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Between the devil and the deep blue sea: Florida's unenviable position with respect to sea level rise

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Abstract This paper introduces and summarizes a series of articles on the potential impacts of sea level rise on Florida's natural and human communities and what might be done to reduce the severity of those impacts. Most of the papers in this special issue of *Climatic Change* were developed from presentations at a symposium held at Archbold Biological Station in January 2010, sponsored by the Florida Institute for Conservation Science. Symposium participants agreed that adaptation to sea level rise for the benefit of human communities should be planned in concert with adaptation to reduce vulnerability and impacts to natural communities and native species. The papers in this special issue discuss both of these categories of impacts and adaptation options. In this introductory paper, I place the subject in context by noting that that the literature in conservation biology related to climate change has been concerned largely about increasing temperatures and reduced moisture availability, rather than about sea level rise. The latter, however, is the most immediate and among the most severe impacts of global warming in low-lying regions such as Florida. I then review the content of this special issue by summarizing and interpreting the following 10 papers. I conclude with a review of the recommendations for research and policy that were developed from group discussions at the Archbold symposium. The main lesson that emerges from this volume is that sea level rise, combined with human population growth, urban development in coastal areas, and landscape fragmentation, poses an enormous threat to human and natural well-being in Florida. How Floridians respond to sea level rise will offer lessons, for better or worse, for other low-lying regions worldwide.

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1 Introduction

The effects of anthropogenic climate change on ecosystems and biodiversity have been discussed for several decades, especially following the seminal paper by Peters and Darling (1985), which put climate change on the agenda of conservation biology. Recent reviews suggest that climate change may soon rival the more direct effects of habitat loss, fragmentation, and degradation as major contributors to the global extinction crisis (Heller and Zavaleta 2009; Parmesan and Matthews 2006; Rosenzweig et al. 2008; Sala et al. 2000; Thomas et al. 2004; Dawson et al. 2011). Evidence is accumulating that many species are responding to a general warming of the global climate in predictable ways, shifting their distributions poleward and upslope and advancing their spring phenology as warm temperatures arrive earlier (Parmesan and Yohe 2003; Root et al. 2003). Nevertheless, in Florida, many plants are instead blooming later in the spring, reflecting a trend of increased climatic variability, with generally warmer summers and falls, but with much of the state showing colder winter and spring temperatures (Von Holle et al. 2010).

The well-documented range shifts and adaptive responses of organisms to changes in climate during the Quaternary cannot be assumed to continue unimpeded today and into the future, especially because urban and agricultural land uses create barriers that disrupt dispersal and gene flow (Davis and Shaw 2001). Although some extinctions attributed to anthropogenic climate change remain controversial, like those of amphibians (Lips et al. 2008; Pounds et al. 2006; Rohr et al. 2008), it is increasingly likely that climate change is causing extinctions of amphibians, butterflies, corals, and other organisms worldwide (Carpenter et al. 2008; Thomas et al. 2006). Thomas et al. (2004) estimated that 15–37% of species in their sample of regions and taxa globally will be "committed to extinction" by 2050. Their estimate may be overly pessimistic given the natural coping mechanisms of populations and the evidence that, so far, range expansion in response to recent climate change has been more common than range contraction (Dawson et al. 2011). Nevertheless, in the case of sea level rise, species are likely in trouble when all known populations are located in areas likely to be inundated over the next several decades and where human development has created barriers to movement (Oetting 2010). Although climate change is a presumed threat to many species listed under the U.S. Endangered Species Act, only about 10 percent of species recovery plans address climate change (Povilitis and Suckling 2010). The interactive effects of climate change, habitat loss, over-harvest, and other stressors on populations (e.g., Carroll 2007) complicate predictions of population responses.

The discussion of climate change among biologists has focused mostly on effects of rising temperatures, changes in precipitation and moisture regimes, increased incidence of droughts and other extreme weather events, and a general increase in climatic variability (Heller and Zavaleta 2009; Parmesan and Matthews 2006). Until recently, there has been little attention to the potential effects of sea level rise. This is despite the availability of credible models more than a quarter-century ago that predicted rises in sea level by 2100 on the order of 70–217 cm (Hoffman et al. 1983; NRC 1983), measured recent increases in sea level that substantially exceed average model predictions (Rahmstorf et al. 2007), and the continued refinement of semi-empirical models that now explain up to 98% of the variance in the relationship between global mean temperature and sea level for the period 1880–2000 (Vermeer and Rahmstorf 2009). These recent models project rises in sea level on the order of 75–190 cm for the period 1990–2100 under the range of future temperatures predicted by the IPCC (2007), with higher levels possible if polar ice sheet dynamics become highly nonlinear (Vermeer and Rahmstorf 2009). In a compelling book, Pilkey and Young (2009) summarized the importance of sea level rise among the effects of anthropogenic climate change:

> Of all the ongoing and expected changes from global warming…the increase in the volume of the oceans and accompanying rise in the level of the sea will be the most immediate, the most certain, the most widespread, and the most economically visible in its effects.

