwest Florida Shelf Barrier Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

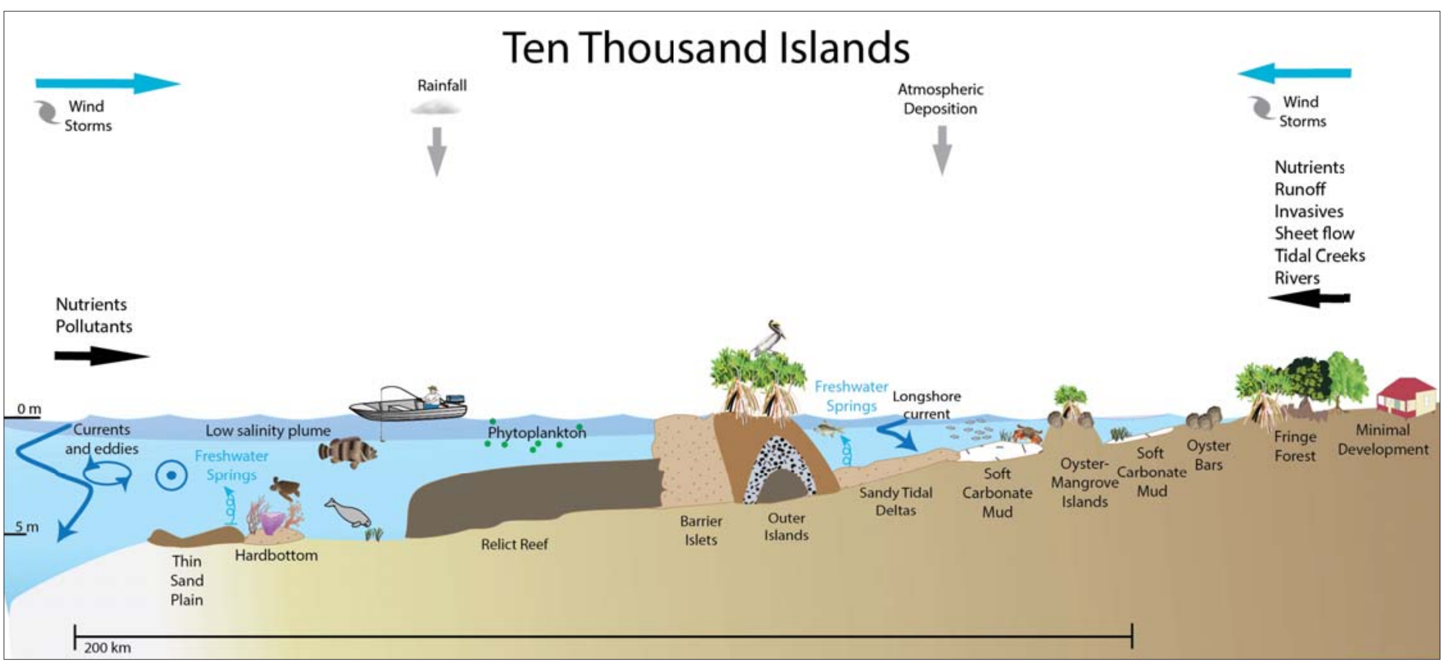

Figure 8. Conceptual diagram of the Southwest Florida Shelf Ten Thousand Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

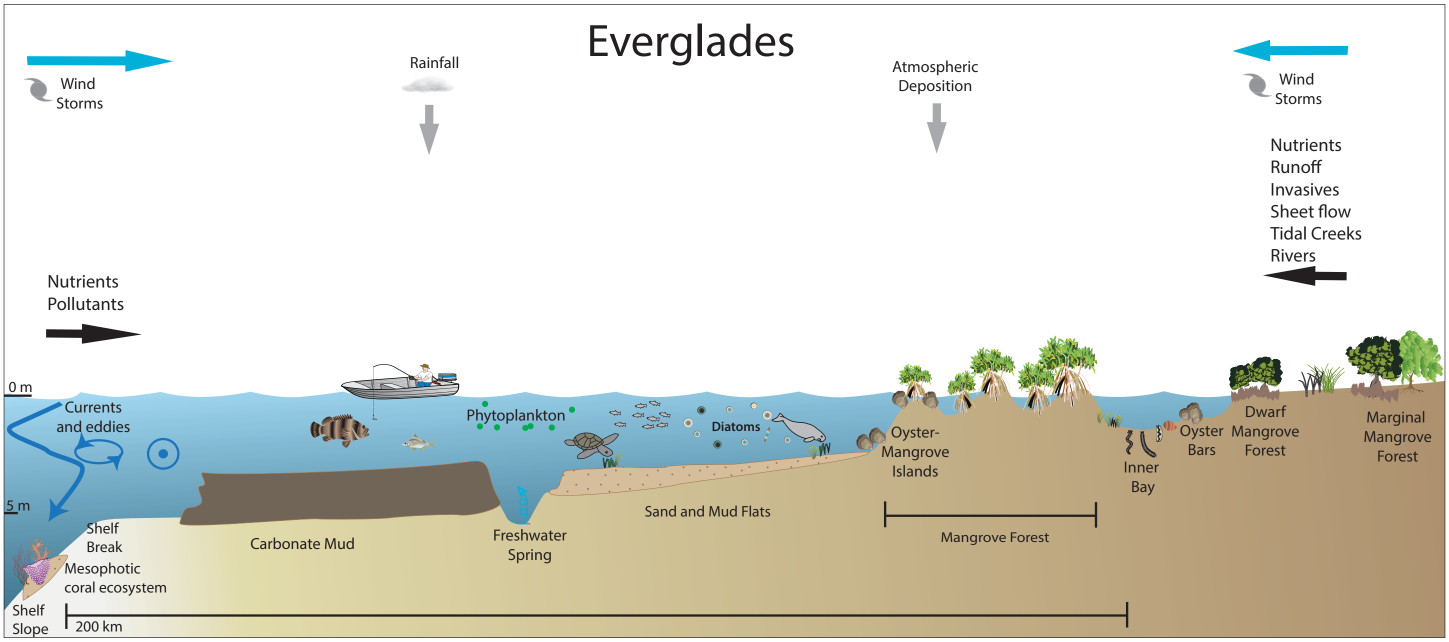

Figure 9. Conceptual diagram of the Southwest Florida Shelf Everglades Province ecosystem, processes operating upon it, and factors affecting its condition.

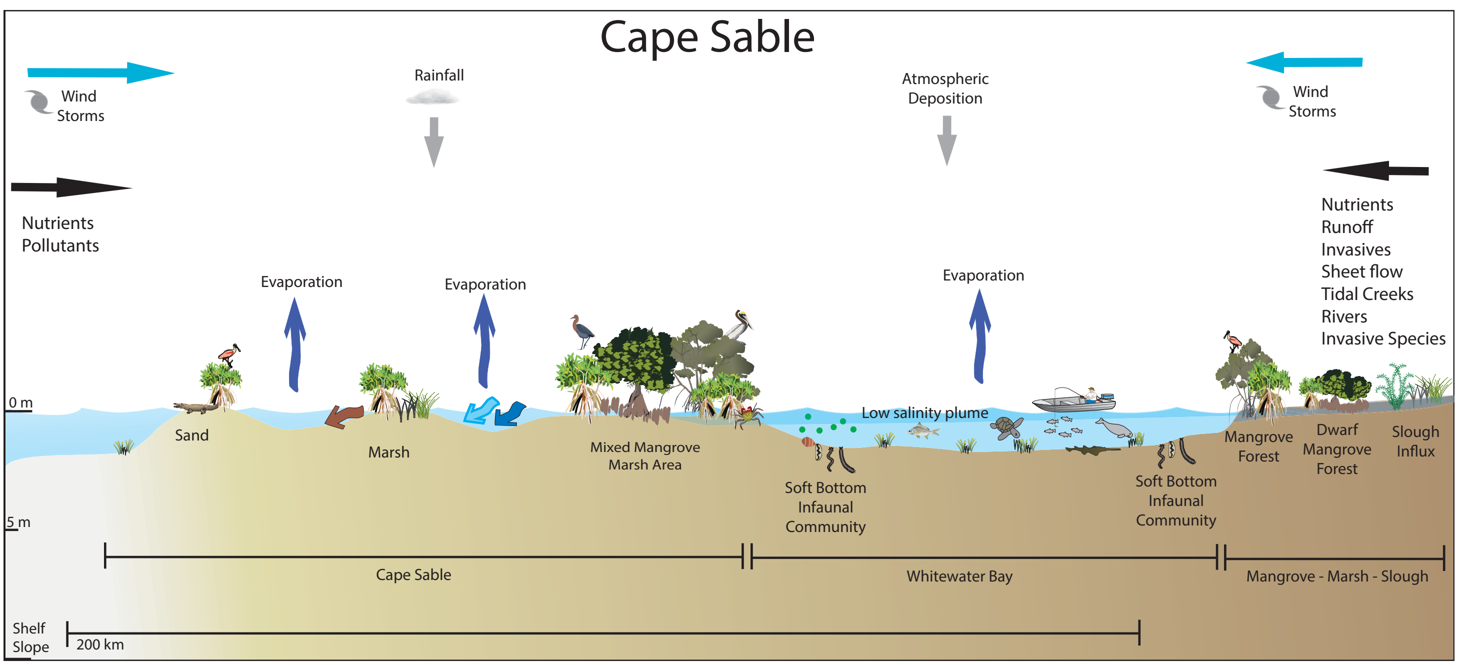

Figure 10. Conceptual diagram of the Southwest Florida Shelf Cape Sable Province ecosystem, processes operating upon it, and factors affecting its condition.

inputs to the water column, while global factors include increasing water temperatures. Application of the DPSER framework leads to construction of narratives of the processes that sustain and change the ecosystem based on elements identified in the conceptual diagram (Figure 11).

Applying the Model in the Southwest Florida Shelf: Altered Freshwater Inflows

To illustrate how elements of the MARES DPSER model can be used to organize and analyze an ecosystem management issue in the SWFS, consider the issue of altered freshwater inflows, which are the focus of a number of management activities. In this case, the *Drivers* of change in the coastal marine ecosystem are regional water management in South Florida and wetland drainage for housing development near the southwest coast. Major concerns related to regional water management focus on the use of the Caloosahatchee Estuary as an artificial outlet from Lake Okeechobee and the use of the lake as a reservoir for regional water supply. The effects of local development are illustrated by efforts to drain the now-defunct Golden Gates Estates development, which involved construction of the Faka-Union Canal (Figure 12). In both cases, the resulting changes to the quantity, quality, timing, and distribution of freshwater inflow represent the *Pressures* acting on the coastal marine ecosystem.

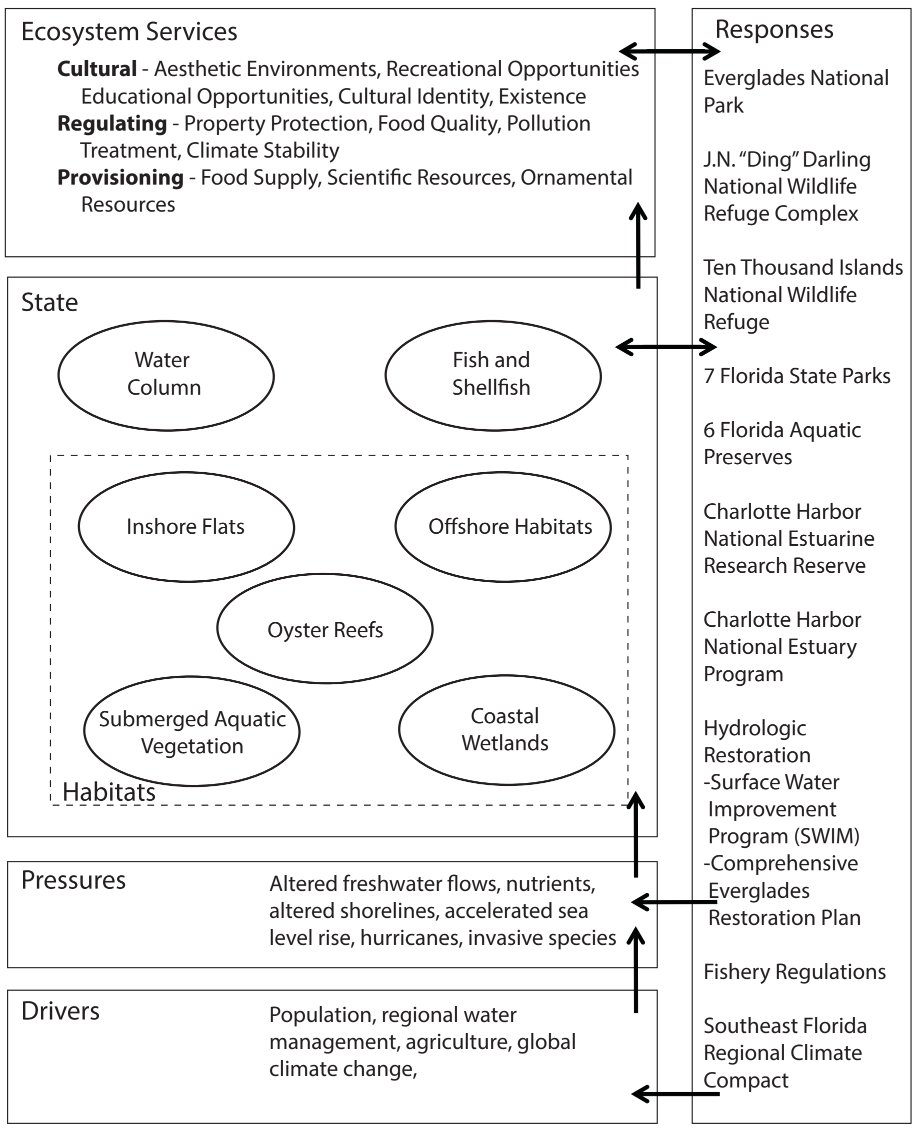

Figure 11. MARES Drivers-Pressures-Ecosystem Services-Response framework for the Southwest Florida Shelf subregion.

