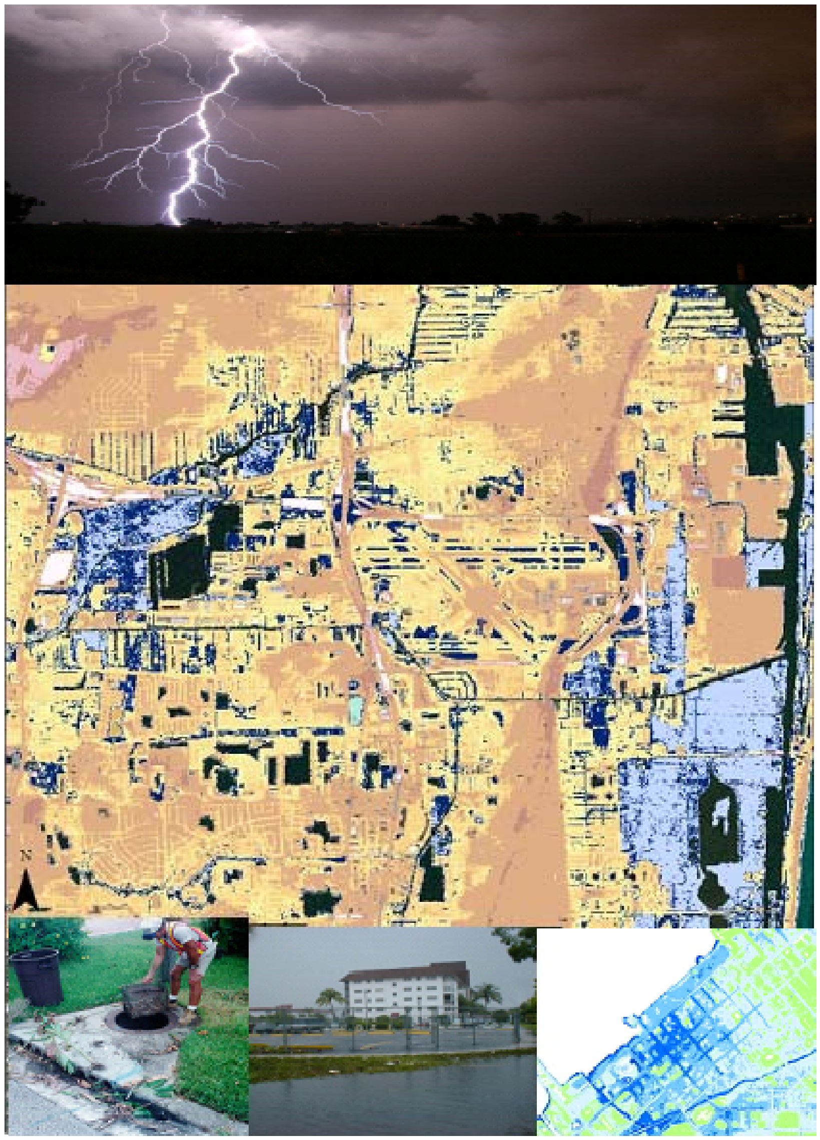
DEVELOPMENT OF A METHODOLOGY FOR THE ASSESSMENT OF SEA LEVEL RISE IMPACTS ON FLORIDA'S TRANSPORTATION MODES AND INFRASTRUCTURE

Synthesis of Studies, Methodologies, Technologies, and Data Sources Used for Predicting Sea Level Rise, Timing, and Affected Areas in Florida



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Disclaimer

Si* (Modern Metric) Conversion Factors

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

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16. Abstract

Many studies and models projecting future rates of sea level rise (SLR) from the global level to regional studies specific to Florida exist. While many different projections and models are available, there is no consensus as to which projections of SLR would be most appropriate to evaluate the vulnerability of transportation infrastructure. This research includes a comprehensive literature review and analysis of SLR projections, studies, models, and methodologies used in Florida. After analyzing the advantages and disadvantages of these various studies, together with workshop reports and expert consultation, the Florida Atlantic University (FAU) researchers recommend using the United States Army Corps of Engineers (USACE) guidance for forecasting SLR in Florida. The USACE guidance considers scenarios of possible future rates of mean sea level change over various planning horizons. These scenarios can be used to identify and assess potentially vulnerable infrastructure and make more informed decisions regarding the timing of when SLR impacts might occur and for implementing adaptation actions. A SLR scientific working group developed consensus projections using the USACE guidance for the Southeast Florida Regional Climate Change Compact (Compact). The Compact is comprised of the governments of Monroe, Miami-Dade, Broward, and Palm Beach Counties. The Compact consensus projections include:

Southeast Florida Regional Climate Change Compact Consensus Projections	
Planning Horizon	**SLR in inches** *(low – high)*
2030	3 - 7
2060	9 - 24

The FAU researchers used the Weiss Overpeck 1-meter SLR projection for Florida to illustrate a downscaling evaluation technique developed to identify potentially vulnerable transportation infrastructure. The evaluation methodology uses readily available ArcGIS data sets, layers, and Light Detection and Ranging (LiDAR) to drill down to localized settings compared with on-the-ground verification of vulnerability. The FAU researchers applied the evaluation techniques to Dania Beach, Punta Gorda, and Key Largo, Florida. This research also includes a discussion of the potential impacts of SLR to transportation infrastructure, including drainage, roadway base, and surface water impacts, and a summary of adaptation strategies and tools. The research includes short-term recommended actions such as developing a sketch planning tool to apply the USACE methodology to produce statewide and regional projections of SLR and downscaling techniques to identify and assess potentially vulnerable infrastructure. Long-term recommendations include developing a no-regrets and gradual adaptive management strategy in transportation planning and integrating SLR projections with groundwater, surface water, and storm surge models to better assess the vulnerabilities of transportation modes and infrastructure.

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Preface

The purpose of the study described in this report is to provide a methodology for assessing the impacts of sea level rise (SLR) on Florida transportation infrastructure for planning purposes. This research, conducted by faculty at Florida Atlantic University (FAU), was made possible through a grant from the Florida Department of Transportation (FDOT). As a result of an extensive literature review, workshop reports, and expert consultation, the scope of this report includes a summary of global and state observations and projections of SLR, a discussion of the methodology used in developing consensus on SLR projections in Southeast Florida, a recommended methodology for projecting SLR in Florida and identifying potentially vulnerable infrastructure, global to regional downscaling approaches, and data gaps in existing SLR scientific knowledge. The report also includes a summary of potential impacts of SLR on transportation physical infrastructure along Florida's coastline and low-lying terrain and a summary of currently available tools for protection of transportation infrastructure and for adaptation of transportation networks and systems. In the appendices, more information about sea level changes in Florida from tidal stations, SLR projection models, storm surge models and applications, adaptation implementation and a brief summary of the impacts of sea level change to transportation infrastructure is provided.. Follow-up work is required to assess the full impact of the roadways along the coastline as it may affect bridge infrastructure and other transportation modes.

Executive Summary

Based on measurements at the Key West, Florida tidal station, sea level has risen about nine inches in the last 100 years (NOAA 2008). Sea level rise (SLR) is projected to continue and accelerate in the future. Many agencies like the Florida Department of Transportation (FDOT) are exploring ways to incorporate this prospect into their long-range planning, programming, and investment decision-making processes. FDOT requested that FAU "develop a methodology for the assessment of SLR impacts on Florida's transportation modes and infrastructure."

A literature review of over 300 reports and published documents has been complemented by the findings of several workshops and input from key scientists. This report reviews SLR forecasts, evaluates the advantages and disadvantages of these different methods and makes recommendations for the best methodology to use in forecasting SLR and assessing SLR impacts on transportation infrastructure. The FAU team preparing this report agrees with the guidance of the United States Army Corps of Engineers (USACE) for projecting SLR and recommends that projections developed using the USACE guidance be revisited in 2013-14 when both the new the USACE guidelines and IPCC projections will be available.

An extensive inventory and review of topographical and geographical data of Florida's transportation network along coastline and low-lying terrain and its vulnerabilities to SLR has been undertaken. Based upon the recommendation to use the USACE guidance document for SLR projections, a methodology was developed for identifying and assessing potentially vulnerable transportation infrastructure and identifying critical data gaps, which, when filled, will enable a more precise evaluation of the physical infrastructure that might be affected by SLR. This methodology was applied to three areas of the state to determine potentially vulnerable transportation infrastructure.

Over time, SLR and its associated tidal ranges and storm surge will have impacts on roadways and bridge access points, rail, airports, and other transportation infrastructure. Therefore, comprehensive analyses and adaptation to these impacts is an important component of medium- and long-range planning, programming, project development, construction and investment decision-making processes. As the USACE has specified, any coastal or near-coastal projects should include consideration of SLR. Similarly, FDOT will need to build the impact of SLR into their FDOT decision-making support systems, project delivery, design, and construction processes for major transportation improvement projects. It will also be important to continually incorporate adaptive management processes into planning as more updated data become available.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

ASCII	American Standard Code for Information Interchange
BISECT	USGS Biscayne and Southern Everglades Coastal Transport Model
BTS	Bureau of Transportation Statistics
CSS	Context Sensitive Solution
CES	Center for Environmental Studies
CO-CAT	Coastal and Oceans Resources Working Group for the California Climate Action Team
DEM	Digital Elevation Model
DM	Dual Model
EA	Environmental Assessment
EC	USACE July 2009 Guidance Document, Engineering Circular
EIS	Environmental Impact Statement
EST	Environmental Screening Tool
ETAT	Environmental Technical Advisory Team
ETDM	Efficient Transportation Decision Making
EPM	USGS South Florida Ecosystem Portfolio Model
FAA	Federal Aviation Administration
FAU	Florida Atlantic University
FCFWRU	Florida Cooperative Fish and Wildlife Research Unit
FDEM	Florida Department of Emergency Management
FDEP	Florida Department of Environmental Protection
FDHSMV	Florida Department of Highway Safety and Motor Vehicles
FDF	Florida Division Of Forestry
FDOT	Florida Department of Transportation
FEMA	Federal Emergency Management Agency
FIHS	Florida Intrastate Highway System
FISCHS	USGS Future Impacts of Sea Level Rise on Coastal Habitats and Species
FNAI	Florida Natural Areas Inventory
FREAC	Florida Resources and Environmental Analysis Center (FSU)
FSG	Florida Sea Grant Program
FWRI	Fish and Wildlife Research Institute
GEOPLAN	FGDL Geoplan Center
GIS	Geographic Information System
IARU	International Alliance of Research Universities
IGSM	MIT Integrated Global Systems Model
IMMAGE	USGS Internet-based Modeling, Mapping, and Analysis for the Greater Everglades
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
LRTP	Long Range Transportation Plan

MGD	Million Gallons Per Day
MIT-IGSM	MIT Integrated Global System Modeling Framework
MPO	Metropolitan Planning Organization
NASNRC	National Academy of Sciences National Research Council
NAV88	North American Vertical Datum
NED	National Elevation Dataset
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanographic and Atmospheric Administration
NPS	National Park Service
NRC	National Research Council
NRCS	National Resource Conservation Service
NWFWMD	Northwest Florida Water Management District
OTG	On the Ground
PD&E	Project Development and Environment
SFFCC	Southeast Florida Four County Compact
SFWMD	South Florida Water Management District
SIS	Strategic Intermodal System
SJRWMD	St. Johns River Water Management District
SLR	Sea Level Rise
SLRRP	Sea Level Rise Rectification Program
SWFRPC	Southwest Florida Regional Planning Council
SWFWMD	South West Florida Water Management District
TIME	USGS Tides and Inflows in the Mangroves of the Everglades
UBR	Unified Base Map
UM	University of Miami
UNEP	United Nations Environment Programme
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Services
USGS	United States Geological Survey
W&O	Weiss and Overpeck

Chapter 1: Introduction

1.1 Statement of Hypothesis

The goal of this project was to determine if there was sufficient data to recommend and develop a methodology to identify critical transportation infrastructure vulnerable to sea level rise (SLR), identify a means for projecting SLR, and recommend downscaling procedures for infrastructure evaluations. The purpose is to provide the Florida Department of Transportation (FDOT) and other agencies with guidance in evaluating the vulnerability of physical transportation infrastructure (State, regional, and/or county) to changes in localized SLR trends. The answer is that such a sketch planning tool is possible and Florida Atlantic University (FAU) has developed a methodology using Arc-GIS to integrate readily available Light Detection and Ranging (LiDAR), topographic, and on-the-ground data from FDOT drawings to accomplish such a tool. To project the SLR planning scenarios, FAU recommends using the United States Army Corps of Engineers (USACE) November 2011 Guidance Document as the starting basis for forecasting SLR until more updated information on future SLR is available, as will be explained in the report.

1.2 Research Objectives

The objectives of the research were:

1) Inventory and summarize research and studies analyzing projected SLR in Florida, including but not limited to; sources of data and methodology used, the forecasted SLR timing, and area of Florida studied and analyzed;

2) Analyze the advantages and disadvantages of different data sources and methods for forecasting SLR and the timing of the forecasts, including level of precision and accuracy of the data/methodology, availability of data statewide, ability to convert to Geographic Information System (GIS) format;

3) Develop recommendations for which methodology for forecasting SLR and related impacts in Florida should be used by the FDOT including during the development of the 2060 Florida Transportation Plan (FTP); and

4) Develop recommendations for how existing data sources could be integrated with other FDOT information systems for identifying infrastructure at risk from SLR, as well as the timing of these potential impacts from climate change in Florida.

1.3 Background

1.3.1 Sea Level Rise Projections

As part of this research project, a comprehensive literature review and analysis of SLR projections, studies, models, and methodologies was conducted. Twelve different projections of SLR and its timing were reviewed, as was the consensus on planning horizons and SLR projections achieved by a SLR scientific working group established by the Southeast Florida Regional Climate Change Compact (Compact). FAU recommends using the USACE November 2011 Guidance Document, Engineering Circular (EC) 1165-2-212, as the basis for forecasting SLR until more updated information on future SLR is available. The USACE methodology for projecting SLR rates was applied in Southeast Florida resulting in a projected rise in mean sea level of 3-7 inches by the year 2030 and 9-24 inches by the year 2060. As there is much uncertainty with a 90-year projection, the USACE derived SLR projections of 19.5–57 inches by the year 2100 are included in this report for information only. Because of the uncertainty, the Compact declined to endorse numerical projections beyond the year 2060.

The USACE guidance for projecting SLR is recommended because of the following:

(a) the USACE derived projections are based on localized data (e.g. historic tidal data) as well as model results from various researchers;
(b) the USACE guidance considers scenarios of possible future rates of mean sea level change over various planning horizons that can be used to assess potential vulnerabilities;
(c) there is still some difference of opinion on the detected rate of increase in recent years and the USACE guidance provides a range of possible rates of sea level change that can be evaluated in the future which allows more informed decision-making for estimating the timing of anticipated impacts and for the development of adaptive and gradual strategies to address infrastructure vulnerability; and
(d) the new Intergovernmental Panel on Climate Change (IPCC) report is due in 2013-2014. Using the USACE guidance, it will be possible to update these projections at that time.

However, we should note that more recent information on ice melt in polar regions suggests that the higher end of these projections is more likely. Furthermore, using the USACE guidance provides consistency with the agreed upon set of projections developed by the Compact which covers a significant part of Southeast Florida and it is important not to have different sets of projections for the same area.

In the preparation of the guidance documents, the USACE has relied entirely on climate change science performed and published by agencies and entities external to USACE because conducting studies as to the causes, potential scenarios, and consequences of climate change is not within the USACE mission. USACE policies are expected to be periodically reviewed and revised as the accepted consensus on the science evolves. The goal of the USACE report is to provide guidance on how all civil works projects will incorporate SLR considerations. The circular stipulates that "impacts to coastal and estuarine zones caused by sea level change must be considered in all phases of Civil Works programs" (USACE 2011).

The USACE model on SLR projections is based on historic tide gauge data from National Oceanic and Atmospheric Administration (NOAA) (see appendix B) and an updated equation from a National Research Council (NRC) report in 1987. Only tidal gauges with over 40 years of record are utilized. The projection model provides three alternatives of future sea level change rates: "*low*," "*intermediate*," and "*high.*" The "*low*" sea level rate is based on historic sea level change rates. The "*intermediate*" rate is determined using the modified Curve I and equations 2 and 3 from NRC 1987. Recent IPCC projections, the modified NRC projections, and local rates of vertical land movement were considered in estimating intermediate rates of mean sea level. The "*high*" rates for the projections are estimated using the modified Curve III and equations 2 and 3 from NRC 1987. Final estimates are created using modified projection equations added to the local rate of vertical land movement. The current three scenarios proposed by the NRC result in global SLR values by the year 2100 of 0.5 meters, 1.0 meters, and 1.5 meters. The NRC committee recommended "projections be updated approximately every decade to incorporate additional data" (1987). At the time the NRC report was prepared, the estimate of global mean sea level change was approximately 1.2 mm/year. The current estimate of 1.7 mm/year for global mean sea level change, as presented by the IPCC (IPCC 2007), results in this equation being modified.

