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Integrated Conceptual Ecosystem Model Development for the Southeast Florida Coastal Marine Ecosystem

MARine Estuarine goal Setting (MARES) for South Florida

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Integrated Conceptual Ecosystem Model Development for the Southeast Florida Coastal Marine Ecosystem

Subregional Principal Investigators:
Kenneth Banks[1]
Christopher Bergh[2]
Joseph N. Boyer[3]
Thomas P. Carsey[4]
David S. Gilliam[5]
Christopher R. Kelble[4]
Donna J. Lee[6]
Thomas N. Lee[7]
David K. Loomis[8]
Frank E. Marshall[9]
Peter B. Ortner[7]
Bernhard M. Riegl[5]

Contributing MARES Project Staff:
Pamela J. Fletcher[10]
Felimon C. Gayanilo[7]
Grace M. Johns[11]
Donna J. Lee[6]
Frank E. Marshall[9]
William K. Nuttle[12]

[1] Broward County Environmental Protection and Growth Management Department, Fort Lauderdale, Florida
[2] The Nature Conservancy, Summerland Key, Florida
[3] Plymouth State University, Plymouth, New Hampshire
[4] NOAA-Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
[5] Nova Southeastern University, Dania Beach, Florida
[6] DJL Environmental Economic Consulting, Honolulu, Hawaii
[7] University of Miami, Miami, Florida
[8] East Carolina University, Greenville, North Carolina
[9] Cetacean Logic Foundation, Inc., New Smyrna Beach, Florida
[10] Florida Sea Grant, Gainesville, Florida
[11] Hazen and Sawyer, Hollywood, Florida
[12] Eco-Hydrology, Ontario, Canada

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UNITED STATES DEPARTMENT OF COMMERCE
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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Dr. Kathryn D. Sullivan, Acting Under Secretary of Commerce for Oceans and Atmosphere and Administrator

NATIONAL OCEAN SERVICE
Dr. Holly Bamford, Assistant Administrator

OFFICE OF OCEANIC AND ATMOSPHERIC RESEARCH
Dr. Robert S. Detrick, Assistant Administrator

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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 "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 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

DPSER	Drivers-Pressures-State-Ecosystem Services-Response
EBM	Ecosystem-based Management
EI	Ecosystem Index
FK/DT	Florida Keys/Dry Tortugas
ICEM	Integrated Conceptual Ecosystem Model
MARES	MARine and Estuarine goal Setting project
QEI	Quantitative Ecosystem Indicator
SEFC	Southeast Florida Coast
SFCME	South Florida coastal marine ecosystem
SWFS	Southwest Florida Shelf

Abstract

The overall goal of the MARES (MARine and Estuarine goal Setting) 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 both by policy makers and by natural resource and environmental management agencies. The document that follows briefly describes MARES overall and this systematic process. It then describes in considerable detail the resulting output from the first step in the process, the development of an Integrated Conceptual Ecosystem Model (ICEM) for the third subregion to be addressed by MARES, the Southeast Florida Coast (SEFC). What follows with regard to the SEFC relies upon the input received from more than 60 scientists, agency resource managers, and representatives of environmental organizations during workshops held throughout 2009–2012 in South 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 third report of the MARES project, documents the development of a conceptual ecosystem model for the coastal marine waters surrounding the Southeast Florida Coast (SEFC). 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 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

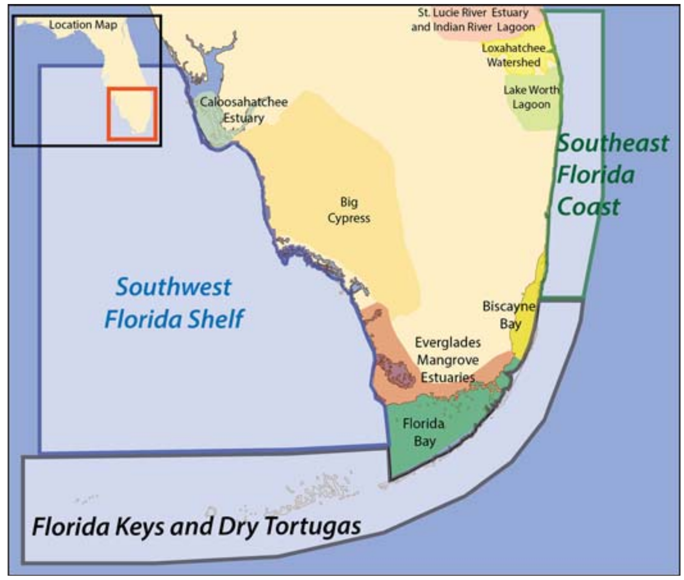


Figure 1. Map of the South Florida coastal marine ecosystem and three MARES subregions.

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

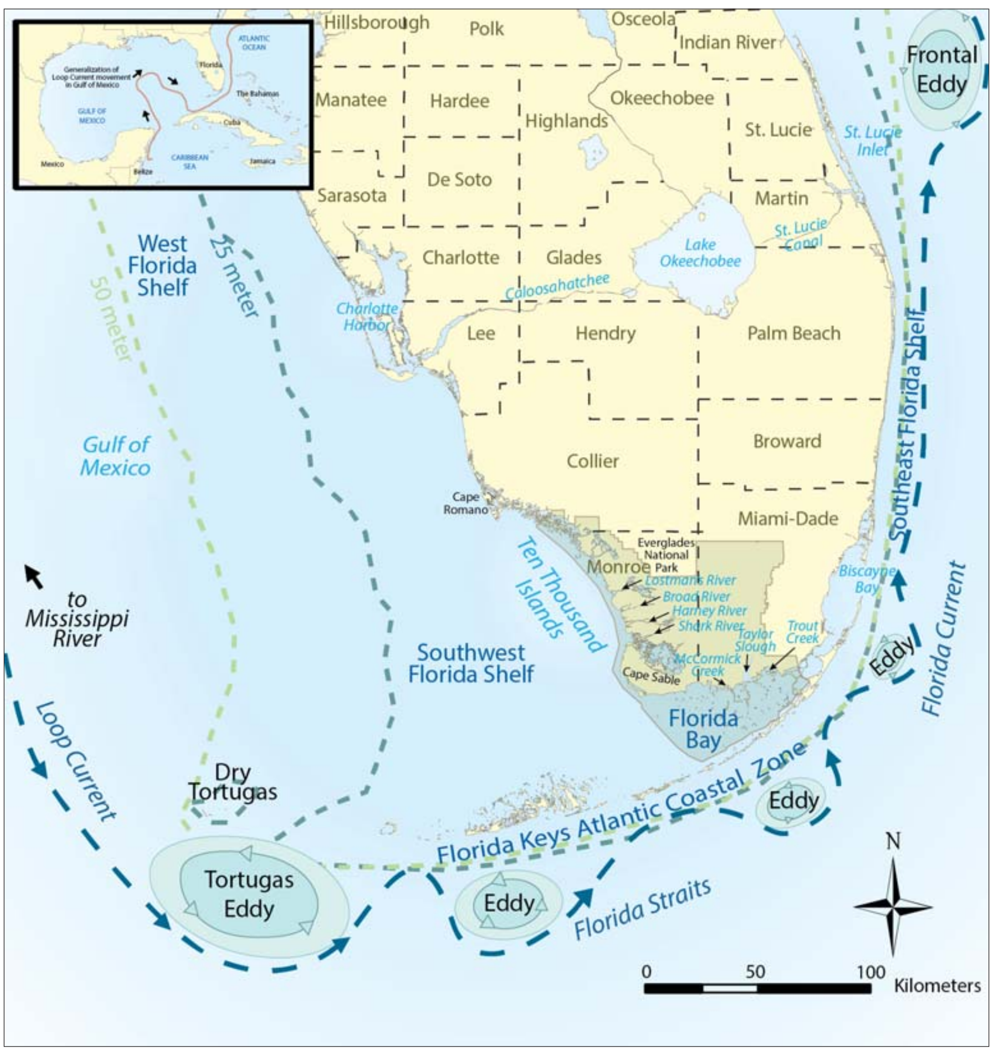
Each subregion exhibits distinct geomorphic and oceanographic characteristics. The SWFS encompasses the broad, shallow shelf from the Caloosahatchee Estuary to the Florida Keys and Dry Tortugas region. Oceanographic conditions here, characterized by long residence time (waters remain in a general location 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 areas 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, diversity, and abundance of South Florida’s valuable coastal



Adapted from Kruczynski and Fletcher (2012).

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

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 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 ecosystem (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 nine 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 SEFC 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

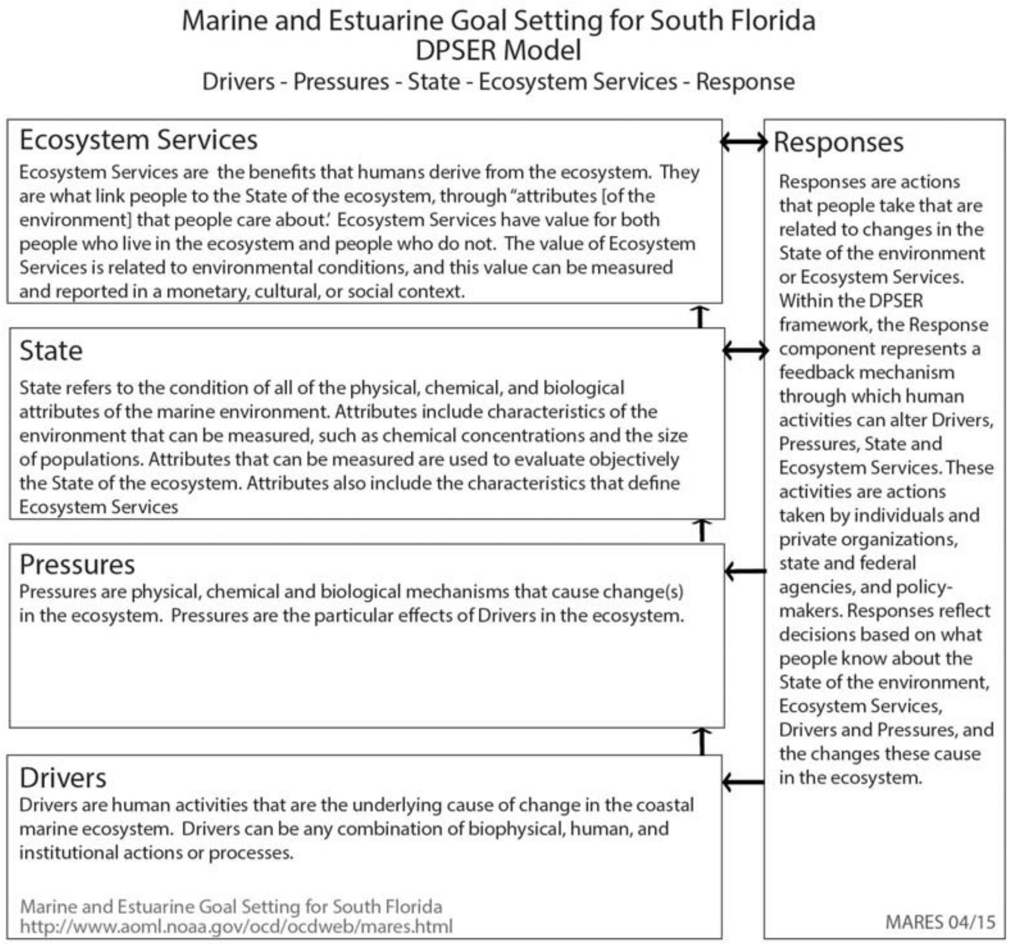


Figure 3. The MARES Drivers-Pressures-State-Ecosystem Services-Response (DPSER) model.

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).

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 SEFC 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 Southeast Florida Coastal Marine Region

Physical Setting

Shallow Inshore Waters

The SEFC region comprises the shoreline and the shallow inshore waters, with depths less than 30 m (100 ft), and extends 176 km (110 miles) north from Biscayne Bay to the St. Lucie Inlet (Figure 4). This region is relatively narrow, 3 km (~2 miles) wide off Palm Beach County and 4 km (~2.5 miles) wide off Miami-Dade County. The shelf widens north of Jupiter, where the shoreline becomes more oriented in a northwest-to-southeast direction; the shelf break continues northward and deepens to about 60 m (200 ft). The bottom is composed of three, in some places two, distinct reef tracts that lie parallel to the coastline with interspersed hardbottom and overlying sand deposits. The reef tracts of the SEFC are continuous with the reefs of the Florida Keys to the south that terminate in a submerged beach ridge complex near Jupiter.