If we accept this conclusion by Pilkey and Young (2009), we must also accept that the impacts of sea level rise constitute one of the greatest potential causes of global species extinctions and ecosystem disruption over coming decades and centuries. In Florida alone, many species of conservation concern have their entire global distribution in coastal areas that are projected to be inundated by rising sea level over the next several decades (Geselbracht et al. 2011, this volume; Hoctor et al. 2010; Maschinski et al. 2011, this volume; Oetting 2010; Ross et al. 2009). These species are often trapped "between the devil and the deep blue sea" (Harris and Cropper 1992), in that human development adjacent to the coasts has destroyed suitable habitat and severed potential dispersal corridors to inland areas that might otherwise accommodate range shifts.

Although the most direct and immediate impacts of sea level rise will be seen in low-lying coastal areas—and, in fact, have already been observed for several decades in places such as the Florida Keys (Alexander 1953, 1974; Maschinski et al. 2011, this volume; Ross et al. 2009; Saha et al. 2011a, b, this volume)—the impacts will quickly extend inland from the coasts. Consider that 53% of the population of the United States lives in coastal counties, which comprise just 17% of the land area (Crossett et al. 2004), and that ocean and coastal activities contribute more than $1 trillion to the national economy (NRC 2010). People living in areas with high relative rates of sea level rise are already experiencing impacts such as saltwater intrusion into freshwater aquifers and wellfields, increased coastal erosion (and concomitant demands for frequent beach 'renourishment'), higher storm surges from hurricanes and other storms, and heavy flooding of low-lying areas (NRC 2010; Pilkey and Young 2009). How long can people be expected to tolerate these risks, inconveniences, and reductions in property values? After some threshold of sea level rise, mass migrations of people from the coasts to inland areas are likely. If much of this inland area is currently undeveloped, home to species of conservation concern, but not formally protected, humans will displace native species and could create a second wave of local and, in some areas, global extinctions (Hoctor et al. 2010).

The response of the environmental community to the problem of climate change has focused on reducing emissions of greenhouse gases (Heller and Zavaleta 2009). Adaptation has been seen by many environmentalists as a 'cop-out,' a diversion from regulation and other mitigation or an admission that carbon regulation and incentive programs have failed. Increasingly, however, as evidence suggests that the earth is committed to a long period of warming even if greenhouse gas emissions were substantially reduced now (NRC 2010; Solomon et al. 2009), adaptation, which can be defined as an adjustment of human and natural systems to accommodate climate change (IPCC 2007), is becoming more acceptable to many in the environmental community.

Florida is at high risk from sea level rise in the near future, making adaptation especially urgent. Approximately 10% of the state's land area is less than 1 m above present sea level (Weiss and Overpeck 2003). With one of the highest rates of species endemism in the temperate and subtropical zones of North America (Gentry 1986; Estill and Cruzan 2001; Sorrie and Weakley 2001), Florida has much to lose biologically from sea level rise. Pitted against Florida's natural diversity is the human population, now 18.8 million, and the rate of population growth, 17.6% over 2000–2010, far above the national growth rate of 9.7% (United States Census Bureau 2010). Florida has 3,660 km of tidal shoreline (Donoghue 2011, this volume), and no point in the state is more than 120 km from the coast (CSO 2010 and references therein). Fifteen of the state's major population centers and more than 75% of the population are in coastal counties, and 86% of the GDP is derived from the coastal economy (CSO 2010; Wilson and Fischetti 2010). Therefore, Florida provides a salient case study on options for adaptation to sea level rise (Fig. 1).

The clash between nature and humanity in Florida stands to escalate substantially as sea level rises and inundates coastal areas inhabited by people as well as areas that remain in generally natural condition. We can anticipate increasing calls for 'coastal hardening' and other engineering quick-fixes to protect property and infrastructure from sea level rise. Although some local shorelines may benefit from coastal hardening, many engineering approaches are doomed to failure and will limit the ability of coastal species and ecosystems to adjust to sea level rise by migrating inland (NRC 2010; Pilkey and Young 2009). This potential conflict between adaptation for the benefit of human communities and adaptation for the benefit of natural communities is of grave concern to conservation biologists, as exemplified by the observation of Turner et al. (2010): "the natural systems upon which people depend, already under direct assault from climate change, are further threatened by how we respond to climate change."