The USACE guidance for evaluating sea level change considerations is found in EC 1165-2-212 issued October 2011, which replaces and supersedes earlier guidance included in EC 1165-2-211 that had expired in June 2011.

1.3.2 Transportation Infrastructure Vulnerability Evaluation

This research project summarizes current SLR projections and recommends SLR projections using the USACE methodology for planning purposes with emphasis on the short and moderate term planning horizons of 2030 and 2060 and includes 2100 for informational purposes. Once SLR projections were determined, downscaling procedures for identifying physical transportation infrastructure along Florida's coastline and low-lying terrain vulnerable to SLR were developed. This downscaling evaluation approach integrates the FDOT information system (Unified Base Map Repository (UBR) and the Strategic Intermodal System (SIS) databases) with existing topographical and geological data and it is divided into the following four evaluations:

1) *State SLR projections:* preliminary identification of all State roadways vulnerable to SLR by the years 2030, 2060, and 2100 (using a statewide SLR projection map to be developed using the USACE projection methodology);

2) *Regional SLR projection:* evaluation of the current and projected years 2030, 2060, and 2100 conditions of vulnerable roadway sections using medium resolution LiDAR data;

3) *Localized SLR projection:* evaluation of projected years 2030, 2060, and 2100 conditions of vulnerable roadway sections using high resolution LiDAR data; and

4) *On-the-ground (OTG)*: verification of roadway vulnerability using construction drawings, site visits, and topographic survey data.

A flow chart of this down-scaling evaluation approach is shown in Figure 1. It should be noted that the proposed approach is not limited to this particular SLR projection: this methodology can be applied to model other scenarios.

FAU has created the basic framework of the sketch planning tool for evaluating potentially vulnerable infrastructure. The assessment of vulnerability should occur in the near-term for the planning horizons of 2030, 2060, and for the long-term of 2100. In addition, this study provides recommendations for the integration of this methodology into the FDOT decision-making support systems, project delivery, design, and construction processes for major transportation improvement projects, including but not limited to: Long Range Transportation Plan (LRTP), Strategic Intermodal System (SIS) Planning process, Statewide Bridge Replacement Program, Efficient Transportation Decision Making (ETDM), etc.

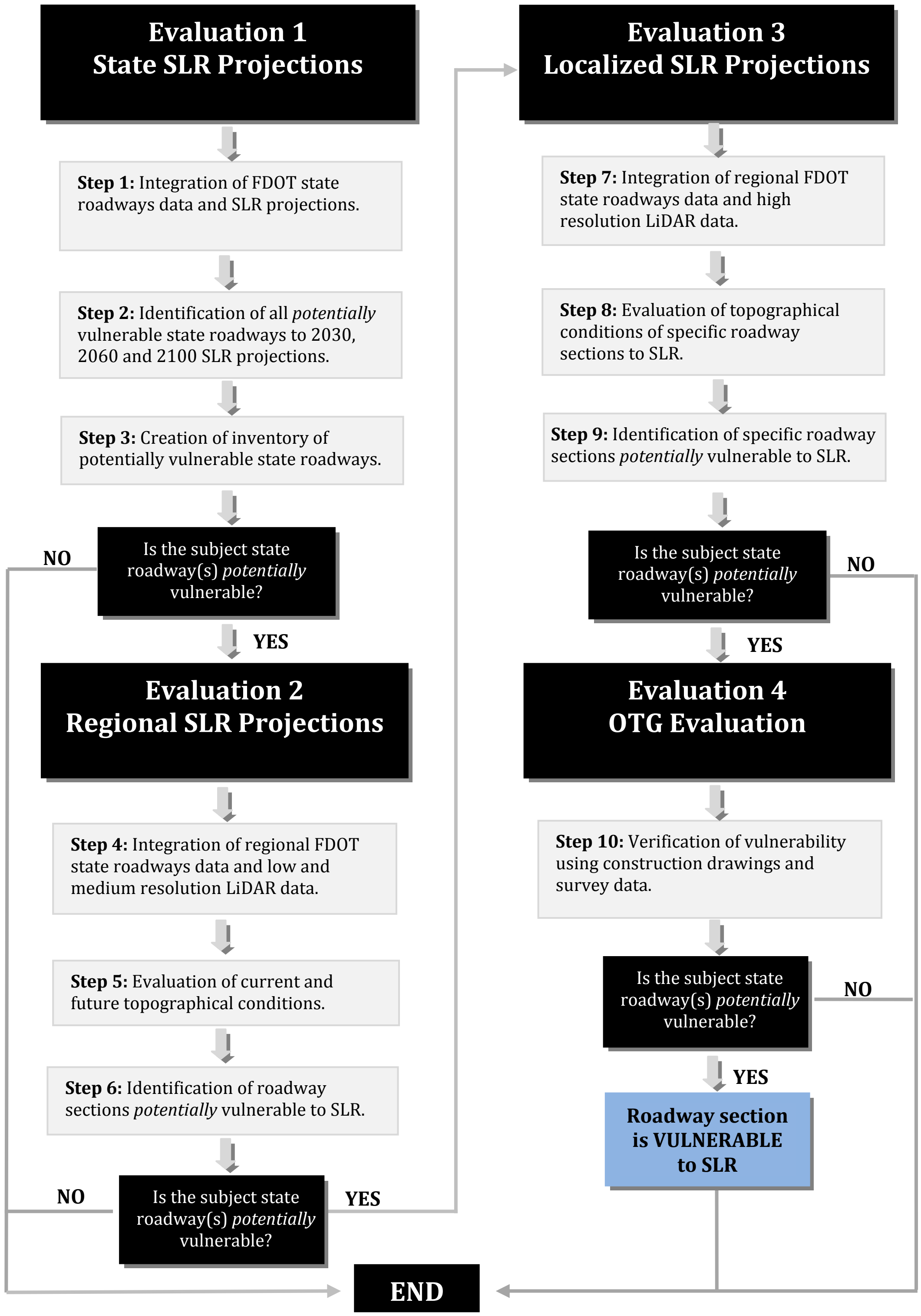


Figure 1: Flow chart of the downscaling evaluation approach developed for the identification of vulnerable state road sections.

Chapter 2: Literature Review

2.1 SLR Observations at the Global Level and in Florida

There is clear scientific evidence that sea level has steadily risen over the past 100 years and is presently rising at an increasing rate (IPCC 2007 – see Figure 2). Global average sea level has risen at 3.1 ± 0.70 mm/year from 1993-2000 as compared to a long-term average over the 20th century of 1.7 mm/year (IPCC 2007). Suggested contributions for this phenomenon include thermal expansion of the oceans resulting from higher ocean temperatures, and receding glacier contributions. The 2007 IPCC report on the global scientific consensus regarding climate change stated that the "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (IPCC 2007). Present-day sea level changes are of significant importance because of the impacts on islands and coastal regions and the human populations that inhabit these areas (IPCC 2007).

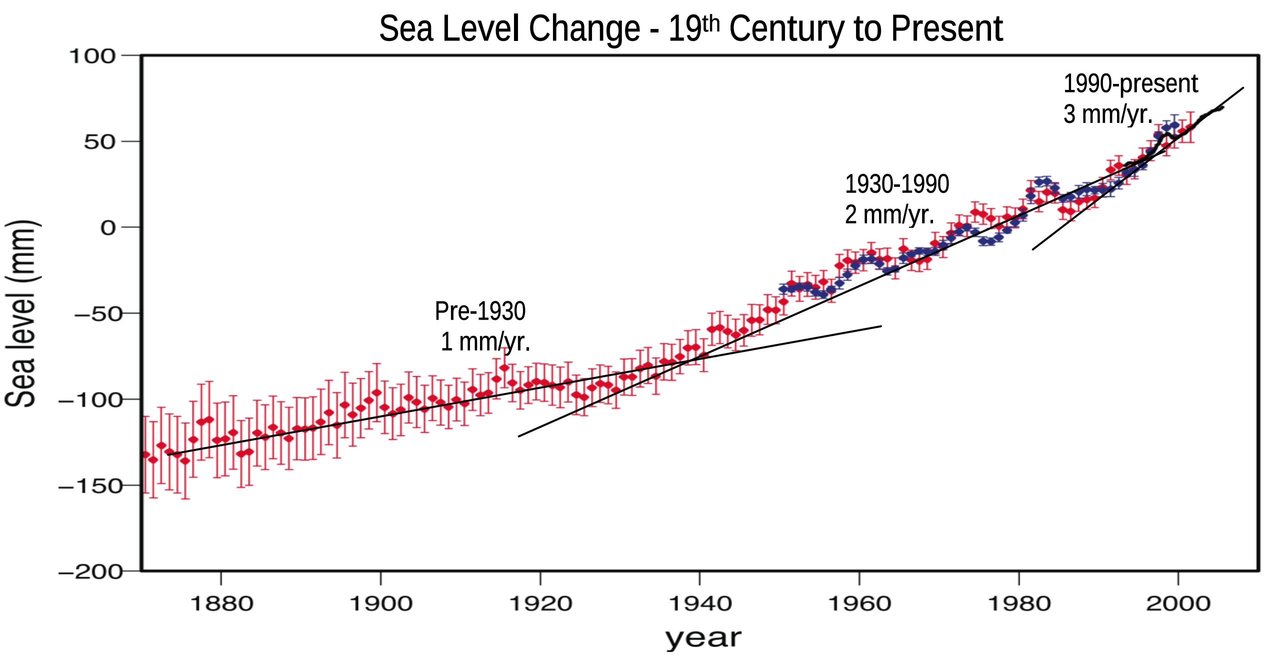


Figure 2: This chart reflects the SLR since the nineteenth century and the accelerated pace over the last few decades (estimates by Bloetscher & Heimlich 2010). Red dots show reconstructed data since 1870, blue dots show coastal tide gauge measurements since 1950, and the black curve is based on modern satellite altimetry. Fifty millimeters is approximately two inches (from Figure 5.13, IPCC 2007).

As shown in Figure 2, SLR trends have been shown to be non-linear (constant change), and therefore, the linear extrapolations of observed rates of SLR may underestimate the possible extent rise in this century. There are other factors that contribute to sea level change, including geomorphologic variations, anthropogenic changes in land hydrology, changes in ocean circulation, and atmospheric pressure, all factors that may result in considerable changes in sea level in some regions while having very little effect in others (IPCC 2007). For example, in the Gulf of Mexico, coastal wetlands have shown high rates of land subsidence attributed to soil decomposition and compaction and deep fluid extraction, among other things, compounding the impacts of SLR (Stevenson et al. 1986; Cahoon et al. 1998). While cyclical changes in climate have been clearly identified, recent changes appear to be outside normal variability (IPCC 2007).

It is important to note that satellite measurements of SLR show considerable variation in rates of SLR around the globe and the validity of satellite measurements, compared to tide gauge measurements, has been questioned (Houston 2010). The current global average SLR data is debated because satellite measurements require corrections for tides and because the short-term values are not consistently increasing. The USACE also does NOT currently use satellite measurements for any of its SLR projections. The USACE requires a continuous record of at least 40 years to establish trends with reduced short-term local variation impacts. SLR is a function of the land/water datum relationship that includes both sea level change and changes in land elevation and accretion. Figure 3 illustrates the tide gauges (green dots) in Florida. Table 1 shows the average tide gauge reading for each of the tidal stations. Measurements in Florida show an average rate of SLR of 2.24 ± 0.04 mm per year from 1913 to 2005 based upon tide gauge readings in Key West, which are the Western Hemisphere's longest sea level record (Maul 2008). From 1913-1999, sea levels in Miami have risen 2.39 ± 0.22 mm/yr. (USEPA 2009). Sea level has risen about 9 inches (228.6 mm) in South Florida since the 1960's (Gassman 2010). Analysis of Florida and global tide gauge records conducted by Barry Heimlich in 2010 shows that average Florida SLR rates are not significantly different from global rates. Therefore, global SLR rate projections are generally applicable to Florida (Heimlich 2010). The measured SLR in South Florida over the past 50+ years, though seemingly small, is sufficient to create the need for reengineering a number of canals and pump stations in South Florida's flat terrain. Throughout the state, existing and projected SLR could cause a similar chain of effects that could adversely impact the physical infrastructure and operations of the entire state's transportation network and systems.

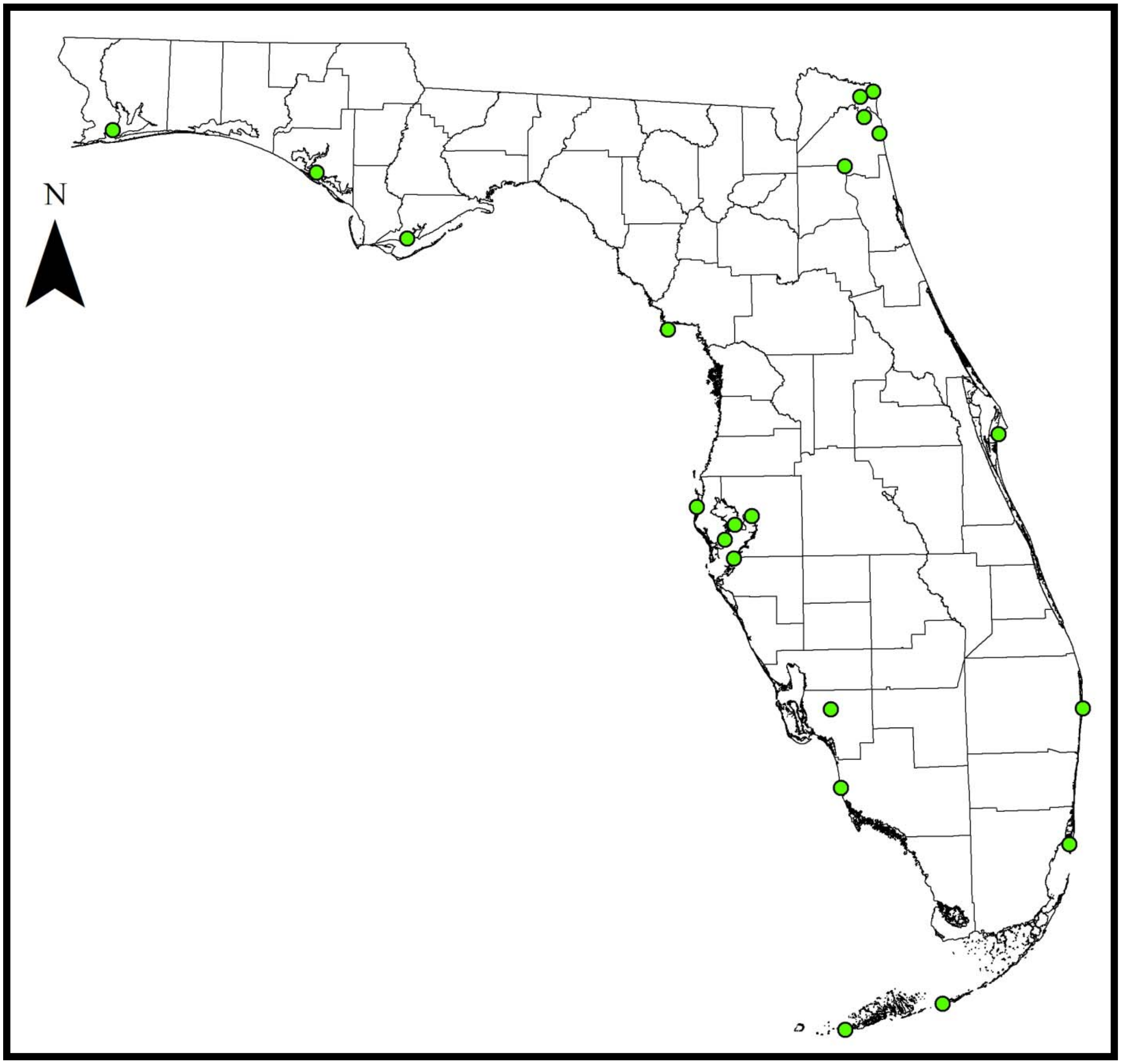


Figure 3: Location of tide gauge stations in Florida.