Over most of its length the shoreline consists of barrier islands separated from the mainland by narrow, mangrove-lined lagoons (Figure 4). North of Biscayne Bay, the lagoons connect with coastal waters through nine narrow tidal inlets. These inlets are localized sources for the inflow of freshwater

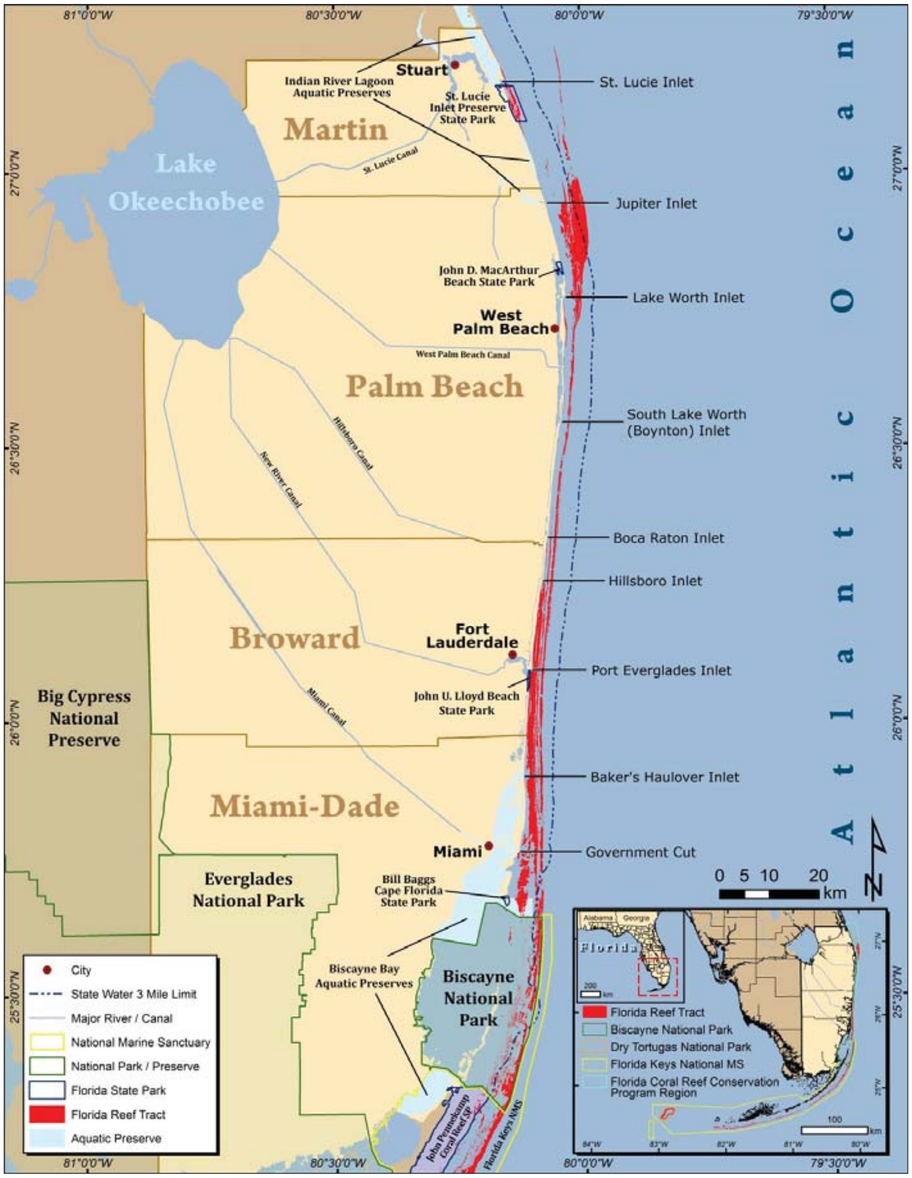


Figure 4. Reef tract along the southeast Florida coastal region.

and nutrients from the mainland. The inlets are also areas of concentrated influence by human activities. Three major seaports are located in Miami, Fort Lauderdale, and Palm Beach. Key Biscayne is the last sandy barrier island in the chain. South of Key Biscayne, the wide, shallow opening of the "Safety Valve" constitutes the seaward boundary of north-central Biscayne Bay, and south of this opening begins the rocky mangrove shoreline that characterizes the Florida Keys to the south.

The narrow shelf along the SEFC does not receive sufficient input of freshwater on a continuous basis to allow buoyancy-driven coastal currents to develop in the inshore region. The inflow of freshwater from the mainland is regulated to prevent upland flooding, and this results in a highly pulsed inflow of freshwater, with high flows occurring in brief periods that coincide with the arrival of tropical storms. South of Palm Beach, ocean disposal of treated wastewater feeds a constant source of freshwater and nutrients in the vicinity of the ocean outfalls, typically 2-5 km (1.5-3 miles) offshore.

Atmospheric forcing controls water temperature, and wind and tides contribute about equally to driving coastal currents (Lee and Mayer, 1977). Tidal currents flow primarily in the alongshore direction, except in areas immediately adjacent to an inlet. Seasonal changes in alongshore winds are primarily responsible for seasonal mean flows. The north-south oriented coastline in the Straits of Florida results in northerly or southerly winds having the greatest influence on currents in these shallow depths. The current response is in the same direction as the wind (north or south) with a lag of less than 6 hours. In the summer, the nearshore mean current is typically toward the north due to the prevailing southeast winds. Prolonged north wind events in the fall result in southward mean flows at the coast. Winter and spring cold front passages cause variable alongshore flows without a preferred mean direction. Magnitudes of seasonally-averaged flows tend to be quite weak in the shallow nearshore region, typically on the order of 1 cm/s.

North of Jupiter Inlet, the shelf widens and opens onto the southern portion of the southeast U.S. continental shelf. Seasonal stratification can develop in the coastal marine waters near St. Lucie, as the result of summer heating and from wind and eddy-induced upwelling of cooler water at the shelf break. The proximity of the continental shelf to the north makes the nearshore region at the northern extent of the ecosystem accessible to penetration of low-salinity coastal flows from the north during strong southward wind events typical of fall. Cross-shelf subsurface intrusions of cooler upwelled waters from the Florida Current are also possible during summer as the shelf stratifies from summer heating combined with both wind and eddy-induced upwelling. In this area of the shelf, the Florida Current is less confined by the Florida Straits channel. The growth of frontal eddies along the Florida Current can undergo explosive growth, causing large onshore transports of upwelled waters and new nutrients that support primary production.

Climate, Waves, and Tides

The climate of southeast Florida is classified in the Köppen Climate Classification System (Trewartha, 1968) as tropical savanna, characterized by a pronounced dry season. Air temperatures average 19.0°C in the winter and 28.2°C in summer, with an overall average of 24°C. Water temperatures are moderated by the proximity of the northward flowing Florida Current, an arm of the Gulf Stream passing through the Straits of Florida. The minimum water temperature measured offshore Broward County during the three-year period of 2001-2003 was 18.3°C and the maximum was 30.5°C (Banks *et al.,* 2008).

During the dry season (November-March), Florida experiences the passage of mid-latitude, synoptic-scale cold fronts (Hodanish *et al.,* 1997) which bring strong winds from the northeast. These "nor'easters" usually last for two to three days. These fronts may have a significant impact on the beach ecosystem by increasing southward sediment transport (littoral transport), offshore loses of course beach sediment (with some burial of nearshore hardbottom), and shoreward aeolian transport of fine sediments which contribute to increases in dune elevation. Strong winds also generate waves which can cause a flattening of the beach profile and may form scarps on the beach berm and erosion of dunes.

In the wet season (late spring to early fall, June-September), differential heating generates mesoscale fronts, creating sea breezes. The convergence of these moisture-laden sea breezes, developing from the different water bodies (Atlantic Ocean, Gulf of Mexico, and Lake Okeechobee), coupled with high humidity in the Everglades, can result in low pressure troughs developing across the Florida peninsula. This leads to intense thunderstorm activity, which moves from inland to the coasts, delivering large amounts of freshwater to the coastal shelf. South Florida receives 70 percent of its annual rainfall during these months. Trewartha (1968) referred to the daily sea breeze circulation as a "diurnal monsoon." The typical wind direction during most of the southeast Florida wet season is from southeast (tropical). During these times, winds tend to be relatively light and cause little beach erosion.

From June through November, Florida is a prime landfall target for tropical cyclones, although storms have been documented as early as March and as late as December. Hurricanes and tropical storms affect beach ecosystems similar to that of winter storms, except alteration of the physical environment is magnified because of stronger winds with the added impact of high water levels caused by storm surge. Because winds in a hurricane shift in direction as the storm passes, longshore sediment transport direction can shift. In the 100-year period from 1899-1999, the region was hit by 27 hurricanes, or about once every four years. Half of these storms were classified as category 3 or higher (Neumann *et al.,* 1999).

The waves in southeast Florida are influenced by the shadowing effect of the Bahamas and, to a lesser extent, Cuba. In the northern part of the southeast Florida region, swells from the north are of relatively high energy since they are not influenced by the shallow Bahamas Banks. Broward and Miami-Dade counties are less affected by this wave energy because of the shadowing effect of the Bahamas Banks.

In winter, low pressure systems form on the Atlantic Ocean coast of the U.S. Short-period, wind-driven waves develop near the center of these lows. As these seas move away from the center of low pressure, they can develop into long period swells, locally known as “ground swells” that may affect southeast Florida. Long-period swells result in increased sediment suspension and turbidity in nearshore waters. Hanes and Dompe (1995) measured turbidity concurrently with waves and currents in situ at depths of 5 m and 10 m offshore Hollywood, Florida (Broward County) from January 1990 to April 1992. They found a significant correlation between wave height and turbidity. In addition, there was a threshold wave height (0.6 m), below which waves did not materially influence turbidity.

Tides in the region are semi-diurnal with amplitudes of approximately 0.8 m. Tidal forces influence coastal circulation near navigation inlets. Nine navigational inlets, approximately 16 km apart, are maintained in southeast Florida. At the southern extent of the region, tidal passes allow the exchange of water from Biscayne Bay onto the coastal shelf. The relative contribution of the inlets to coastal circulation can be estimated by comparing inlet tidal prisms (the volume of water exchanged in the estuary between high and low tide). Coastal circulation is affected by the tidal prism, inlet dimensions, shelf width at the inlets, offshore distance of the Florida Current, tidal plume constituents, and salinity. The salinity of the plumes discharging from the inlets is significantly different in the wet season compared with the dry season.

Connectivity

Conditions in the ecosystem are influenced by interactions with the strong northward flowing Florida Current at the shelf break and by freshwater inflows from one of the most densely populated urban areas in the U.S. The Florida Current connects outflow from the eastern Gulf of Mexico (the Loop Current) with the Gulf Stream in the North Atlantic (Figure 5). The Straits of Florida lie between the Florida southeast coast and the Bahamas and forms a conduit for the Florida Current. The Florida Current is made up of about equal

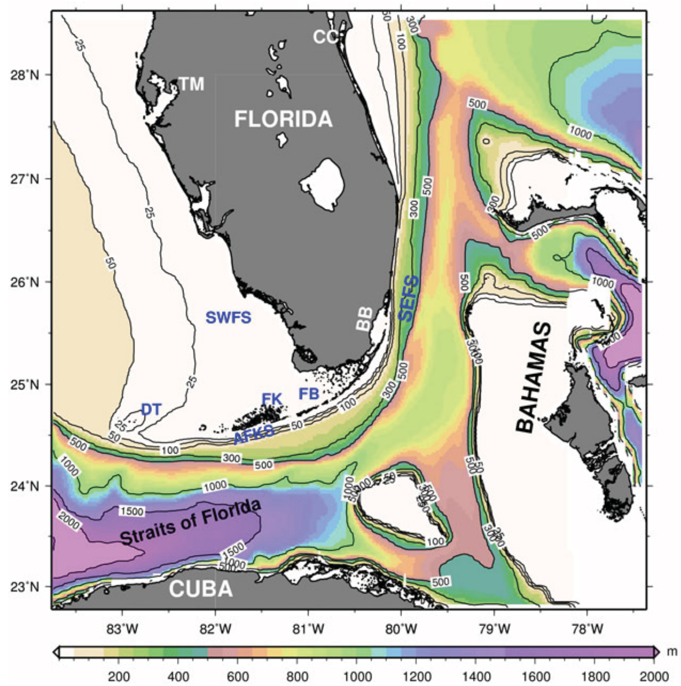


Figure 5. Bathymetry of the Straits of Florida and south Florida shelf areas. The Southeast Florida Shelf (SEFS) extends from Biscayne Bay (BB) to St. Lucie estuary near 27°N; the Atlantic Florida Keys Shelf (AFKS); Southwest Florida Shelf (SWFS); Florida Bay (FB); and Dry Tortugas (DT).

parts of waters originating in the South Atlantic and North Atlantic subtropical gyres (Schmitz and Richardson, 1991; Wilson and Johns, 1997) and is, therefore, an important link in both the North Atlantic Sverdrup circulation (Leetmaa *et al.,* 1977) and the global thermohaline circulation (Gordon, 1986). The upper layer waters of the Florida Current with temperatures greater than 24°C are derived primarily from the South Atlantic (Schmitz and Richardson, 1991) and are transported across the equator and through the Caribbean by the combined influence of the North Brazil Current and the North Atlantic wind-driven subtropical gyre.