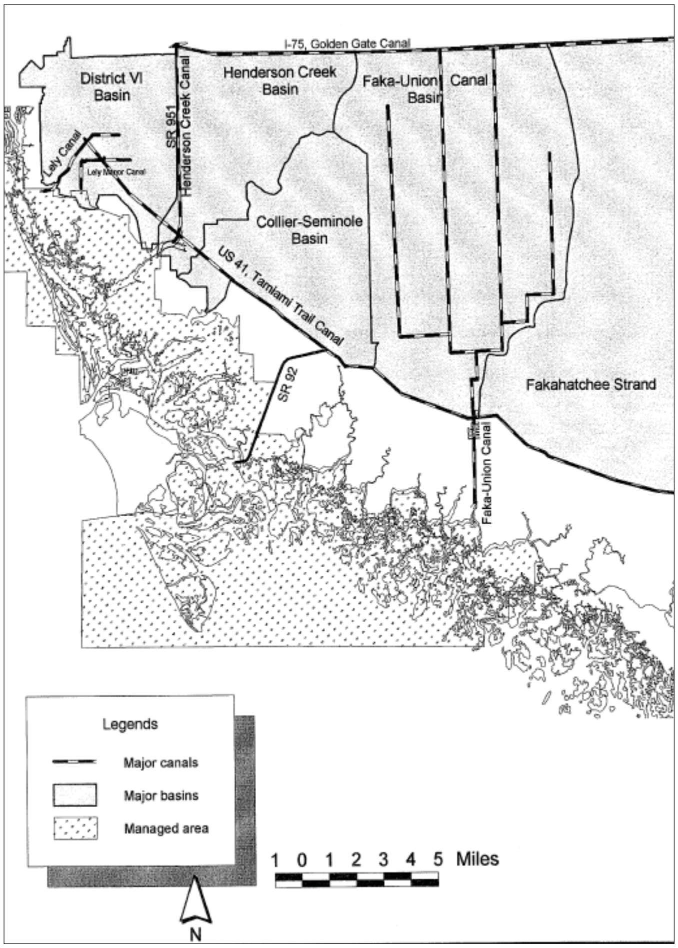

Figure 12. Canals affecting freshwater inflow into the Ten Thousand Island Province (from Rookery Bay management plan).

These *Pressures* cause a change in the *State* of the ecosystem, most directly on conditions in the water column. In both cases, the major effect of altered inflow has been to exacerbate extreme flows. Inflow to the Caloosahatchee Estuary fluctuates between extremely high flow and no flow. Construction of the Faka-Union Canal has had the effect of collecting and focusing freshwater inflow from wetland discharge in the vicinity of the canal outlet while reducing freshwater inflow in adjacent areas of the coast. Changes in freshwater inflow alter salinity patterns and the availability of nutrients, particularly in nearshore waters.

These changes, in turn, alter the distribution and quality of wetland and benthic habitats and the *Ecosystem Services* they provide. For example, both oyster reefs and SAV beds are sensitive to changes in salinity and nutrients in the water column, and both serve as nursery and feeding habitats that support commercial and recreational fisheries in the region. Freshwater discharge from Lake Okeechobee is a factor in the development of harmful algal blooms that directly affect people's enjoyment of coastal waters.

In *Response* to interest to maintain and improve these *Ecosystem Services*, water managers have initiated various efforts to mitigate the adverse effects of altered freshwater inflow. In the area of the Faka-Union Canal, there are efforts to restore more natural hydrologic conditions in the drained wetlands and redistribute flows to the coast. In the case of managing inflows into the Caloosahatchee Estuary, water managers must weigh the impacts and benefits in the coastal marine ecosystem against competing impacts and benefits in other parts of the South Florida region that are now also tied to Lake Okeechobee. Here, the management *Response* includes efforts to monitor changes in conditions in the estuary and coastal waters and better document and evaluate the impacts of changes in freshwater inflows.

Drivers and Pressures: Sources of Change

It is useful to distinguish between *Pressures* arising from far-field causes and those arising from near-field causes. The distinction between far-field and near-field *Pressures* has practical implications in deciding how to respond to the resulting changes in the ecosystem. Far-field *Pressures* alter environmental conditions at the boundary of the ecosystem, and their effects propagate throughout the ecosystem. Far-field *Pressures* of concern in the SWFS region include pressures related to climate change and pollution from freshwater runoff into the Gulf of Mexico from distant sources like the Mississippi River. Near-field *Pressures* are generated internally, and their effect varies in intensity across the ecosystem. Near-field *Pressures* of concern include altered freshwater flows generated from within South Florida and nutrient runoff from agriculture and coastal communities in the region. Concern is growing over the impact of the lionfish, a recently arrived invasive species, on native fisheries.

Far-Field Drivers and Pressures: Global Climate Change

Although far-field factors are outside of the realm of management control within the SWFS, it is important that the general public and decision makers are aware of their influence to better understand the impact of management actions against the broader suite of *Pressures* acting upon the ecosystem (Table 1). Global processes that influence the SWFS will be particularly difficult to manage given that global treaty agreements or global behavioral changes are required for a response that can effectively mitigate the pressure. The most prevalent global driver that produces direct impacts in the SWFS is climate change resulting from the rising concentration of CO_2 in the atmosphere. Long-term changes caused by ocean acidification, sea-level rise, sea surface temperature, rainfall, and hurricane severity and frequency are expected to occur as a result. South Florida, with its low elevation, high coastal population density, and unique ecosystems, including the Everglades and coastal wetlands, will likely be dramatically affected by these changes. It remains to be seen just how, and to what extent, the salinity, water quality, and coastal circulation of South Florida's coastal waters, bays, and estuaries will be affected by global climate change.

Ocean Acidification

Increasing concentrations of CO_2 in the atmosphere and the ocean affect the chemistry of ocean waters. Roughly 30 percent of the anthropogenically-released CO_2 has been absorbed by the global oceans (Feely *et al.,* 2004). Increased concentration of CO_2 lowers the pH of seawater, making it more acidic and decreasing the saturation state of aragonite. This makes it more difficult for marine organisms like corals

Table 1. Far-field drivers and pressures of greatest importance to the Southwest Florida Shelf.

Driver: Climate Change	Pressure: All pressures that arise from increasing CO_2
Ocean acidification	
Sea-level rise	
Increasing water and air temperature	
Altered regional rainfall and evaporation patterns	
Changes in tropical storm intensity, duration, and/or frequency	
Driver: Water-Based Activities:	**Pressure: Recreation, fishing, tourism, commerce/shipping**
Fishing	Commercial, recreational, and subsistence
Marine debris	Ghost traps, fishing line, waste
Contaminant releases	Marine spills, pathogen shedding, disease transport
Driver: Land-Based Activities:	**Pressure: Tourism, agriculture, shelter, water management, waste management, and human population**
Changes in freshwater inflow	Quality (nutrient loading, contaminants), quantity, timing, or distribution
Contaminant releases	Septic tanks, fertilizers, industrial waste, construction debris, manufacturing, and industrial pollutants (e.g., mercury from coal plants)

to build and support their skeletal structures (Kleypas *et al.,* 2006; Manzello *et al.,* 2007). This potential impact on corals deserves significant attention in the Florida Keys because they are such an important contributor to the economy (Johns *et al.,* 2001). Increased concentrations of CO_2 and $HCO3^-$ (bicarbonate) also increase seagrass production (Hall-Spencer *et al.,* 2008), leaf photosynthetic rates (Zimmerman *et al.,* 1997), and plant reproductive output (Palacios and Zimmerman, 2007). Moreover, acidification will occur relatively slowly, allowing some organisms to adapt. Because the interactions among different ecosystem components are complex (Hendriks *et al.,* 2010), it is not yet clear what effects acidification will have on the coastal marine ecosystem of South Florida.

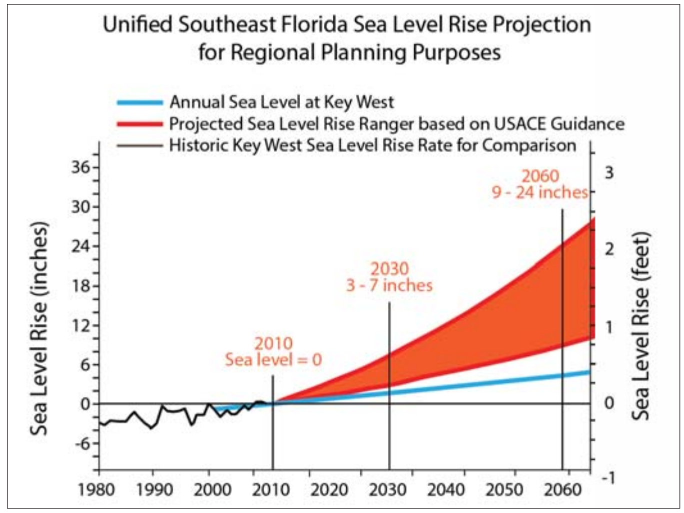

Figure 13. Unified southeast Florida sea-level rise projection for regional planning (Southeast Florida Regional Climate Change Compact, 2011; calculations courtesy of K. Esterson, U.S. Army Corps of Engineers).

Accelerated Sea-Level Rise

The SWFS is situated at a low elevation and is vulnerable to sea-level rise in the United States. The IPCC 2007 projections for sea-level rise range from 20-60 cm during the 21st century; however, these rates do not include factors such as ice sheet flow dynamics that could significantly increase the rate. The more recent *Copenhagen Report* (Allison *et al*., 2009) states that the IPCC (2007) report underestimated sea-level rise and that it may be as much as twice what has been projected. "For unmitigated emissions [sea-level rise] may well exceed 1 meter" by 2100, with an upper limit at approximately 2 meters (Allison *et al*., 2009).

The Southeast Florida Regional Climate Change Compact (2011) counties have developed a consensus trajectory for sea level through 2060 (Figure 13). The consensus sea level projections are based on "(1) global and local sea level measurements which document an accelerating rate of sea-level rise, (2) the preponderance of scientific evidence that recent land-based ice loss is increasing, and (3) global climate models that conclude the rate of sea-level rise will continue to accelerate." The projected trajectory is enveloped by an upper and lower rate projection, reflecting the underlying scientific uncertainties. Sea level in South Florida is projected to rise one foot above the 2010 reference level, relative to land surface, sometime between 2040 and 2070. A two-foot rise is considered possible by 2060. By 2060, it is expected that the rate of sea-level rise will have increased to between 2 and 6 inches per decade. Sea level rose at an average rate of 0.88 inches per decade between 1913 and 1999.

The global phenomenon of climate change and sea-level rise will alter the relative position of sea level, tides, and currents along the SWFS. The geomorphology of the extensive shallow water, including numerous mangrove islands, reflect the influence of a stable regime of slowly rising sea level (average rate of 4 cm/100 years) during the past ~3200 years (Wanless *et al*., 1994, 2000). Since about 1930, the relative rate of sea-level rise has increased substantially, averaging 30-40 cm/100 years (Wanless *et al*., 1994). As a result, significant changes have occurred in the coastal systems, including increased erosion and saltwater encroachment. Continuation of this rate will push marine water far into freshwater environments, resulting in a substantial loss of freshwater wetlands (on mainland South Florida) and diminished groundwater resources. An important aspect of sea-level rise for the SWFS is that this will also push storm surge from storms further inshore.

Unless matched by a compensating increase in sediment accretion, the acceleration of sea-level rise will alter the balance between these two processes that has prevailed in recent times. The result will be potentially rapid changes in the geomorphology of the coast. Over decadal and centennial time scales, a high rate of sea level rise increases the tidal prism. Intertidal flats may become subtidal; subtidal flats may deepen and experience lower ambient light levels and greater frequencies or intensities of hypoxia. With deepening comes a concomitant change in sedimentary character, with substrates becoming finer grained and more mud rich. Oyster reefs become less productive with increasing subtidal depth and can effectively "drown" and disappear; such phenomena have been documented in Holocene sediment cores. Mangrove-forested islands can also drown when the rate of the sea-level rise exceeds the rate of peat production.

Accelerated sea-level rise and the resulting change in shoreline morphology also affects the distribution of salinities within the estuaries and, therefore, the position of the salinity gradient and ecotones. Shifts in salinity affect an organism's ability to osmoregulate and can cause physiologic stress and mortality. Changes in the salinity gradient not only shift the biogeographic distribution of organisms, but may also place appropriate salinities in what is otherwise a less hospitable habitat due to other environmental conditions. For example, the incursion of higher salinity water within estuaries of the Ten Thousand Islands has placed the most productive waters for oyster growth and reproduction within the river channels, rather than the inner bays. River channels have much less accommodation space for oyster reef development than inner bays, and river channel substrates are generally too mobile to permit oyster settlement and survival.

Increasing Temperature

Climate forecasts predict an increase in summer air temperatures of between 2-4°C and an increase in winter air temperatures by 3°C over the next century. Warmer temperatures will be accompanied by changes in rainfall and the frequency and intensity of storms (IPCC, 2007). Within the Gulf of Mexico, a 2-3°C temperature increase is predicted based upon IPCC scenarios and downscaled global climate circulation models (Liu *et al*., 2000). These changes in temperature will have a significant impact on the biota of the SWFS.