Many of the authors in this volume, plus others not represented in the papers here (see http://www.flconservationscience.org/programs/symposium.shtml), met at Archbold Biological Station in Lake Placid, Florida, on January 18–20, 2010, to discuss impacts of sea level rise in Florida and options for adaptation. The meeting was organized by the Florida Institute for Conservation Science, a non-profit think tank, with the help of several sponsors (see Acknowledgements). The 50 participants were distinctly interdisciplinary and included geologists, oceanographers, paleoecologists, biologists, landscape ecologists, engineers, anthropologists, regional planners, conservation area managers, and others. This interdisciplinarity was considered essential to the adequate consideration of impacts and adaptation options for both human and natural communities. The goals of the symposium were to (1) summarize the science regarding the existing and potential impacts of sea level rise in Florida; (2) look at past changes in climate and sea level for contextual understanding and as a window to the future; (3) identify and discuss options for adaptation to sea level rise in Florida; (4) identify priorities for future research and monitoring related to sea level; and (5) develop alternative future scenarios and preliminary recommendations on adaptation to sea level rise and introduce them to policy makers for their consideration.

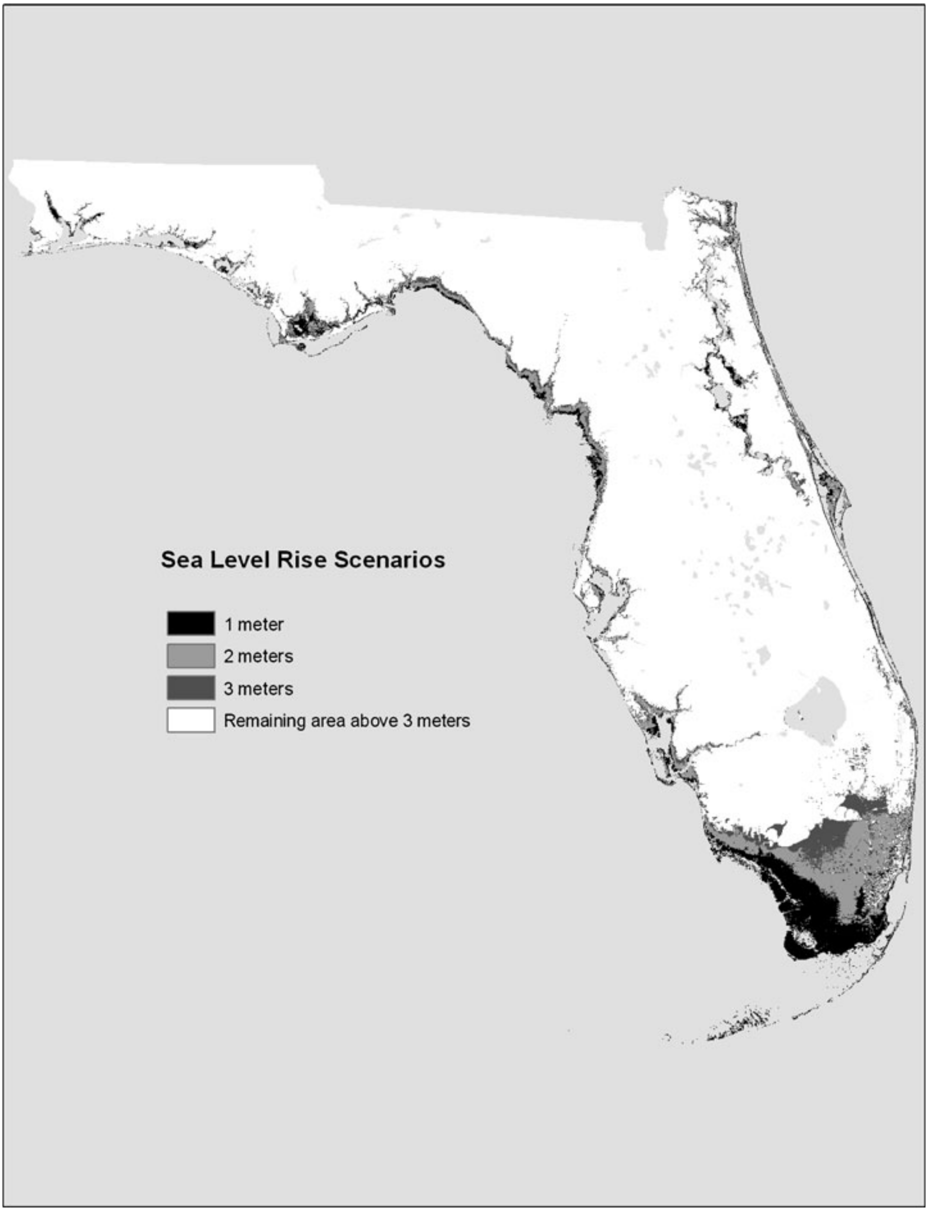

Fig. 1 Projected inundation of current land area in Florida with 1, 2, and 3 m of sea level rise. Map is from J. Oetting, Florida Natural Areas Inventory, based on an unpublished digital elevation model (DEM) created by the Florida Fish and Wildlife Conservation Commission. The DEM has a spatial resolution of 10 m with elevation in centimeters