Interaction between the Florida Current and shallow inshore waters is driven by a continually-evolving stream of frontal meanders and eddies that form along the current’s western edge. These features influence characteristics of the water column at the offshore boundary of the coastal marine ecosystem. Eddies form in a couple of ways. Some that have their origin in the Loop Current can carry water from distant sources, such as the plume at the mouth of the Mississippi River (Ortner *et al.,* 1995). Eddies are also generated along the southeast Florida coast by the interaction of the Florida

Current with the topography of the Florida shelf (Lee, 1975; Lee and Mayer, 1977; Shay *et al.,* 1998; Lee *et al.,* 1991).

The movement of eddies downstream (north) along the outer Florida shelf drives an exchange of water masses between the Florida Current and the adjacent shelf (Figure 6). Upwelling in the core of an eddy can inject nutrient-rich water from depths along the shelf slope up into the euphotic zone, stimulating primary production and other changes in the water column. Variations in current and temperature at the boundary of the coastal marine ecosystem reflect the passage of eddies that occur at the 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 the resident shelf waters and new water from within the eddy. Displacement of shelf waters by eddies at an average weekly interval represents a flushing mechanism and mean residence time of shelf waters, outside the ecosystem, of approximately one week.

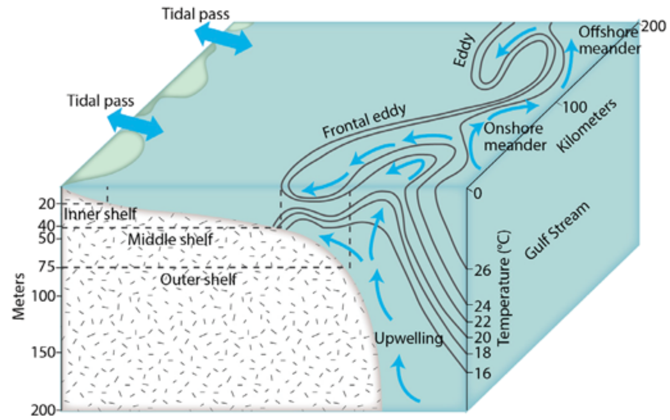


Figure 6. Schematic of Gulf Stream frontal eddies and meanders, together with shelf flow regimes on the southeast U.S. shelf.

Human Population

South Florida experienced a rapid change in economic and demographic factors within the last century. Florida was the only state in the U.S. 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 happened in the five southern counties adjacent to coral reefs (Palm Beach, Broward, Miami-Dade, Monroe, and Collier) (Figure 7). In 2030, southeast Florida will have a population of 8.5 million, 2.9 million more than in 2010 (Bureau of Census, 2010). The population size of South Florida influences many regional- and local-scale *Drivers* like coastal development, agriculture, wastewater, fishing, and boating.

Martin County

Martin County is on the southeast coast of Florida bordering the Atlantic Ocean, between Jupiter and St. Lucie Inlet. In 2010, 146,318 people lived in the county, 15.4 percent more than lived there in 2000. About 10 percent of county residents live in Stuart, which is by far the largest incorporated municipality. Other municipalities include Jupiter Island, Ocean Breeze Park, and Sewall's Point. The University of Florida, Bureau of Economic Research projects that the population will grow by 8 percent by 2020.

Palm Beach County

Palm Beach County is on the southeast coast of Florida bordering the Atlantic Ocean, between Jupiter and Boca Raton. In 2010, 1.32 million people lived in the county, 16.7 percent more than livedw there in 2000. About half the residents live in one of 38 incorporated municipalities, most of which are clustered along the Atlantic coast. West Palm Beach and Boca Raton are the largest cities in the county, with 100,000 and 84,000 residents, respectively. The University of Florida, Bureau of Economic Research projects that the population will grow by 7.2 percent by 2020.

Broward County

Broward County is on the southeast coast of Florida bordering the Atlantic Ocean, between Boca Raton and Hallandale Beach, north of Miami. In 2010, 1.75 million people lived in the county, 7.7 percent more than lived there in 2000. Nearly all of the residents live in one of 31 incorporated municipalities clustered in the eastern third of the county, along the Atlantic coast. Fort Lauderdale and Pembroke Pines are the largest cities in the county, with 166,000 and 155,000 residents, respectively. The University of Florida, Bureau of Economic Research projects that the population will grow by 4.3 percent by 2020.

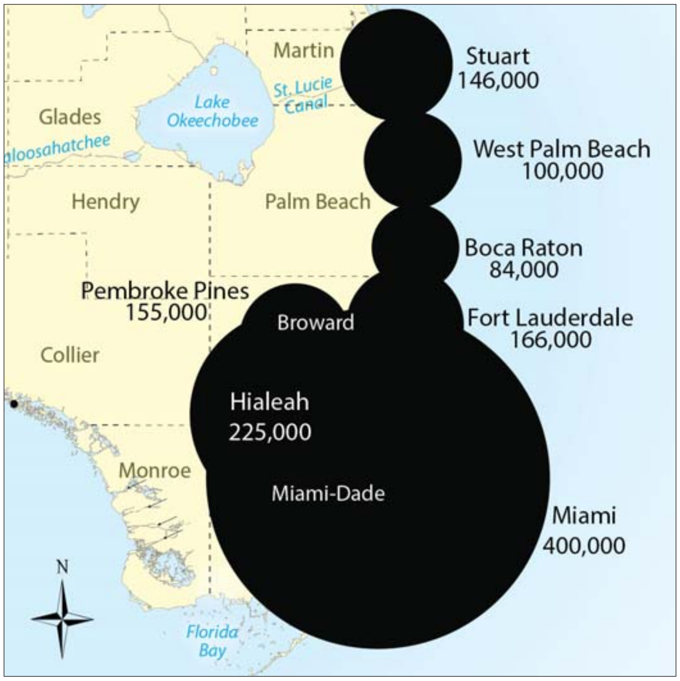


Figure 7. Population centers along the southeast Florida coast (Bureau of Census, 2010).

Miami-Dade County

Miami-Dade County is on the southeast coast of Florida bordering the Atlantic Ocean, between Hallandale Beach and the Florida Keys. In 2010, 2.5 million people lived in the county, 10.8 percent more than lived there in 2000. About half of the residents live in one of 35 incorporated municipalities, most of which are clustered along the Atlantic coast. The urbanized area of south Miami-Dade County is unique in the U.S. for bordering on two national parks, Everglades and Biscayne, and the Big Cypress National Reserve. The University of Florida, Bureau of Economic Research projects that the population will grow by 6.7 percent by 2020.

The Miami urbanized area (as defined by the Census Bureau) encompasses the contiguous urbanized coastline of Palm Beach, Broward, and Miami-Dade counties from Jupiter south to Florida City. In 2010, 5.7 million people lived in this area (Bureau of Census, 2010). In 2008, it became the fourth largest urbanized area in the U.S., behind New York City, Los Angeles, and Chicago. The ports of Miami and Fort Lauderdale are the busiest cruise ship passenger ports in the world in both passenger traffic and cruise lines. The Miami region is one of the largest tourist destinations in Florida and the U.S.

The Southeast Florida Coast Integrated Conceptual Ecosystem Model

Conceptual Diagram: Picturing the Ecosystem

The first step in the systematic MARES process is to develop a conceptual diagram of the ecosystem (here a cross-section and a plan view of the coast) that identifies the main components of the ecosystem, the processes operating upon it, and the factors affecting its condition (Figures 8 and 9). The SEFC ecosystem consists of coral and hardbottom habitats of the reef, seagrass beds in the south, beaches and mangroves along the shoreline, as well as the overlying water column and the fish and shellfish that move among these habitats (see appendices for more information).

The degradation of beaches and coral and hardbottom habitats are major concerns for the SEFC because these reduce ecosystem services that residents rely upon, including services that support beach activities, diving and snorkeling, recreational and commercial fishing, and tourism. Local factors that affect the ecosystem and its services are fishing, diving, and other uses of the marine environment, land-based sources of pollution, and marine construction. Regional factors that affect the ecosystem include the growing urban population, agriculture, regional water management, and nutrient inputs to the water column, while global factors include climate change and the related processes of ocean acidification and accelerated sea-level rise. The application of the DPSER framework leads to the construction of narratives of the processes that sustain and change the ecosystem based on elements identified in the conceptual diagram.

Applying the Model in the Southeast Florida Coast: Coral Reef Conservation Program

To illustrate how elements of the MARES DPSER model can be used to organize an analysis of ecosystem management issues along the SEFC, consider the development and implementation of the Local Action Strategy by the state's Coral Reef Conservation Program. Florida's coastal waters contain a substantial proportion of the United State's coral reef ecosystems. Coral reef ecosystems are defined by their

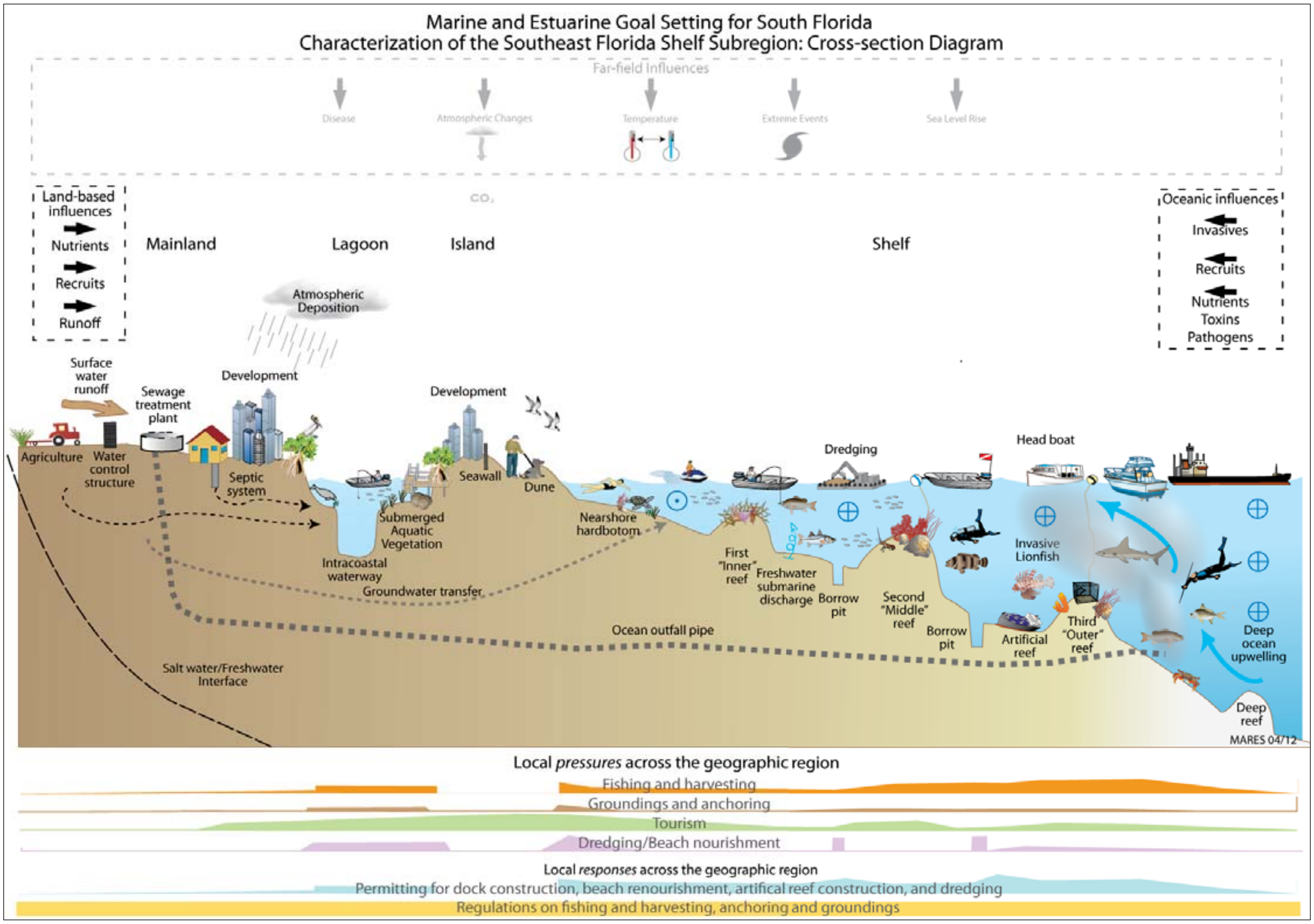


Figure 8. Southeast Florida coast integrated conceptual ecosystem model—cross-sectional diagram.

distinctive benthic habitat and by associated communities of fish and shellfish and the conditions required in the water column to sustain these, e.g., low nutrients and clear water. In the ICEM model based on the DPSER framework (Figure 10), the benthic habitat formed by the coral reef, fish and shellfish communities, and overlying water column are elements included in the *State* component of the SEFC coastal marine ecosystem.