Altered Rainfall and Evaporation

The net effect that global climate change will have on rainfall and evaporation in South Florida is uncertain. The IPCC (2007) report indicates that there will be a likely decrease in precipitation over subtropical land regions and increased evaporation rates (Allison *et al*., 2009). However, increased temperatures are also associated with an increase in the frequency of thunderstorms, particularly in the tropics and southeastern United States (Trap *et al*., 2007; Aumann *et al*., 2008). Thunderstorms are the major source of rainfall during the summer wet season in South Florida. In addition to rainfall, thunderstorms play a role in fire generation in south Florida (Gunderson and Synder, 1994).

Frequency and Intensity of Tropical Storms

The IPCC Summary Report for Policymakers (2007, p. 12) states that "it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and heavier precipitation associated with ongoing increases of tropical SSTs" [sea surface temperatures]. The Copenhagen Report (Allison *et al*., 2009) discusses evidence that hurricane activity has increased over the past decade, and the number of number of category 4 and 5 hurricanes has also increased globally. An increase in tropical storms promises increased rainfall over land and increased mixing of shallow surface waters of the Florida Shelf during the passage of these storms (e.g., Ortner *et al*., 1984). The passage of intense storms can resuspend sediments and reduce the transparency of the water column (e.g., Chen *et al*., 2009), resulting in a potential reduction in pelagic primary production in coastal waters. The combination of wind and storm surges have caused substantial die-off in the mangrove forests of the southwest coast (Smith *et al*., 1994, 2009; Wanless *et al*., 1994) with a number of related effects including increased erosion due to an uprooting of trees, increases in carbon and nutrients released into the waters, and repopulation of denuded areas by invasive species.

Near-Field Drivers and Pressures

Near-field *Drivers* and *Pressures* relate to the high rate of population growth and development occurring in Collier and Lee counties, which affect the coastal marine ecosystem directly through changes to the shoreline and indirectly through degradation of water quality and altered freshwater inflows (Charlotte Harbor National Estuary Program, 2008), Table 2. Water quality is affected by nutrient loads and pollutants carried in runoff from developed and agricultural areas, in discharge from septic tanks and waste treatment plants, and deposition from the atmosphere. Development alters the hydrological functioning of wetlands locally, and water management for the South Florida region has altered the flow regime of rivers in the region. These hydrologic changes alter the amount, timing, and location of freshwater

Table 2. Near-field drivers and pressures of greatest importance to the Southwest Florida Shelf.

Water-Based Activities:	Recreation, fishing, tourism, commerce/shipping
Fishing	Commercial, recreational, and subsistence
Groundings	Benthic habitat/community destruction, propeller scars, anchor damage
Dredging	Damage to bottom benthic habitat/community destruction, sedimentation, and altered circulation
Marine debris	Ghost traps, fishing line, waste
Noise	Boating, military, oil exploration, and drilling
Invasive species	For example, lionfish
Contaminant releases	Marine spills, pathogen shedding, disease transport
Land-Based Activities:	**Tourism, agriculture, shelter, water management, waste management**
Alteration of shorelines	Shoreline hardening, increased impermeable surface area, loss of wetlands, dredging
Changes in freshwater inflow	Quality (nutrient loading, contaminants), quantity, timing, or distribution
Contaminant releases	Septic tanks, fertilizers, industrial waste, construction debris, manufacturing and industrial pollutants (e.g., mercury from coal plants)

inflow to estuaries and inshore areas of the coastal marine ecosystem. This, in turn, affects the salinity of inshore waters and the many species of plants and animals that are sensitive to salinity.

Nutrients

Eutrophication of coastal waters, resulting from increased nutrient loads, can increase the occurrence of harmful algal blooms. The link between coastal eutrophication and harmful algal blooms has not been made definitively for the SWFS region (Walsh *et al.*, 2009; Vargo, 2009); however, eutrophication has been demonstrated to enhance the development of harmful algal blooms in other regions (cf., Anderson *et al.,* 2008).

Several sources contribute nutrients to the water column of the SWFS, including nutrient loading from freshwater inflows, nutrients released from benthic communities, and the intrusion of bottom waters from the Gulf of Mexico Loop Current. Estuaries are a major source of nutrients, in both dissolved inorganic and organic forms, that support primary production near the shore (Vargo *et al.*, 2008). In particular, dissolved organic forms of nitrogen are the major form of this essential nutrient in the rivers that flow into the SWFS coastal waters (McPherson and Miller, 1990). Further offshore, nitrogen and phosphorus enter the shelf ecosystem from upwelling of subsurface waters in the Loop Current (Walsh *et al.*, 2006). Additional biological inputs occur from the nitrogen-fixing cyanobacteria *Trichodesmium* spp., which often blooms in summer in response to the seasonal input of iron from atmospheric dust transported westward from the Sahara (Walsh and Steidinger, 2001). When *Trichodesmium* spp. bloom, they release measurable quantities of dissolved organic nitrogen that subsequently supports primary production in the water column. Direct atmospheric inputs of nitrogen also occur through wet and dry deposition in the eastern Gulf of Mexico (Paerl *et al.*, 2002). In total, these sources can support dense algal blooms on the SWFS, although no individual nutrient source is apparently sufficient to maintain prolonged bloom events (Vargo *et al.*, 2008; Vargo, 2009).

Altered Freshwater Inflows

The balance between saltwater influx from the marine systems and freshwater flow from the terrestrial systems is what defines the transitions within any coastal wetland environment. Landscape alterations and water management practices that change natural flow patterns are one of the primary drivers in coastal ecosystems (Davis *et al*., 2005; Sklar and Browder, 1998). Changes in flow cause a cascade of changes to other key physical components of the ecosystems, including water depth, salinity, nutrients, and dissolved oxygen, which cause changes in biological components such as productivity, community structure, and species composition (Sklar and Browder, 1998). Diverting or limiting water flow affects the sediments carried by the rivers, which affects the supply of raw materials needed to maintain or build up the coast, and the nutrients to promote plant growth, critical factors that enable the coastal wetlands to keep pace with rising sea levels (Sklar and Browder, 1998). Altered freshwater flow patterns also have damaging consequences for eastern oysters (*Crassostrea virginica*) and, therefore, the entire oyster reef ecosystem (Volety *et al.*, 2009).

Freshwater is over discharged into some estuaries (e.g., Faka Union Bay in the Ten Thousand Islands and the Caloosahatchee River in the Barrier Islands Province), and the magnitude of freshwater releases can be extreme, causing freshets that can unduly stress faunas and floras. In other estuaries, freshwater sheetflow is interrupted because of drainage canal networks that redirect freshwater to one bay. This phenomenon has been particularly devastating to the bays west of Faka Union Bay in the Ten Thousand Islands which, as a result, have anomalously high salinities. The timing of freshwater delivery is also of importance. Freshets during times of spawning or larval recruitment can obviate an entire year's reproductive effort.

Freshwater inflows to the Caloosahatchee Estuary have been modified by construction of an artificial outlet from Lake Okeechobee into the Caloosahatchee River. Freshwater diversion into the Caloosahatchee Estuary is controlled by the Franklin Lock and Dam (S-79). The flow of water from the lake into the river is managed as part of efforts to control water levels in the lake. Freshwater release can be of great magnitude and result in dramatic fluctuations between near-marine salinity and freshwater. At low flow times, a salinity wedge threatens the upper limits of tolerance of the tape grass (*Vallisneria americana)* communities found in the upper Caloosahatchee Estuary. At the other extreme, dramatic freshwater discharge can lower salinities in San Carlos Bay to levels deleterious to seagrasses. Natural cycles of precipitation and the resulting increases and decreases in salinity do not always follow wet season (June through October) and dry season patterns (November through May) in the river downstream from the dam (Kraemer *et al*., 1999).

The quantity, timing, and distribution of freshwater inflow to Faka Union Bay and adjacent areas of the Ten Thousand Islands changed substantially with construction of a system of canals to drain the Golden Gate Estates development (Figure 12). Originally, the bay received freshwater inflow from the Wood River, a small natural tributary of Picayune Strand. The Faka Union Canal watershed now includes Southern Golden Gate Estates (SGGE, site of the present Picayune Strand Restoration Project, located between U.S. Highway 75 and State Road 41) and part of Northern Golden Gate Estates (NGGE), which lies north of U.S.Highway 75.

Popowski *et al*. (2004) provides the following summary of the resulting changes. Faka Union Canal discharge records measured at the gauging station located upstream from the outfall weir are available starting in 1969. The average discharges for the period of record are 115 cubic feet per second (cfs) during the dry season (November through May) and 460 cfs during the wet season (June through October) (SFWMD, 1996). An extreme discharge of 3,200 cfs occurred right after the canals were built. Flows exceeding 2000 cfs have occurred in recent years (i.e., 1995 and 1999) (District DBHydro database).

The canal system greatly increases the inflow of freshwater into Faka Union Bay at the expense of inflow to other nearby areas. Inflows are increased during the wet season and decreased during the dry. As a result, the transition between wet season flow and dry season flow has become more abrupt, and the natural seasonal difference flows accentuated. The canal system diverted surface and groundwater flow from Fakahatchee Bay, which lies directly east of Faka Union Bay and downstream from Fakahatchee Strand. The diversion reduced both wet season and dry season flows to the larger bay, although Fakahatchee Bay was influenced by low-salinity water entering from Faka Union Bay through a direct connection between the two bays. The canal system and associated road system also diverted surface and groundwater away from the small rivers and bays immediately west of Faka Union Bay, including Pumpkin River and Pumpkin Bay. Both spatial and temporal changes in salinity patterns occurred as a result of changes in freshwater inflow regimes (Popowski *et al.*, 2004).

In the southwest coastal area of the Everglades, the altered freshwater regime has altered the hydroperiods and delivers relatively high nitrogen loads, stimulating productivity and leading to the invasion of opportunistic native plants and invasive exotics (Sklar and Browder, 1998). Childers *et al.* (2006) found that reduced freshwater flow was associated with higher total phosphorus from marine sources in the Shark River Slough mangrove estuaries. The volume of flow is also critical to productivity. There is an optimum flow level, below which nutrient deficiencies and soil oxidation can occur and above which abrasive flows and waterlogging of the wetlands can occur (Sklar and Browder, 1998).

Other Pressures: Invasive Species Introduction

The animal trade industry has resulted in the release of numerous non-native species to South Florida, including the marine ecosystem of the Florida Keys. One example is the spread of lionfish, *Pterois volitans*, that now inhabit the Bahamas and the east coast of the United States, including the Florida Keys National Marine Sanctuary (Whitfield *et al.*, 2002, 2007). These predatory fish have been reported to kill 1.44 native fish per hour on average in nearby Bahamian coral reefs (Cote and Maljkovic, 2010). In fact, this high predation rate has resulted in a reduction of native fish recruitment by an average of 79 percent in reefs with *P. volitans* (Albins and Hixon, 2008).

State: Key Attributes of the Ecosystem

The *State* of the ecosystem is defined, operationally, by attributes. Attributes are a parsimonious subset of all descriptive characteristics of an environment that represent its overall condition (Ogden *et al.,* 2005). The marine waters of the Florida Keys support an ecologically-diverse environment, which can be divided into five components to better describe its defining attributes and underlying processes: (1) water column; (2) fish and shellfish; and five habitat communities: (3) inshore flats; (4) submerged aquatic vegetation; (5) oyster reefs; (6) benthic offshore; and (7) coastal wetlands. *State* submodels for each are provided as appendices to this report.

Water Column

The water column encompasses the physical, chemical, and biological characteristics of the water column, including benthic sediment, phytoplankton, and zooplankton suspended in the water column. Water quality on the SWFS is affected by the biogeochemical processes that regulate the cycling and concentration of particulate and dissolved materials in the water column. A diverse set of sources and sinks for these constituents occur at the boundaries of the shelf waters and include bottom sediments, the contiguous oceanic waters of the Gulf of Mexico, and the riverine inflows along the west Florida coast. The spatial gradients in dissolved and particulate matter are mainly from higher levels at the coast to lower levels in offshore waters, with maximum concentrations of dissolved and particulate materials near the coastal inflows and estuaries. The constituents are modified through biogeochemical cycling in both the water column and the sediments. Residence times of dissolved and particulate matter on the Florida Shelf can be on the order of weeks to months, as the flow regime constrains surface waters onshore of a convergent boundary at mid-shelf (Yang *et al.*, 1999). Thus, two of the ecosystem attributes that people care about, harmful algal blooms dominated by the toxic dinoflagellate *Karenia brevis* (Steidinger *et al.*, 1998) and "blackwater" events (Hu *et al.*, 2003), can be retained on the inner shelf for periods of weeks to months.

Fish and Shellfish

The fish and macroinvertebrate fauna of the Ten Thousand Islands support both recreational and commercial fishing. The short list of target species inshore includes snook, tarpon, red drum, spotted seatrout, pompano, and sharks. Offshore, the principal target species are snapper, grouper, cobia, permit, barracuda, king and Spanish mackerels, and more sharks. Inshore are many other fish that provide good opportunities for anglers, as well as a myriad of smaller fish that serve as bait for fishermen and the prey of fishing targets. The first category includes spotted and sand seatrout, sheepshead porgy, and hardhead catfish. Browder *et al*. (1986) documented at least 79 fish species and 70 macroinvertebrate species that fit the lower and middle levels of the faunal food web. Dominant fish were bay anchovy, yellowfin menhaden, scaled sardine, striped anchovy, pinfish, and silver perch. Shirley *et al*. (2005) listed as dominants spotfin mojarra, silver jenny, fringed flounder, pigfish, and blackcheeked tonguefish. Pink shrimp were among the numerically dominant species in Shirley *et al*. (2005), and the total catch of pink shrimp was of similar magnitude in a 1972 trawl study of Fakahatchee and Faka Union bays by Carter *et al*. (1973). Pink shrimp were the second most abundant decapod, following caridean shrimp in abundance, in Browder *et al*. (1986). Species composition changes seasonally and varies by bay system (Shirley *et al*., 2005).