Table 1: Summary of Tide Gauge Station Data (NOAA)

Tidal Station	Avg. Gain mm/yr.	CI mm/yr.	Continuous data (yr.)	USACE Compliant (40 yr.)	Comments
Naples	2.02	0.06	45	Yes	
Fort Myers	2.4	0.065	45	Yes	
Fernandina Beach	2.02	0.02	70	Yes	
Mayport	2.4	0.31	85	Yes	
Cedar Key	1.8	0.19	75	Yes	
Apalachicola	1.38	0.87	37	No	
Panama City	0.75	0.83	37	No	Land subsidence impacts
Pensacola	2.1	0.26	90	Yes	
Daytona Beach	2.32	0.63	15	No	No data since 1985
Miami Beach	2.39	0.43	55	Yes	No data since 1983
Vaca Key	2.78	0.6	37	No	
Key West	2.24	0.16	100	Yes	
St. Petersburg	2.36	0.29	63	Yes	
Clearwater Beach	2.43	0.8	15	No	
Global Level	2				

(CI=confidence Interval)

2.2 SLR Projections and Models

Projections of future SLR depend on an assessment of the continued pace of global warming and its impact on sea temperatures, ice sheet melting, and other potential contributing factors. Since the 2007 IPCC report, which focused mainly on the impacts of global temperature rise and thermal expansion of world oceans on sea level, most scientific observations have identified SLR acceleration in key processes. Many different models calculate SLR projections. Table 2 shows a listing of different projections and the model or methodology used to derive the projection. Further analysis of SLR projection, models and methodologies, and identified limitations can be found in Appendices B and C.

Some of the models or projections on SLR researched include:

- IPCC 4th Assessment Report (AR4) (2007)
- International Alliance of Research Universities (IARU) Report (2009)
- Inverse Statistical Model (Jevrejeva, Moore, & Grinsted, 2010)
- Glaciation Synthesis (Meier et al. 2007)
- UNEP Compendium(McMullen & Jabbour 2009)
- Semi-empirical Method (R07) & the Dual Model (Vermeer & Rahmstorf, 2009)
- MIT Integrated Global Systems Model (IGSM) & MUSIC (Sokolov et al. 2009)
- USACE – EC 1165-2-221 Sea Level Rise Projection Guidelines (2009)

- Quadratic Acceleration Equation (Heimlich et al. 2009)
- Miami-Dade County Climate Change Projection (2008)
- South West Florida Regional Planning Council (SWFRPC) Assessment (Beever et al. 2010)
- SimCLIM (Tak 2010)
- North Florida – Gulf Coast Alliance Project (2009)
- Plus the following applications:
    - USGS South Florida Ecosystem Portfolio Model (EMP) (Labiosa et al. 2009)
    - USGS Internet-based Modeling, Mapping, and Analysis for the Greater Everglades (IMMAGE) (Hearn et al. 2010)
    - USGS Biscayne and Southern Everglades Coastal Transport Model (BISECT) (Lohmann, Swain, & Decker 2010)
    - USGS Tides and Inflows in the Mangroves of the Everglades (TIME) (Bahm et al. 2010)
    - USGS Future Impacts of Sea Level Rise on Coastal Habitats and Species (FISCITS) South Florida Water Management District (SFWMD) Model – Multi-Model Ensemble Projections (Langtimm et al. 2010)
    - Sea Level Rise Rectification Program (SLRRP) Model (Potter, Burkett, & Savonis 2008)

Table 3 outlines the benefits and concerns with each of the models reviewed (see Appendix C for more details)

Table 2: SLR Predictions

Region	SLR Prediction (ft.)	Range/ Time Frame	Data Source	Date Published	Model(s)/ Method Used
Global	0.26 – 2.0 ft	2100	**IPCC**	2007	Hierarchy of 23 models – not directly related to SLR
Global	1.6 – 4.9 ft	2100	**IARU**	2009	Linear correlations
Global	1.9–5.25 ft, (CI: 1.93-0.9 ft)	2100	**Jeverjeva, Moore & Grinstead**	2010	Inverse Statistical Model
Global	3.0 – 4.0 ft	2100	**Meier et al.**	2007	Glacier melt acceleration
Global	n/a	2100	**UNEP**	2009	Summary of ice melt contributions from Pfeffer, Church and others
Global	1.0 ft	2100	**Church & White**	2006	Statistical analysis of historic sea level data/ trends (used in UNEP analysis)
Global	4.27- 20.67 ft	Not Given	**Mitrovica et al.**	2009	Modified calculations and models (Fingerprinting, IPCC)
Global	2.5 – 6.2 ft	2100	**Vermeer & Rahmstrof**	2010	Semi-empirical Dual Model
Global	3.12 – 3.94 ft	2250	**MIT-IGSM**	2009	Bayesian Delphi Consensus
Florida	3.0 – 5.0 ft	2100	**Heimlich et al.**	2009	Quadratic Equation- SLR only
Florida	3.0 – 5.0 ft		**Miami-Dade CC Advisory Task Force**	2008	Uses IPCC data – not a model
Florida	0.59 – 4.4 ft	2100	**SWFRPC Beever et al.**	2010	Modified EPA and Stanton and Ackerman, based on tide gauge data
Local	n/a	n/a	**CH2MHILL**	2010	SimCLIM – propriety model for use in local planning agencies –not peer reviewed.
North Florida	2.0 – 4.0 ft	2100	**Gulf Coast Alliance**	2014	Not released yet
Florida (Key West)	0.1-0.3ft-0.6 ft 0.7-1.6ft-4.8 ft 0.7-1.9ft-5.6 ft	2060 2100 2110	**Landers [USACE] correspond.**	2010	USACE EC 1165-2-211 method and historic SLR data (2.24mm/yr.) at Key West. These values are very similar to values for other NOAA tides stations around Florida with at least a 40-yr. continuous record. They are considered suitable for use in all Florida coastal locations except perhaps the extreme western FL Panhandle.
Florida	0.42 – 1.67 ft	2060	**SFWMD**	2009	Based on information from multiple sources including: CERP Guidance Memorandum, NRC, Miami-Dade County Task Force, Florida State University and IPCC.

Table 3: Summary of Model Advantages and Disadvantages

Data Source	Date Published	Models/ Method Used	Benefits	Limitations
IPCC	2007	Hierarchy of several models	Florida tracks with world projections for SLR, but this is not the focus of the models.	Present understanding of some important effects is limited, does not have a SLR projection per se, global model difficult to downscale. Florida is very small to downscale.
Jeverjeva, Moore and Grinstead	2010	Inverse Statistical Model	Results are based on observed relationships between forcing and sea level, future ice and ocean responses to 21st century climate change	They utilized the central estimates of radiative forcing projections from six IPCC Special Report on Emission Scenarios (SRES) scenarios: A1B, A1Fi, A1T, A2, B1, B2 (Meehl et al. 2007). These scenarios combine anthropogenic and natural forcings. Results to 21st century climate change may be systematically in error. The model is not transferable to Florida nor does it permit drilldown.
USACE	2009/2011	Modified NRC Curves with Modified Equations and IPCC Projections	Relies on tidal and other localized data which ties to actual results. Allows for an analysis of scenarios of possible future rates of sea level change over time. Can be easily updated based on new data/science.	Relies on external entities for science; not a model per se but a collection of other data/models.
Mitrovica	2008	Modified calculations and Models (Fingerprintin g, IPCC)		Global model difficult to downscale, Florida very small to downscale.
Vermeer & Rahmstrof	2010	Semi-empirical Dual Model	Tracks with worldwide changes in SLR resulting from melting, and thermal expansion. Tracks with observations, theory known.	Uncertainty in thermal expansion. Provides no modeling input.
Pfeffer, Harper & O'Neel	2008	Calculation of Ice Sheet Dynamics	Focuses on melt impact on SLR which was ignored in initial thermal expansion models.	Uncertainties and sinks and sources of SLR, i.e. terrestrial water storage.
Church & White	2006	Statistical analysis of historic sea level data/ trends	SLR model. Older data updated by Rahmsdorf and others.	Limited analysis of uncertainties
MIT-IGSM	2009	Integrated Global Systems Model	Innovative approach to use Delphi to achieve solutions. The intent was to arrive at consensus on up to 35 variables, noting that only 3 properties are commonly recognized as being major contributors to the uncertainty in simulations of future climate change.	Anthropogenic emissions were held constant at 2100. It applies to a global scale of professional opinion. Such a process could be suggested for Florida at a later date. This is focused a risk assessment

Data Source	Date Published	Models/ Method Used	Benefits	Limitations
Meier et al.	2007	Glacier melt acceleration	This model addresses a major drawback of the IPCC 2007 report and IARU models which did not account for actual and potential glacier and ice cap melt. This partially remedies that omission and forecasts higher SLR by the year 2100.	Uses IPCC 2007 data with additional SLR due to accelerated glacier melt considerations. Global model difficult to downscale. Florida is very small to downscale.
IARU	2009	Linear Correlations	Uses thermal expansion (Rahmsdorf) and update IPCC data. One output is SLR projections.	This projection leans heavily on Rahmstorf 2007 (linear regression of SLR vs. Time), which is later superseded by the better correlation of Vermeer & Rahmstorf 2009. Which includes both linear and second-order term and leads to quadratic acceleration model. Vermeer and Rahmstorf (2009) is the preferred consensus. Global model is difficult to downscale. Florida is very small to downscale.
Heimlich et al.		Quadratic Equation	Addresses IPCC issues with thermal expansion of oceans as well as increases melt. Combines efforts identified by others. Projections well within range of others. FAU based. Ties to local conditions. Applicable state-wide.	Does not address limitations due to changes in melt or thermal expansion. Does not tie directly to any forcing agent
Miami-Dade CC Advisory Task Force	2008	Modified IPCC	The report uses detailed information about infrastructure in the area to determine potential risks. Application of IPCC AR4 model.	The project is not a model but an application of the IPCC AR4 projections for the coming century, with some of the assumptions altered. Focus is Miami-Dade County only.
SWFRPC, Beever et al.	2010	Modified EPA and Stanton and Ackerman	This is a SLR projection model based on a report by the EPA (Titus & Narayanan 1995) and Stanton and Ackerman (2007). The EPA project uses three climate change probability of occurrence scenarios; *1) Lower*: a condition that involves a future in which significant mitigation actions are undertaken to reduce the human influence on climate change, *2) Intermediate*: a scenario which falls within various forecasts, and *3) Upper*: a future in which few actions are taken to address climate change.	These models need to be revisited with a range of changes due to possible climate changes. Defines a limited area.
Potter, Burkett, & Savonis	2008	Gulf Coast Study, Phase I	Update in progress.	This project is intended as a guidance document with suggested measures to improve infrastructure and reduce risk, not project sea level.

Data Source	Date Published	Models/ Method Used	Benefits	Limitations
Landers, USACE	2010	USACE EC 1165-2-211 method & Historic SLR data (2.24mm/yr.)	Southeast Florida Regional Climate Change Compact consensus. Uses real data. Not a model per se but a summary of data used to generate low, medium and high projections.	Relies on observational data only, and external sources. Is not a model, but a projection

2.3 Consensus SLR Projections for Southeast Florida

The Southeast Florida Regional Climate Change Compact (Compact) comprised of the governments of Monroe, Miami-Dade, Broward, and Palm Beach Counties established a scientific working group of SLR experts and after multiple meetings over a three-month period, the group agreed that the USACE 2009 guidelines were the most useful for projecting SLR through the year 2100, though some members thought those estimations were conservative. The scientific working group was composed of representatives of USACE, South Florida Water Management District (SFWMD), FAU (represented by Dr. Leonard Berry), Florida International University (FIU), University of Miami (UM), and local, county, and private sector representatives of the governments of Monroe, Miami-Dade, Broward, and Palm Beach Counties. The scientific working group concluded that the best available projections allow for a 3–7 inches rise in mean sea level by the year 2030 and 9–24 inches by the year 2060. The USACE derived SLR projections of 19.5–57 inches by the year 2100 are included in the report for information, but the group declined to endorse numerical projections beyond the year 2060 (see Figures 4 and 5).

The USACE projection model outlines three alternatives of future sea level change rates: "*low (historic)*," "*intermediate*," and "*high.*" As explained in Figure 5, the Compact adopted by intermediate and high curves to represent the lower and upper range for projected SLR in Southeast Florida. The NRC committee recommended "projections be updated approximately every decade to incorporate additional data" (1987). At the time the NRC report was prepared, the estimate of global mean sea level change was approximately 1.2 mm/year. Using the current estimate of 1.7 mm/year for global mean sea level change, as presented by the IPCC (IPCC 2007), results in this equation being modified. It should be noted that all but one tidal station in Florida suggests that 2.1 mm/yr is more appropriate. Final estimates are created using modified projection equations added to the local rate of vertical land movement. By accommodating accelerated glacier loss, the high rates exceed the upper bounds of the IPCC 2007 estimates.

The USACE model on SLR projections is a projection based on historic tide gauge data from NOAA and an updated equation from a NRC report in 1987. Only tide gauges with over 40 years of record are utilized. Global mean sea level (GMSL) over the past several million years has varied principally in response to global climate change (NRC 1987; IPCC 2007). The USACE derived projections developed by the scientific working group use Key West NOAA tidal data from 1913-1999 as the foundation of the calculation and references the year 2010 as the starting date of the projection. The scientific working group relied on the USACE guidelines that were effective from 1 July 2009 through 30 June 2011. Although the USACE guidance was replaced in

October 2011 with EC 1165-2-212 the revised guidance does not alter the projections derived from the core model. USACE policies are expected to be periodically reviewed and revised as the accepted consensus on the science changes.

To stay abreast of the rapidly growing science on potential SLR, the scientific working group recommended that their current SLR projections be reviewed and updated in two years (see report recommendations.) By that time, several important new studies are expected to be published including a new study by the NRC on future sea level projections for the Pacific coast states of California, Oregon, and Washington. The FAU team preparing this report agrees with the findings of the Compact, but also sets a projection of over 36 inches (this is the mid-range of USACE projections) for the year 2100. These projections emphasize the importance of incorporating the impacts of SLR and associated storm surge in the planning, design, construction, operation, and maintenance of transportation infrastructure while including a recommended margin of safety approach to adaptive management. This report reviews what the literature says on the potential impacts of SLR and identifies critical data gaps which, when filled, will enable more precise predictions of physical infrastructure that might be potentially affected by SLR.

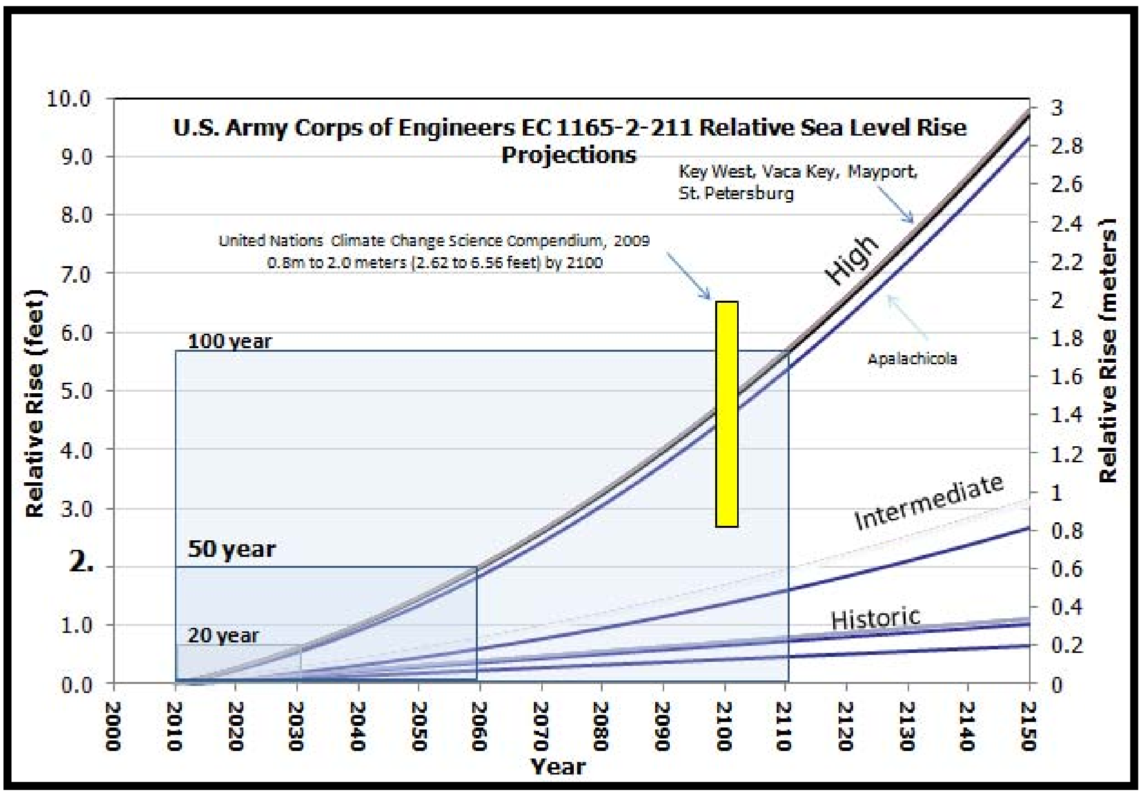


Figure 4: USACE SLR projections for Florida based on tide stations around Florida with at least a 40-year continuous record. The SLR projection for Key West is suitable for most generalized statewide planning purposes since there are only small differences in the various projections across locations even at the 100-year planning horizon. Note these projections are for locations directly influenced by ocean conditions. Some interior locations and the western Florida Panhandle may require adjustments based on local tidal records.