Florida's coral reefs are a valuable local and national resource. People come to South Florida to enjoy the subtropical climate and the services its ecosystems provide and, for the vast majority, this means the coastal marine ecosystem. People come to southeast Florida to enjoy its beaches, to fish or dive on coral reefs, and engage in a variety of other water-based activities. These benefits are the *Ecosystem Services* provided by the SEFC coastal marine ecosystem. Recreational activities on the southeast Florida reef tract are a major component of the South Florida economy, accounting for $3.8 billion during the period 2001-2003 (Johns *et al.,* 2001, 2004). Sustaining the *Ecosystem Services* that support this economic activity depends on maintaining the *State* of the coastal marine ecosystem.

Coral reef ecosystem health is in decline (Wilkinson, 2002, 2008; Keller *et al.,* 2009). This threatens a reduction in the benefits that people receive. This has generated widespread concern that, in 1998, resulted in the formation of the U.S. Coral Reef Task Force to coordinate a *Response* to this decline by federal, state, and local agencies. Preservation and protection of these ecosystems is the mandate for the U.S. Coral Reef Task Force, of which Florida is one of the seven states, commonwealths, and territories that are members of the task force. In southeast Florida, the result of the work of

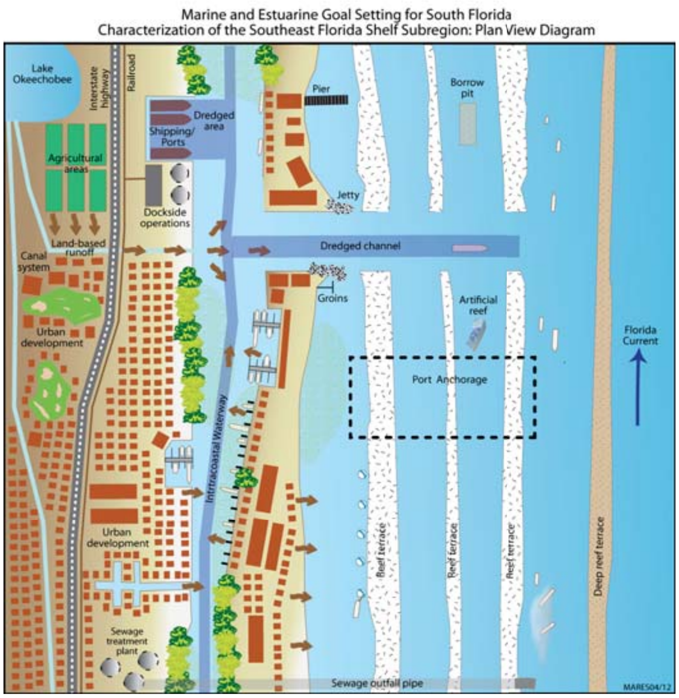


Figure 9. Southeast Florida coast integrated conceptual ecosystem model—plan view diagram.

the Task Force has been to formulate a Local Action Strategy for the purpose of preserving and managing the reef. The Southeast Florida Coral Reef Initiative (SEFCRI) guides the implementation of the Local Action Strategy with leadership provided by the Coral Reef Conservation Program (CRCP), a program of the Florida Department of Environmental Protection. SEFCRI consists of an interagency team of marine resource professionals drawn from federal, state, and local agencies, universities, and industry.

The Local Action Strategy consists of a number of projects and activities designed to mitigate *Pressures* causing change in the coastal marine ecosystem and to restore the *State* of the coral reef, where this is possible. Intensive development of the SEFC, intensive use of its coastal waters, and phenomena related to global climate change are recognized as the underlying *Drivers*. The work of SEFCRI and the CRCP is focused in four main areas related to major *Pressures* affecting the reef: (1) land-based sources of pollution; (2) impacts of the maritime industry and coastal construction; (3) impacts of fishing, diving, and other activities on the reef; and (4) promoting sustainable use through awareness and appreciation by the public.

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 through the ecosystem. Far-field pressures of concern in the SEFC region include *Pressures* related to climate change and the rising concentration of carbon dioxide in the atmosphere, including the effects of ocean acidification and accelerated sea-level rise. Near-field pressures are generated internally, and their effect varies in intensity across the ecosystem. At the scale of the South Florida region, agricultural, municipal, and regional water management practices affect water quality and other characteristics of nearshore, coastal water. Locally, human activities in southeast Florida impose their own set of pressures on the surrounding marine environment. Near-field pressures of concern include the effects of land-based sources of pollution, maritime industry, coastal construction, and intensive use of the reef for fishing, diving, and other activities. Concern is growing over the impact of the lionfish, an invasive species, on native fisheries.

Far-Field Drivers and Pressures

Although far-field factors are outside the realm of management control within the SEFC, it is important that the general public and decision-makers are aware of their influence so they can understand the impact of management actions against the broader suite of *Pressures* acting upon the ecosystem (Table 1). Global processes that influence the SEFC 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 on the SEFC is climate change related to the rising concentration of carbon dioxide in the atmosphere. Resulting changes in salinity, temperature, and aragonite saturation state of the water column will affect the health of marine organisms by changing the efficiency of their physiological processes. The impact of ocean acidification on marine organisms is highly variable, although it

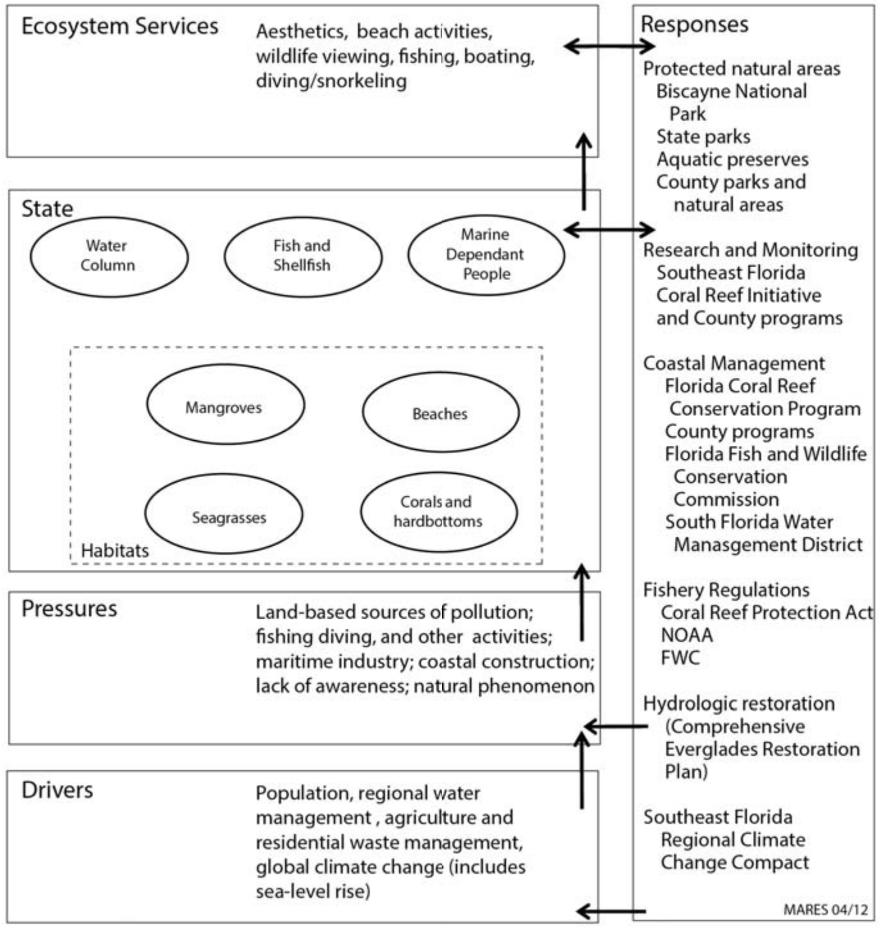


Figure 10. Integrated conceptual ecosystem model based on the DPSER framework.

appears unlikely that effects will be dramatic in the short-term (Hendriks *et al.,* 2010). However, changes due to temperature increases could be more pronounced because many organisms in southeast Florida are already living near their thermal maximums (Manzello *et al.,* 2007).

Ocean Acidification

Increasing concentrations of carbon dioxide (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). An increased concentration of CO_2 lowers the pH of seawater, i.e., making it more acidic, and decreases the saturation state of aragonite. This has the detrimental effect of making it more difficult for marine organisms, like corals, to build and support their skeletal structures (Andersson *et al.,* 2005; Kleypas *et al.,* 2006; Manzello *et al.,* 2008; Cohen and Holcomb, 2009). An increased concentration of CO_2 and HCO_3^- (bicarbonate) also increases seagrass production (Hall-Spencer *et al.,* 2008), leaf photosynthetic rates (Zimmerman *et al.,* 1997), and plant reproductive output (Palacios and Zimmerman, 2007). However, because acidification will occur relatively slowly, allowing some organisms to adapt, and 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.

Accelerated Sea-Level Rise

The SEFC is situated at a low elevation and is vulnerable to sea-level rise. The global phenomenon of climate change and accelerated sea-level rise alters the relative position of sea level, tides, and currents along the SEFC. The existing geomorphology of the barrier island coastline, with mangrove-lined lagoons behind, reflects 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). 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 already occurred in the coastal systems unaltered by development, including increased erosion and saltwater encroachment.

Acceleration of sea-level rise is expected to continue into the foreseeable future. The "Copenhagen Report" (Allison *et al.,* 2009) states that, "For unmitigated emissions [sea-level rise] may well exceed 1 meter" by 2100, with an upper limit at approximately 2 meters. This revises the widely-quoted projections contained in the IPCC (2007) report, which did not take into account melting of the Greenland and Antarctic ice sheets. Accelerated sea-level rise will push marine water far into freshwater environments, resulting in a substantial loss of freshwater wetlands (on mainland South Florida) and diminished groundwater resources. Indirect impacts of sea-level rise, due to impingement of the sea on the developed coastline, may be greater than direct impacts of rising water levels on natural components of the coast. The anticipated rise in sea level and the increased likelihood of flooding in residential and commercial areas will motivate shoreline protection activities, and disturbances due to the coastal construction associated with these activities will have effects in the nearshore environment with cascading effects further offshore.

Increasing Temperature

Worldwide temperatures have increased over the past century by 0.74°C. Strong thermal anomalies leading to bleaching events on coral reefs have been observed with increasing frequency since the 1980s (Baker *et al.,* 2008).

Table 1. Far-field drivers and pressures of greatest importance to the southeast Florida coast.

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)

It has also been demonstrated that disease outbreaks are favored by unusually warm temperatures (Bruno *et al.,* 2007). In the Florida Keys, a series of repeated bleaching and disease outbreaks have served to reduce average coral cover from near 15 percent to less than 5 percent, and losses in the dominant reef builders *Acropora palmata*, *A. cervicornis,* and the *Montastraea annularis* complex have been particularly striking (Jaap *et al.,* 2008). Many Florida Keys reefs are presently comparable in coral cover and diversity to those on the higher-latitude southeast Florida reef tract. The latter has so far escaped similar depredation of its coral populations by weather and diseases and may, therefore, constitute an important refuge for the Florida Keys reef tract populations.

The two drivers which influence seawater temperature are climate change and storms. Seawater temperatures are predicted to rise due to climate change (Twilley *et al.,* 2001). Storms, on the other hand, can lower seawater temperatures (Manzello *et al.,* 2007). Both high (>30°C) and low (<15°C) temperatures have been shown to cause coral bleaching (i.e., expulsion of symbiotic dinoflagellates) and, if prolonged, significant mortality to corals and other benthic organisms (van Oppen and Lough, 2009). Coral bleaching and mortality in the Florida reef tract have been recorded during the 1998 and 2005 bleaching events. Cold-water mortality of corals and other organisms was observed historically (Davis, 1982; Jaap and Sargent, 1994) and, more recently, in the winter of 2010 (Lirman, personal observation).

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 more heavy 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 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.

Southeast Florida beaches can experience major hurricanes that may cause significant changes to the form of the beach and wash away large numbers of sea turtle eggs. A natural beach is resilient to the frequent coastal storms that are common to the SEFC (may occur several times each year). However, less frequent (may occur every 5-30 years) hurricanes, tropical storms, and nor'easters can significantly alter beach morphology, destroy dune vegetation, and negatively affect habitat. Where the energy-absorbing dune system has been replaced by urban development, even relatively minor storms cause some negative impact on the habitat and recreational uses of the beach, and the habitat loss (if any is present) can be permanent.