Several species of special concern are a part of the aquatic fauna of the Ten Thousand Islands. Southwest Florida is the last stronghold for the endangered smalltooth sawfish, and 619,013 acres of the combined Ten Thousand Islands and Everglades regions have been declared critical habitat for this species. Waters of the Ten Thousand Islands are also important habitat for the goliath grouper, once an important fishery species. The West Indian manatee is another major endangered species living in the Ten Thousand Islands. Kemp's Ridley, green, leatherback, and Atlantic loggerhead sea turtles are other listed endangered species for which the Ten Thousand Islands are an important habitat.

Habitats

Inshore Flats

Inshore flats are defined as flat bottom, sub- or intertidal habitats that lack an epifaunal oyster or sea grass community and are located inside the outer coastal margin. The two most significant environmental characteristics that control the communities of infauna and epifauna on a flat are the height of the substrate relative to mean sea level and the sedimentary consistency of the substrate. The distinguishing characteristics of relative water depth with respect to mean sea level and the sedimentary substrate composition are used to define inshore flat habitat types: habitats may be subtidal or intertidal; subtidal substrates may be composed of sand and mud or mud; and intertidal substrates are composed of sand. Additionally, intertidal sand flats occur as one of two varieties that are distinguished by the relative stability and residence time of the sands. Storm tidal deltas form on the inside edges of the outer and inner bays landward of tidal inlets. During storm flood tides, sands are transported landward and deposited on these deltas (ebb flood deltas may also occur seaward, but tend to be ephemeral, as the sands deposited in these features are quickly remobilized and transported away; El-Ashry and Wanless, 1965). Consequently, storm tidal deltas remain stable between storm and extreme tidal events. Intertidal sand flats also occur as beach aprons on the bayside of islands. These structures are influenced by waves and by tidal cycle fluctuations.

Submerged Aquatic Vegetation (SAV)

SAV, for the purpose of this conceptual model, includes the vascular underwater plants that live in estuarine and nearshore coastal waters. SAV beds are primarily comprised of three seagrasses: turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), and Cuban shoal grass (*Halodule wrightii*). Seagrass beds are extensive in the shallow Gulf waters south of Cape Romano. Marine seagrasses that occur in the Ten Thousand Islands include the three species already mentioned and two *Halophila* species, star grass (*H. engelmannii*) and paddle grass (*H. decipiens*). In areas of low salinity, such as near the mouth of freshwater rivers and creeks, widgeon grass (*Ruppia maritima*) can be found. *Ruppia* is generally found in waters of 25 ppt or less; however, it can tolerate a wide range of salinities from fresh to 32 ppt. As a result, the distribution and abundance of *Ruppia* can vary seasonally. Tape grass (*V. americana*) is the dominant SAV in the upper Caloosahatchee Estuary and occurs in well-defined beds in shallow water.

Oyster Reefs

Oysters, *Crassostrea virginica,* are natural components of estuaries along the eastern seaboard of the United States, as well as the estuaries in the Gulf of Mexico, and were once abundant in the estuaries of southwest and southeast Florida (RECOVER, 2007). Along the southwest Florida coast, oysters exist within the estuarine and coastal areas as extensive reefs or isolated clusters or are attached to prop roots of red mangroves, often extending out at the base of mangroves. Oyster reef development occurred along the southwest Florida coast over the last 3500 years, with reef development having a significant impact on coastal geomorphology. As reefs become emergent at low tide, they become the centers for red mangrove propagule settlement, and reefs transform into mangrove-forested islands. These islands entrap freshwater and predispose the region to estuarine conditions (Parkinson, 1989; Wohlpart, 2007). In the present day, oyster reefs are extensive along the Charlotte Harbor to the Ten Thousand Islands, with reef development decreasing southeast of Chatam River towards Everglades National Park (Savarese *et al.*, 2004; Volety *et al.*, 2009). In estuaries north of Lostman's and Broad rivers, oysters are also found on the prop-roots of red mangroves fringing the inner bays. In most of the estuaries, the extent of oyster reef coverage ranges between 5-20 acres (Volety and Savarese, 2001; Savarese *et al.*, 2004; Volety *et al.*, 2009).

Benthic Offshore

The "live bottom" and other benthic offshore habitats on the continental shelf support the biological diversity of the SWFS region, although the connectivity to inshore estuarine areas and to the Florida Keys is not well understood. Commercially valuable fish and invertebrate species (e.g., red drum, pink shrimp, stone crab) use the shelf and estuaries for part of their life cycle and depend on benthic habitats in the Gulf of Mexico. Benthic offshore habitats are thought to be the source of shells that are a characteristic feature of beaches in the region, especially on Sanibel Island.

Benthic offshore habitats in southwest Florida include hardbottom communities with a diverse epibiota that includes hard and soft corals, macroalgae, and is used by abundant populations of fish species. The hardbottom areas are typically at intermediate depths where limestone outcroppings occur. A thin veneer of overlying sand, when combined with storms and waves, can cause scouring and dislodging of epibiota and transport to barrier island beaches. The shallow depths are colonized by pen shells and quartz sands with shells and other mollusks, such as fighting conchs (*Butrycon* spp.) and calico scallops (*Argopectin* sp.). Deeper depths contain low relief limestone with barrel sponges interspersed with areas of crushed shell and carbonate sediments and occasional *Halophila decipiens*, especially in the Cape Sable Province and northwestern Florida Bay.

There are many attributes of benthic offshore habitats that people care about. In the Barrier Islands Province, beaches are popular shelling destinations. The benthic offshore habitats are the source of the shells, which are transported to the barrier islands during tropical storms and cold fronts. Changes affecting the productive offshore habitats or delivery could threaten the tourism economy. In Lee County, tourism employs one out of every five people, with over five million visitors per year generating over $3 billion in economic revenues (http://www.leevcb.com/statistics/index.php). Commercially valuable fish and invertebrate species (e.g., red drum, pink shrimp, stone crab) use the shelf and estuaries for part of their life cycle and depend on the offshore benthic habitats.

Coastal Wetlands

Within the context of the SWFS ICEM, coastal wetlands are defined as the saltwater zone landward of the coastal margin, which includes the marshes, flats, and mangroves and the intermittent creeks, channels, and rivulets that flow through these areas. The coastal wetlands form a critical ecotone at the boundary between freshwater and marine environments, making them particularly vulnerable to impacts from sea-level rise and changes in intensity and frequency of coastal storms. The IPCC (IPCC, 2007) has identified coastal mangroves and salt marshes as environments that "are likely to be especially affected by climate change" due to "multiple stresses" associated with changing climatic patterns. The four provinces of the southwest coast differ in the nature and extent of their coastal wetlands habitat. The Barrier Islands are predominantly marshes, whereas the region from Ten Thousand Islands south to Cape Sable is described by Davis *et al.* (2005) as "a brackish water ecotone of coastal bays and lakes, mangrove and buttonwood forests, salt marshes, tidal creeks, and upland hammocks." Around Cape Sable and Whitewater Bay, the dwarf mangrove forests are found. The southwest coastal zone includes more than 148,263 acres of mangroves (Smith *et al.*, 1994) and 54,800 acres of salt marshes. NOAA's Coastal Wetlands Inventory (Field *et al.*, 1991) lists the Ten Thousand Islands as having the largest extent of coastal wetlands of any estuarine drainage in the continental United States (2,165,000 acres).

The coastal wetlands of the FSWS region are highly productive in small demersal fishes and invertebrates (Heald *et al.*, 1984; Lorenz, 1999) that, during relatively low water periods, become highly exploited by water bird species (Lorenz *et al.*, 2002; Odum *et al.*, 1982; Ogden, 1994; Powell, 1987) and game fish (Odum *et al.*, 1982; Odum and Heald, 1975). These wetlands also provide critical nesting habitat for water birds (Kushlan and Frohring, 1986; Ogden, 1994) and nursery habitat for fishery species (Ashton and Eggleston, 2008; Comp and Seaman, 1985; Lewis *et al.*, 1988; Manson *et al.*, 2005). In addition, these wetlands enhance the fish biomass on nearby seagrass beds (Manson *et al.*, 2005; Thayer and Chester, 1989), and oysters have been found to assimilate mangrove organic material (Surge *et al.*, 2003; Cannicci *et al.*, 2008), thereby playing a role in seagrass and oyster reef ecosystems. Furthermore, organic export from mangrove forests provides nutrients to surrounding ecosystems (Lugo and Snedaker, 1974; Odum and Heald, 1975; Twilley, 1985, 1988; Nixon, 1980) but mangrove forests, depending on the type, can also sequester nutrients and act as a wastewater filter (Ewel *et al.*, 1998), thereby playing a role in water quality as well.

Ecosystem Services: What People Care About

Ecosystem Services are the benefits that humans derive from the ecosystem. They are what link people to the *State* of the ecosystem, through "attributes [of the environment] that people care about." *Ecosystem Services* have value for people who live in the ecosystem and people who do not. The value of *Ecosystem Services* is related to environmental conditions, and this value can be measured and reported in a monetary, cultural, or social context.

The MARES project identifies 12 distinct *Ecosystem Services* provided by the SFCME (Table 3). These can be categorized as cultural, regulating, and provisioning services, following the approach taken in the Millennium Ecosystem Assessment project (cf., Farber *et al.,* 2006). In this context, cultural services and goods are defined as the non-material benefits obtained from ecosystems such as spiritual and religious, recreation and ecotourism, aesthetic, inspirational, educational, sense of place, and cultural heritage. Provisioning services and goods are products obtained from ecosystems such as food, fresh water, fiber, biochemicals, and genetic resources. Regulating services and goods are benefits obtained from regulation of ecosystem processes such as climate regulation, disease regulation, water regulation, water purification, and pollination.

The importance of ecosystem services that support recreation and tourism in the SWFS region cannot be overstated. Florida leads the nation as the number one destination for saltwater fishing. Recreational boating is also a very popular activity. In 2009, Lee and Collier counties had 67,098 registered recreational boats (Florida Fish and Wildlife Conservation Commission, 2010). This is about one boat for every 11 residents, compared with a statewide average of one boat for every 18 residents (Sidman *et al.*, 2009). An economic study of Florida's beaches was compiled with data from 2003 and revealed that over 80 percent of all tourists to southwest Florida visited local beaches (Murley *et al.*, 2003). The annual value of recreational saltwater fishing was estimated at $5.6 billion, statewide, in 2000 (Morgan *et al.*, 2010). In 1995, all tourism and recreation activities, including saltwater fishing, had an annual value of almost $2 billion just in the area covered by the Charlotte Harbor National Estuary Program (Hazen and Sawyer, 1998). This area is at the northernmost extent of the SWFS region. Comparable figures are not yet available for the much larger remaining portion of the region.

Attributes People Care About: Linking State to Ecosystem Services

Ecosystem Services refer to attributes of the coastal marine environment. The value of *Ecosystem Services* derives from the attributes that people care about. The set of "attributes that people care about" combines the idea of "attribute," as a characteristic that reflects the overall condition of the environment, with people's expectations and/or what they consider to be good. "Attributes that people care about" are difficult to define quantitatively compared with environmental parameters that can be simply and directly measured. Nonetheless, they are essential aspects of the benefits that people obtain from the environment and are often directly related to readily-measured parameters.

In general, people care about the sustainability of the coastal marine ecosystem. A sustainable ecosystem is required as the home to particular species that people are interested in,

Table 3. Ecosystem services provided by the South Florida coastal marine ecosystem.

Cultural	Aesthetic and Existence—Provide aesthetic quality of aquatic and terrestrial environments (visual, olfactory, and auditory), therapeutic benefits, pristine wilderness for future generations.
	Recreation—Provide suitable environment/setting for beach activities and other marine activities such as fishing, diving, snorkeling, motor and non-motor boating.
	Science and Education—Provide a living laboratory for formal and informal education and for scientific research.
	Cultural Amenity—Support a maritime way of life, sense of place, maritime tradition, spiritual experience.
Provisioning	Food/Fisheries—Provide safe-to-eat seafood.
	Ornamental Resources—Provide materials for jewelry, fashion, aquaria, etc.
	Medicinal/Biotechnology Resources—Provide natural materials and substances for inventions and cures.
Regulating	Hazard Moderation—Moderate to extreme environmental events (i.e., mitigation of waves and storm surge in the case of hurricanes).
	Waste Treatment—Retain storm water, remove nutrients, contaminants, and sediment from water, and dampen noise. etc.
	Climate Regulation—Moderate temperature and influence/control other processes such as wind, precipitation, and evaporation.
	Atmospheric Regulation—Exchange carbon dioxide, oxygen, mercury, etc.
	Biological Interactions—Regulate species interactions to maintain beneficial functions such as seed dispersal, pest/invasive control, herbivory, etc.

such as sport fish, marine birds, and large animals like sea turtles, dolphins, and mantees that people find engaging and interesting to watch in their native habitat. The attribute of sustainability requires a well-functioning, whole ecosystem in which all elements are healthy and functioning well, e.g., the water column, fish and shellfish populations, coastal wetlands, oyster reefs, seagrasses, and other benthic communities. Fish make use of the entire mosaic of benthic habitats over their life spans. In turn, the communities of organisms responsible for maintaining these habitats require just the right combination of characteristics in the water column, i.e., temperature, salinity, clarity, and nutrient concentrations, to thrive.