2 The papers in this volume

Sea level in Florida closely matches global (eustatic) sea level due to a lack of major areas of subsidence or tectonic uplift. This simplifies the problem in some respects, but Florida's low-lying topography leads to rapid rates of inundation with sea level rise. In the first paper in the following collection, Donoghue (2011, this volume) reviews the sea level history of the northern Gulf of Mexico during recent geologic time. During full-glacial stages of the Pleistocene, sea level dropped as much as 120 m below the present position, extending the shoreline more than 100 km seaward in some areas. As recently as 10,000 years ago, sea level was still 20 m below present. Since the last glacial maximum 20,000 years ago, rates of sea level rise have been highly variable, but at times exceeded 45 mm/year, 20 times faster than today's rate and faster than all but the very highest estimates for the next century (e.g., Hansen 2007). During past periods of abrupt rise, shorelines were drowned in place and overstepped. Coastal and near-coastal communities such as coral reefs, mangroves, and salt marshes may have been virtually eliminated from the region. Sea level stabilized about 6,000 years ago, with shorelines in equilibrium with small changes in sea level; this stability perhaps provided a false sense of security to human residents. The projected rise over the next century and beyond will create conditions more similar to those during the last deglaciation than during any time in recent history. Shorelines will likely again be overstepped and drowned.

In the following paper, Geselbracht et al. (2011, this volume) show that biological effects of sea level rise are already evident in the 'Big Bend' region of Florida's Gulf of Mexico coast, which has a very gentle elevation gradient. These authors used the Sea Level Affecting Marshes Model (SLAMM) to simulate the magnitude and location of impacts from sea level rise in this region. Their study is unique in that SLAMM is used for both hindcasts and forecasts of vegetation change. For the hindcast they compare model results to 30 years of field plot data and demonstrate that SLAMM shows the same pattern of coastal forest loss as observed. Prospective runs of the model using 0.64, 1, and 2 m sea level rise scenarios predict large changes in vegetation, including net losses of coastal forests (69%, 83%, and 99%, respectively) and inland forests (33%, 50%, and 88%), but net gains of tidal flats (17%, 142%, and 3837%). The authors identify a number of species that are at risk of population decline or extirpation as a result of these changes. Protection of undeveloped lands inland from the present coastal forest would help accommodate upslope migration of this community and associated species in response to sea level rise. Other potential adaptation options are restoration and enhancement of oyster reefs to reduce wave-generated erosion and enhance accretion of sediments, and hydrologic restoration of wetlands that have been dredged.

The paper by Willard and Bernhardt (2011, this volume) brings us to South Florida and reviews the relative impacts of sea level rise, climate variability, and human alteration of hydrology on wetland plant communities during the 7,000-year history of the Everglades. Freshwater peat began accumulating on the platform underlying what is now Florida Bay around 6,000–7,000 years ago, when sea level was about 6.2 m lower than today. By 5,000 years ago, sawgrass and water lily peats covered the region. When sea level rise slowed about 3,000 years ago, the South Florida coastline stabilized, but during the last 2,000 years the Everglades was affected by regional and global fluctuations in climate and sea level. Regional-scale droughts lasting two to four centuries occurred around 1,000 and 400 years ago and changed the composition of wetland communities, allowing development of such characteristic Everglades habitats as sawgrass ridges and tree islands. Although droughts and sea level rise during the Holocene had substantial effects on the Everglades, changes initiated during the twentieth century, including reductions in freshwater flow, compartmentalization of the wetlands, and accelerated rates of sea level rise, are having unprecedented impacts on the distribution of vegetation.

Some of the major current changes in vegetation in the Everglades, which are related to sea level rise, are described in the paper by Saha et al. (2011a, this volume). They show that substantial changes, including loss of coastal hardwood hammocks and buttonwood forests, will occur long before inundation. The rising water table that accompanies sea level rise leads to shrinking of the soil vadose zone and increases salinity in the bottom portion of the freshwater lens, subjecting plants to salt water stress and physiological drought. The constraining effect of salinity on transpiration limits the distribution of freshwater-dependent communities. The authors conclude that, along with causing changes in vegetation patterns, sea level rise threatens 21 rare coastal species in Everglades National Park. Restoring the flow of freshwater into the Park may mitigate the effects of rising sea level, albeit only in the short term.