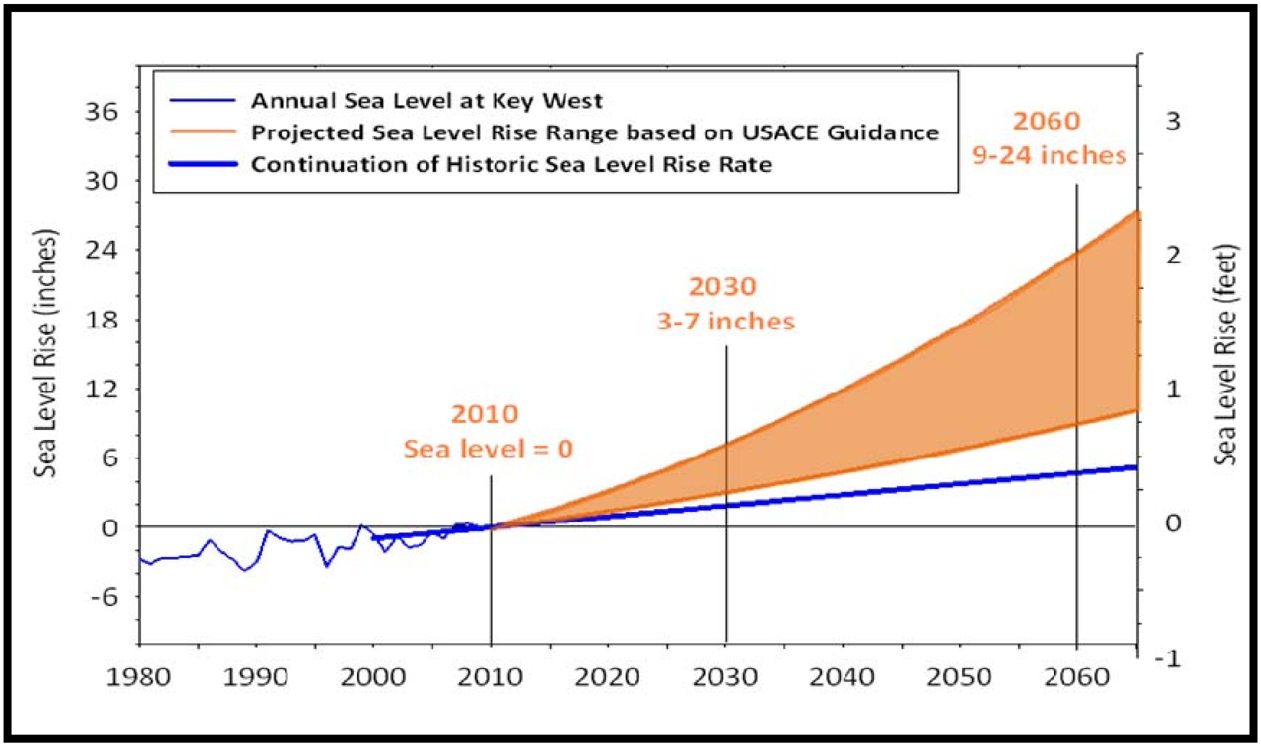


Figure 5: Southeast Florida SLR projection for regional planning purposes. This projection is calculated using the USACE guidance (USACE 2009) intermediate and high curves to represent the lower and upper bound for projected SLR. The historic Key West tidal data shows current trends in the recent past. The recent rate of SLR from tidal data is extrapolated to show how historic rates compare to projected rates.

2.4 FAU SLR Workshop Findings

The Center for Environmental Studies (CES) at FAU, the Florida Sea Grant College Program (FSG), and the U.S. Geological Survey (USGS) held a two-day workshop at FAU in February 2010. The purpose of this workshop was to engage Florida university faculty and Florida resource management agencies on the issue of SLR and its effects on coastal zone marine (upland ecosystems), the built environment, and hydrological dynamics that might be impacted by future SLR and storm surge (Berry 2010). The conclusions were:

- SLR in South Florida is already a problem: significant impacts are occurring along the coast and are affecting canal function. Malfunctioning canal systems cannot discharge water from low-lying areas during periods of high rainfall and high tide.
- Based on satellite data, the current mean global rate of SLR is approximately 3 mm per year. However, within a relatively broad band of certainty, projections of future SLR consistently indicate a non-linear increase in this rate in future years.
- A rise of at least one meter (about 3.28 ft) before the end of the century is an increasingly likely possibility.
- Regardless of the rate of increase, it is prudent and essential to prepare for and adjust activities and infrastructure to SLR immediately: the projected rates of rise will result in sea levels that

have significant impacts on coastal ecosystems and the coastal infrastructure and economy. The long-term trend for accelerating future SLR is clear.

- For both natural and built systems and for Everglades restoration planning and action, ongoing monitoring of the rate of rise in sea level and its impacts is critical.
- In the face of SLR at an uncertain rate, adaptive management in the greater Everglades is even more critical.
- Due to the impact of SLR on ground water levels, flooding, drainage, and saltwater intrusion, impacts may occur in inland areas before direct shoreline impacts are apparent.
- There will be critical levels of SLR that are thresholds of impact. In a majority of cases, these rates are determined by the state's topography.
- Impacts may escalate during hurricane-driven storm surge events as higher sea levels will result in substantially greater inland incursion of saltwater.
- Both urban and natural systems need to be considered in research and planning because impacts on one will have impacts on the other.
- Monitoring and adaptive management measures need to be implemented.

2.5 Data Gaps in Current SLR Information

Many groups have researched data gaps associated with SLR. This research shows that a wide range of data is still required and the lack of data may inhibit the ability to engage public officials about the issue. To develop a meaningful and effective SLR adaptation plan, state and local planners must: (1) understand the vulnerabilities specific to their communities and, (2) be able to generate a clear understanding of the communities' dynamics and overall composition, perspectives on risk, economic drivers, and potential challenges in adopting new guidelines or adaptation measures. For SLR planning and implementation (as with any science-based decision-making process), the requirements for high quality data and information are vast. Overall, a need for data interoperability is important to: (1) eliminate known incompatibilities and, (2) ensure that users are able to apply data from a variety of sources (Culver et al. 2010). The following six categories of data are needed to support future SLR planning and implementation:

1) Data to understand land forms and where and how water will flow: this includes data on geomorphology, topography, bathymetry, vertical datums, etc. to identify direct and indirect hydrological connections;

2) Monitoring data and environmental drivers: this includes data on tides, surface and groundwater levels, waves, precipitation, historical and predictive shoreline erosion data, local sediment budget, saltwater intrusion monitoring, etc. including an understanding of changes in equilibrium conditions following major storm events;

3) Consistent SLR scenarios and projections across agencies to support local planning: this includes data not only on the amount of SLR projected within a given area, but also on storm frequency information and the general time frame within which these changes are anticipated. Often different neighboring entities with differing projections only serve to muddle the issue;

4) Data to characterize vulnerabilities and impacts of SLR: this includes data on population, current and future land use, buildings and critical infrastructure, natural resources, economic impacts, etc.;

5) Community characteristics: this includes data on demographics, societal vulnerabilities, economic activity, public attitudes and understanding of risks, etc. and;

6) Legal frameworks and administrative structure: this includes data on zoning, permitting regimes, legislative restrictions, etc.

Table 4 shows the gaps identified by different groups. Further descriptions of these gaps can be found in Appendix D.

It is important to address how and when, or if, canal structures will be raised in South Florida to prevent migration of saltwater inland and to permit the drainage systems to work as planned. This will increase flood risks in some areas and higher groundwater levels may increase road maintenance costs. There is a critical need to address increasing community level flood risks due to rising sea levels, and related increases in financing and insurance rates. These are likely to shift development patterns and future transportation needs.

2.6 Quality of Existing Information

Data and models that are currently in use each have pitfalls and benefits. Databases, land data variables and models each have to be considered according to quality. SLR databases generally use two types of SLR data, tidal levels from tide stations and satellite altimetry. Tidal data is generally of high quality and the only consideration needed is tide station running time. Stations that do not have 40 years of continuous data collection are not considered compliant with USACE guidelines, and therefore are not used by the USACE for SLR studies (USACE 2011)-see Figure 3. Based on data in Appendix B, 9 of the 14 stations in Florida meet this requirement and three others are just short of this requirement (Panama City is one of the three stations not yet near 40 years). Satellite altimetry has gained influence for use in global interpretations of SLR, but not as much with local SLR studies. The two main types of data used for land analysis in SLR studies are LiDAR and contour DEMs (Digital Elevation Model). LiDAR has better vertical accuracy than DEMs, but is expensive and currently covers smaller areas across Florida. DEMs cover all land areas in Florida, but the best vertical contours are usually 5 ft contours with a margin of error of 2.5 ft (Beever et al. 2010), which is not useful in areas that are 0-5 ft above sea level and are likely to be inundated in the future. SLR projection model integrity varies according to the projection date of the model. Practitioners using inundation models need to develop a better understanding of datum. The LiDAR elevation equal to zero is not equivalent to mean sea level so adjustments are required (vertical datum changes as sea level rises so corrections are required).

Table 4: Workshop Specific Data and Knowledge Gaps

Group	Coverage	Gaps Identified
Florida Keys Workshop	Florida Keys	LiDAR for entire Keys
		Improve National Elevation Dataset (NED)-based SLR modeling
		Complete Sea Level Affecting Marshes Model (SLAMM) (WPC, Inc. 2010)
		Develop region specific SLR projections
SFWMD Workshop	South Florida	Uncertainty in rainfall projections
		Strategies for retrofitting flood control gates
		Refine climate predictions
Broward County Climate Change Task Force	Broward	Strategies for raising/relocating railroad tracks
National Academy of Science: "Advancing the Science of Climate Change America's Climate Choices"	Nation	Comprehensive climate observations
		Research on climate variability
		Comprehensive scenarios on climate drivers
		Increase knowledge of climate forcing, feedbacks and sensitivity
		Improve regional climate models
		Greater understanding of thresholds and climate "surprises"
		Foster adaptive coastal management
		Local vulnerability in context of multiple stresses
		Reduce scientific uncertainties
		Improve understanding of ocean dynamics
		Develop tools/approaches for understanding/predicting vulnerability to SLR
		Expand ability to assess/Identify vulnerable coastal regions/populations
		Develop decision support capabilities for all levels of governance

Projection models of SLR in the year 2060 are generally in agreement about the amount of projected SLR. Beyond the year 2050 models start to diverge significantly and potential SLR ranges increase dramatically. Model projections after the year 2050 are uncertain because the projections depend on the rate of emission reductions that can be achieved by the international community. Caution needs to be taken with model projections beyond the year 2050, with considerations such as "adaptive capacity, impacts, and risk tolerance to guide the decision of whether to use low, medium, or high SLR projections." In order to remain up to date with information as it is released, projections should be revisited regularly. The Coastal and Oceans Resources Working Group for the California Climate Action Team report recommends updates every 1–2 years. Developing such short-term updates is unlikely to yield significant changes in the projections. However, the longer-term changes may be significant (CO-CAT 2010).

One of the issues to understand is that SLR will affect different areas differently. In addition, because it advances slowly, the effects may not be obvious until certain thresholds are met. Figures 6-8 are designed to illustrate this point. In each figure, colors are used to depict elevation heights: the lighter the blue color the higher is the vulnerability of the area. Figure 6 shows the City of Dania Beach around the Fort Lauderdale-Hollywood International Airport, with 1 ft of SLR (the recommended planning scenario for 2030 ─ high prediction─ also low prediction for 2060). In this map, areas in tan, green, and dark blue indicate elevations higher than 2 ft, 1-2 ft and 0- 1 ft above the sea level, respectively. Colors of light blue and white represent sea level and below sea level elevations, respectively. The areas affected are represented in blue color (newly inundated lands). As shown in Figure 6, the affected areas are relatively limited and close to inland waterways. Most of the U.S. Highway 1 (US 1) (represented by a vertical black line) appears to be at least 1 ft above the sea level and only a short section of the roadway seems to be affected by the 1 ft SLR (blue area). Figure 7 shows the same area (illustrated in Figure 6) with 2 ft of SLR─ this is the recommended planning scenario for 2060. As can be observed, the areas affected change considerably with neighborhoods being impacted on the east side of US 1 and west of the airport. The scenario of 3 ft of SLR (the recommended planning scenario for 2100) illustrated in Figure 8 shows large areas inundated (more blue and white areas). The coastal ridge along US 1 in clearly visible (more on this later). The point of these figures is that the SLR issue is not as gradual as might be thought, but that passing certain milestones will subject ever-larger areas and some fairly disconnected areas to inundation.

More knowledge is needed about the hydrology of specific coastal systems. For example, Southeast Florida has a very porous geologic formation that may make groundwater levels more difficult to control. The same cannot be said for other areas of the state. In addition, under surge conditions, where does the water go and how fast? What effects will storm surge with higher sea levels have on existing manmade structures (canals, barriers, stormwater systems, etc.)? Highway/roadway drainage modifications are likely going to be one of the major modifiers of where storm surge flows go and where there are impacts. Are there things we can do to minimize adverse effects through better management of drainage systems established for transportation systems?

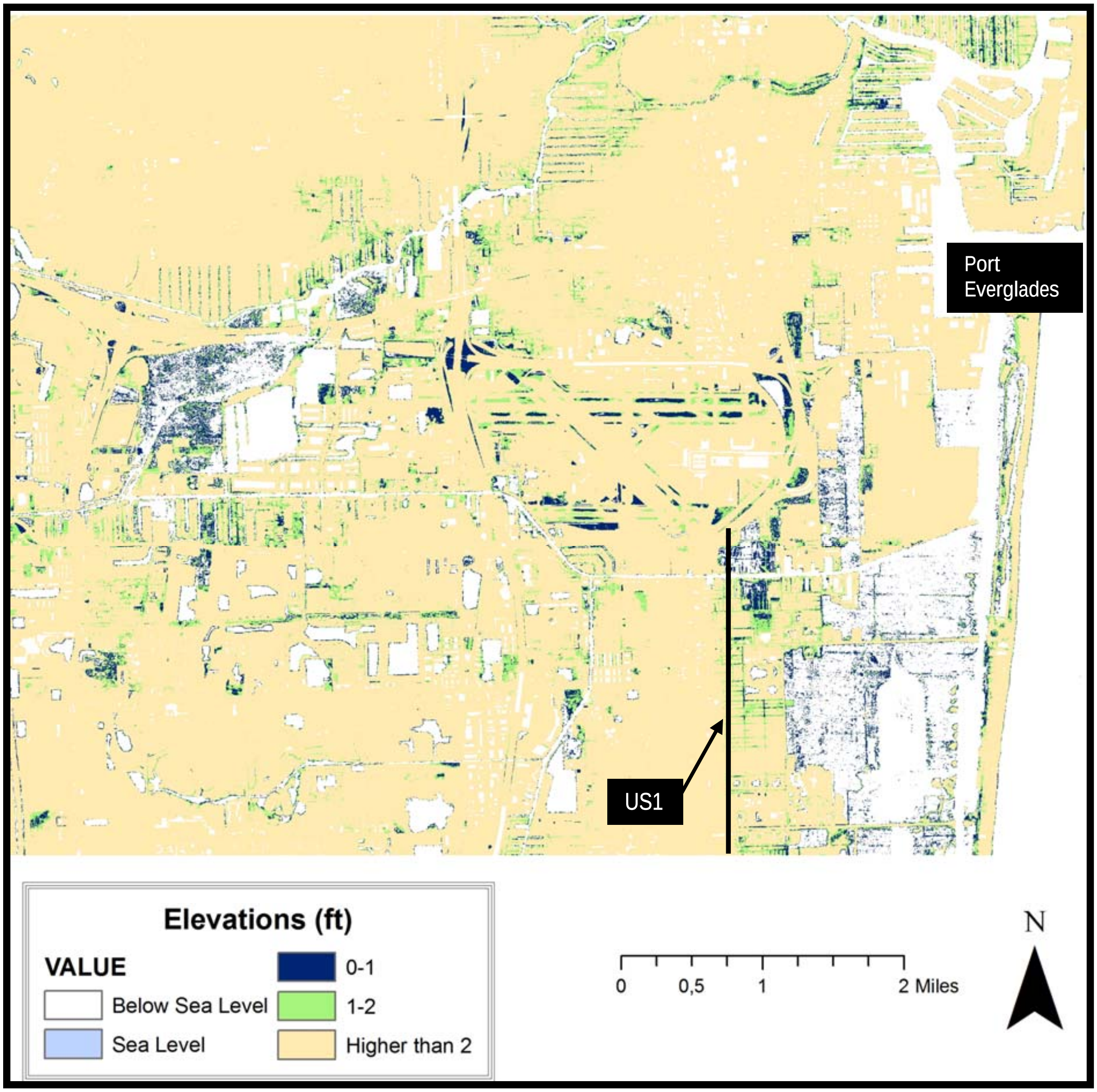


Figure 6: Example of changes with 1 ft SLR. Blue areas indicate lands newly inundated, with green areas subject to future SLR. The black line indicates the US1 roadway.