In the SWFS region, people are particularly concerned with threats to the quality of inshore and coastal waters. Characteristics of the water column, like clarity and cleanliness, i.e., the general absence of objectionable odor, nuisance, or disease-causing organisms, contributes to the aesthetic appeal of the coastal marine environment as a whole. Water quality is a factor in the main attributes of the coastal marine environment that people care about: the quality of the beaches, the enjoyment of other activities on the water, and the safety of seafood. Red tides, i.e., harmful algal blooms, occur on the SWFS almost every year (Steidinger *et al*., 1998). In three of the last five years, bloom initiation has occurred in the nearshore coastal waters adjacent to Fort Myers. The Florida Department of Agriculture surveys seafood for health risks related to red tides, and shellfish beds are closed when concentrations of the concentration of *Karenia brevis*, the toxic dinoflagellate responsible for neurotoxic shellfish poisoning (NSP), get too high. Consumers are also concerned about the effects of pollution on the safety of seafood. A recent reduction in seafood consumption in response to the Deepwater Horizon oil spill of 2010 illustrates how perceived effects of pollutants can alter people's attitudes regarding seafood safety.

People care about the size and health of fish and shelfish populations and about maintaining a variety of species in the ecosystem. People care most of all about the species that support fisheries—for this area, the tarpon, snook, red drum, pompano, snappers, groupers, and other large sport fish, as well as pink shrimp and stone crabs. Additionally, most fishermen understand the importance of a diverse and abundant prey base to support their principal species of interest. People also can connect good fishing to productive, relatively undisturbed nursery habitat for fishery species and their prey. Commercial fisheries in the Ten Thousand Islands are focused on blue crab inshore and pink shrimp, stone crab, snapper, and grouper offshore. The two major shrimp trawling grounds are offshore near the Dry Tortugas and near Sanibel-Captiva. Shrimp trawling also occurs in waters where there is an absence of reefs between the two main areas.

The Ten Thousand Islands area provides important habitat for endangered species, two fish species, one marine mammal, and five turtle species that are endangered, threatened, or otherwise of special concern. The threatened wood stork, *Mycteria americana*, also forages in the Ten Thousand Islands (Browder, 1984).

People care about benthic habitats. The intertidal and shallow water areas of inshore flats serve as feeding grounds for fish and marine birds. Healthy SAV communities provide food and habitat for ecologically and economically important aquatic organisms, such as redfish, pink shrimp, and blue crab. SAV grazers include blue crabs (*Callinectes sapidis*) (Zieman, 1982), invertebrates (Lodge, 1991; Newman, 1991), fish (Agami and Waisel, 1988), and the endangered West Indian manatee (*Trichechus manatus*) (Koelsch and Pitchford, 1998).

Oyster reefs support diverse fish populations, crustaceans, and other invertebrates; they mitigate coastal erosion and boat wakes; provide critical nursery and food habitat for recreationally- and commercially-important species; act as a natural filter for phytoplankton, detritus, bacteria, and contaminants in the water column; and sequester carbon in their shell. The "live bottom" and other benthic offshore habitats on the continental shelf are thought to be the source of the shells that make up the beaches in the region and contribute to people's enjoyment of them.

People care about coastal wetlands because they provide tremendous functional, economic, and ecologic value including: (1) shoreline stabilization and storm protection; (2) flood protection; (3) water quality improvement through the filtering of nutrients; (4) critical habitat for wildlife and marine organisms, including threatened and endangered species, in at least some stage of their life cycles; and (5) aesthetic, educational, sport, and tourist value (Field *et al*., 1991; Odum *et al*., 1982). Mangroves provide critical habitat in the life cycle of many important commercial and recreational fishes as both shelter and detritus-based food sources (Estevez, 1998; Heald *et al*., 1984; Lugo and Snedaker, 1974; Odum *et al*., 1982). Salt marshes also serve as important nursery and feeding grounds for estuarine animals (Montague and Wiegert, 1990). Coastal food webs are supported by the regional movement of organic matter from coastal marshes to the estuarine and marine systems (Nixon, 1980). Important species include oysters, blue crabs, Caribbean spiny lobsters, pink shrimp, snook, mullet, menhaden, red drum, spotted sea trout, snapper, tarpon, ladyfish, jacks, and others (Odum *et al*., 1982). The characteristic plant species of the coastal wetlands form critical habitat for a number of vertebrate and invertebrate species (Odum *et al*., 1982), including seven species and four subspecies listed by U.S. Fish and Wildlife Service as endangered, threatened, or of concern (Odum and McIvor, 1990).

Valuing Ecosystem Services

Use and non-use values and avoided costs can be estimated and used in cost-benefit analyses of management actions deemed necessary to protect the quality of the environment. For example, recreational boating is a popular activity in southwest Florida, where it is one of the principal means by which people use the coastal marine environment (Sidman *et al*., 2009). Recreational boating, recreational fishing, other related water activities, and support activities onshore generate economic benefits for the region worth several billion dollars per year (cf. Hazen and Sawyer, 1998). This economic benefit depends critically on the quality of the SWFS coastal marine environment that people travel to enjoy. It also depends on facilities to provide large numbers of people with access to the water, such as boat ramps, marinas, roads, bridges, and dredged channels. Providing these facilities necessarily alters the marine environment, which often conflicts with the objective to maintain the self-sustaining, natural marine ecosystem that people value.

Ecosystem Services that have a supportive function within the ecosystem, such as biodiversity, nutrient cycling, and soil formation, have an indirect, less commonly understood relationship to people's welfare. Evaluating these services is problematic with valuation techniques that require direct expressions of value. In these circumstances, it may be necessary to construct values indirectly, by tying services to things people directly value. Non-monetizing methods do not require a connection between values and money, but still provide information about relative values, equivalencies, or rankings. The equivalencies and relative ranking methodologies can be used to weigh changes in ecological services resulting from management decisions.

A simple conceptual model of the economics of natural resource and environmental change is provided in Leeworthy and Bowker (1997). This model shows how actual and perceived changes in environmental attributes and ecosystem services can change the demand for and economic value of outdoor recreation and tourism. Economic values include market and nonmarket values received by users (those participating in recreation activities) and non users.

Market values are (1) the expenditures made by users to participate in a recreation activity such as fishing, and (2) the dollar value of commercial fish and shellfish purchases. Non-market values are those values that are not directly observable in a market and include the use value of a recreation activity such as fishing that is the net of the expenditures made to participate in the activity and the non-use value of ecosystem services. Non-use values, also referred to as passive economic use value, is a person's willingness to pay to know that a resource is protected in a certain condition even though the person never plans to directly use the resource. Specific names for non-use values reflect a person's motive for the value. Existence value is the willingness to pay to know that the ecosystem exists in a certain condition. Bequest value is the willingness to pay to leave the ecosystem in a certain condition for future generations.

Another important value is the economic contribution of the ecosystem as it is enjoyed for recreation and to produce goods such as fish and shellfish harvests. Economic contribution is the impact of an ecosystem on recreation expenditures and fish and shellfish purchases including the multiplier effect as this money moves through the local, regional, and state economies of the United States. This economic contribution includes the value of production (output), income, employment, and tax revenues generated in local, regional, state, and U.S. economies.

While benefit-cost analysis using these economic values is an important criterion for measuring the impacts of management alternatives on social welfare, other considerations, including equity, sustainability, ecological stewardship, and cultural and ethical values, are also important to consider in the decision-making process (Costanza and Folke, 1997). Equity analysis requires an estimation of who receives the benefits and who pays the costs of management alternatives. Sustainability and stewardship analyses focus on the intertemporal distribution of those services. Cultural and ethical considerations may place constraints on acceptable management decisions (Farber *et al.*, 2006).

In addition to the benefits related to recreational boating mentioned above, the SWFS coastal marine ecosystem provides *Ecosystem Services* for wildlife-viewing opportunities; nutrient regulation and filtration; coastal erosion and storm protection; and carbon sequestration.

Wildlife viewing activities contributed approximately $3.1 billion in retail sales to the Florida economy in 2006 with a total estimated economic effect of $5.2 billion (Southwick and Allen, 2008). It is estimated that the region has close to 2000 species of birds, fish, mammals, and other animals (Estevez, 1998). Viewing this diverse wildlife enhances the visitor experience for all tourists, even those who did not travel specifically to view wildlife. Bird watching constitutes one of the largest wildlife-viewing activities (Carver, 2009), and the coastal wetlands and mangrove forests of the southwest coast provide prime opportunities for viewing the diverse community of birds and other animals that utilize the habitat (Estevez, 1998; Montague and Wiegert, 1990; Odum *et al.*, 1982). According to Carver (2009), waterfowl and birds of prey are the largest categories of birds watched away from the home, and these types of birds are abundant in the southwest coastal marshes. In addition, numerous species of birds use the wetlands as wintering or stopover sites during their annual migration (Odum *et al.*, 1982).

Mangroves and coastal marsh systems generally act as filters or traps for a number of elements, including nitrogen, phosphorus, trace elements, and heavy metals through combined interaction of the plants themselves, the soils, and the organisms that live there (Odum and McIvor, 1990; Estevez, 1998; Sklar and Browder, 1998). These elements may be stored in the wetlands for many years. This filtration reduces the amount of nutrients and potential pollutants entering the estuaries and marine system via runoff (Estevez, 1998; Sklar and Browder, 1998).

Mangroves and coastal marshes are a natural barrier to shoreline erosion because the plants trap, hold, and stabilize sediments (Carlton, 1974; Estevez, 1998; Montague and Wiegert, 1990; Odum *et al.*, 1982). In addition, they mitigate the impact of waves and storm surges, providing protection to inland areas (Badola and Hussain, 2005; Montague and Wiegert, 1990; Odum *et al.*, 1982). Barbier *et al.* (2008), in a worldwide study, found that mangroves protected coastal communities from tropical storms up to 5 km inland and that there was an exponential decrease in wave height with increasing mangrove distance inland from the shoreline. For salt marshes, they found a four-fold decrease in wave height with increasing distance inland (Barbier *et al.*, 2008).

Coastal wetlands provide globally important carbon reservoirs. It has been estimated that the litter fall in fringing mangrove swamps of South Florida ranges between 1.86 and 12.98 metric tons ha^{-1} yr^{-1} (Twilley *et al.*, 1986). These environments sequester more carbon per unit area (210 g CO_2 m^{-2} yr^{-1}) than freshwater marshes and peatlands (20-30 g CO_2 m^{-2} yr^{-1}) and release less methane gas because of the abundant presence of sulfates (Chmura *et al.*, 2003).

Overall, very little recent research has been conducted to estimate the value of the SWFS' ecosystem services. The most notable research related to the SWFS, the *Regional Socioeconomic Artificial Reef Project*, was conducted by Florida Sea Grant for the West Coast Inland Navigation District (Swett *et al.,* 2011).

The only other relatively recent study of socioeconomic values of some of the ecosystem services for part of the SWFS was conducted by Hazen and Sawyer for the Charlotte Harbor National Estuary Program (CHNEP) in 1998. The report is entitled *Estimated Economic Value of Resources* (Hazen and Sawyer, 1998). This study concluded that the estimated consumer surplus associated with water-based recreation activities, including fishing and non-use wetland values in the CHNEP study area that includes the coastal and surface water resources of Charlotte, Lee, Sarasota, and Polk counties, was $3.8 billion in 1998. This value does not include the expenditures made to participate in the recreation activities, which is part of the total value of water-based recreation to users. This study is still cited in CHNEP documents, in particular, the 2009 Comprehensive Southwest Florida/Charlotte Harbor Climate Change Vulnerability Assessment prepared by the Southwest Florida Regional Planning Council and the CHNEP (Technical Report 09-3).

Response: Taking Action

The *Response* element of the MARES DPSER model encompasses the activities for gathering information, decision making, and implementation by agencies charged with making policies and taking actions to manage the coastal marine environment. *Responses* also include changes in attitudes and perceptions of the environment and related changes in individual behavior that, while perhaps less purposeful than the activities of management agencies, can have a large effect on *Drivers* and *Pressures*. Actions that have the effect of altering *Drivers, Pressures,* or the *State* of the ecosystem introduce a mechanism for feedback and, thus, the possibility of control.

Protected Areas

Everglades National Park

Coordinated efforts to preserve the Florida Everglades as wilderness started early in the 20th century with the creation of protected areas (Figure 14). In 1916, Royal Palm State Park, located around the Royal Palm hammock about halfway between Florida City and Flamingo on the old Ingram Highway, was designated. Everglades National Park grew from this nucleus to enclose most of its current extent when dedicated in 1947. Goals for management of the park

Figure 14. Protected natural areas in the Southwest Florida Shelf region.

are to set aside a permanent wilderness, preserving essential primitive conditions including the natural abundance, diversity, behavior, and ecological integrity of the unique flora and fauna. This was the first national park dedicated for its biologic diversity. Establishment of Everglades National Park protected the southern half of the coast along the SWFS region from the direct effects of coastal development.

National Wildlife Refuges

J.N. "Ding" Darling National Wildlife Refuge Complex: The J.N. "Ding" Darling National Wildlife Refuge complex in Lee County consists of the Darling Refuge, located on Sanibel Island, and the nearby Caloosahatchee, Island Bay, Matlacha, and Pine Island National Wildlife refuges. The Darling Refuge was established in 1976 and encompasses 5200 acres of undeveloped mangrove forest. The refuge complex is managed to provide wildlife habitat, with special attention to providing habitat needed by the spring and fall migration of shorebirds.