Altered Rainfall and Evaporation

The net effect that global climate change will have on rainfall and evaporation in South Florida is uncertain. The IPCC report indicates that there will be a likely decrease in precipitation over subtropical land regions and increased evaporation rates (IPCC, 2007; Allison *et al.,* 2009). However, increased temperatures are also associated with increases in the frequency of thunderstorms, particularly in the tropics and southeastern U.S. (Trap *et al.,* 2007; Aumann *et al.,* 2008). Thunderstorms are the major source of rainfall during the summer wet season in South Florida.

Near-Field Drivers and Pressures

Near-field *Drivers* and *Pressures* are related to the pressures already identified above, i.e., land-based sources of pollution, maritime industry and coastal construction, and fishing, diving, and other uses of the reef and, more generally, to agricultural and urban development in the region (Table 2). Development in South Florida during the 20th century drastically altered the coastal hydrology of the region. Water management activities, undertaken to accommodate urban and agricultural land uses, have altered the timing, distribution, quantity, and quality of freshwater inflows to coastal waters. The large urban population along the southeast coast relies on the adjacent coastal marine environment for disposal of treated wastewater, mostly through outfalls in deeper water, away from the shoreline.

Urban and Shoreline Development

Urban development along the SEFC has altered the shoreline and disrupted natural processes that contribute to maintaining shoreline habitats. *Drivers* of change on the South Florida shoreline range over relatively large temporal and spatial scales, from localized overuse to very large spatial scale sea-level rise (Defeo *et al.,* 2009; Schlacher *et al.,* 2007). Coastal engineering projects and urban development permanently impact the beach over tens of kilometers; impacts from climate change continue for millennia over larger spatial extents. Recreation, nourishment, and pollution impact beaches at temporal scales of weeks to years and over spatial scales of 10-100 kilometers (Defeo *et al.,* 2009).

The pre-development shoreline of southeast Florida was typical of the barrier island complexes of north and central Florida. Inlets associated with river drainage (e.g., Jupiter Inlet/Loxahatchee River, New River/New River Inlet in Fort Lauderdale) were open much of the time. Many other inlets were ephemeral, frequently changing locations or periodically opening and closing, the dynamics of which were controlled by inland water discharge, wind patterns, and offshore storms.

As coastal development and commerce increased in southeast Florida, a need arose for stable navigational inlets. The implemented solution installed rock jetties at desired locations and dredged channels from inland water through the barrier islands to the ocean. The construction of jetties interrupted the littoral sediment drift process, and down-drift beaches have been starved of their sediment supply. Some of the barrier islands/spits subsequently migrated shoreward (west) until they were welded to the mainland shoreline whose position is fixed by underlying rock formations. A prime example of a natural beach becoming beach eroded by inlet jetties is at Port Everglades in Broward County.

There are numerous federal, state, county, city, and non-government organization owned beachfront parks in the southeast Florida region. Most of these areas were designed to protect the remaining coastal flora and fauna, provide access to the public, facilitate beach restoration, or a combination of these purposes. However, the majority of beachfront

Table 2. Near-field drivers and pressures of greatest importance to the southeast Florida coast.

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)

parks in the southeast Florida region were developed to accommodate parking for public access to the beach. As a result, the development, operation, and maintenance of beach parks have resulted in a significant loss of the natural aspects of the coastal landscape and an increased use of the beach for recreation.

Regional Water Management

Potable water needs in Miami-Dade, Broward, and southeastern Palm Beach counties are primarily met by withdrawing water from the surficial Biscayne Aquifer, whose waters are derived from local rainfall and, during dry periods, from canals ultimately linked to Lake Okeechobee (Carriker, 2008). Agriculture water needs and flood control issues, as well as groundwater control (e.g., saltwater intrusion, phosphorus reduction), have been addressed through construction of an extensive canal system (SFWMD, 2010). In addition, an Intracoastal Waterway extends 374 miles along the southeast coast, from Fernandina Harbor to Miami Harbor (Florida Inland Navigation District, 2000). The Intracoastal Waterway enhances the north-south movement of water through the lagoons behind the barrier island coastline.

Inlets must be considered as major sources of land-based pollution. For northern Miami-Dade, Broward, and Palm Beach counties, surface waters flowing into the ocean, including canal and Intracoastal Waterway waters, are predominantly constrained to a series of inlets: Norris Cut, Bear Cut, Government Cut, Haulover Inlet, Port Everglades Inlet, Hillsboro Inlet, Boca Raton Inlet, Boynton Inlet, and Palm Beach (North Lake Worth) Inlet. In a 1998 study of water quality in South Florida, the U.S. Geological Survey listed domestic wastewater facility discharges (1500 facilities), industrial wastewater discharges (including leachage and runoff from contaminated land), septic tank discharge (nearly a half-million), agricultural wastewater runoff (citrus farming, dairy and beef operations), runoff from landfills (40 active landfills), and urban wastewater (stormwater) runoff as the leading categories of land-based pollution (Marella, 1998). Anthropogenic materials from inlets have been implicated in bloom activity on coral reefs (Lapointe and Bedford, 2011).

Treated-wastewater outfalls are point sources of anthropogenic materials (EPA, 1992). There are five treated-wastewater outfalls continuously operating in southeast Florida; their combined flow in 2011 was 199 millions gallons per day (Carsey *et al.,* 2012). The number of ocean outfalls has decreased significantly over the years; there were ten operating in 1972 (Lee and McGuire, 1972). Current legislation (Leah Schad Memorial Ocean Outfall Act) requires termination of ocean outfalls for routine effluent discharge by 2025 and requires that a majority of the wastewater previously discharged be beneficially reused (FDEP, 2010). This, however, presents a significant challenge to municipalities who must design, finance, and implement these alternative systems.

A significant transport of water to the coastal ocean is through submarine groundwater discharge, now recognized as a major vector of anthropogenic materials and thus an area of growing interest and concern, due to activities such as wastewater disposal from septic systems and agricultural and urban uses of fertilizers (Howarth *et al.,* 2003; Lapointe *et al.,* 1990; Finkl and Charlier, 2003; Paytan *et al.,* 2006). Submarine groundwater discharge is an efficient transport of nutrients; it has been estimated that nitrates from submarine groundwater discharge sources in west-central Florida may exceed that of rivers and atmospheric deposition (Hu *et al.,* 2006). Finkl and Krupa (2003) estimated that groundwater fluxes of nutrients to Palm Beach County averaged 15,690 kgN/d and 1134 kgP/d, more than double that of surface water fluxes (6775 kgN/d and 540 kgP/d).

Changes in salinity, in either direction, due to altered freshwater discharge to the coast, can lead to increased or decreased respiration depending on the coral species (Vernberg and Vernberg, 1972). Reduced salinity can also lead to local coral bleaching (Brown, 1997). It is generally agreed that most scleractinian corals can survive only small variations in salinity, with death resulting when salinity drops below 25 percent or increases above 40 percent (Edmondson, 1928; Jokiel *et al.,* 1974). While mean terrestrial runoff may decline in the future as the result of climate change, stormwater delivery and pulsed runoffs that tend to bring pollutant and nutrient pulses to reefs may indeed increase. Heavy rainfall can lead to the outflow of freshwater, reducing the salinity around the inlets. Changes in atmospheric heat content are predicted to change global rainfall patterns, leading potentially to increased dryness in Florida. This would, however, be counteracted by increased moisture content of the tropical atmosphere, delivering more precipitation associated with cyclonic disturbances.

Land-Based Sources of Pollution

Pollution impacts caused by human activities are associated with oil spills (Jackson *et al.,* 1989), urban and agricultural stormwater and overland runoff (Glynn *et al.,* 1989; Jones, 2005; Fauth *et al.,* 2006), and physical impacts caused by solid waste disposal and others causes (Peters et al., 1997). Increased nutrients can have both direct and indirect impacts on benthic organisms (Szmant, 2002). Direct impacts include the impairment of calcification and growth in stony corals under high nutrient conditions (Koop *et al.,* 2001). Indirect effects include the disruption of the coral-zooxanthellae symbiosis and a reduction in the translocation of carbon to the host (Fabricius, 2005), increased phytoplankton in the water column leading to reduced light penetration and even toxicity (Brand and Compton, 2007; Butler *et al.,* 2005; Boyer *et al.,* 2009), and enhanced growth of macroalgae, a competitor for space in coral reefs and hardbottom habitats (Lapointe and Clark, 1992; Lapointe *et al.,* 2002, 2004).

The addition of nutrients from land-based sources, on top of the natural source of nutrients from upwelling along the shelf margin, stimulates the occurrence of harmful algal blooms. Wastewater discharge and agricultural runoff are the two largest sources of nutrients from land-based sources. A bloom occurs when an alga rapidly increases in number to the extent that it dominates the local planktonic or benthic community (Kirkpatrick *et al.,* 2004). Harmful algal blooms in southeast Florida are primarily composed of the dinoflagellate, *Karenia brevis*, which contains a brevetoxin compound that can aerate and cause respiratory distress. It can also cause paralytic shellfish poisoning via consumption of contaminated shellfish from an area with a recent *K. brevis* bloom (Kirkpatrick *et al.,* 2004). Large blooms of *K. brevis* may result in hypoxic conditions (low dissolved oxygen) fatal to many species (Hu *et al.,* 2006).

A related problem is in macroalgal blooms. The macroalgae in southeast Florida waters include *Dictyota* ssp. and *Halimeda* ssp. (Banks *et al.,* 2008). Macroalgal blooms are usually associated with non-indigenous species such as *Lyngbya, Caulerpa,* and *Codium* ssp. (Collier *et al.,* 2008). These blooms are harmful not through chemical toxicity but through disturbance of the ecosystem, crowding out other species (Collier *et al.,* 2008). Blooms may be related to a variety of causes including increased nutrient availability or removal of macroalgal grazers ("bottom up" versus "top down" control) (Valiela *et al.,* 1997).

Toxification can result from wastewater or from phytoplankton blooms. The following chemicals commonly found in wastewater induce toxic effects on corals and other reef organisms: polychlorinated biphenyls, metals, chlorine, phosphate, pesticides, and petroleum hydrocarbons (Pastorok and Bilyard, 1985). Cyanobacteria blooms can be directly toxic to corals and indirectly affect them by stimulating the growth of bacteria. This can lead to corals suffering from black band disease (Gantar *et al.,* 2009). In southeast Florida, a bloom by the cyanobacteria *Lyngbia* spp. caused significant coral mortality. Toxins from phytoplankton can be carried up the food web by zooplankton and even lead to the death of fish, whales, dolphins, and sea birds, changing the community surrounding the coral reefs (Steidinger, 1983; Burkholder *et al.,* 1995; Anderson and White, 1992; Gerachi *et al.,* 1989; Work *et al.,* 1993).

Maritime Industry

Southeast Florida is home to three major ports: Port Everglades, Port of Miami, and the Port of Palm Beach. Port Everglades is one of the most active cargo ports in the U.S. and South Florida's main seaport for petroleum products like gasoline and jet fuel. In 2009, Port Everglades opened the world's largest cruise terminal, overtaking the Port of Miami as the most important cruise passenger port of the world (Broward County, 2011). The Port of Miami is planning to dredge its harbor deeper to minus 50 feet to accommodate the new, larger class of Panamax vessels able to use the enlarged Panama Canal locks. This will increase trade with East Asia, resulting in a doubling of the cargo output of this port (Johnson, 2010). The Port of Palm Beach is an export port and the fourth busiest container port in Florida. It also has a cruise ship based at the port, the Bahamas Celebration cruise (Port of Palm Beach District, 2011).

The physical damage caused by vessel groundings is a major source of disturbance to shallow habitats found within and adjacent to busy shipping lanes. In Florida, impacts by large and small vessels to coral reefs are a significant source of coral mortality and reef-framework modification (Lutz, 2006; Lirman *et al.,* 2010). Damage to coral reefs can range from superficial, where only the living surfaces of corals are damaged, to structural where the geomorphologic reef matrix is fractured and exposed (Lirman *et al.,* 2010). Fishing gear impacts have been documented for both coral reefs and hardbottom communities. These impacts include the removal of sponges and soft corals by drag nets, as well as trap and line impacts on reef organisms (Ault *et al.,* 1997; Chiappone *et al.,* 2005).

Coastal Construction

Coastal construction includes dredging for harbors, laying of pipes and cables on the seafloor, and restoration of eroded beaches. Dredging causes direct physical damage to benthic habitat on the reef, as well as increased sedimentation. Since virtually the entire coastline of the southeast Florida region is built up and artificially hardened in many places, movements of sediment have been significantly altered. This has caused problems to nearshore hardgrounds both by smothering due to altered sedimentary movements and the requirement for beach renourishment that tends to lead to significant impacts by turbidity and smothering by newly-introduced sediments. Turbidity influences the amount of light that corals receive. Aller and Dodge (1974) and Dodge *et al.* (1974) discovered that coral growth slows down when water becomes more turbid, while other scientists have concluded that turbidity does not prohibit or even increase coral growth (Roy and Smith, 1971; Maragos 1974a, 1974b). A study conducted in the Florida Keys found that the coral cover was less in more turbid water (Yentsch *et al.,* 2002). Sedimentation can impact coral reef and hardbottom organisms through light reduction, smothering and burial, and toxicity (Bastidas *et al.,* 1999; Fabricius, 2005). Reductions in coral growth, photosynthesis, reproductive output, lesion regeneration, feeding activities, and recruitment have all been documented for corals under high sediment loading (Rogers, 1983, 1990; Riegl, 1995; Babcock and Smith, 2000; Lirman *et al.,* 2003; Philipp and Fabricius, 2003). Sedimentation tends to be increased by artificial alteration of shorelines and coastal construction activities.