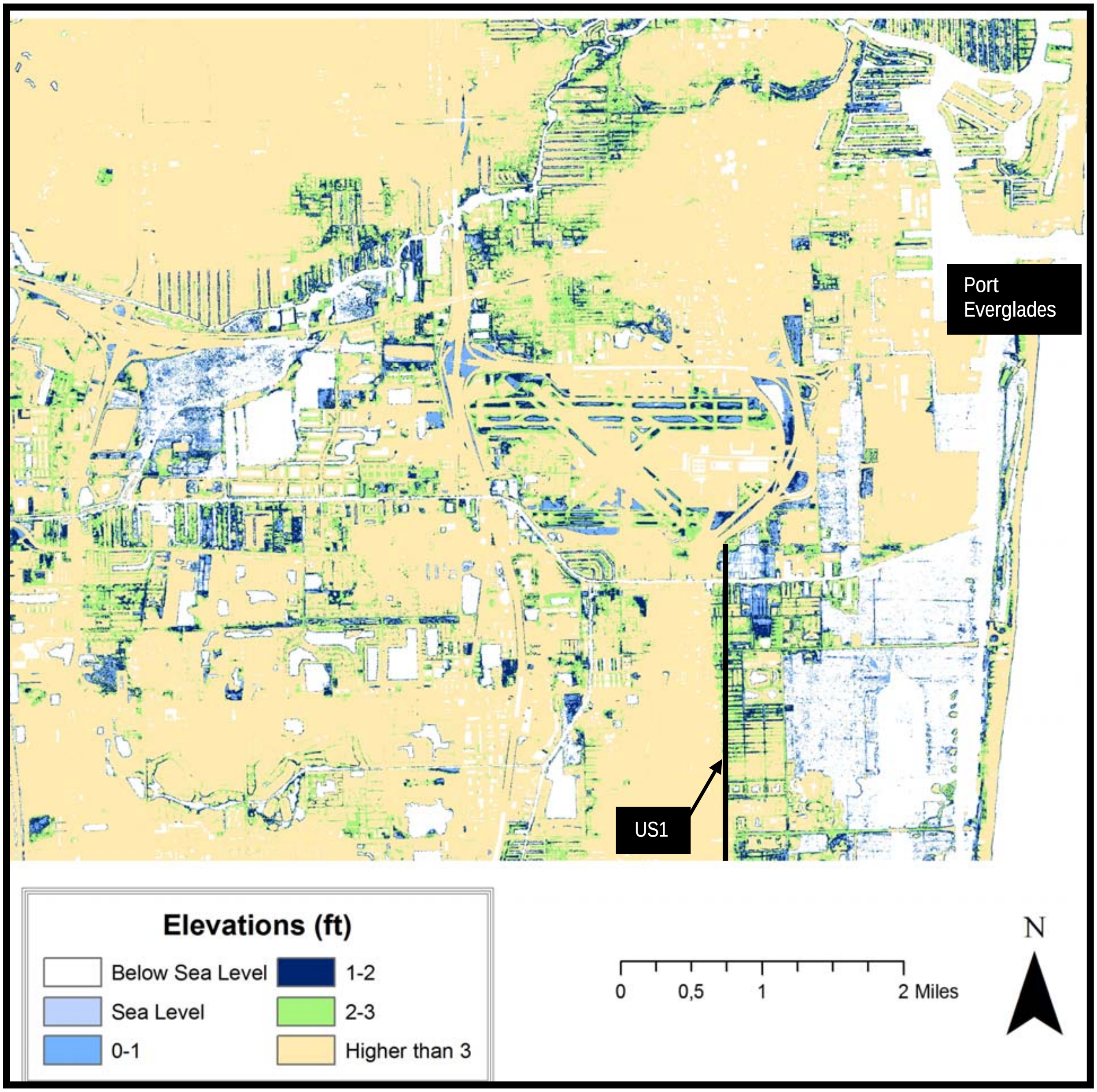


Figure 7: Example of changes with 2 ft SLR. Blue areas indicate lands newly inundated and green areas subject to near future inundation. The black line indicates the US1 roadway.

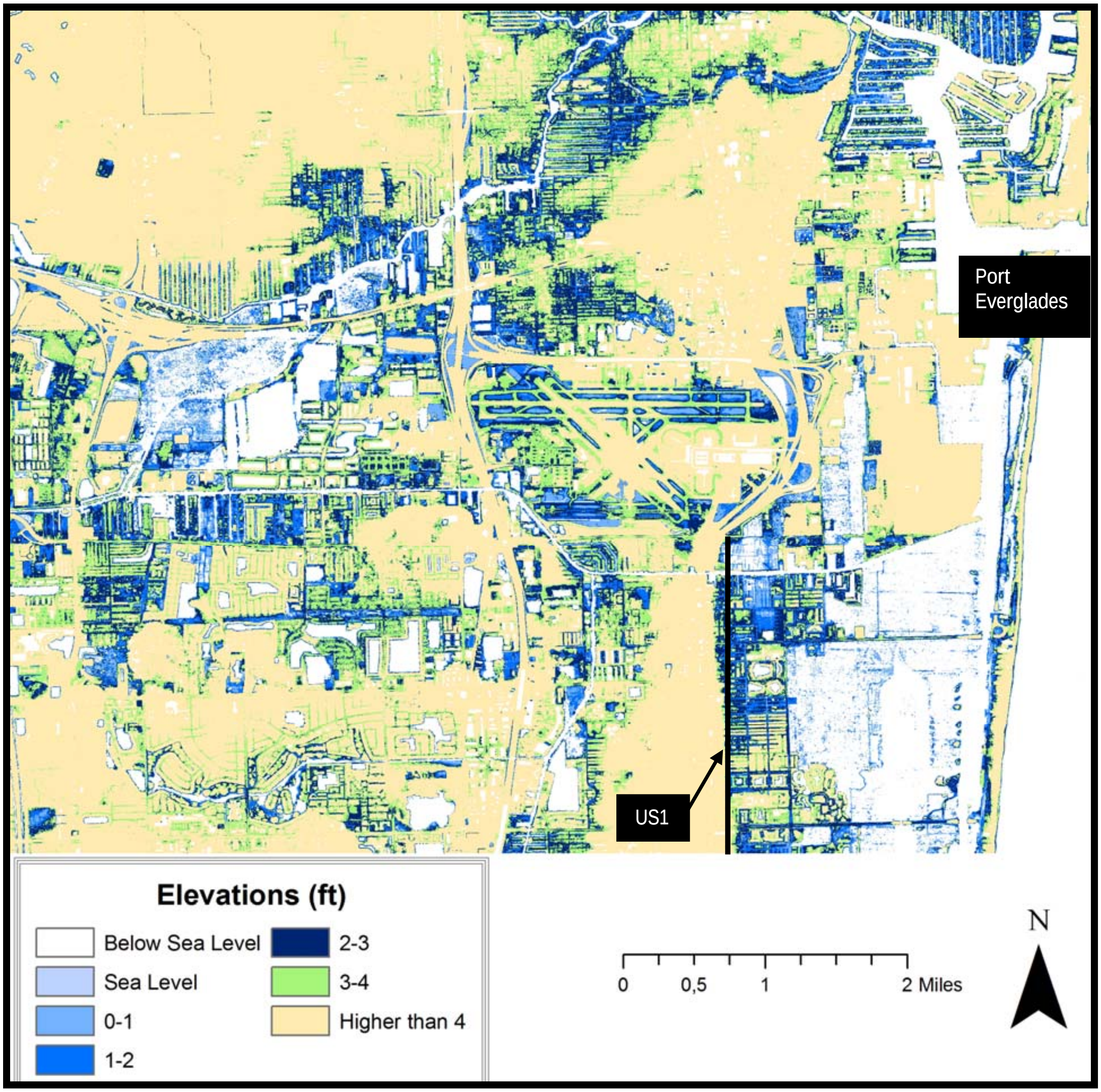


Figure 8: Example of changes with 3 ft SLR. Blue areas are lands newly inundated, with additional green areas subject to near future inundation. The black line indicates US 1.

2.7 Potential Impacts on Infrastructure

In general, direct effects of SLR are possible on transportation, affecting navigation, marinas, ports, bridges, aviation, rail lines, and roads (Titus 2002). SLR can potentially affect bridge clearance and the point of flocculation/sedimentation for navigation, airports along tidal waterways, rail lines that cut across marsh land and road drainage (Titus 2002). The adaptation measures to current SLR being studied in South Florida require, among other things, restructuring septic systems in the Keys and reengineering outlets of canals to prevent flooding at high tide. It is estimated that some 30 coastal salinity structures in Miami-Dade and Broward County will be further affected over the next couple of decades (Obeysekera 2010). Local water supplies have been threatened for years because of saltwater intrusion into freshwater aquifers when wetlands are drained (Obeysekera 2010). Florida communities that draw water from surficial aquifers (i.e., the Tamiami aquifer on the west coast, Biscayne aquifer on the southeast coast, and Floridan aquifer in northeast and central Florida and Tampa Bay) are already experiencing problems related to saltwater intrusion (Deyle, Bailey, & Matheny 2007). In 2001, a USGS study found that "Elevated chloride concentrations have been observed in more than 70 wells tapping the Upper Floridan and the upper zone of the lower Floridan aquifers. In Duval and northern St. Johns County, increased chloride concentrations in water from some wells along the coast and up to 14 miles inland indicate that saline water is gradually intruding into the freshwater zones of the Floridan aquifer system." While saltwater intrusion may remain an issue, a bigger issue will be that groundwater levels will rise, flooding low-lying land that was drained as a reuslt of the canal project. Flooding will be more tangible to homeowners and affect roadway bases.

2.8 Tools for Protection of Transportation Infrastructure

Flooding of coastal land can affect the base of roadways and structural integrity of other transportation facilities. Also, transportation infrastructure not directly impacted by flooding could experience traffic saturation conditions and traffic operation safety and management problems through a number of secondary impacts. Therefore, SLR could cause a chain of effects that would impact the entire state's transportation network and systems. The vulnerability of transportation infrastructure will require the development of new design criteria and standards for more resistant and adaptive facilities and systems: relocation and in some cases abandonment of some transportation facilities; and re-routing of traffic, freight, and transit routes. Consequently, the traffic operations of the overall transportation system will experience a shift on trip patterns and transportation mode preferences, and increase travel times and fuel cost that can significantly affect the efficiency, operations, and safety of an entire transportation network and systems. Planning for current transportation network and systems will need to anticipate potential structural and operational problems. See Appendix G for the full suite of options.

2.9 Summary of Tools Needed for Adaptation and Planning of Transportation Infrastructure

The tools necessary for adaptation planning are difficult to prioritize because they depend upon site-specific considerations, including where each community is in the planning process. Adaptation tools need to be understood in terms of data inputs requirements, assumptions of the method, and the reliability and utility of the outputs (Culver et al. 2010). The following list summarizes the categories of tools needed for adaptation planning. These are detailed in the subsequent text:

- Communication tools for stakeholder engagement, visioning, and consensus building
- Tools to monitor and model current and future rates of SLR
- Visualization and scenario-building tools
- Implementation tools to build institutional capacity and implement adaptation plans
- Interagency coordination on research, policy agendas, and funding are needed to provide the package of data, tools, and processes
- Regional coordination of transportation planning

- GIS maps as tools to evaluate infrastructure potentially at risk from SLR and to coordinate infrastructure changes with existing or proposed wildlife corridors, coastal ecosystem buffer zones, rare species relocations, etc. and facilitate the permitting process

Communication Tools
These include tools for stakeholder engagement, visioning, and consensus building, such as:

- Definitions to establish a common language to discuss climate impacts and adaptation strategies
- Tools to educate the public on the science, impacts, and risk
- Guidance and best practices for the planning and decision making process
- Tools for facilitation and conflict management

Monitoring and Modeling Tools
These include tools for monitoring and modeling current and future states, such as (Culver et al. 2010):

- Estimates of SLR that are negotiated and acceptable by multiple agencies and are useful at regional and local levels for comparability across jurisdictional boundaries
- Standards and data architecture to integrate existing databases of observations of water level and other relevant data
- Sophisticated diagnostic models that include:
    - Storm surge models with wave measurements
    - Advanced air and ocean circulation models
    - Geomorphic models
    - Geospatial models for SLR
    - Flooding/inundation models
    - Habitat models
    - Long-term erosion models
    - El Niño Southern Oscillation/climatological impact projections
    - Transportation network models to predict congestion during storm surges
- Downscaling techniques for these models for use in regional or smaller scale scenarios
- Regional information on extreme climate events like hurricanes and intense thunderstorms
- Recurring and continued development of local integrated models and continuous data collection to better help predict the impacts of SLR on groundwater levels, saltwater intrusion (saltwater intrusion affects flooding and has impacts on corrosion), and drainage infrastructure including:
    - Better understanding of model integration in the context of SLR
    - Enhanced development and application of local hydrologic models
- Use of down-scaled climate models to improve knowledge of potential climate change impacts locally (Broward County Climate Change Task Force 2010)
- Long-term and regional monitoring of critical parameters to support related modeling efforts

Visualization and Scenario Building Tools
These include tools that would help communities identify and explore alternative adaptation solutions, such as:

- Visualizations using commonly used viewers (such as Google Earth) for different SLR, storm frequency, and inundation scenarios that are interactive, offer planar and oblique views, and show critical infrastructure, relevant landmarks, and other information that allows communities and decision makers to understand impacts; definitions and analysis of economic impacts and loss
- Conversions of vulnerability into risk information
- Scenario evaluations that:
    - Identify key assumptions
    - Test alternative outcomes
    - Identify thresholds based on monitoring data
    - Evaluate policy tradeoffs based on key unknowns

Implementation Tools
These include tools that are used to build institutional capacity and implement adaptation approaches, such as (Culver et al. 2010):

- Legislation and policy to address SLR and coastal/barrier island development and zoning that considers SLR (Treasure Coast Regional Planning Council 2005)
- Long-term policy analysis tools to help choose among options
- Database of case studies and best practices that can be queried
- Resource (such as a clearinghouse or points of contact) to understand agency activities and potential funding sources
- Evaluation tools to assess the effectiveness of adaptation strategies
- Operational tools that address current conditions and risks (that is, not only long-term planning tools)
- Engineering and solution tools

More information on implementation tools can be found in Appendix E.