Ten Thousand Islands National Wildlife Refuge: The Ten Thousand Islands National Wildlife Refuge in Collier County is located at the northern extend of the Ten Thousand Islands Province. The 35,000-acre refuge was established in 1996, and it surrounds the town of Marco Island and includes the Rookery Bay National Estuarine Research Reserve. Approximately two-thirds of the reserve is mangrove forest. The landscape in the remaining portion of the reserve is brackish marsh interspersed by ponds and hammocks of oak, cabbage palm, and tropical hardwoods. The refuge provides a habitat for endangered and threatened species, including the West Indies manatee, bald eagle, peregrin falcon, wood stork, and the Atlantic loggerhead, green, and Kemp's Ridley turtles.

Florida State Parks

Florida's system of state parks was established in 1925 to preserve areas of natural beauty, historical sites, and memorials. Beginning in the 1970s, the emphasis shifted to implementing natural systems management aimed at restoring and maintaining natural biological communities and processes while also providing for public access and use of the parks. The SWFS region includes the following Florida state parks:

- Barefoot Beach State Preserve
- Cayo Costa State Park
- Charlotte Harbor Preserve State Park
- Delnor-Wiggins Pass State Park
- Estero Bay Preserve State Park
- Mound Key Archeological State Park
- Stump Pass Beach State Park

Florida State Aquatic Preserves

Florida's system of aquatic preserves was established in 1975 for the purpose of preserving the aesthetic, biological, and scientific values of the protected areas for the enjoyment of future generations. Some of the preserves along the southwest coast were established prior to this date. Aquatic preserves protect submerged lands that provide critical nursery and feeding habitat needed to support coastal fisheries and marine wading birds. Aquatic preserves also protect areas of cultural value, archaeological and historic sites, and provide opportunities for recreation, e.g., swimming, fishing, and boating. The SWFS region includes the following aquatic preserves.

- Cape-Romano–Ten Thousand Islands Aquatic Preserve
- Estero Bay Aquatic Preserve
- Mattacha Pass Aquatic Preserve
- Gasparilla Sound–Charlotte Harbor Aquatic Preserve
- Cape Haze Aquatic Preserve
- Pine Island Sound Aquatic Preserve

Ecosystem Research and Monitoring

Rookery Bay National Estuarine Research Reserve

The Rookery Bay National Estuarine Research Reserve in Collier County is located at the northern extent of the Ten Thousand Islands Province. The reserve encompasses 110,000 acres of mangrove forest, upland and estuarine, and inshore coastal waters surrounding the town of Marco Island. The Florida Department of Environmental Protection and NOAA jointly manage research at the reserve. The goal is to provide information needed in management decisions for ecosystem restoration and coastal management, education, and outreach to promote coastal stewardship.

Charlotte Harbor National Estuary Program

The Charlotte Harbor National Estuary Program coordinates management activities to improve water quality and ecological integrity of the Greater Charlotte Harbor estuarine system. The geographic area covered by this program, 4,700 square miles, encompasses the estuarine waters of Charlotte Harbor, Lemon Bay, and Estero Bay, and the watersheds of three large rivers: the Myakka, Peace, and Caloosahatchee. The governing management council for the program represents citizens, non-profit groups, and the state and federal agencies responsible for environmental management in the area.

Hydrologic Restoration

The Southwest Florida Water Management District and the South Florida Water Management District implement Florida state water policy through various programs. Ongoing programs that affect the SWFS coastal marine ecosystem include the Lower Charlotte Harbor Surface Water Improvement and Management (SWIM) Plan, the Caloosahatchee River minimum flows and levels criteria, and the Picayune Strand restoration project.

The Lower Charlotte Harbor SWIM plan implements a watershed-based approach to protect the estuarine and nearshore waters of Charlotte Harbor from impacts of point and non-point source pollution and the resulting loss of aquatic habitats. The plan outlines initiatives related to mitigating sources of pollution, restoring a more natural hydrologic regime for freshwater inflows by managing stormwater, implementing a watershed master plan, and protecting and restoring SAV and shellfish habitats in the estuary.

The Caloosahatchee River minimum flows and levels criteria prescribe minimum flows that must be maintained in the Caloosahatchee River during drought to avoid significant harm to the ecology of the river and estuary. Flows in the Caloosahatchee River are controlled by regulating discharge from Lake Okeechobee through the S-79 structure, upstream from Fort Myers. It is recognized that setting minimum flows alone does not suffice to avoid significant ecological harm to the river and estuary. Maximum flow criteria are also being considered in implementing a regional water supply plan, which includes setting a maximum water level for Lake Okeechobee.

The Picayne Strand restoration project is a component of CERP, the cooperative effort led by the South Florida Water Management District and the U.S. Army Corps of Engineers to restore a more natural hydrologic regime in the remaining portion of the Florida Everglades. Restoring the hydrology of the Everglades benefits the coastal marine environment impacted by altered freshwater inflows. The Picayune Strand project seeks to reverse hydrologic changes on a large tract of land in Collier County that was drained for development. The restoration project is plugging the drainage canals. This will increase groundwater recharge, reduce the large, unnatural inflows into the downstream estuaries, and improve estuarine water quality.

Regulation of the Commercial Fishery

The story of fisheries activity in Collier and Lee counties is one of moving from unregulated fisheries to overfishing and subsequent management with regulations. This story is written in the landings data, which show the effects of changes in fisheries management. Fishery landings data maintained by the National Marine Fisheries Service, Southeast Fisheries Science Center, in collaboration with the Florida Fish and Wildlife Conservation Commission, started in 1962 and are ongoing. The landings data show the highest landings in the earliest years of the fishery, a gradual decline in response to a fished stock, and a more abrupt decline when regulations went into effect (Table 4).

Different species have dominated the landings almost by decades. In offshore fishing, mackerel was king in the 1970s before the fishery was declared seriously overfished in the 1980s, and a series of state and federal regulations gradually were set in place. Pink shrimp, caught on both Tortugas and Sanibel grounds, became king of offshore landings in Lee County. Red grouper and other snapper and grouper species became a prominent part of the landings from the SWFS in the mid 1980s. These species declined, however, when gear restrictions and other regulations were imposed on both state and federal waters in the mid 1990s. The use of bottom trawls for catching reef fish species was prohibited, and fish traps were banned in 2005.

Silver mullet was the major fishery species in inshore waters in both Collier and Lee counties until the monofilament gillnet was banned for use in most fishing operations in state waters by Constitutional amendment and became effective

Table 4. Average annual landings and ex-vessel value, by decade, in Collier and Lee counties.

	Collier		Lee	
Year	Pounds	Dollars	Pounds	Dollars
1962-1970*	7,030,288	856,439	17,210,931	4,270,830
1971-1980	4,977,514	1,983,576	16,381,833	10,516,951
1981-1990	4,694,588	5,319,458	13,139,891	15,136,392
1991-2000	4,095,861	6,869,130	10,520,219	17,372,006
2001-2010	1,940,075	5,042,877	6,259,558	11,097,070

*The first year of the decade is missing from the first period 1962-1970.

statewide in 2003. Mullet dominated landings records in both Collier and Lee counties in the first four decades of the record, almost always accounting for more than 2 million pounds annually in Collier County landings and 4 million pounds annually in Lee County landings. The gillnet ban affected not only mullet landings, but also commercial catches of other inshore species such as spotted seatrout, pompano, and crevalle jack. These species are still caught in southwest Florida, but on a smaller scale.

Based on both landings and value averaged for the past 10 years, stone crab claws, taken from offshore waters, are the leading fishery product in Collier County today. Other major species in offshore landings in Collier County are king, cero, and Spanish mackerel (combined landings), pompano, sharks of various species, and Caribbean spiny lobster. Striped mullet (marketed as flesh and roe) and blue crab are the major species harvested from inshore waters and landed in Collier County today. Averaged for the past 10 years, these species alone make up more than 96 percent of the ex-vessel landings value in Collier County, i.e., $1,871,261.

Pink shrimp is the major fishery species landed in Lee County, making up 51 percent of landings as food shrimp, followed by red grouper and stone crab claws offshore and striped mullet (marketed as flesh and roe) and blue crab inshore. Other species contributing the most to Lee County landings are tenpounders, brown shrimp (probably brought into the region from the northen Gulf of Mexico by migrating shrimp vessels), shrimp harvested as bait, rock shrimp, pompano, mojarras, and crevalle jack. Together, the above species make up slightly more than 95 percent of Lee County landings. With a few other species of higher value (i.e., gag and black grouper, Atlantic littleneck and middleneck clams, king and cero mackerel, and pinfish), they make up almost 98 percent of Lee County landings value.

While total landings decreased by decade, ex-vessel values increased through the next to last decade (1991-2000) in both Collier and Lee counties (Table 4). Decreases in landings of stone crab claws, blue crab, striped mullet, king and cero mackerel, and red grouper appear to be the reason for the decrease in Collier landings in the last decade. A large reduction in red grouper landings, a slight reduction in blue crab landings, and a decrease in the average price of shrimp appear to be the main reasons for the decline in ex-vessel fishery value in Lee County in the last decade (2001-2010).

References

Agami, M., and Y. Waisel. 1988. The role of fish in distribution and germination of seeds of the submerged macrophytes *Najas marina L.* and *Ruppia maritima L.* Oecologia, 76:83-88.

Albins, M.A., and M.A. Hixon. 2008. Invasive Indo-Pacific lionfish *Pterois volitans* reduce recruitment of Atlantic coral reef fishes. Marine Ecology Progress Series, 367:233-238.

Allison, I., N.L. Bindoff, R.A. Bindschadler, P.M. Cox, N. de Noblet, M.H. England, J.E. Francis, N. Gruber, A.M. Haywood, D.J. Karoly, G. Kaser, C. Le Quéré, T.M. Lenton, M.E. Mann, B.I. McNeil, A.J. Pitman, S. Rahmstorf, E. Rignot, H.J. Schellnhuber, S.H. Schneider, S.C. Sherwood, R.C.J. Somerville, K. Steffen, E.J. Steig, M. Visbeck, and A.J. Weaver. 2009. *The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science.* The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 60 pp.

Anderson, D.M., J.M. Burkholder, W.P. Cochlan, P.M. Glibert, C.J. Gobler, C.A. Heil, R.M. Kudela, M.L. Parsons, J.E.J. Rensel, D.W. Townsend, V.L. Trainer, and G.A. Vargo. 2008. Harmful algal blooms and eutrophication: Examining linkages from selected coastal regions of the United States. Harmful Algae, 8(1):39-53.

Ashton, D.C., and D.B. Eggleston. 2008. Juvenile fish densities in Florida Keys mangroves correlate with landscape characteristics. Marine Ecology Progress Series, 362:233-243.

Atkins, J.P., D. Burdon, M. Elliott, and A.J. Gregory. 2011. Management of the marine environment: Integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. Marine Pollution Bulletin, 62:215-226 (doi:10.1016/j.marpolbul.2010.12.012).

Aumann, H.H., A. Ruzmaikin, and J. Teixeira. 2008. Frequency of severe storms and global warming. Geophysical Research Letters, 35:L19805 (doi: 10.1029/2008GL034562), 4 pp.

Badola, R., and S.A. Hussain. 2005. Valuing ecosystem functions: An empirical study on the storm protection function of Bhitarkanika mangrove ecosystem, India. Environmental Conservation, 32:85-92.

Barbier, E.B., E.W. Koch, and B.R. Silliman. 2008. Coastal ecosystem-based management with nonlinear ecological function and values. Science, 319:321-323.

Browder, J.A. 1984. Wood stork feeding areas in southwest Florida. Florida Field Naturalist, 12:81-96.

Browder, J.A., A. Dragovich, J. Tashiro, E. Coleman-Duffie, C. Foltz, and J. Zweifel. 1986. A comparison of biological abundances in three adjacent bay systems downstream from the Golden Gate Estates canal system. NOAA Technical Memorandum, NMFS-SEFC-185, 26 pp.

Bureau of Census. 2010. Available from http://www.bebr.ufl.edu/content/census-population-counts-county-and-city-florida-2000-2010-new).

Cannicci, S., D. Burrows, S. Fratini, T.J. Smith, III, J. Offenberg, and F. Dahdouh-Guebas. 2008. Faunal impact on vegetation structure and ecosystem function in mangrove forests: A review. Aquatic Botony, 89(2):186-200.

Carlton, J.M. 1974. Land-building and stabilization by mangroves. Environmental Conservation, 1:285-294.

Carter, M.R., L.A. Burns, T.R. Cavinder, K.R. Dugger, P.L. Fore, D.B. Hicks, H.L. Revells, and T.W. Schmidt. 1973. Ecosystems analysis of the Big Cypress swamp and estuaries. U.S. Environmental Protection Agency, Region IV, Atlanta GA, Report EPA 904/9-74-002.

Carver, E. 2009. Birding in the United States: A demographic and economic analysis. Addendum to the 2006 National Survey of Fishing, Hunting, and Wildlife Associated Recreation. U.S. Fish and Wildlife Service, Report No. 2006-4.

Charlotte Harbor National Estuary Program. 2008. The Comprehensive Conservation and Management Plan. Adopted by the CHNEP Policy Committee on April 13, 2000 and updated March 24, 2008. Charlotte Harbor National Estuary Program, Fort Myers, FL.

Chen, S., W. Huang, H. Wang, and D. Li. 2009. Remote sensing assessment of sediment resuspension during Hurricane Frances in Apalachicola Bay, USA. Remote Sensing of Environment, 113:2670-2681.

Cheong, S. 2008. A new direction in coastal management. Marine Policy, 32:1090-1093.

Childers, D.L., J.N. Boyer, S.E. Davis, C.J. Madden, D.T. Rudnick, and F.H. Sklar. 2006. Relating precipitation and water management to nutrient concentrations in the oligotrophic "upside-down" estuaries of the Florida Everglades. Limnology and Oceanography, 51:602-616.