Fishing, Diving, and Other Uses of the Reef

Fishing is a very popular recreational and important commercial activity in southeast Florida. Fishing and harvesting activities, both recreational and commercial, are key components of the economy (Johns *et al.,* 2001). The removal and collection of marine organisms has both direct and indirect impacts. Direct impacts include the targeted removal of organisms such as fish, sponges, lobsters, shrimp, anemones, live rock, and others. For example, the removal of predators may result in an increase in the abundance of damselfish that can result in increased coral mortality. This is due to their territorial activities that include killing coral tissue to grow macroalgae (Kaufman, 1977). Another cascading effect of predator removal, in this case lobsters, may be the increase in the abundance of corallivorous gastropods (*Coralliophila abbreviata*) that cause significant tissue mortality on colonies of reef-building corals and are known prey items for this once abundant taxon (Johnston and Miller, 2007). Indirect impacts include physical disturbance associated with harvesting activities, fishing and collecting gear, boating, pollution, and modifications to the trophic structure through removal of key organisms that can have cascading impacts on benthic communities. Fishing gear impacts have been documented for both coral reefs and hardbottom communities. These impacts include the removal of sponges and soft corals by drag nets (Ault *et al.,* 1997), as well as trap and line impacts on reef organisms (Chiappone *et al.,* 2005).

Other Pressures: Disease and Invasive Species

Diseases in the coastal marine environment are caused by increased pathogen and toxin concentrations in the water column, and they can infect both humans and marine life. With respect to threats to human health, even the perception that dangerous levels of pathogens or toxins are present in the water column affects *Ecosystem Servic*es such as swimming, diving, and consumption of marine life (Abdelzaher *et al.,* 2011). Diseases have been implicated as one of the main causal factors in the drastic decline in the abundance and distribution of corals recorded over the past three decades in Florida and elsewhere (Aronson and Precht, 2001; Kim and Harvell, 2002; Richardson and Voss, 2005). Many (if not most) of the epizootic agents and transmission pathways that affect soft and hard corals and sponges have not been fully described. Nevertheless, studies have found that increased temperatures are related to disease prevalence (especially after bleaching events, Brandt and McManus, 2009), human pathogens may cause disease in nearshore corals (Sutherland and Ritchie, 2004), and that the predatory and territorial activities of snails, polychaete worms, and fish may be a mechanism for inter-colony transmission of diseases vectors (Williams and Miller, 2005).

Invasive species can alter the ecosystem balance of a region. In South Florida, the invasive lionfish is a major threat to coral reef communities. Many adults and juveniles have been found, which indicates that they are established and reproducing here (Hare and Whitfield, 2003). Lionfish could impact the native ecosystem of the southeast Florida shelf through predatory interactions. Lionfish feed on a wide variety of smaller fish, shrimp, and crabs which are abundant in this area (Fishelson, 1975; Sano *et al.,* 1984; Wenner *et al.,* 1983). Predation on lionfish is thought to be limited because they only have a few predators within the native range (Bernadsky and Goulet, 1991). Moreover, predators along the southeast U.S. have no experience with the venomous spines of the lionfish (Ray and Coates, 1958; Halstead, 1965).

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 the marine environment that represent its overall condition (Ogden *et al.,* 2005). The marine waters of the SEFC support a diverse ecosystem which can be divided into seven submodels that describe the coastal marine environment: (1) water column; (2) fish and shellfish; two benthic communities – (3) coral and hardbottom on the reef tract; and (4) seagrass beds, located predominantly in Biscayne Bay; and two shoreline habitats – (5) beaches; and (6) mangrove-lined lagoons. Marine-dependent people (7) must also be included as an integral part of the ecosystem. *State* submodels describe these components in detail in the appendices to this report.

Water Column

The water column submodel encompasses the physical, chemical, and biological characteristics of the water column, including sediment, phytoplankton, and zooplankton suspended in the water column. Currently, the water column of the SEFC is highly oligotrophic with low phytoplankton biomass, low nutrient concentrations, and clear water (Hitchcock *et al.,* 2005; Boyer and Jones, 2002). The water column must remain oligotrophic to support the highly valuable and characteristic benthic habitats, including seagrass, coral reefs, and hardbottom. In turn, these benthic habitats support the highly valuable and productive fish community.

Characteristics of the water column along the SEFC reflect the influence of several sources. The waters on the shallow shelf are a mixture of clear, oligotrophic tropical water, carried by the Florida Current, and nutrient-rich freshwater discharged from canals, as runoff, and as treated wastewater from the urbanized coast. Eddies that move along the edge of the Florida Current can inject nutrient-rich water from upwelling along the shelf slope, and long-lived eddies can transport nutrients, pollutants, eggs, and larvae from distant sources in the Caribbean and Gulf of Mexico. At the region's north end, near St. Lucie, the shallow southeast U.S. continental shelf is another source of nutrient-rich water.

Fish and Shellfish

The fish and shellfish populations along the SEFC resemble populations in the Florida Keys. Over 400 species of fish have been identified in surveys conducted in Palm Beach, Broward, and Miami-Dade counties. The fish and shellfish submodel includes populations that are harvested by commercial and recreational fisheries, endangered species, and the prey species. Populations of many species are seeded by larvae transported into the region from spawning areas in the Gulf of Mexico and the Caribbean (Banks *et al.,* 2008).

Individuals move throughout the region and beyond. In general, the structure of fish assemblages varies in the cross-shelf direction, with depth, and with bottom type. Deeper, outer reef sites harbor higher fish densities and more species than shallower, inner reef sites (Ferro *et al.,* 2005). Inshore hardbottom habitats contain disproportionately higher densities of juvenile fishes (Lindeman and Snyder, 1999; Baron *et al.,* 2004; Jordan and Spieler, 2006). The inshore hardbottom habitat is ephemeral due to disturbances caused by storms that can redistribute large amounts of sediment in the shallow waters. Inshore areas are also vulnerable to impacts by coastal construction activities, such as dredge and fill operations for beach renourishment. The inshore hardbottom functions as nursery habitat, and its ephemeral nature contributes to large annual fluctuations in fish populations in the region (Jordan and Spieler, 2006).

Benthic Habitats

Coral and Hardbottom

The coral reefs and hard bottom communities of the SEFC are comprised of a complex of relict Holocene shelf-edge, mid-shelf reefs, and limestone ridges (Lighty, 1977; Banks *et al.,* 2007, 2008). These pre-existing structures, along with the present-day biological/physical conditions of the SEFC, allow formation of hardbottom areas, patch reefs, and worm reefs that support rich and diverse biological communities of octocoral, stony coral, macroalgae, and sponge assemblages (Moyer *et al.,* 2003; Banks *et al.,* 2007, 2008). An estimated 19,653 km^2 of inshore area (<18.3 m water depth) exists in southeast Florida that could potentially support shallow-water coral reef ecosystems, and this represents one of the largest such areas in the U.S. (Rohmann *et al.,* 2005; Banks *et al.,* 2008).

In addition to hermatypic, accreting reefs, low-relief hardbottom communities are a key component of the coastal habitats of southeast Florida. Hardbottom habitats in the southeast Florida reef tract can be found adjacent to the mainland at depths from <1 m to >20 m. Nearshore hardbottom communities are characterized by limestone platform with local, strongly-undulating morphology consisting of lithified Pleistocene Anastasia Formation (shelly sands) or early Holocene beachrock ridges. This hardground can be covered by a thin layer of sediment and harbors a similar fauna to the shallow reefs—a sparse mixture of stony corals, soft corals, macroalgae, and sponges. As in the Florida Keys, any of these communities are found on remnant, low-profile habitats lacking significant zonation and topographical development (<1 m of vertical relief) in areas where sediment accumulation is <5 cm (Lirman *et al.,* 2003). These habitats, which can be important nursery habitats for lobsters, are characterized by low coral cover and small coral colony size (Blair and Flynn, 1999; Chiappone and Sullivan, 1994; Butler *et al.,* 1995).

Seagrasses

Extensive seagrass beds, similar to those found in Florida Bay and the Florida Keys, are found in the south portion of the SEFC, in and around Biscayne Bay. Five species of rooted aquatic vascular plants, or seagrasses, are commonly found in South Florida: turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), shoal grass (*Halodule wrightii*), paddle grass (*Halophila decipiens*), and widgeon grass (*Ruppia maritime*). In the shallow water nearest shore, seagrasses are especially prevalent; over 90 percent of the area in water less than 10 m deep supports seagrass.

Seagrass beds are recognized as among the most productive and economically valuable of ecosystems (Zieman and Wetzel, 1980; Costanza *et al.,* 1997). The proximity of seagrass meadows to coral reef and mangrove ecosystems provides critical feeding grounds and nursery areas for species who rest on coral reefs or in mangroves as adults (Beck *et al.,* 2001). These associations are essential in maintaining the abundance of some coral reef and mangrove species (Valentine and Heck, 2005). In addition, seagrasses help maintain water quality. They trap sediments produced in other parts of the ecosystem (Kennedy *et al.,* 2010) and decrease sediment resuspension (Green *et al.,* 1997), thereby contributing to clearer water. They are also sites of active nutrient uptake to fuel their high primary productivity; nutrients taken up by seagrasses can not be used by phytoplankton and macroalgae.

Shoreline Habitats

Beaches

The beach and shoreline for this study of the southeast Florida MARES region extends from St. Lucie Inlet to Cape Florida and includes some of the most densely populated coastal areas in the world. A sandy beach of some form is present and uninterrupted for almost 100 miles in the study area except for several coquina (limestone) outcroppings and inlets. The study area is comprised of several beach types including barrier islands and spits/peninsulas, as well as oceanfront areas where the Atlantic Coastal Ridge fronts directly on the Atlantic Ocean. Many oceanfront areas have been subjected to sand nourishment projects as a response to erosion caused by natural beach and barrier island processes, sea-level rise, and development practices. The inlets that separate the sections of beach are in locations where inlets have historically existed (e.g., Jupiter Inlet) and inlets that were created by dredging, often in locations where ephemeral inlets have existed over time. All of the inlets in the South Florida study area are protected by jetties.

Mangroves

Three species of mangrove are native to Florida: red (*Rhizophora mangle*), black (*Avicennia germanans*), and white (*Laguncularia recemosa*) mangroves. Buttonwood (*Conocarpus erectus*), a mangrove associate, is also common in mangrove forests in southern Florida. Mangroves along the SEFC are found mainly as stands fringing the shoreline of Biscayne Bay and the tidal lagoons sheltered behind the barrier islands. The arrangement of the species within forest type determines the biota that occur within the mangrove forests (Lugo and Snedaker, 1974). Epiphytes and sessile invertebrates frequently grow on specialized root adaptations of mangroves (prop roots and pneumatephores) and these, plus the mangrove leaf litter, are the basis of mangrove food webs (Odum and Heald, 1975). Odum *et al.* (1982) reported 220 species of fish, 21 reptiles, 3 amphibians, 18 mammals, and 181 birds that utilize the mangroves of South Florida.

Mangrove forests provide important nursery habitat for numerous fishery species of economic importance and critical foraging habitat for adults of some of these same species (Odum *et al.,* 1982; Lewis *et al.,* 1985; Faunce and Serafy, 2006). Mangroves also provide foraging and nesting habitat for South Florida's ubiquitous fish-eating birds, as well as nesting and stopover habitat for resident and migratory passerine bird species (Odum *et al.,* 1982). Mangroves are also highly effective at sequestering carbon dioxide, nutrients, and protecting shorelines from erosion and storm surges (Odum and McIvor, 1990).

Marine-Dependent People

The SEFC ICEM includes marine-dependent people as an integral part of the coastal marine ecosystem, i.e., as a component of the *State* element in the DPSER framework. The category "marine-dependent people" includes people who are directly engaged in the coastal marine environment, for commercial fishing and for recreational uses, and people indirectly engaged by providing support services. There are three distinct but related classes of users of the coastal marine environment:

- Primary users are those individuals or groups that actively engage in activities in or on the water and that are directly dependent on the marine resource. Examples are anglers, divers, and swimmers.
- Secondary users are those one step removed from direct interaction with the marine resource, but who provide enabling support for the primary users. Examples include marina operators, dive shops, or bait and tackle shops.
- Tertiary users are those who don't directly interact with the coastal marine environment, but whose activities support the primary and secondary users in an indirect fashion. Examples include hotels, restaurants, souvenir shops, transportation, etc.