2.10 Summary of SLR Impacts on Urban Infrastructure

Transportation infrastructure in U.S. coastal areas is increasingly vulnerable to SLR. Given the high population density near the coasts, the potential exposure of transportation infrastructure to flooding is immense (NOAA 2010). Engineering options are already available for strengthening and protecting transportation facilities such as bridges, ports, and railroads from coastal storms and flooding, but inundation is a different issue. The former are temporal in nature: SLR is permanent. The development and implementation of technologies that monitor major transportation facilities and infrastructure, and the development, update, and re-evaluation of current design standards, are required for adapting to SLR in coastal areas. Issues like elevation of roadway surfaces, well-pointing (continuous pumping of small wells along the roadway for dewatering), additional drainage systems, and roadway diversion/abandonment are issues that require policy input. However, little attention has been given to evaluation approaches for where and when such options should be pursued, or to the potential co-benefits or unintended consequences of them (The National Academy of Sciences National Research Council 2010).

Planning for SLR adaptation in transportation infrastructure will require new approaches to engineering analysis including: the development and use of risk analysis based on uncertain SLR and the development of new engineering standards to reflect future climate conditions (The National Academy of Sciences National Research Council 2010, 325).

The U.S. Climate Change Science Program has recommended the following approaches to incorporate climate information into transportation decision-making, which will be explained in detail below:

- Planning time frames
- Risk assessment approach
- Integrated climate data and projections
- Risk analysis tools
- Region-based analysis
- Interdisciplinary research
- Identification of vulnerable assets and locations
- Identification of opportunities for adaptation of specific facilities
- Understanding changes in the life span of facilities caused by SLR
- Understanding the modes and consequences of failure
- Assessing the risks, costs, and benefits of adaptation

These recommended approaches are further explained in Appendix F. Information on the projected impacts of climate change on transportation infrastructure can be found in Appendix G.

2.11 SLR Literature Review Conclusions

After an extensive analysis of current research on SLR, the FAU project team has concluded that the USACE methodology produces the best available projections which, when applied to Southeast Florida, allow for a 3-7 inches rise in sea level by the year 2030, 9-24 inches by the year 2060 and 19.5-57 inches by the year 2100. Planning within these time horizons should take these rates of sea level rise into account. These results may well prove to be conservative projections and should be reviewed after the next IPCC report is available. Since all but one tidal station shows the same basic SLR, the USACE derived projections for Southeast Florida may be used as the statewide projection of SLR for Florida, except perhaps for the Panama City tidal station. While these projection rates are useful guidelines for the whole of Florida, local conditions of coastline subsidence should be taken into account. A more refined analysis of regional variations in SLR and impacts should be included in next steps.

Chapter 3: Methodology

3. 1 Downscaling Evaluation Approach

3.1.1 Evaluation 1: State SLR Projections

The purpose of Evaluation 1 is to identify segments of state roads in Florida that are potentially vulnerable to SLR, including those that might be at risk of flooding due to SLR. Note that roads, railroads, airports, and property can be evaluated using this methodology. FAU was able to combine readily available data sources to accomplish a drill down process that could identify potentially vulnerable infrastructure and then applied this process to multiple areas of the state. Three of those areas are outlined in this chapter.

Step 1: Integration of FDOT state roadways data and State SLR Projections for the years 2030, 2060, and 2100 using the USACE methodology. USACE derived SLR projections rely on current tidal station data that has a minimum of a 40 year continuous record. FAU suggested that since all but one of the tidal gauging stations in Florida are statistically the same, and the results of these stations is similar to global trends, *the same projection can be used for all areas of the state except Panama City*. As previously stated, the 2100 projection derived from the USACE method is approximately 3 feet, which is fortuitous since Weiss and Overpeck at the University of Arizona, have developed a 1-meter SLR projection map for the entire state at the macro level. Dr. Weiss sent FAU the GIS layer for the statewide map, which was used as an initial starting point. Any roads within the 1-meter projection will be potentially vulnerable to flooding from inundation, either completely or the road base only.

The intent of the methodology to evaluate potentially vulnerable infrastructure was designed so that roads, railroads, airports, and property could all be evaluated using the same process. However, it should be noted that bridges are more site-specific and are often missing in LiDAR images that do not reflect back over water. However, they are generally higher than the adjacent roadway sections, and are less vulnerable to SLR than they are to storm surge. The initial assumption for identifying sections of roadway that are vulnerable to SLR is that if the elevation of the roadway is below 5 feet using the 1988 North American Vertical Datum (NAV88), then the road is more likely to be inundated by 2100. Additionally, the roadway base may be saturated prior to 2060, which would indicate future pavement failure and additional roadway maintenance.

NAV88 is the base sea level condition established in 1988, which replaced the 1929 national geodetic vertical datum (NGVD) system. The reason 5 ft NAV88 is significant is that mean high tide is currently 2 ft NAV88, and because in Florida, the tides fluctuate ±2 ft each day, and by 6 to 8 inches annually (fall tide is higher than spring tide). Because of the speed of groundwater movement relative to the tidal cycle, groundwater will tend to maintain its minimum level at mean high tide, making it difficult to draw groundwater below 2 ft (NAV88) in a natural condition. Consequently, the actual groundwater table is +2 ft, since the mean sea level is 0.0 NAV88. If the SLR is 3 ft, most groundwater will not be able to be drawn below 5 ft NGVD. Therefore, it is reasonable to assume that if the projected SLR is 3 ft, then any land lying below 5 ft NGVD (or below 1-meter in the Weiss and Overpeck SLR projection map) is more likely to be flooded because the groundwater level of the area will tend to be above the surface. Groundwater is expected to have a significant impact on flooding in these low lying areas as a result of the loss of soil storage capacity and the rise of groundwater upward. Using a basic “bathtub” model, the potentially vulnerable infrastructure can be identified for further investigation. The 5 ft contour is a means to identify where likely future problems may occur.

ArcGIS was used as the base program to integrate data from a variety of sources for the evaluation. The Weiss and Overpeck 1-meter SLR projection map for Florida is shown in Figure 9: the red color on the map indicates the areas throughout the State that are more likely to be inundated if the SLR is 1-meter (about 3.28 ft). The map suggests areas where a more drill down investigation should be used for the short- and medium-term planning horizons of 2030 and 2060. These relative SLR benchmarks will need to be adjusted to create maps estimating SLR trends with associated tidal fluctuations (both mean and annual high tides).

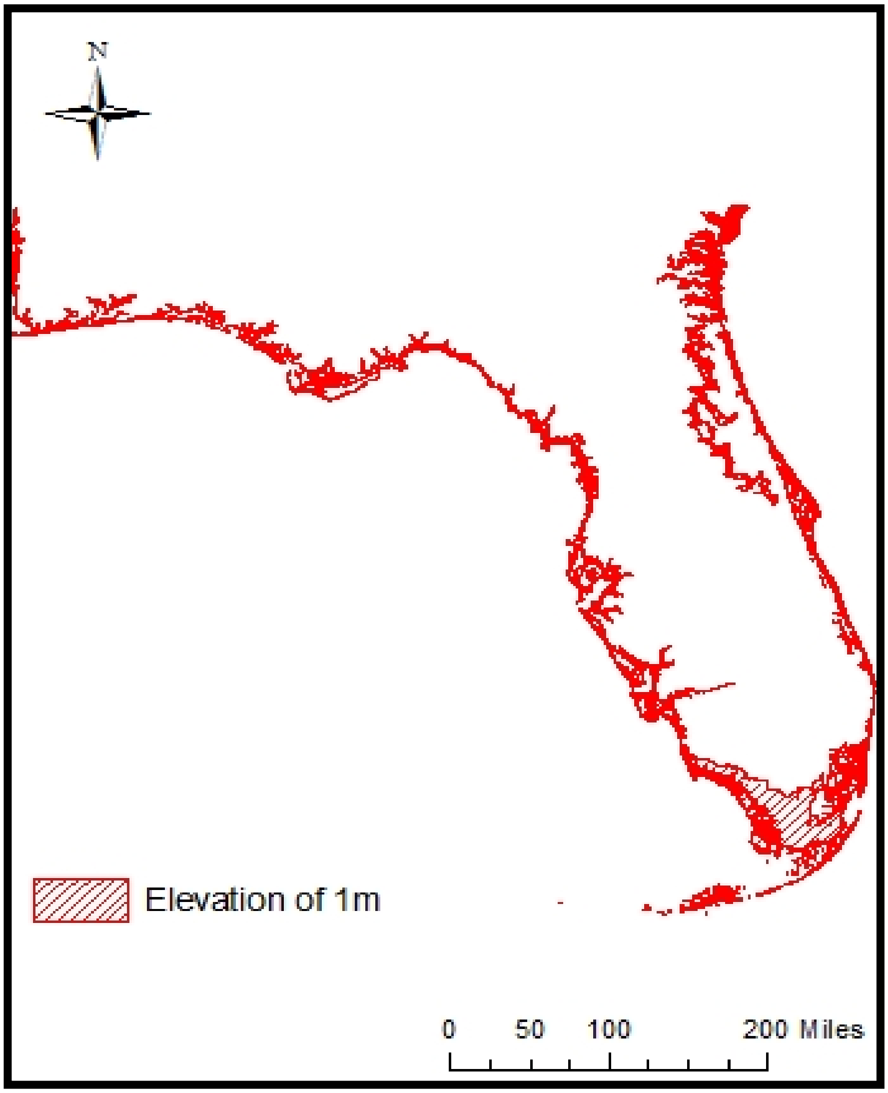


Figure 9: Weiss and Overpeck 1-meter SLR projection map for

Step 2: Preliminary identification of State road segments potentially vulnerable to a 3 ft of SLR.

The FAU research group acquired the shape files of state roads from the FDOT UBR and the SIS databases to overlay the 1-meter above sea level zone from the Weiss and Overpeck map. The resulting map is illustrated in Figure 10. It shows the statewide roadway system (represented by green lines) and the areas under 1-meter elevation (colored in red). The state roads falling in the red area are initially considered potentially vulnerable because they exist below a 3 ft SLR. From this map, statewide spreadsheets of all potentially vulnerable roads can be developed from GIS mapping of each segment of road. Based on this initial condition, every roadway falling in the 1-meter zone (red color) is considered "potentially vulnerable." However, "potentially vulnerable" is a preliminary finding of vulnerability. This stage of the evaluation does not indicate the roadways actually are vulnerable to SLR, but that they require further investigation. To identify the vulnerable infrastructure, the use of localized LiDAR data is required.

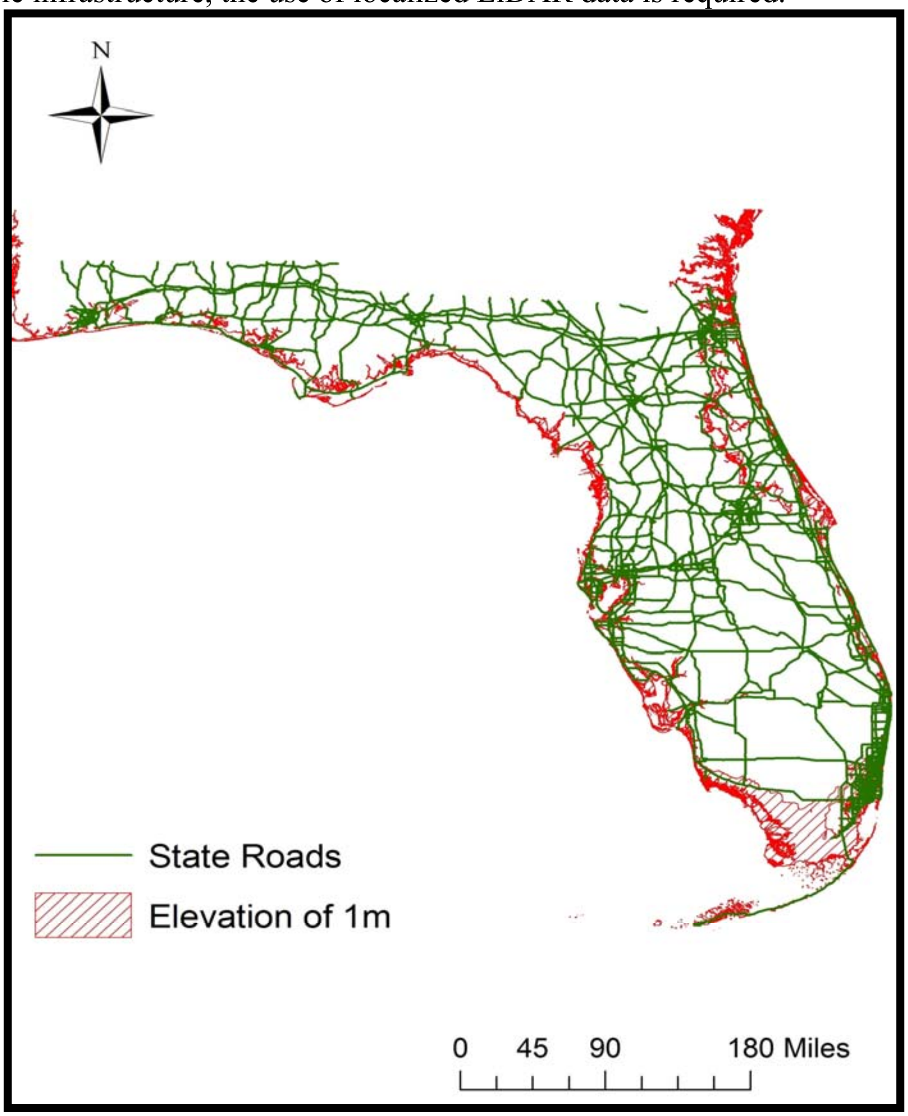


Figure 10: State roads overlaid on Weiss and Overpeck 1-meter SLR projection map for Florida.

Method Illustration:

The low-lying area of Dania Beach in the southeast region of Florida is used to illustrate this methodology. Dania Beach is the area inside the yellow square in Figure 11. As shown on the map, most of the Dania Beach area has elevations of less than 1-meter. After visually inspecting the Weiss and Overpeck map, the following state roads are identified as potentially vulnerable roads: US 1 (Federal Highway), US A1A (Dania Beach Blvd.), Griffin Road, Stirling Road and Sheridan Street.

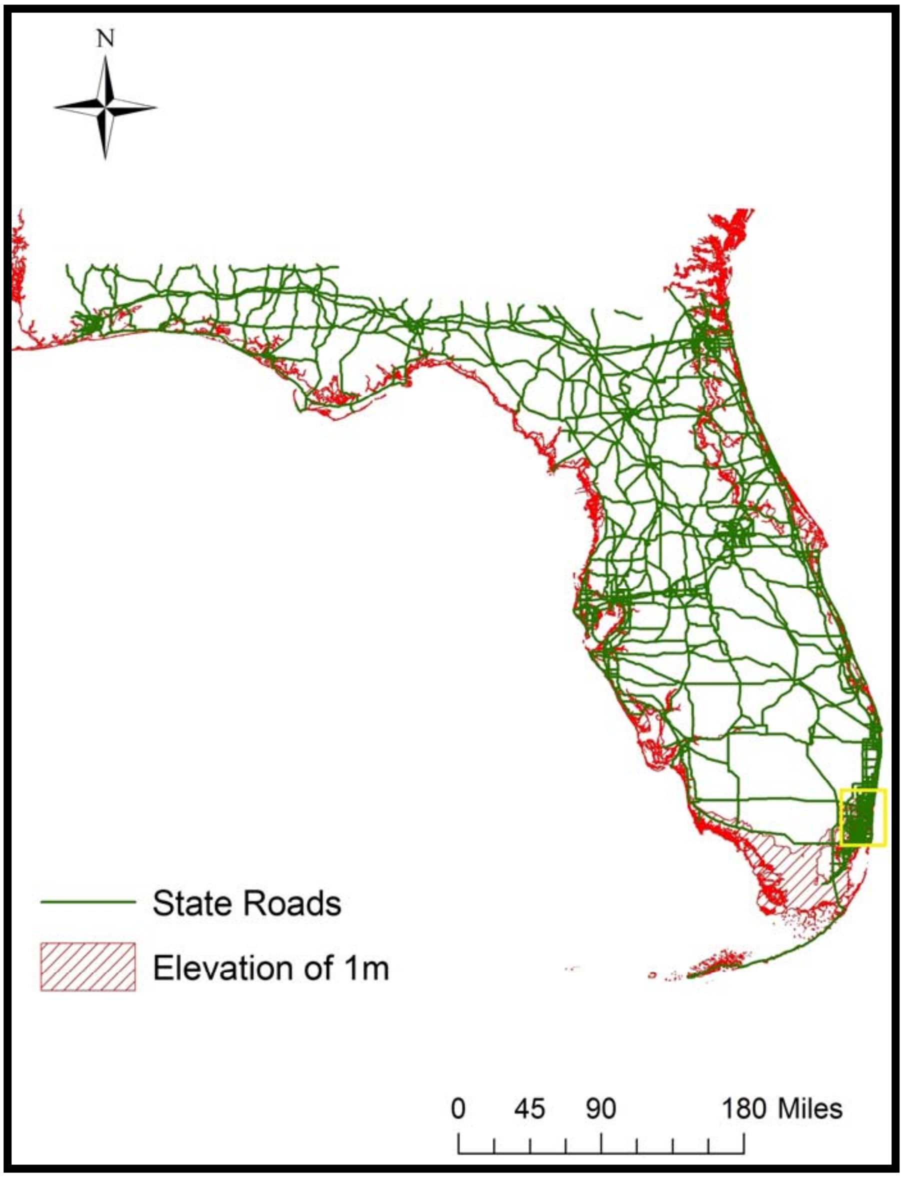


Figure 11: Location of Dania Beach area. Yellow square indicates the study area, state roads overlaid on Weiss and Overpeck 1-meter SLR projection map for Florida.