The human communities of South Florida are every bit as threatened by sea level rise as natural communities. The water management system of South Florida is as complex and highly manipulated as any in the world, yet decision-support tools for coastal infrastructure and water management, especially in response to environmental change, are largely lacking. The canal networks in the region are managed to reduce saltwater intrusion (requiring high water levels) and to provide flood protection (requiring low water levels), which are conflicting goals. Park et al. (2011, this volume) demonstrate how rising sea level and storm surge will have serious impacts on freshwater supplies and flood drainage capability, as well as on the natural ecosystems of South Florida. They analyze long term tidal records from three coastal sites and apply a nonlinear sea level rise model to project storm surge return levels and periods. They document a statistically significant dependence between surge distributions and the Atlantic Multidecadal Oscillation (AMO). Using a probabilistic model for AMO phase changes, they project AMO-dependent surge distributions and show the vulnerability of flood control structures as sea level rises and the intensity of hurricanes increases.

The Florida Keys, with most of their land area below 2 m in elevation, are 'ground zero' for human and natural communities vulnerable to sea level rise. Zhang et al. (2011, this volume) use a digital elevation model (DEM) derived from airborne light detection and ranging (LiDAR) measurements to project the impacts of inundation of land, population, and property in 0.15 m increments of sea level rise in the Keys. The results are alarming, to put it mildly. A 0.6 m rise in sea level would inundate about 70% of the total land surface, 17% of the population, and 12% of the real property. A 1.5 m rise would inundate 91% of the land surface, 71% of the population, and 68% of the property, with the most catastrophic impacts in the lower-elevation Lower Keys. Moreover, inundation dynamics are non-linear, with tipping points beyond which inundation accelerates. These dynamics are reminiscent of the overstepping and drowning of shorelines in the recent geologic record, as reviewed by Donoghue (2011). If rates of sea level rise keep increasing, tipping points will be reached sooner. Before populated areas are inundated, sea level rise will exacerbate existing problems in the Keys, such as flooding associated with storm surge and saltwater intrusion into freshwater aquifers. Zhang and coauthors imply that there is some urgency for governments and residents to plan for relocation of the majority of the human population of the Keys to higher ground elsewhere. Because of the uncertainty surrounding the rates and tipping points of sea level rise, monitoring should be conducted with the objective of activating appropriate policies when identified threshold values are reached.

The losses to sea level rise in the Florida Keys will include things less replaceable than real estate. The Florida Keys are home to many imperiled taxa of plants and animals, including narrow endemics found nowhere else but on these low-lying islands. Maschinski et al. (2011, this volume) address the thorny question of what to do for these populations as their only native habitat disappears under the sea. As in the Gulf Coast case study presented by Geselbracht et al. (2011, this volume), shifts in vegetation and declines of species' populations are already well underway in the Florida Keys. Using two rare plant and two rare animal species as examples, Maschinski and coauthors describe a process for evaluating conservation options for species whose habitat is projected to be lost by the end of this century. They suggest that multiple strategies will be required to reduce extinction probabilities, and that different actions will be effective for different time periods. The controversial and potentially risky action of managed relocation may be the only alternative to extinction after some threshold of sea level rise. The Florida Keys case study exemplifies the growing acceptance in conservation science that policies governing management of endangered species that were conceived under assumptions of equilibrium will need to be re-evaluated given the probable no-analog future imposed by climate change.

As shown in several papers in this volume, sea level change is not a steady, linear process, but rather is characterized by variable, nonlinear rates and by tipping points and impacts that are challenging to predict. As sea level rises and hurricane intensity increase, storm surges will inevitably have greater impacts on human and natural communities. Saha et al. (2011b, this volume) examine the effects of Hurricane Wilma's storm surge (23–24 October 2005) on the dominant tree, South Florida slash pine, and rare plant species in pine rocklands of the Lower Florida Keys. Comparison of densities before and after Hurricane Wilma shows a strong effect of elevation for some species. Rare species restricted to pine rocklands showed dramatic declines after Hurricane Wilma and were eliminated at elevations <0.5 m. However, effects of Hurricane Wilma were not significant for rare species that were distributed more widely, including in habitats other than pine rocklands. As sea level rises, it can be expected that safe elevations for pine rockland plants during hurricanes will become progressively higher, until no safe habitat remains.

Sea level rise and other effects of global climate change produce a decision-making environment marked by high uncertainty. Martin et al. (2011, this volume) describe structured decision making (SDM) as a proactive approach to addressing sea level rise. SDM is a process for identifying decisions that are optimal with respect to management objectives and knowledge of the system. So far, however, most examples of SDM in the literature are based on the assumption that the managed systems are governed by stationary processes. Martin and coauthors recognize that, in the face of sea level rise and climate change generally, the systems being managed are continuously changing. Therefore, management objectives may have to be reconsidered frequently, and the set of potential actions adapted over time as conditions change. They illustrate the challenge of adaptive resource management in the face of sea level rise with a numerical example, where a wetland impoundment in coastal Florida serves dual purposes of storing water for irrigation and providing habitat for a species of concern. They also discuss problems faced by the Florida manatee as an example of how SDM can be applied to the management of species affected by sea level rise.