Similar designations have been used by others to identify people who depend directly on the coastal marine environment either for their livelihood or for recreation. As defined here, primary users correspond with people identified as "reef users" in the economic valuation by Johns *et al.* (2001), with the exception that the Johns *et al.* study excludes commercial fishers. The group of stakeholders identified by the Florida Department of Environmental Protection's Coral Reef Conservation Program is more inclusive. In addition to the primary users defined here, the stakeholders include management agencies at the federal, state, and local level, researchers, non-governmental organizations, port authorities, environmental consultants, teachers, and water resource managers (Jamie Monty, personal communication). In terms of sectors of the marine economy identified by Pendleton (n.d.) "marine-dependent people" correspond to Pendleton's commercial fishery sector and coastal and estuarine recreation sector combined. In addition to these, Pendleton identifies critical energy infrastructure, marine transportation, and coastal real estate as comprising the marine economy.

Marine-dependent people act as intermediaries between other components of the coastal marine environment and the provision of ecosystem services. The class of primary users includes most of the recreational users in the coastal marine ecosystem. Primary users also include commercial fishers, who harvest the seafood that constitute the provisioning service to the general human population. The activities of primary users directly impact other components of the coastal marine environment through various pressures. For example, the harvest activities of both recreational and commercial fishers have a significant effect on the species composition and population characteristics of fish and shellfish. The activities of secondary and tertiary users of the coastal marine environment support the activities of primary users. This support facilitates the provision of *Ecosystem Services*. Often, this is essential, as in the role of marinas and dive shops, in providing access for primary users into the coastal marine environment, but the activities of secondary and tertiary users generally occur away from marine waters.

Ecosystem Services: What People Care About

Ecosystem Services are the benefits that people receive 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 that can be measured in a monetary, cultural, or social context, and the value of *Ecosystem Services* depends on conditions in the environment.

The MARES project identifies 12 distinct Ecosystem Services provided by the South Florida coastal marine ecosystem (Table 3). These can be categorized as cultural, provisioning, and regulating services, following the approach taken in the Millennial Assessment project (cf., Millennial Ecosystem Assessment, 2005; 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* in supporting the recreation and tourism industry in the SEFC region cannot be overstated. During the 12-month period from June 2000 to May 2001, reef-related expenditures generated $505 million in sales in Palm Beach County, $2.1 billion in sales in Broward County, $1.3 billion in sales in Miami-Dade County, and $504 million in sales in Monroe County (Johns *et al.,* 2001). These sales resulted in $194 million in income to Palm Beach County residents, $1.1 billion in income to Broward County residents, $614 million in income to Miami-Dade County residents, and $140 million in income to Monroe County residents during the same time period (Johns *et al.,* 2001). Reef-related expenditures provided 6,300 jobs in Palm Beach County, 35,500 jobs in Broward County, 18,600 jobs in Miami-Dade County, and 10,000 jobs in Monroe County (Johns *et al.,* 2001).

Attributes People Care About: Linking State to Ecosystem Services

In general, people care about the sustainability of the coastal marine ecosystem. In the SEFC region, people are concerned with protecting and restoring the natural habitats, populations of native plants and animals, and sustaining ecological processes of the coastal marine ecosystem. The coastline in this region is the most densely-developed region in the state of Florida. People are attracted to this region, to live or to visit, by the natural beauty and amenities of the region's beaches and its coastal waters. Tourism and recreation power the region's economy, and these activities depend on sustaining the coastal marine ecosystem.

The attribute of sustainability requires a well-functioning, whole ecosystem in which all elements are healthy and functioning, i.e., the water column, fish and shellfish populations, and the coral and hardbottom, seagrass, and mangrove habitats. Reef 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, in order to thrive.

Other "attributes that people care about" relate more directly to particular elements of the coastal marine environment. For example, 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. Good water quality is an important factor in people's enjoyment of beaches and other shoreline locations as places to visit.

People care about the size and health of fish and shellfish populations and about maintaining a variety of species in the ecosystem. Species that are important to the commercial fishery include the Caribbean spiny lobster, pink shrimp, and various species of finfish. Many species of interest for both commercial and recreational fishing and for divers and snorkelers are the large predator species. These species prey upon invertebrates and smaller individuals of their own kind. Hardbottom communities are valuable nursery areas for many invertebrates and fishes of both the patch reef and seagrass communities, providing microhabitats for many juvenile fishes.

People care about the extent and variety of healthy coral and hardbottom communities and areas to enjoy while diving or snorkeling. Coral reef systems provide protection and shelter for colorful and diverse macrofauna, including

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.

small shrimp, crabs, fish, and several species of lobsters. Many species, especially the larger predators, are important species for local fisheries. Hardbottom communities are valuable nursery areas for many invertebrates and fish of both the patch reef and seagrass communities, providing microhabitats for many juvenile fish. The three-dimensional structure of coral reefs provides protection from the impacts of storm waves, surge, and tides, protecting both natural shorelines and property from physical damage.

People care about seagrass beds as a popular destination for fishing and boating. Seagrass beds also protect shallow, unconsolidated sediments from erosion, and they help maintain water clarity by trapping suspended sediments and controlling the concentration of nutrients in the water column. Seagrass beds are also highly productive systems and provide habitat to a wide variety of commercial and recreational species as feeding grounds, nurseries, and refuges from predation. Their position at the base of the detrital food web provides food for various organisms.

People care about mangroves as a place to go to find a large number and variety of species of birds. Mangroves are also a component of the natural shoreline in the Florida Keys, which has few beaches compared with the southeast Florida coast. Mangroves help prevent erosion of the shoreline and provide natural protection for developed upland areas from storm tides and wave action during high water. Mangroves provide critical habitat in the life cycle of many important commercial and recreational fishes as both shelter and detritus-based food source (Estevez, 1998; Heald *et al.,* 1984; Lugo and Snedaker, 1974; Odum *et al.,* 1982).

People care about the beach and shoreline for access to the ocean, as an area to recreate, for storm protection, and for its ecological function as habitat. There are three main economic benefits attributed to the maintenance of healthy beach systems in the state (Murley *et al.,* 2003). These include enhanced property values; increased sales, income, and employment opportunities resulting from resident and non-resident spending; and expansion of the federal, state, and local tax base. As an international tourist destination, the beaches of southeast Florida contribute to the local, state, and national economies by enhancing opportunities for labor and capital and by making net contributions to the tax base of local, state, and federal governments.

Valuing Ecosystem Services

Use and non-use values and avoided costs can be estimated and used in benefit-cost analysis of management actions deemed necessary to protect the quality of the environment. For example, economic values for ecosystem services from survey-based research are reported in the documents "Socioeconomic Study of Reefs in Southeast Florida" and "Socioeconomic Study of Reefs in Martin County, Florida" (Johns *et al.,* 2001; Hazen and Sawyer, 2004). These studies provide estimates of the following values that represent the time period June 2000 to May 2001: (1) Total reef use of residents and visitors in each of the five counties as measured in terms of the number of person-days by recreation activity (fishing, diving, snorkeling, glass bottom boats); (2) Economic contribution of the natural and artificial reefs as residents and visitors spend money in each of the five counties to participate in reef-related recreation; (3) Willingness of reef users to pay to maintain the natural and artificial reefs of southeast Florida in their existing condition; (4) Willingness of reef users to pay for additional artificial reefs in southeast Florida; and (5) Socioeconomic characteristics of reef users. Economic contribution is measured by total sales, income, and employment generated within each county from residents and visitors who use the reefs. In addition, the opinions of residents regarding the existence or establishment of "no-take" zones as a tool to protect existing artificial and natural reefs are presented.

The use value of coral and artificial reefs to those who fish, snorkel, and SCUBA dive is $3.33 billion per year which includes $3.0 billion in reef-related recreation expenditures and $330 million in willingness to pay to protect the reefs in their existing condition (Johns *et al.,* 2001). Reef users would be willing to pay an additional $31 million per year to fund the development and maintenance of new artificial reefs in southeast Florida (Johns *et al.,* 2001). Southeast Florida coral and artificial reef-related recreation expenditures generated $4.4 billion in local production, $2.0 billion in resident income, and 70,000 jobs in the five-county area (Johns *et al.,* 2001; Hazen and Sawyer, 2004). The studies did not estimate the non-use value associated with the reefs of southeast Florida. However, this value is expected to be significant given the non-use values of natural resources used for recreation estimated in other studies throughout the U.S. and in Florida (e.g., Hazen and Sawyer, 2008).

A study was undertaken by the Center for Urban and Environmental Solutions at Florida Atlantic University in 2005 to better understand the economics of beach tourism in various parts of Florida (CUES, 2005). Over one-third of out-of-state visitors from 2000 to 2003 visited a beach. These visitors spent $19.1 billion in 2003, an amount equal to 3.8 percent of the gross state product, and paid about $600 million in state sales taxes. Almost one-half of the more than 500,000 jobs created in Florida by beach tourism is from spending in the region.

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 for people to exert a degree of control on the ecosystem.

The current SEFC coastal marine ecosystem differs markedly from what existed 40 years ago. The urban area in southeast Florida has been among the most rapidly-growing areas in the U.S. during the last half of the 20th century, and it continues to grow, albeit at a reduced rate in recent years. As a consequence, there is more development, more human activity in the marine environment and, thus, potentially more *Pressures* acting to change the ecosystem away from sustainability. However, human behavior in the ecosystem has also changed over this time period. New behaviors, some manifested in new institutions, have introduced into the ecosystem a capacity to regulate local *Drivers* and *Pressures* which did not exist 40 years ago. The changes in human behavior have occurred in *Response* to the perception that *Pressures* have increased and to evidence of decline in conditions in the marine environment, such as water quality and the quality of coral reefs.

Protected Natural Areas

The designation of protected areas is one way of controlling *Pressures* caused by human activities in the ecosystem. Protected areas can be used to restrict a variety of different human activities.

Biscayne National Park

Biscayne National Park was established first as a national monument in 1968 and finally as a national park in 1980 to preserve Biscayne Bay and Elliot Key from development. The park encompasses most of central Biscayne Bay and the reef tract from Key Biscayne and Cutler Ridge, at its northern boundary, to Key Largo and Turkey Point at its southern boundary. The purpose of Biscayne National Park, as established by its originating legislation is:

> *To preserve and protect for the education, inspiration, recreation, and enjoyment of present and future generations a rare combination of terrestrial, marine, and amphibious life in a tropical setting of great natural beauty.*

Currently, the waters of the park are used extensively for recreation by residents and visitors to the Miami area. A new general management plan, expected to be finalized in 2013, proposes to establish marine protected areas within the park where boat access and fishing will be restricted.

National Wildlife Refuges

The Hobe Sound National Wildlife Refuge, in Martin County, consists of 1000 acres of land encompassing sea turtle nesting habitat, on Jupiter Island, and sand scrub community on the mainland. The refuge was established in 1969 for the purpose of preserving nature habitat and populations, the preservation of cultural resources, recreation, and education. The refuge preserves some of the last remaining pristine dune and pine scrub habitat in the region.

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 SEFC region includes the following Florida state parks (Figure 11):

- Jonathan Dickinson State Park
- Seabranch Preserve State Park
- John D. MacAuthur Beach State Park
- John U. Lloyd Beach State Park
- Oleta River State Park
- Bill Baggs Cape Florida State Park
- Hugh Taylor Birch State Park

Florida State Aquatic Preserves

Florida's system of aquatic preserves was established in 1975 for the purpose to preserve the aesthetic, biological, and scientific values in 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 SEFC region includes the following aquatic preserves (Figure 11):

- Biscayne Bay
- Biscayne Bay–Cape Florida to Monroe County line
- Loxahatchee River–Lake Worth Creek
- Jensen Beach to Jupiter Inlet

In addition to the Florida state parks and aquatic preserves, the SEFC region also has a large number of county parks that protect natural areas of the coast.

Coastal Management

The Coral Reef Conservation Program (CRCP), administered by the Florida Department of Environmental Protection, coordinates activities among a large number of partners toward the goal of preserving and restoring the coral reefs along the southeast coast. The CRCP was created in 2004 to implement the local action strategy for the U.S. Coral Reef Task Force for protection of the reefs. Partners in this effort include local stakeholder groups and agencies of the county, state, and national governments. The local action strategies consist of research, monitoring, outreach, and education activities. In addition, the CRCP also has responsibility for responding to incidents, such as ship groundings, that physically damage the reef.