Chmura, G.L., S.C. Anisfeld, D.R. Cahoon, and J.C. Lynch. 2003. Global carbon sequestration in tidal saline wetland soils. Global Biogeochemical Cycles, 17:22-1 to 22-12.

Church, J.A., and N.J. White. 2006. A 20th century acceleration in global sea-level rise. Geophysical Research Letters, 33:L01602 (doi:10.1029/2005GL024826), 4 pp.

Comp, G.S., and W. Seaman, Jr. 1985. Estuarine habitat and fishery resources of Florida. In *Florida Aquatic Habitat and Fishery Resources*, W. Seaman, Jr. (ed.). Florida Chapter of the American Fisheries Society, Eustis, FL, 337-435.

Costanza, R., and C. Folke. 1997. Valuing ecosystem services with efficiency, fairness, and sustainability as goals. In *Nature's Services: Societal Dependence on Natural Ecosystems,* G. Daily (ed.). Island Press, Washington, DC, 392 pp.

Cote, I.M., and A. Maljkovic. 2010. Predation rates of Indo-Pacific lionfish on Bahamian coral reefs. Marine Ecology Progress Series, 404:219-225.

Davis, S.M., D.L. Childers, J.J. Lorenz, H.R. Wanless, and T.E. Hopkins. 2005. A conceptual model of ecological interactions in the mangrove estuaries of the Florida Everglades. Wetlands, 25(4):832-842.

El-Ashry, M.T., and H.R. Wanless. 1965. Birth and early growth of a tidal delta. The Journal of Geology, 73(2):404-406.

Estevez, E. 1998. The story of the greater Charlotte Harbor watershed. Charlotte Harbor National Estuary Program, Fort Myers, FL, 144 pp.

Ewel, K.C., R.R. Twilley, and J.E. Ong. 1998. Different kinds of mangrove forests provide different goods and services. Global Ecology and Biogeography Letters, 7:83-94.

Farber, S., R. Costanza, D.L. Childers, J. Erickson, K. Gross, M. Grove, C.S. Hopkinson, J. Kahn, S. Pincetl, A. Troy, P. Warren, and M. Wilson. 2006. Linking ecology and economics for ecosystem management. Bioscience, 56:121-133.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Millero. 2004. Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. Science, 305:362-366.

Field, D.W., A.J. Reyer, P.V. Genovese, and B.D. Shearer. 1991. Coastal wetlands of the United States: An accounting of a valuable national resource. NOAA Special Report, 59 pp.

Florida Fish and Wildlife Conservation Commission. 2010. Boating accidents statistical report (available at http://myfwc.com/media/1406840/2010_boating_statbook_final1.pdf).

Fratantoni, P.S., T.N. Lee, G. Podesta, and F. Muller-Karger. 1998. The influence of Loop Current perturbations on the formation and evolution of Tortugas eddies in the southern Straits of Florida. Journal of Geophysical Research, 103(C11):24,759-24,779.

Gunderson, L.H., and J.R. Snyder. 1994. Fire patterns in the southern Everglades. In *Everglades: The Ecosystem and Its Restoration,* S.M. Davis and J.C. Ogden (eds.). St. Lucie Press, Boca Raton, FL, 291-305.

Hall-Spencer, J.M., R. Rodolfo-Metalpa, S. Martin, E. Ransome, M. Fine, S.M. Turner, S.J. Rowley, D. Tedesco, and M. Buia. 2008. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. Nature, 454:96-99.

Hamilton, P., and T.N. Lee. 2005. Eddies and jets over the slope of the northeast Gulf of Mexico. In *Circulation in the Gulf of Mexico: Observations and Models,* W. Sturges and A. Lugo-Fernandez (eds.). Geophysical Monograph Series, AGU, Washington, DC, 161:123-142 (doi:10.1029/161GM010).

Hazen and Sawyer. 1998. Estimated economic value of resources. Report prepared for the Charlotte Harbor National Estuary Program, North Fort Myers, FL, March 5, 1998.

Heald, E.J., W.E. Odum, and D.C. Tabb. 1984. Mangroves in the estuarine food chain. In *Environments of South Florida Present and Past II,* P.J. Gleason (ed.). Miami Geological Society, Coral Gables, FL, 149-156.

Hendriks, I.E., C.M. Duarte, and M. Álvarez. 2010. Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. Estuarine, Coastal and Shelf Science, 86(2):157-164.

Hetland, R.D., Y. Hsueh, R. Leben, and P.P. Niiler. 1999. A Loop Current-induced jet along the edge of the West Florida Shelf. Geophysical Research Letters, 26:2239-2242.

Hitchcock, G.L., T.N. Lee, P.B. Ortner, S. Cummings, C. Kelble, and E. Williams. 2005. Property fields in a Tortugas eddy in the southern Straits of Florida. Deep-Sea Research, Part I, 52(12):2195-2213.

Hobbs, F., and N. Stoops. 2002. Demographic trends in the 20th century, U.S. Census Bureau, Census 2000 Special Reports, Series CENSR-4. U.S. Government Printing Office, Washington, DC (available at www.census.gov/prod/2002pubs/CENSR-4.pdf) (Accessed 02 Jan 2012).

Hoye, B.R. 2009. Holocene history of the coastal geomorphology of Everglades National Park: The roles of reef development, tidal pond formation, and sea-level rise. M.S. Thesis, Florida Gulf Coast University, Ft. Myers, FL, 210 pp.

Hu, C., K.E. Hackett, M.K. Callahan, S. Andréfouët, J.L. Wheaton, J.W. Porter, and F.E. Muller-Karger. 2003. The 2002 ocean color anomaly in the Florida Bight: A cause of local coral reef decline. Geophysical Research Letters, 30:1151 (doi:10.1029/2002GL016479), 4 pp.

IPCC (Intergovernmental Panel on Climate Change). 2007. Summary for Policymakers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4),* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, Cambridge, UK and New York, NY, 996 pp.

Johns, G.M., V.R. Leeworthy, F.W. Bell, and M.A. Bonn. 2001. Socioeconomic study of reefs in southeast Florida. Broward County Environmental Protection Department, Final Report, Technical Report No. 01-10 (available at http://www.dep.state.fl.us/coastal/programs/coral/pub/Reef_Valuation_DadeBrowardPBMonroe2001.pdf) (Accessed 17 April 2012).

Karl, H.A., L.E. Susskind, and K.H. Wallace. 2007. A dialogue, not a diatribe: Effective integration of science and policy through joint fact finding. Environment, 49(1):20-34.

Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, and L.L. Robbins. 2006. Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research. Report of a workshop sponsored by NSF, NOAA, and the U.S. Geological Survey. St. Petersburg, FL, 88 pp.

Koelsch, J.K., and T.D. Pitchford. 1998. Florida manatee (*Trichechus manatus latirostris*) in Charlotte Harbor. *Proceedings, 1997 Charlotte Harbor Public Conference and Technical Symposium,* S.F. Treat (ed.). Charlotte Harbor National Estuary Program, Technical Report No. 98-02, 171-185.

Kraemer, G.P., R.H. Chamberlain, P.H. Doering, A.D. Steinman, and M.D. Hanisak. 1999. Physiological responses of *Vallisneria americana* transplants along a salinity gradient in the Caloosahatchee Estuary (SW Florida). Estuaries, 22:138-148.

Kushlan, J.A., and P.C. Frohring. 1986. The history of the southern Florida wood stork population. Wilson Bulletin, 98(3):368-386.

Lee, T.N. 1975. Florida Current spin-off eddies. Deep-Sea Research, 22(11):753-763.

Lee, T.N., and D.A. Mayer. 1977. Low-frequency current variability and spin-off eddies on the shelf off southeast Florida. Journal of Marine Research, 35(1):193-220.

Lee, T.N., and E. Williams. 1999. Mean distribution and seasonal variability of coastal currents and temperature in the Florida Keys with implications for larval recruitment. *Bulletin of Marine Science,* 64(1):35-56.

Lee, T.N., J.A. Yoder, and L.P. Atkinson. 1991. Gulf Stream frontal eddy influence on productivity of the southeast U.S. continental shelf. Journal of Geophysical Research, 96:22,191-22,205.

Lee, T.N., E. Williams, E. Johns, D. Wilson, and N.P. Smith. 2002. Transport processes linking south Florida coastal ecosystems. In *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook,* J. W. Porter and K.G. Porter (eds.). CRC Press, Boca Raton, FL, 309-342.

Leeworthy, V.R., and J.M. Bowker. 1997. Non-market economic user values of the Florida Keys/Key West: Linking the economy and environment of Florida Keys/Florida Bay. National Oceanic and Atmospheric Administration, United States Department of Agriculture, Forest Service.

Lewis, R.R., R.G. Gilmore, D.W. Crewz, and W.E. Odum. 1988. Mangrove habitat and fishery resources of Florida. In *Florida Aquatic Habitat and Fishery Resources,* Florida Chapter of the American Fisheries Society, Eustis, FL, 281-336.

Liu, Z., J. Kutzbach, and L. Wu. 2000. Modeling climate shift of El Niño variability in the Holocene. Geophysical Research Letters, 27(15):2265-2268 (doi:10.1029/2000GL011452).

Lodge, D.M. 1991. Herbivory on freshwater macrophytes. Aquatic Botany, 41:195-224.

Lorenz, J.J. 1999. The response of fishes to physicochemical changes in the mangroves of northeast Florida Bay. Estuaries, 22:500-517.

Lorenz, J.J., J.C. Ogden, R.D. Bjork, and G.V.N. Powell. 2002. Nesting patterns of roseate spoonbills in Florida Bay 1935-1999: Implications of landscape scale anthropogenic impacts. In *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook,* J.W. Porter and K.G. Porter (eds.). CRC Press, Boca Raton, FL, 563-606.

Lubchenco, J. 1999. Entering the century of the environment: A new social contract for science. Science, 279:491-497.

Lubchenco, J., and N. Sutley. 2010. Proposed U.S. Policy for ocean, coast, and Great Lakes stewardship. Science, 328:1485-1486.

Lugo, A.E., and S.C. Snedaker. 1974. The ecology of mangroves. Annual Review Ecological Systematics, 5:39-63.

Mangi, S.C., C.M. Roberts, and L.D. Rodwell. 2007. Reef fisheries management in Kenya: Preliminary approach using the Driver-Pressure-State-Impacts-Response (DPSIR) scheme of indicators. Ocean Coastal Management, 50:463-480.

Manson, F.J., N.R. Loneragen, G.A. Skilleter, and S.R. Phinn. 2005. An evaluation of the evidence for linkages between mangroves and fisheries: A synthesis of the literature and identifications of research directions. Oceanography and Marine Biology: An Annual Review, 43:485-515.

Manzello, D.P., J.A. Kleypas, D.A. Budd, C.M. Eakin, P.W. Glynn, and C. Langdon. 2007. Poorly cemented coral reefs of the eastern tropical Pacific: Possible insights into reef development in a high-CO_2 world. Proceedings of the National Academy of Sciences USA, 105(30):10,450-10,455.

McPherson, B.F., and R.L. Miller. 1990. Nutrient distribution and variability in the Charlotte Harbor estuarine system, Florida. Water Research Bulletin, 26:67-80.

Mitchum, G.T., and W. Sturges. 1982. Wind-driven currents on the West Florida Shelf. Journal of Physical Oceanography, 12:1310-1317.

Montague, C.L., and R.G. Wiegert. 1990. Salt Marshes. In *Ecosystems of Florida*, R.L. Myers and J.J. Ewel (eds.). University of Central Florida Press, Orlando, FL, 481-516.

Morgan, K.L., S.L. Larkin, and C. A. Adams. 2010. Red tides and participation in marine-based activities: Estimating the response of southwest Florida residents. Harmful Algae, 9(3):333-341.

Murley, J.F., L. Alpert, M.J. Matthews, C. Bryk, B. Woods, and A. Grooms. 2003. Economics of Florida's beaches: The impact of beach restoration. Florida Atlantic University, Catanese Center for Urban and Environmental Solutions, 141 pp.

Newman, R.M. 1991. Herbivory and detritivory on freshwater macrophytes by invertebrates: A review. Journal of the North American Benthological Society, 10(2):89-114.

Nixon, S.W. 1980. Between coastal marshes and coastal waters: A review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. In *Estuarine and Wetland Processes,* P. Hamilton and K. MacDonald (eds.). Plenum Press, New York, 437-525.

Odum, W.E., and E.J. Heald. 1975. The detritus-based food web of an estuarine mangrove community. In *Estuarine Research,* L.E. Cronin (ed.). Academic Press, New York, 265-286.

Odum, W.E., and C.C. McIvor. 1990. Mangroves. In *Ecosystems of Florida,* R.L. Myers and J.J. Ewel (eds). University of Central Florida Press, Orlando, FL, 517-548.

Odum, W.C., C.C. McIvor, and T.J. Smith, III. 1982. The ecology of mangroves of South Florida: A community profile. U.S. Fish and Wildlife Service, Office of Biological Services, FES/OBS-81-24.

OECD (Organisation for Economic Development and Cooperation). 1993. Core set of indicators for environmental performance reviews. Environment Monograph, No. 83, Paris (Accessed 17 April 2012).

Ogden, J.C. 1994. A comparison of wading bird nesting colony dynamics (1931-1946 and 1974-1989) as an indication of ecosystem conditions in the southern Everglades. In *Everglades, the Ecosystem and Its Restoration,* S.M. Davis and J.C. Ogden (eds.). St. Lucie Press, Boca Raton, FL, 533-570.