Human communities in low-lying coastal areas cannot afford to be in denial about sea level rise. In the absence of guidance from federal and state agencies and policy-makers about how to respond to sea level rise, coastal municipalities will have to devise their own adaptation strategies. Parkinson and McCue (2011, this volume) are involved in an effort by the City of Satellite Beach, on the Atlantic coast of Florida, to develop an adaptation strategy. This project is one of the first in the state to confront the potential consequences of sea level rise. The authors report the results of an initial study of vulnerability, which suggests the tipping point between relatively benign impacts and those that will disrupt the municipal landscape is 0.6 m above present sea level, forecast to occur around 2050. This gives the City about 40 years to formulate and implement an adaptation plan. Parkinson and McCue describe the process by which the City is expected to revise its Comprehensive Plan and make preparations for adaptation to sea level rise. This project provides a commendable example of a citizen-initiated planning process, which other municipalities should emulate.

Considered together, the papers in this special issue strongly suggest that human communities, natural communities, and rare species in low-lying areas of Florida are at high risk from sea level rise in the near future and, in some cases, have been for some time. Although sea level has varied substantially in Florida over geologic time, rates of rise forecast for coming decades may rival the highest seen in the geologic record since the last deglaciation began ca. 20,000 years ago. Conspicuously absent from the papers in this volume is any mention of existing planning guidance from federal or state authorities. Indeed, politicians and much of the public in Florida appear to be strongly in denial about sea level rise (R.F. Noss, personal observation), making it imperative that local communities, regional planners, and conservationists inform themselves about the problem, educate others, and take action in the very near future to address this threat that will not go away through wishful thinking. Suggestions for such actions can be found in the following section.

3 Implications for policy and management, especially with respect to conservation

Although the Archbold symposium and this volume are focused on the science of sea level rise and adaptation in Florida, science that is relevant to policy but is not considered or implemented by policy-makers and managers represents wasted effort. The participants in the Archbold symposium, which include most of the authors in this volume, generally agreed with the proposition of Pilkey and Young (2009) that Florida has more to lose from sea level rise than any other U.S. state, yet has done less than any other coastal state to prepare for it. While the pace of development has slowed recently due to economic conditions, no policies or incentives have been instituted that would control coastal development when the economy improves. We continue to develop in low-lying coastal areas, including the construction of condominiums and hotels directly on our beaches.

These observations impart a sense of urgency to getting the facts of climate change, and sea level rise in particular, to decision makers at the federal, state, and local levels who will determine how Florida responds to sea level rise. In a biologically diverse region such as Florida, it will be particularly important to ensure

Table 1 Information and research needs for adaptation to sea level rise, with particular relevance to Florida. Each item is placed in the single category where it most directly applies, although some items could be placed into multiple categories

Data analysis and synthesis
A synthesis of environmental (e.g., sea level, erosion) and biological (e.g., species and community range shifts) changes observed to date
A thorough inventory of the natural and human resources and elements at risk of loss or damage from sea level rise locally and regionally
Identification of the coastal natural communities/ecosystems that are most likely to adapt in situ or migrate inland, where these communities are located, and what rates of sea level rise might allow adaptation
Identification of species and natural communities/ecosystems that are at high risk of loss or degradation due to sea level rise and increased storm surge (ideally in scaled categories of endangerment)
Identification of imperiled species that may be capable of in situ adaptation vs. those (e.g., in the Florida Keys) whose future survival probably depends on ex situ conservation or managed relocation
Identification of specific coastal areas likely to experience high vs. low physical changes and other impacts of sea level rise
Spatially-explicit identification of where coastal development currently presents barriers to species migration and natural community shifts and where projected development over the next few decades is likely to create new or more severe barriers
Identification of areas where existing conservation areas should be enlarged (i.e., boundaries expanded inland), where corridors should be established from coastal to inland sites, and where new conservation areas (e.g., inland refugia and marine/estuarine reserves) should be created
Identification of where coastal hardening and other protection of property and infrastructure is a viable option, at least in the short term, vs. areas where abandonment or relocation of existing structures are better options
Improved models, predictions, and understanding
Refinement of relative sea level rise predictions, with reduced uncertainty, for Florida, including range and variability of rates, which can be used to create more defensible alternative scenarios for planning
More reliable mechanistic models of impacts of sea level rise that will allow for better predictions
Better understanding of the effects of sea level rise on the freshwater aquifer
Better understanding of how sea level rise will affect microclimate
Improved understanding of how other climate change phenomena will interact with sea level rise – in particular, the interactive effects of sea level rise and increased storm surge related to more intense hurricanes
Improved estimates of the short-term and long-term economic costs of sea level rise and of the various options for adaptation to sea level rise (i.e., economists need to become involved in this issue)
Reliable projections of the relationship between sea level rise and coastal property values
Knowledge of the current insurance infrastructure that pays for the risks of living on the coasts, and projections of how the insurance industry will respond to increasing costs of sea level rise and storm surges
Reliable estimates how sea level rise will affect existing infrastructure, including the level at which infrastructure will become non-functional
Better knowledge and predictive capacity for how businesses, economies, human communities, and individuals will respond to sea level rise (i.e., will they relocate, and if so, to where?)
Understanding of how land-use planning (e.g., county comprehensive plans) should be revised to include explicit consideration of sea level rise