The Florida Fish and Wildlife Conservation Commission (FWC) is authorized by the Florida Constitution to enact rules and regulations regarding the state's fish and wildlife resources. Created in 1999, its goals are to manage fish and wildlife resources for their long-term well-being and the benefit of people (FWC, 2012a). Fishing regulations set in place by the FWC include size limits, the amount of fish one

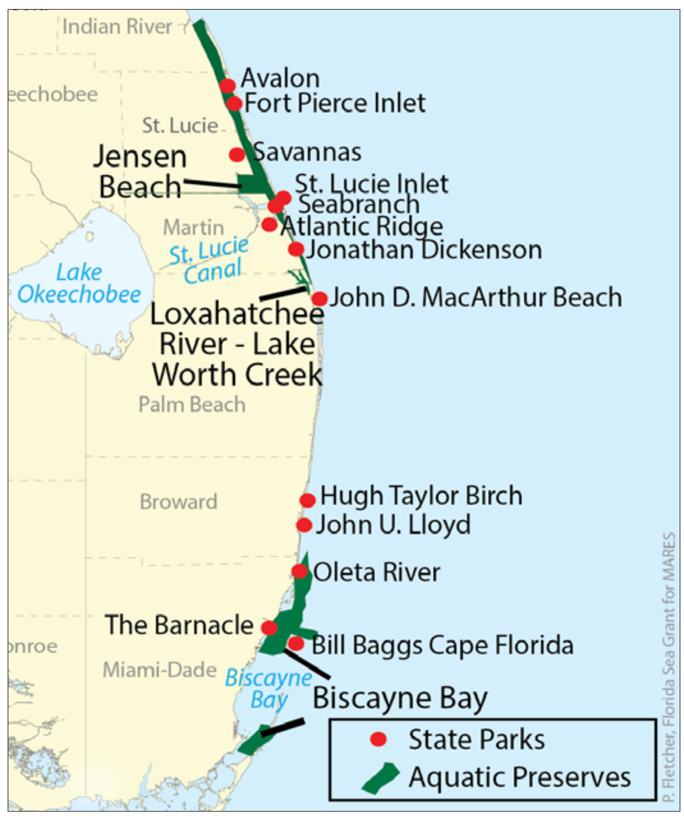


Figure 11. Map depicting southeast Florida's state parks and aquatic preserves.

is allowed to catch (bag limits), closed seasons, and species which are prohibited to fish. With these measures, the FWC tries to manage the different fish species depending on their conservation needs (FWC, 2012b). Next to the harvest of fish, fishing gear can also have a negative impact on coral reef and hardbottom. To diminish the physical damage done to coral reef and hardbottom by lost traps, the FWC has two programs dedicated to removing lost and abandoned traps from state waters (FWC, 2012a).

Florida currently has implemented strong management controls on recreational and commercial fishing (FWC, 2012a; FWC, 2012b). One control mechanism that has been successful is the establishment of Marine Protected Areas and "no-take" sanctuaries (Lester *et al.,* 2009). A "no-take" region of the Merritt Island National Wildlife Refuge was established in 1962; in a recent study, samples from the no-take areas had significantly greater abundance and larger fishes than fished areas (Johnson *et al.,* 1999). This concept has also been successfully applied in the Florida Keys (Toth *et al.,* 2010), and has been suggested for the southeast coast (SEFCRI, 2004). A survey published in 2001 (Johns *et al.,* 2001) indicated that a majority of residents of the three counties would support "no take" zones on 20-25 percent of the existing natural reefs.

Ecosystem Research and Monitoring

The Southeast Florida Coral Reef Initiative (SEFCRI) supports a team of marine resource professionals, scientists, and stakeholders from government agencies and other organizations who coordinate research and monitoring and develop strategies for protection and restoration of the reef. The work of SEFCRI supports CRCP and its partners in their management responsibilities. From its beginning in 2003, the activities of SEFCRI have been focused on four main areas of concern: land-based sources of pollution; impacts of the maritime industry and coastal construction; impact of fishing, diving, and others uses of the reef; and public education and awareness. In southeast Florida, water quality monitoring is limited to inland waters (Trnka *et al.,* 2006; Caccia and Boyer, 2005; Torres *et al.,* 2003; Carter, 2001). There are no long-term data available for ocean waters, but the Broward County Environmental Protection Department began a coastal water quality monitoring program in 2005 with nutrients, chlorophyll, salinity, dissolved oxygen, and pH measured at three sites in Port Everglades on a monthly basis (Craig, 2004; Banks *et al.,* 2008).

Hydrologic Restoration

Different agencies work together to implement more sustainable water management in southeast Florida. These agencies include the South Florida Water Management District (SFWMD) and its Water Resources Advisory Commission (WRAC). The SFWMD is a regional governmental agency in charge of the water resource. Created in 1949, the agency is responsible for managing and protecting the water resources of South Florida by balancing and improving water quality, flood control, natural systems, and water supply. Its goal is to manage stormwater flows to rivers and freshwater discharge to South Florida's estuaries in a way that preserves, protects, and, where possible, restores these essential resources (SFWMD, 2011a). The WRAC is an advisory body to the South Florida Water Management Governing Board and the South Florida Ecosystem Restoration Task Force. Its main purpose is to improve public participation and decision-making in water resource-related topics. For this reason, the members of the Commission come from the following different backgrounds: business, agricultural, environmental, tribal, governmental, and public interests (SFWMD, 2011c).

The SFWMD implements Florida state water policy through various programs. Ongoing programs that affect the SEFC coastal marine ecosystem include the following:

- The Biscayne Bay Surface Water Improvement and Management (SWIM) plan coordinates federal, state, and local government and the private sector in efforts to restore this damaged ecosystem, prevent pollution from runoff and other sources, and educate the public. In addition to addressing these issues, identified in 1988, the updated plan analyzes the extensive data collected since 1988 to document the effectiveness of the initial plan's strategies and identify new issues and solutions to problems facing Biscayne Bay and its watershed.

- Minimum flows and levels criteria have been established for the Northwest Fork of the Loxahatchee River and the St. Lucie estuary. Along with water reservations, the minimum flows and levels criteria guide regional water management practices to better protect fish and wildlife in these estuarine ecosystems from changes in salinity and other changes associated with the regulation of freshwater inflows.

- Biscayne Bay Coastal Wetlands Project is designed to replace lost overland freshwater inflow and groundwater inflow into central Biscayne Bay. The goal is to improve the ecological health of the bay, especially in its tidal creeks and nearshore habitat. The Biscayne Bay Coastal Wetlands project is a component of the regional CERP.

Southeast Florida Regional Climate Change Compact

Climate change threatens millions of people and businesses along the SEFC by shifting weather patterns, increased hurricane intensity, and rising seas (South Florida Regional Planning Council, 2008). For these reasons the South Florida Regional Planning Council wants to take actions against climate change. Between 1990 and 2005 greenhouse gas emissions increased in Florida by about 35 percent, and a business-as-usual projection to 2025 showed an increase in greenhouse gas emissions of 86 percent compared to the 1990 level (Strait *et al.,* 2008). On July 13, 2007, Governor Charlie Crist signed executive orders (07-126, 07-127, 07-128) which required South Florida to reduce its GHG emissions to 80 percent below the level of 1990 by 2050 (South Florida Regional Planning Council, 2008). Recent actions that Florida has undertaken, such as the electric utility cap and adoption of the California Clean Car Standards, will lower the increase of greenhouse gas emissions to 55 percent of the 1990 level by 2025 (Strait *et al.,* 2008).

In *Response* to the relatively new threat of climate change and accelerated sea-level rise, Miami-Dade, Broward, and Palm Beach counties joined with Monroe County in 2009 to form the Southeast Florida Regional Climate Change Compact. The Compact is developing a regional strategy to foster collaboration in southeast Florida on mitigating the causes and adapting to the consequences of climate change.

As a first step towards mitigating the effects of accelerated sea-level rise, as a consequence of climate change, the Compact has developed a consensus trajectory for sea level projected until 2060 (Figure 12) (Southeast Florida Regional Climate Change Compact Counties, 2011). The consensus projection is 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 (Figure 12). Sea level in South Florida is projected to rise 1 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. For reference, between 1913 and 1919, sea level rose at an average rate of 0.88 inches per decade.

Response by Individuals

People change their use of the coastal marine environment for reasons that are unique to each individual. Factors that contribute to these decisions can be categorized as related to

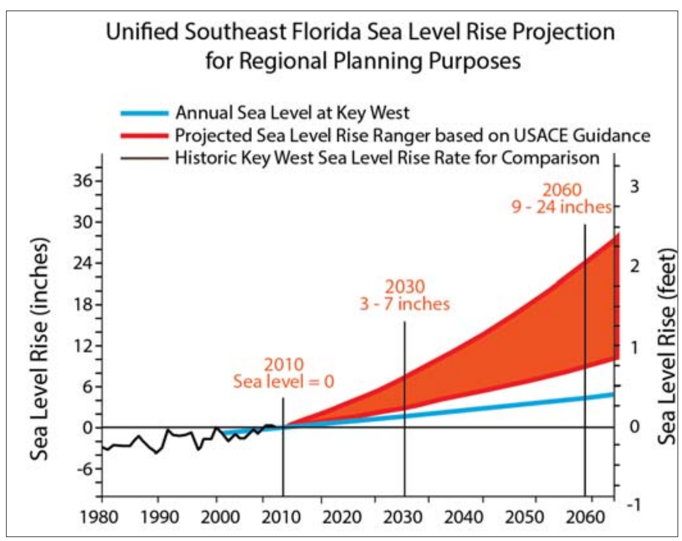


Figure 12. Unified southeast Florida sea-level rise projection for regional planning (Southeast Florida Regional Climate Change Compact, 2011; calculations courtesy of K. Esterson, U.S. Army Corps of Engineers).

their demand for services provided by the ecosystem or their level of satisfaction obtained while in the coastal marine environment. Changes in demand often can be understood as a response to economic conditions, such as costs and ability to pay, and regulations that restrict access and/or use of the environment. Satisfaction is typically viewed as one of the most important management goals when providing quality recreational opportunities.

Unfortunately, satisfaction is a difficult concept to measure. Simply asking an individual how satisfied they are does not inform a manager why they are or aren't satisfied or what contributed to their response. Other factors must be considered that include subjective personal and social aspects of a user's experience; these include conflict, crowding, expectations, normative standards, etc. While these other factors can be easily justified on their own (particularly for the commercial operators), they need to be considered when seeking to understand satisfaction.

The recreational user seeks satisfaction in the experience of obtaining a desired ecosystem service facilitated/delivered through resource management. The user's experience has two parts: the environmental and the social. The first, the environmental, is determined by the attributes typically thought of as being provided via a marine ecosystem; these are characterized by the "attributes that people care about." The second, the social, is determined by interactions with other people. These are related to the services that individuals often think of as services when participating in their activity. It should be noted that there are additional social "services" that should be considered for inclusion. These might include relaxation, solitude, education, family time, etc. These services are not based directly on the physical attributes, but rather the management goals in combination with the resource.

Crowding

Perceived crowding is a concept that is at best only weakly related to user density. Instead, it is related to factors such as goal interference, expectations and discrepancies, normative standards, etc. The "ecosystem service" being desired by users, and delivered through resource management, would be a mix of user types, user levels, and experiences consistent with what the combination of the resource and management goals are intended to provide.

For example, crowding may be a factor limiting recreational boating use in Broward County. Measured on a per capita basis, fewer residents of Broward County engage in recreational boating than in the rest of Florida. Broward County residents have higher-than average incomes and this, combined with residents' proximity to the coast, would argue for a higher demand for recreational boating. An explanation for this anomaly might be found on the supply side. People may be deterred from engaging in recreational boating activities by crowding or congestion at boat ramps, to get out onto the water, or at recreational resources such as artificial reefs or prime fishing locations (Johns *et al.,* 2001).

Conflict

Conflict is typically defined by the mixing of motorized and non-motorized users. The two typically don't mix. A second characteristic of conflict is that it is typically asymmetrical in that one group (fishermen, for example) will experience conflict while the other group (motor boaters or jet skis, for example) will not experience conflict. Conflict is related to perceived crowding, which is then related to satisfaction. Users desire the ecosystem service of limited user conflict.

Expectation

Humans do things in the expectation that certain outcomes (ecosystem services) will follow. Users in this case have certain expectations for certain ecosystem services. They might expect certain a number of fish to catch or a number of other divers to be in the water at the same time (not too many or too few), or a healthy and pristine ecosystem. This does not mean that user expectations should automatically be met. Expectations are often unrealistic or inappropriate for a given environmental condition or management mandate. Instead, expectations should be considered in the sense that they influence how users evaluate conflict, crowding, or satisfaction. Thus, expectations aren't a true ecosystem service but rather an intervening variable in understanding other ecosystem services.

Normative Standards

Normative standards are socially agreed upon standards of what should be. Users can generally agree on what constitutes an acceptable level of coral bleaching, or use levels, or coastal impacts due to human use, or management mandates for particular resource types or classifications. It is usually necessary and best to examine norms according to meaningful subgroups, since an overall average user really doesn't exist. Like expectations, norms are not ecosystem services. They are the standards against the extent to which ecosystem services are being delivered or met. They are a comparative device.

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