Ogden, J.C., S.M. Davis, K.J. Jacobs, T. Barnes, and H.E. Fling. 2005. The use of conceptual ecological models to guide ecosystem restoration in South Florida. Wetlands, 25:795-809.

Ortner, P.B., R.L. Ferguson, S.R. Piotrowicz, L. Chesal, G.A. Berberian, and A.V. Palumbo. 1984. Biological consequences of hydrographic and atmospheric advection within the Gulf Loop Intrusion. Deep-Sea Research, 31:1101-1120.

Ortner, P.B., T.N. Lee, P.J. Milne, R.G. Zika, M.E. Clarke, G.P. Podesta, P.K. Swart, P.A. Tester, L.P. Atkinson, and W.R. Johnson. 1995. Mississippi River flood waters that reached the Gulf Stream. Journal of Geophysical Research, 100(C7):13,595-13,601.

Paerl, H.W., R.L. Dennis, and D.R. Whitall. 2002. Atmospheric deposition of nitrogen: Implications for nutrient over-enrichment of coastal waters. Estuaries, 25:677-693.

Palacios, S.L., and R.C. Zimmerman. 2007. Response of eelgrass *Zostera marina* to CO_2 enrichment: Possible impacts of climate change and potential for remediation of coastal habitats. Marine Ecology Progress Series, 344:1-13.

Paluszkiewicz, T., L.P. Atkinson, E.S. Posmentier, and C.R. McClain. 1983. Observations of a Loop Current frontal eddy intrusion onto the West Florida Shelf. Journal of Geophysical Research, 88(C14):9639-9651 (doi:10.1029/JC088iC14p09639).

Parkinson, R.W. 1989. Decelerating Holocene sea-level rise and its influence on southwest Florida coastal evolution; a transgressive/regressive stratigraphy. Journal of Sedimentary Petrology, 59(6): 960-972.

Perlmutter, M.A. 1982. The recognition and reconstruction of storm sedimentation [unpubl. Ph.D. dissert.]. University of Miami.

Popowski, R., J.A. Browder, M. Shirley, and M. Savarese. 2004. Hydrological and ecological performance measures and targets for the Faka Union canal and bay. Final Draft Performance Measures: Faka Union Canal. U.S. Fish and Wildlife Service, Technical Document, 22 pp.

Powell, G.V.N. 1987. Habitat use by wading birds in a subtropical estuary: Implications of hydrography. Auk, 104:740-749.

RECOVER (Restoration Coordination and Verification). 2007. Development and application of Comprehensive Everglades Restoration Plan system-wide performance measures. South Florida Water Management District, West Palm Beach, FL and U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, October 12, 2007 (available at http://www.evergladesplan.org/pm/recover/perf_systemwide.aspx).

Risi, J.A., H.R. Wanless, L.P. Tedesco, and S. Gelsanliter. 1995. Catastrophic sedimentation from Hurricane Andrew along the southwest Florida coast. Journal of Coastal Research, S1(21):83-102.

Savarese, M., A. Volety, and S.G. Tolley. 2004. Oyster health and habitat quality in Fakahatchee Estuary: Establishing a baseline performance for Ten Thousand Islands estuarine restoration. South Florida Water Management District, Technical Report, 27 pp.

Scholl, D.W. 1963. Sedimentation in modern coastal swamps, southwestern Florida. Bulletin of the American Association of Petroleum Geologists, 47(8):1581-1603.

SFWMD (South Florida Water Management District). 1996. Hydrological restoration of Southern Golden Gates Estates. Final Report, Big Cypress Basin Board, 206 pp.

Shirley, M., P. O'Donnell, V. McGee, and T. Jones. 2005. Nekton species composition as a biological indicator of altered freshwater inflow into estuaries. In *Estuarine Indicators,* S.A. Bortone (ed.). CRC Press, Boca Raton, FL, 351-364.

Sidman, C., T. Fik, R. Swett, B. Sargent, S. Fann, and D. Fann. 2009. A recreational boating characterization for Collier County. Florida Sea Grant, University of Florida, Gainesville, FL, Report TP 168.

Sklar, F.H., and J.A. Browder. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. Environmental Management, 22:547-562.

Smith, T.J., III, M.B. Robblee, H.R. Wanless, and T.W. Doyle. 1994. Mangroves, hurricanes, and lightning strikes. Bioscience, 44:256-262.

Smith, T.J., III, G.H. Anderson, K. Balentine, G. Tiling, G.A. Ward, and K.R.T. Whelan. 2009. Cumulative impacts of hurricanes on Florida mangrove ecosystems: Sediment deposition, storm surges, and vegetation. Wetlands, 29:24-34.

Southeast Florida Regional Climate Change Compact. 2011. Available at www.broward.org/NATURALRESOURCES/CLIMATECHANGE/Pages/SoutheastFloridaRegionalClimateCompact.aspx (Accessed 10 November 2011).

South Florida Economic Forecasting Paternship. 2006. Available at http://www.sfrpc.com/remi.htm (Accessed 17 April 2012).

Southwick, R., and T. Allen. 2008. The 2006 economic benefits of wildlife viewing recreation in Florida. Report to the Florida Fish and Wildlife Conservation Commission. Available from: http://myfwc.com/media/131044/WldlfViewing_economics_report.pdf. (Accessed 02 Jan 2012).

Sponaugle, S., T.N. Lee, V. Kourafalou, and D. Pinkard. 2005. Florida Current frontal eddies and the settlement of coral reef fishes. Limnology and Oceanography, 50(4):1033-1048.

Steidinger, K.A., G.A. Vargo, P.A. Tester, and C.R. Tomas. 1998. Bloom dynamics and physiology of *Gymnodinium breve* with emphasis on the Gulf of Mexico. In *Physiological Ecology of Harmful Algal Blooms,* D. M. Anderson, A.D. Cembella, and G.M. Hallegraeff (eds.). Springer-Verlag, Berlin, 133-153.

Surge, D.M., K.C. Lohmann, and G.A. Goodfriend. 2003. Reconstructing estuarine conditions: Oyster shells as recorders of environmental change, southwest Florida. Estuarine, Coastal and Shelf Science, 57(5-6):737-756.

Swett, R.A., C. Adams, S. Larkin, A.W. Hodges, and T.J. Stevens. 2011. Economic impacts of artificial reefs for six southwest Florida counties. Florida Sea Grant TP-178 (available at http://nsgl.gso.uri.edu/flsgp/flsgps11002.pdf).

Tedesco, L.P., H.R. Wanless, L.A. Scusa, J.A. Risi, and S. Gelsanliter. 1995. Impact of Hurricane Andrew on south Florida's sandy coastlines: Impact of Hurricane Andrew on the coastal zones of Florida and Louisiana, 22-26 August 1992. Journal of Coastal Research, Special Issue 21:59-82.

Thayer, G.W., and A.J. Chester. 1989. Distribution and abundance of fishes among basin and channel habitats in Florida Bay. Bulletin of Marine Science, 44:200-219.

Trap, R.J., N.S. Diffenbaugh, H.E. Brooks, M.E. Baldwin, E.D. Robinson, and J.S. Pal. 2007. Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. Proceedings of the National Academy of Sciences USA, 104:19,719-19,723.

Tscherning, K., K. Helming, B. Krippner, S. Sieber, and S. Gomez y Paloma. 2012. Does research applying the DPSIR framework support decision making. Land Use Policy, 29:102-110.

Turner, R.K. 2000. Integrating natural and socio-economic science in coastal management. Journal of Marine Systems, 25:447-460.

Twilley, R.R. 1985. The exchange of organic carbon in basin mangrove forests in a southwest Florida estuary. Estuarine, Coastal and Shelf Science, 20:543-557.

Twilley, R.R. 1988. Coupling of mangroves to the productivity of estuarine and coastal waters. In *Coastal-Offshore Ecosystem Interactions,* B.O. Jansson (ed.). Springer-Verlag, Germany, 155-180.

Twilley, R.W., A.E. Lugo, and C. Patterson-Zucca. 1986. Litter production and turnover in basin mangrove forests in southwest Florida. Ecology, 67:670-683.

Vargo, G.A. 2009. A brief summary of the physiology and ecology of *Karenia brevis* red tides on the West Florida Shelf and of hypotheses posed for their initiation, growth, maintenance, and termination. Harmful Algae, 8:573-584.

Vargo, G.A., C.A. Heil, K.A. Fanning, L.K. Dixon, M.B. Neely, K.A. Lester, D. Ault, S. Murasko, J.A. Havens, J.J. Walsh, and S. Bell. 2008. Nutrient availability in support of *Karenia brevis* blooms on the central West Florida Shelf: What keeps *Karenia* blooming? Continental Shelf Research, 28:73-98.

Visser, L. 1999. Coastal zone management from the social scientific perspective. Journal of Coastal Conservation, 5:145-148.

Volety, A.K., and M. Savarese. 2001. Oysters as indicators of ecosystem health: Determining the impacts of watershed alterations and implications for restoration. Final Report submitted to National Fish and Wildlife Foundation, South Florida Water Management District (Big Cypress Basin), and Florida Gulf Coast University Foundation, 104 pp.

Volety, A.K., M. Savarese, B. Hoye, and A.N. Loh. 2009. Landscape pattern: Present and past distribution of oysters in South Florida coastal complex (Whitewater Bay/Oyster Bay/Shark to Robert's Rivers). South Florida Water Management District, Technical Report, 105 pp. + 46 figs.

Walsh, J.J., and K.A. Steidinger. 2001. Saharan dust and Florida red tides: The cyanophyte connection. Journal of Geophysical Research, 106:11,597-11,612.

Walsh, J.J., J.K. Jolliff, B.P. Darrow, J.M. Lenes, S.P. Milroy, D.A. Dieterle, K.L. Carder, F.R. Chen, G.A. Vargo, R.H. Weisberg, K.A. Fanning, F.E. Muller-Karger, K.A. Steidinger, C.A. Heil, C.R. Tomas, J.S. Prospero, T.N. Lee, G.J. Kirkpatrick, T.E. Whitledge, D.A. Stockwell, T.A. Villareal, A.E. Jochens, and P.S. Bontempi. 2006. Red tides in the Gulf of Mexico: Where, when and why? Journal of Geophysical Research, 111:11,003-11,039.

Walsh, J.J., R.H. Weisberg, J.M. Lenes, F.R. Chen, D.A. Dieterle, L. Zheng, K.L. Carder, G.A. Vargo, J.A. Havens, E. Peebles, D.J Hollander, R. He, C. Heil, B. Mahmoudi, and J. H. Landsberg. 2009. Isotopic evidence for dead fish maintenance of Florida red tides, with implications for coastal fisheries over both source regions of the West Florida Shelf and within downstream waters of the South Atlantic Bight. Progress in Oceanography, 70:51-73 (doi:10.1015/j.pocean.2008.12.005).

Wanless, H.R., R.W. Parkinson, and L.P. Tedesco. 1994. Sea level control on stability of Everglades wetlands. In *Everglades: The Ecosystem and Its Restoration,* S.M. Davis and J.C. Ogden (eds.). St. Lucie Press, Boca Raton, FL, 199-224.

Wanless, H.R., P. Oleck, L.P. Tedesco, and B.E. Hall. 2000. The next 100 years of evolution of the Greater Everglades ecosystem in response to anticipated sea level rise: Nature, extent, and causes. Greater Everglades Ecosystem Restoration Science Conference, Abstracts, 174-176.

Wegner, G., and U. Pascual. 2011. Cost-benefit analysis in the context of ecosystem services for human well-being: A multidisciplinary critique. Global Environmental Change, 21:492-504.

Weinstein, M.P. 2009. The road ahead: The sustainability transition and coastal research. Estuaries and Coasts, 32:1044-1053.

Weisberg, R.H., B.D. Black, and H. Yang. 1996. Seasonal modulation of the West Florida Shelf circulation. Geophysical Research Letters, 23:2247-2250.

Whitfield, P.E., T. Gardner, S.P. Vives, M.R. Gilligan, W.R. Courtenay, G.C. Ray, and J.A. Hare. 2002. Biological invasion of the Indo-Pacific lionfish, *Pterois volitans,* along the Atlantic coast of North America. Marine Ecology Progress Series, 235:289-297.

Whitfield, P.E., J.A. Hare, A.W. David, S.L. Harter, R.C. Munoz, and C.M. Addison. 2007. Abundance estimates of the Indo-Pacific lionfish *Pterois volitans*/miles complex in the western North Atlantic. Biological Invasions, 9:53-64.

Wohlpart, S.L. 2007. The development of estuarine systems in Southwest Florida: A perspective from the Late Holocene history of oyster reef development. Master's thesis, Gulf Coast University, Fort Myers, FL, 160 pp.

Yang, H., R.H. Weisberg, P.P. Niiler, W. Sturges, and W. Johnson. 1999. Lagrangian circulation and the forbidden zone on the west Florida shelf. Continental Shelf Research, 19:1221-1245.

Yoskowitz, D., C. Santos, B. Allee, C. Carollo, J. Henderson, S. Jordan, and J. Ritchie. 2010. Proceedings of the Gulf of Mexico Ecosystem Services Workshop: Bay St. Louis, Mississippi, June 16-18, 2010. Harte Research Institute for Gulf of Mexico Studies. Texas A&M University-Corpus Christi, 16 pp.

Zieman, J.C. 1982. The ecology of seagrasses of South Florida: A community profile. U.S. Fish and Wildlife Service, Office of Biological Services, FWS/OBS-82-85.

Zimmerman, R.C., D.G. Kohrs, S.L. Steller, and R.S. Alberte. 1997. Impacts of CO2 enrichment on productivity and light requirements of eelgrass. Plant Physiology, 115(2):599-607.