Step 3: Creation of inventory of potentially vulnerable State roadways.
Results from Step 2 were used to develop an inventory table with the roads that could be inundated due to SLR within the Dania Beach study area. A matrix containing the roadway segments identified as potentially vulnerable roads, the latitude/longitude coordinates of the road section, and the county was created on an EXCEL spreadsheet. GIS data was used to determine the latitude/longitude coordinates for each vulnerable road. The FDOT district and the county of each potentially vulnerable roadway section were identified. However, the matrices do not indicate that the road is vulnerable, only that it is potentially vulnerable. Further analysis is needed to determine which roads actually may be vulnerable (verification of vulnerability using construction drawings and survey data, Step 10 in Evaluation 4).

To verify if a roadway listed in the inventory matrix is potentially vulnerable or not, the Weiss and Overpeck 1-meter SLR were loaded onto ArcGIS's ArcMap program and the shapefiles for the state roadway system were added as a layer on the map. Then the state road sections that fell within the 1-meter elevation of the Weiss and Overpeck map were extracted (clipped) as a new shapefile. Using the clipped state roads shapefile, a new map was created and enlarged view of the sections of the Weiss and Overpeck map that fall within the area of interest area are generated. If a roadway section that was previously identified as potentially vulnerable is located in the 1-meter zone, then the section is identified as still potentially vulnerable. Then the inventory matrix is updated. Otherwise, the section is marked as conflicting roadway segments.

Method Illustration:
Figure 12 shows the enlarged view of the Weiss and Overpeck map for the area of Dania Beach, and yellow lines on the map represent the state roads. As can be observed in the figure, the north-south road US A1A (Dania Beach Blvd.) and most of Griffin and Stirling Roads fall in the red crosshatched area (the area potentially subject to inundation). Meanwhile, east of Sheridan Street (east of US 1) and a small portion west of Sheridan Street (west of I-95) falls in the red zone. Moreover, US 1 is clearly outside the red crosshatch area. According to this second evaluation, US A1A, Griffin Road, Stirling Road, and Sheridan Street are considered potentially vulnerable (see Table 5). Table 5 summarizes the results after conducting the State projections and zooming-in to the Dania Beach area (Evaluation 1). The 'x' indicates that the roadway is still potentially vulnerable to a 3 ft SLR.

Table 5: Downscaling Evaluations for Dania Beach Area and Potentially Vulnerable Roads

State Road	Downscaling Evaluations				
	1		2	3	4
	W&O Map	Localized W&O Map (Blow Up)	Medium Resolution LiDAR	High Resolution LiDAR	OTG
US1 (Federal Highway)	x				
US A1A (Dania Beach Blvd.)	x	x			
Griffin Road	x	x			
Stirling Road	x	x			
Sheridan Street	x	x			

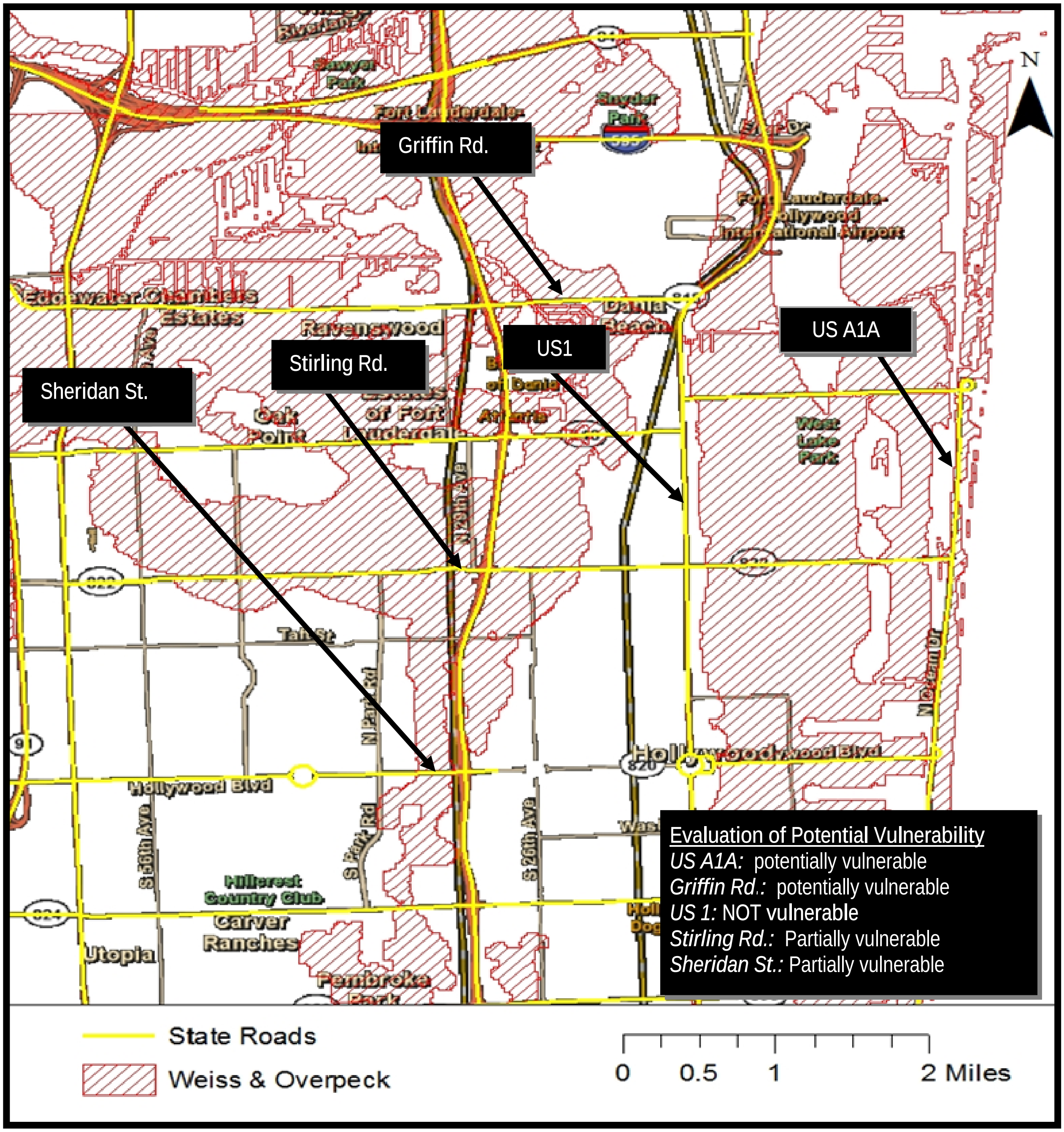


Figure 12: Overlay of state roads and Weiss and Overpeck map for Dania Beach area.

3.1.2 Evaluation 2: Regional SLR Projections

Once the roadway segments that are potentially vulnerable to SLR are identified, the next part of the methodology is to evaluate the roadways with more detailed topographic information. This section presents the steps followed to integrate the data from FDOT information systems (UBR and SIS databases) and GIS data, LiDAR.

GIS Data Coverage

The FDOT UBR and SIS databases were primarily used to determine the location of existing roads, bridges, and rail systems of the statewide transportation system. To understand the location of areas vulnerable to SLR current, accurate, topographical data is required. Multiple sources of elevation data and the level of accuracy were identified and they are listed in Table 6. The topographical data repository sources are organized by the following categories: national, state, and other type of organization.

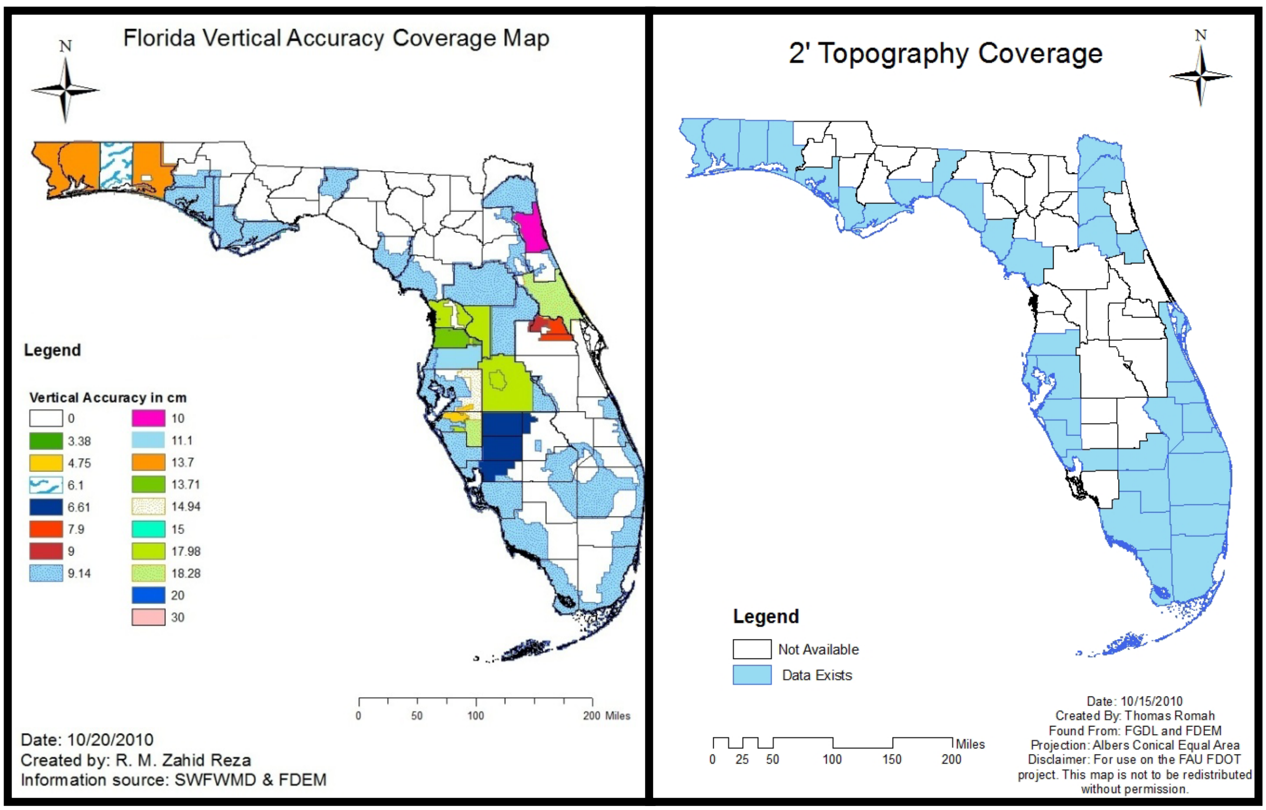
Table 6: Inventory of Topographical Data Repository Sources

Data Source	Meaning Of Acronym (Organization)	Relevant Data Available	Format
	National		
USACE	United States Army Corps of Engineers	*	
USGS	United States Geological Survey	YES	
USFWS	United States Fish and Wildlife Services	YES	
NOAA	National Oceanographic and Atmospheric Administration	YES	
FAA	Federal Aviation Administration	YES	
USDA	United States Department of Agriculture	YES	
FEMA	Federal Emergency Management Agency	NO	
NPS	National Park Service	NO	
NRCS	National Resource Conservation Service	NO	
USEPA	United States Environmental Protection Agency	NO	
USFS	United States Forest Service	NO	
	State		
FWRI	Fish and Wildlife Research Institute	YES	
FDEP	Florida Department of Environmental Protection	YES	
FDOT	Florida Department Of Transportation	YES	
FREAC	Florida Resources and Environmental Analysis Center (FSU)	YES	
SWFRPC	Southwest Florida Regional Planning Council	YES	
NWFWMD	Northwest Florida Water Management District	YES	
FDEM	Florida Department of Emergency Management	**	
SFWMD	South Florida Water Management District	YES	
SJRWMD	St. Johns River Water Management District	YES	
SWFWMD	Southwest Florida Water Management District	YES	
FDOF	Florida Division Of Forestry	NO	
FCFWRU	Florida Cooperative Fish and Wildlife Research Unit	NO	
FNAI	Florida Natural Areas Inventory	NO	
FDHSMV	Florida Department of Highway Safety and Motor Vehicles	NO	
	Other		
GEOPLAN	FGDL Geoplan Center	YES	
BTS	Bureau of Transportation Statistics	YES	
Counties	Individual County government GIS departments	YES	
Universities	State Universities (FSU and FIU)	YES	
NRC	National Research Council	NO	
MPO	Metropolitan Planning Organization	NO	

*Have not been able to contact to source to access available information.

** FDEM administers topography information but does not act as a publisher or repository location. Updated 10/21/2010

In general, three main data types, topographic contour maps (USGS and others), Digital DEM, and LiDAR, were available for use in the next step of the evaluations. To facilitate the identification of areas where current high resolution information is available, topographical data coverage and accuracy maps were created. Figure 13 illustrates two maps with the topographic data available for the State of Florida. In Figure 13, (a) shows the locations where high resolution LiDAR data exists and the color indicates the level of vertical accuracy in cm─ the color indicates the level of vertical accuracy. Most of this LiDAR information has been created by Florida International University (FIU), Florida Division of Emergency Management (FDEM), and USACE, and collected by FDEM. Figure 13(b) indicates the areas through the State that have 2 ft (24 inches) contour information available (in blue). As shown in Figure 13, topographic contour maps are available for most of the State and LiDAR is available in many counties, to varying degrees. It should be noted that the accuracy of the data varies throughout the State and there are areas where there are multiple data sets available. Of critical concern is the vertical accuracy of the data sets as large vertical contours are not useful for analyzing either SLR or flooding incidents.



(a) LiDAR Data and vertical accuracy **(b) Topographic data (2ft contour)**

Figure 13: (a) High resolution LiDAR (color represents level of vertical accuracy in cm) and (b) topographic data available for the State of Florida.

After evaluating the different types of topographic data available for Florida, it was determined that LiDAR data is the most appropriate format for this methodology. LiDAR was selected primarily because of its high vertical accuracy and significant coverage area of available data. Although 2 ft contour information is available, for most parts of the State it does not provide the best level of accuracy when compared to LiDAR information. However, there are various degrees of accuracy of the LiDAR:

- *Low resolution LiDAR* is 1 arc, has a vertical accuracy of +/- 7 to 15 meter, and is not useful for Climate Change modeling. This study did not use any low resolution LiDAR data.

- *Medium Resolution LiDAR* is 1/3 and 1/9 arc. The 1/3 arc has 7 meter vertical accuracy, and is not useful. The 1/9 arc data is the same vertical scale of that of Weiss and Overpeck map. It has 1-meter vertical accuracy, which is potentially useful as shapefiles.

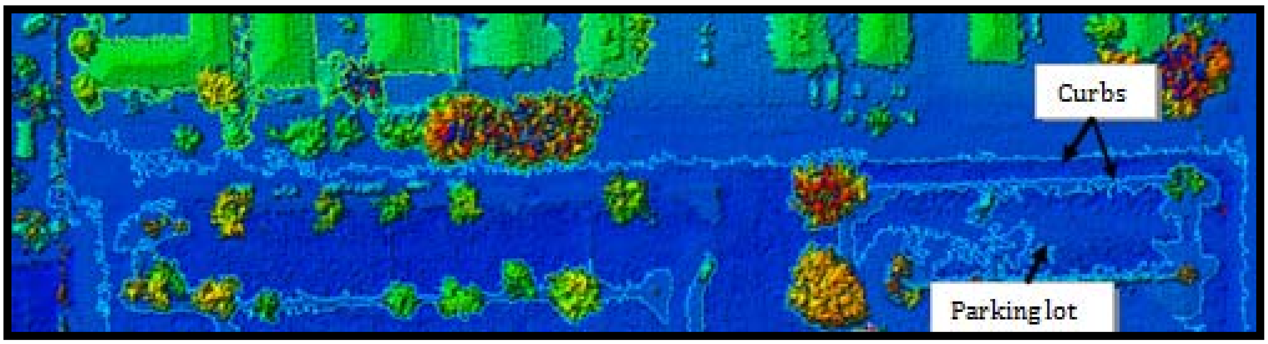
- *High Resolution LiDAR* has a vertical accuracy of 7 inches, and is very useful. The disadvantage is the large size of the files. For the case of Dania Beach, a small area of 4 x 4 miles (3-4 files) required 2 hours to process the data. The Florida Keys (>200 files) required 24 hours of constant computing.