Table 1 (continued)

Improved research, monitoring, and management programs and infrastructure
Understanding of the type of monitoring program, and specific indicators, needed to assess the impacts of sea level rise on physical, biological, and social/cultural systems (in an integrated manner)
Implementation of a statewide, integrated monitoring network
Establishment of a clearinghouse of ongoing and proposed research on sea level rise and its impacts in Florida and other southeastern states
Identification and fostering of opportunities for collaborative research and funding within and outside Florida
Better engagement of social scientists in sea level rise research
Better understanding of how to convey the sea level rise problem to policy makers and the general public (including a range of audiences) and influence public opinion

that efforts to protect humans and their property from the damaging effects of sea level rise, storm surges, and other climate-driven phenomena do not interfere with the adaptive responses of natural systems. Moreover, in many cases humans will need to facilitate or augment natural adaptive responses in order to prevent extinctions and enhance ecosystem resilience.

In breakout and full-group discussions near the close of the two-and-a-half day meeting, participants in the Archbold symposium identified the following priorities for science-based policy regarding response and adaptation to sea level rise in Florida.

1. Provide policy makers with the best available information on rates of sea level rise and coastal erosion, including a credible range of scenarios and associated probabilities, and with a prioritized list of adaptation options. This information should be presented in a succinct, user-friendly format, avoiding technical jargon. Information should be framed within the paradigm that change, rather than stasis, is the norm in physical, biological, and social systems, but that human activities can dramatically alter rates of change. A key point is that exposure is only one aspect of vulnerability to sea level rise (Dawson et al. 2011). For a variety of reasons, some geographical areas within Florida are much more vulnerable to ecological, social, and economic damage than other areas.
2. Scientific information and research needs related to sea level rise should be prioritized by groups of scientists, policy makers, and managers (e.g., conservation area managers) working together. Information/research needs important for Florida are listed in Table 1.
3. Policy makers should establish a series of sea level rise benchmarks that will trigger specific actions. That is, when sea level rises by *x* amount, a series of specific actions will be implemented; when sea level rises by *y* amount, another series of actions will be implemented, and so on. These benchmarks will need to be tailored to specific stretches of coastline, given differences in topography and inundation dynamics.
4. Sea level rise adaptation strategies need to be developed in much more detail, including identification of mechanisms for achieving each strategy and the costs, benefits, and level of priority of each potential strategy. Such planning should be hierarchical, in the sense that broad (national and statewide) goals inform

practice at local levels, but specific decisions and authority for implementation are local.

5. Adaptation strategies should be developed for both the human environment (human-dominated landscapes) and the natural environment (landscapes dominated by natural ecosystems), with priority given to biological hotspots, i.e., areas that stand to lose irreplaceable biological elements such as endemic taxa or natural communities. Essential components of adaptation strategies in Florida are listed in Table 2.

Table 2 Key components of an adaptation strategy for the human environment and the natural environment (species and ecosystems) in Florida

The human (built) environment
Minimize immediate and long-term negative impacts to people and property from rising sea level
Take into account sea level rise in zoning decisions, building codes (e.g., elevating structures), beach renourishment, and engineering (including civil engineering and transportation infrastructure)
Require consideration of sea level rise in county comprehensive plans and other land-use ordinances and policies
Keep natural areas and native species populations healthy within the built environment and the human-dominated landscape, e.g., by reducing other threats to population viability and ecosystem integrity
Maintain or restore functional connectivity among natural areas through habitat corridors or a structurally rich landscape matrix outside intensive urban zones
Clean up infrastructure before inundation by sea level rise to reduce pollution
Buy out coastal properties at designated benchmarks of sea level rise and implement 'rolling easements' (Titus 1998)
Do not rebuild in low-lying coastal areas after destruction or heavy damage of structures by storms
Revise engineering and building standards to facilitate relocation or recycling/re-use of structures
Establish a legal and political support system for structural abandonment and managed withdrawal of human communities within sea level risk zones
Develop a relocation strategy for displaced people that includes new housing and employment opportunities for sustainable communities
Natural ecosystems and species
Enhance resistance and resilience to change by maintaining or restoring biodiversity, landscape connectivity, natural disturbance and hydrologic regimes, etc., and better define the meaning of resilience for ecosystems that are changing to no-analog futures
Maintain and enhance opportunities for inland migration of intertidal and other coastal habitats and associated species by such measures as prohibiting new development in low-lying coastal areas and expanding coastal conservation area boundaries upslope
Manage fire, invasive species, hydrology, species populations, and other ecosystem components in light of sea level rise scenarios
Manage and facilitate populations of endemic and highly imperiled taxa that have a chance of maintaining in situ populations in coastal areas or migrating (dispersing inland) in pace with sea level rise
Facilitate dispersal and, where reasonable, assist colonization of imperiled taxa that are not able to disperse quickly enough on their own to avoid the rising sea; these decisions must be made cautiously with guidance by experts, but experience elsewhere (e.g., Willis et al. 2009) shows that assisted colonization (managed relocation) can be a feasible and cost-effective means of helping species track climate change
Establish ex situ populations and seed/gene banks of species likely to go extinct in the wild or suffer major population declines due to sea level rise

6. Integrate adaptation strategies for human and natural ecosystems (Table 2) so that they are harmonious and complementary rather than conflicting. For example, do not build seawalls and other protective structures in areas where they will inhibit inland migration of wetlands, beaches, barrier islands, etc. Recognize that human displacement from sea level rise will impinge on inland natural communities unless managed carefully. Biologically important inland areas, which might serve as sea level rise refugia, should be identified and protected as soon as possible, before development for human uses occurs.
7. Develop incentives for adaptation and disincentives for business-as-usual development. For example, develop policy that links disaster assistance to prior implementation of adaptation strategies, i.e., communities that failed to implement adaptation strategies get no assistance or less assistance than communities that implemented such strategies.
8. Greatly accelerate conservation land acquisition (including easements) to expand boundaries of coastal conservation areas upslope and inland, establish broad coast-inland habitat corridors, and protect inland refugia. Again, emphasis should be given to biological hotspots at high risk of impoverishment—the places that have the most to lose. Funding should be restored to critical land acquisition programs such as Florida Forever (http://www.dep.state.fl.us/lands/fl_forever.htm). In addition, agencies should identify criteria for the permitted uses of conservation areas as they become state sovereignty submerged waters rather than public lands. Identifying now which new coastal waters may warrant protective designations such as no-take marine reserves will be helpful.
9. Develop policies to ameliorate the major economic inequities that are likely to result from sea level rise in Florida, with coastal areas being likely economic losers and inland areas being potential economic winners.
10. Scientists and policy makers should jointly educate the public about the risks of sea level rise (under various scenarios) and associated impacts such as increased storm surges, as well as options for adaptation. Identify hotspots of high vulnerability to capture public attention. Make scenarios graphic and compelling.

Scientists, by nature of their aptitude and training, tend to emphasize what they do not know rather than what they know. When talking to non-scientists, however, emphasizing ignorance or uncertainty may be counter-productive (Oreskes and Conway 2010). Scientists need to tell people what they, collectively, do know. In communications with the public and policy makers, scientists should stress the point that, despite considerable uncertainties and the probabilistic nature of all predictions, sea level rise today and over coming decades is certain. It is not something that might happen sometime in the future; it is happening now. After being relatively stable for several thousand years, the rate of sea level rise has been increasing over recent decades as a direct consequence of increases in temperature on a global scale (Pilkey and Young 2009).

The messages that scientists send to policy makers must be honest, but should avoid purveying doom and gloom. The ancient wisdom of crisis being equivalent to opportunity is highly pertinent to the problem of sea level rise. Sea level rise might be portrayed as a disaster, and of course in many ways it is. But an alternative and equally honest portrayal is that sea level rise is a challenge that society must use its best intelligence and ingenuity to confront. Perhaps, if American society were to put the same level of effort into confronting the sea level challenge (or climate change in general) as they put into the Manhattan Project or the Apollo Mission, the problem might be soluble with minimal losses of biodiversity and ecosystem services.

In communicating with the public, scientists and policy makers alike would do well to emphasize what individuals can do to address this major challenge, but also not shy away from stating the responsibilities of government at all levels to serve the long-term interests of society. Because we cannot yet predict precisely how much the sea will rise on any given coastline, it is wise to plan for a range of future scenarios, with trigger points identified for the implementation of specific adaptation measures—including managed withdrawal of human communities from the coasts. In Florida and other low-lying coastal regions worldwide, thoughtful planning to accommodate future sea levels and storminess is long overdue.

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