Figures 14 and 16, which will be discussed in the next section, show the differences between the 1/9 arc medium resolution LiDAR and the high resolution LiDAR. For this approach, the LiDAR data type format used was the American Standard Code for Information Interchange (ASCII). The reason why this data format was chosen was because the ArcGIS software can easily understand and import this data format. The ASCII format is comprised of the raw LAS LiDAR data type format, translated into an X, Y, Z global coordinate plane system that is geographically referenced. Of the different topographical data repository sources NOAA offered the data originally in ASCII format.

Limitations of LiDAR

LiDAR reconnaissance planes send out signals that bounce off of points called posts that are coordinated in a grid pattern. Because the information is collected in a non-consecutive point system assumptions and interpretation of the elevation between posts are made by the software. Additionally, raw LiDAR has to be converted into bare earth elevations to account for posts that reflect off objects that do not indicate the actual ground elevation such as vegetation. As a result, interpretation of data is involved that affects the vertical accuracy of the collected data, limiting the reliability of the data's use for small increments.

(a) Aerial photograph



(b) LiDAR image

Figure 14: (a) Aerial photograph of the site and (b) high resolution image of LiDAR (7-inch vertical accuracy) showing trees, curbs, houses and other objects on the ground.

Step 4: Integration of regional FDOT state roadways data and low resolution LiDAR data.
In this step, medium resolution LiDAR data, state roadway system GIS data, and the Weiss and Overpeck map are integrated, creating an overlay map in ArcGIS. Because of the geographical extents of Florida, it was decided that the different regions of the state would be projected using the 1983 North American Datum (NAD83) HARN projection coordinate system for the appropriate region.

The initial overlay map was created by adding a base map of Florida into ArcGIS. The LiDAR elevation data from NOAA is layered onto the base map. LiDAR data is obtained from NOAA Digital Coast/ Data Viewer and the data has an ASCII Grid format, a drilldown type of data (file format). Then the data from NOAA is broken down into small files due to large file sizes for the data. The LIDAR data is projected using:

- Horizontal Datum: NAD83
- Vertical Datum: NAVD88

All elevation data was referenced horizontally to the NAD83 and vertically from the 1988 North American Vertical Datum (NAVD88). After the elevation data is obtained, the elevation data is manipulated to create the color bands that represent different elevation heights. Then the geographically referenced roadway system is imported into ArcGIS.
The advantage of working in the ArcGIS software environment is that different incremental elevation heights and colors can be selected by the user. Although ArcGIS allows the breakdown

of elevation heights into fractional inch increments, it is important to remember the limitations of the source data and how it is collected.

Step 5: Evaluation of current and year 2100 topographical conditions.
The advantages of layering LiDAR data onto a base map is that by changing the color coding of the established elevations, the map can be manipulated to indicate where certain heights above the referenced vertical datum would be estimated to be inundated with ground water. In Figure 15, the variations in blue indicate the potential for SLR impacts (darker blue means more potential) in the Dania Beach area.

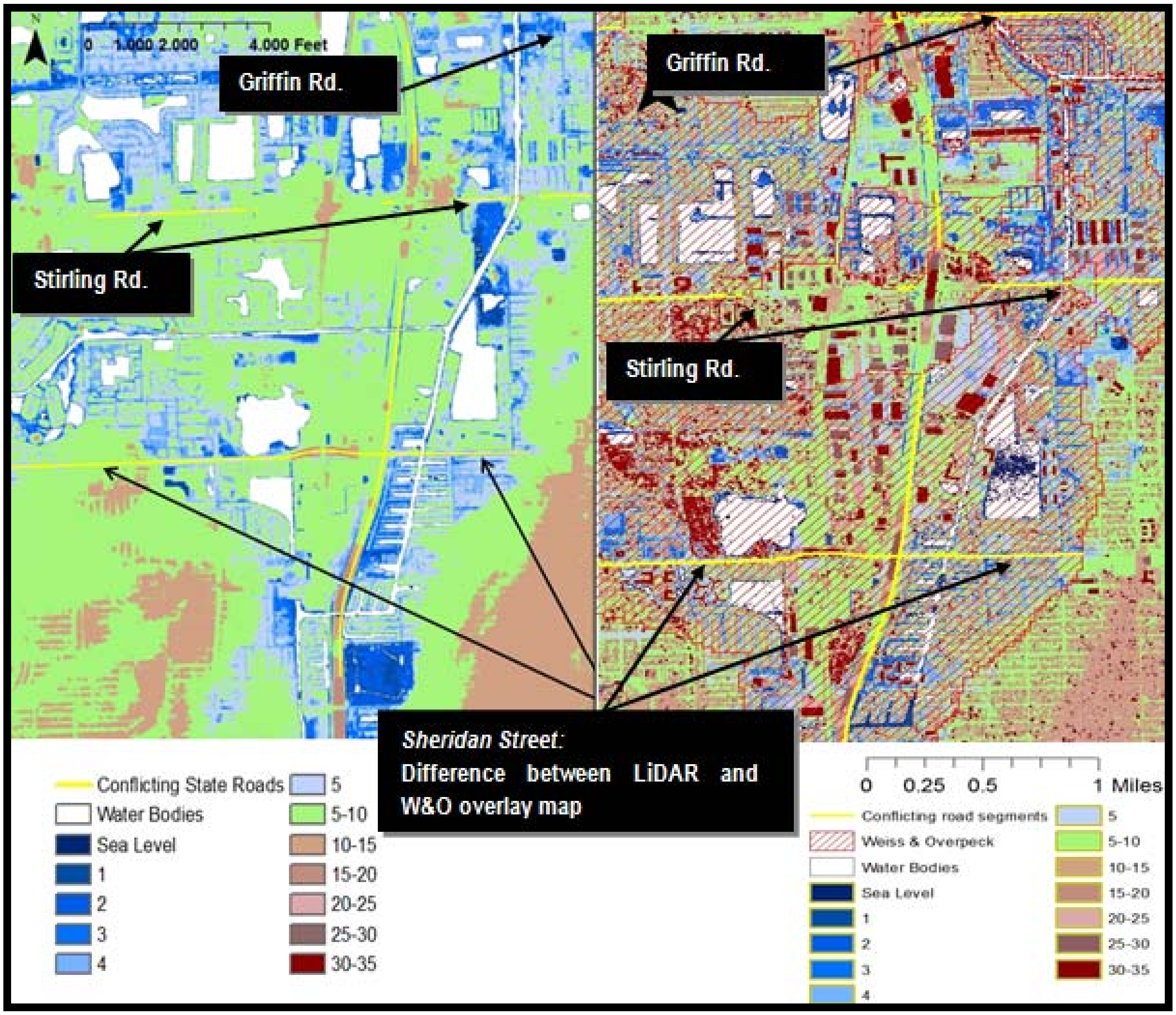
Step 6: Identification of specific roadway sections potentially vulnerable to SLR.
The identification of potentially vulnerable infrastructure was done by visually identifying the areas on the map that show infrastructure below the color banded elevation that is representative of the projected SLR used in the model. The case of Dania Beach is used to explain and illustrate this step.

Method Illustration:
In Figure 15, (a) shows the LiDAR overlay map with medium resolution of 1-meter vertical accuracy for Dania Beach. The blue color suggests that local streets in residential area could be underwater. Similarly, the LiDAR map shows that only US A1A and some sections of Stirling Road and Sheridan Street identified as potentially vulnerable in the Evaluation 1 remain vulnerable in the second evaluation. This is summarized in Table 7.

Figure 15, (b) shows that the same road segments showed up as vulnerable in both the Weiss and Overpeck overlay map and the LiDAR medium resolution overlay map. Meanwhile, most of the roadways fall in the red crosshatched area on the Weiss and Overpeck maps, but the LiDAR data reveals that only a portion of the roadway can be considered potentially vulnerable. For example, in the Weiss and Overpeck map, the Sheridan Street falls in the red zone but the LiDAR overlay map shows that only East Sheridan and small portion of West Sheridan is under 5 ft above sea level.

Table 7: Evaluations 1-2 for Dania Beach area and Potentially Vulnerable Roads

State Road	Downscaling Evaluations				
	1		2	3	4
	W&O Map	Localized W&O Map (Blow Up)	Medium Resolution LiDAR	High Resolution LiDAR	OTG
US1 (Federal Highway)	x				
US A1A (Dania Beach Blvd.)	x	x	x		
Griffin Road	x	x			
Stirling Road	x	x	partial		
Sheridan Street	x	x	partial		



(a) LiDAR overlay map **(b) Weiss and Overpeck 1-m maps overlay map**

Figure 15: Dania Beach (a) overlay map using medium resolution LiDAR data and (b) Weiss and Overpeck overlay map.

3.1.3 Evaluation 3: Localized SLR Projections

Step 7: Integration of regional FDOT state roadways data and high resolution LiDAR data

The benefits of overlaying high resolution LiDAR data onto a base map is that it allows for the creation of more detailed maps which can be examined at scales down to hundreds of feet (see Figure 16).

Steps 8-9: Evaluation of year 2100 topographical conditions of specific roadway links/ identification of specific roadway sections potentially vulnerable to SLR.

Similar to Step 6 in Evaluation 2, potentially vulnerable roads were identified by visually identifying the areas on the map that show infrastructure below the color of the elevation that is representative of the projected SLR. FAU used various shades of blue for areas under 5 ft in elevation. Subsequently, any area that is potentially vulnerable will appear in blue. Green represents areas between 5 and 10 ft above sea level. For these roads, the road base may become potentially vulnerable as SLR progresses.

Method Illustration:
In this case, high resolution LiDAR data (7-inches vertical accuracy) is used to determine whether or not US 1 and sections of Stirling Road and Sheridan Street remain potentially vulnerable. The overlay map in Figure 16 demonstrated that after using high resolution LiDAR, these road sections are at potential risk of continuous flooding due to the SLR.

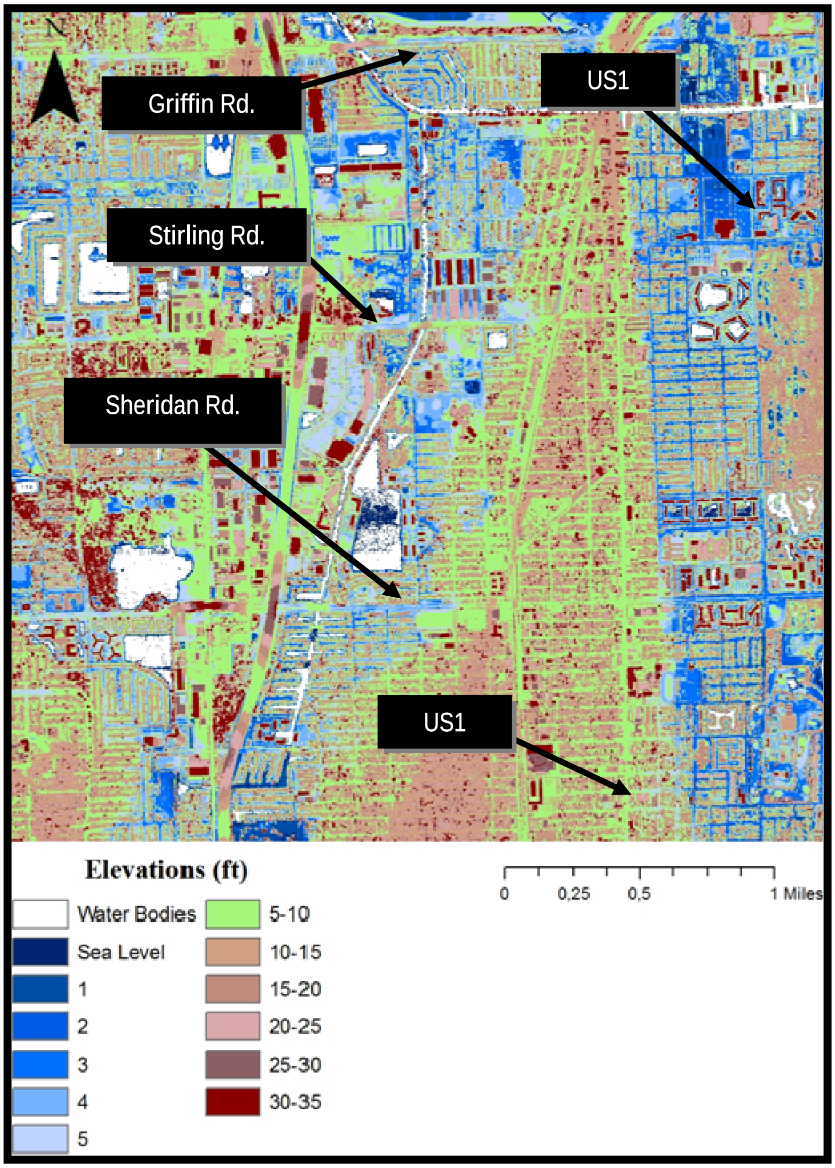


Figure 16: Dania Beach overlay map using high resolution LiDAR data (7-inch vertical accuracy).

3.1.4 Evaluation 4: On-The-Ground Evaluation

Step 10: Verification of vulnerability using construction drawings & survey data

After using high resolution LiDAR, it might be necessary to conduct more detailed evaluations that can indicate areas potentially vulnerable and needing on-the-ground (OTG) evaluations. Later OTG verification can show that there are areas that are subject to inundation. Figure 17 shows an evaluation of a state road in Dania Beach. The blue indicates areas below 5 ft NGVD and suggests survey data and construction drawing evaluations. Figure 17 shows the same building parking area and what OTG can provide. It should be noted that design drawings for this particular roadway section confirm the findings of the LiDAR evaluation (Figure 18). The result of the evaluation is as shown in Table 8.

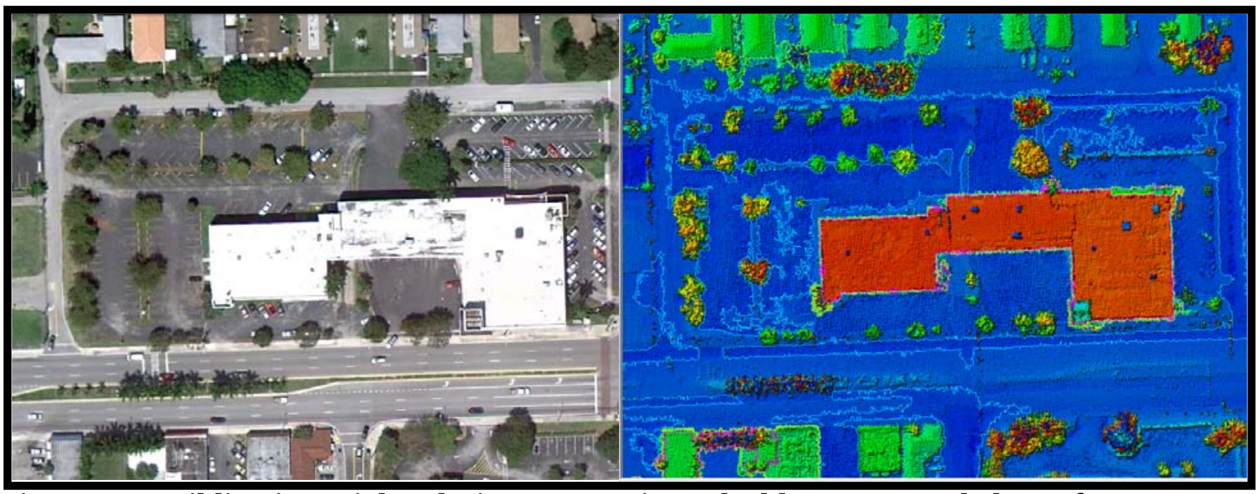


Figure 17: Building in aerial and LiDAR mapping. The blue areas are below 5 ft NGVD. The mapping shows other features like trees, curbing, and islands in the road.

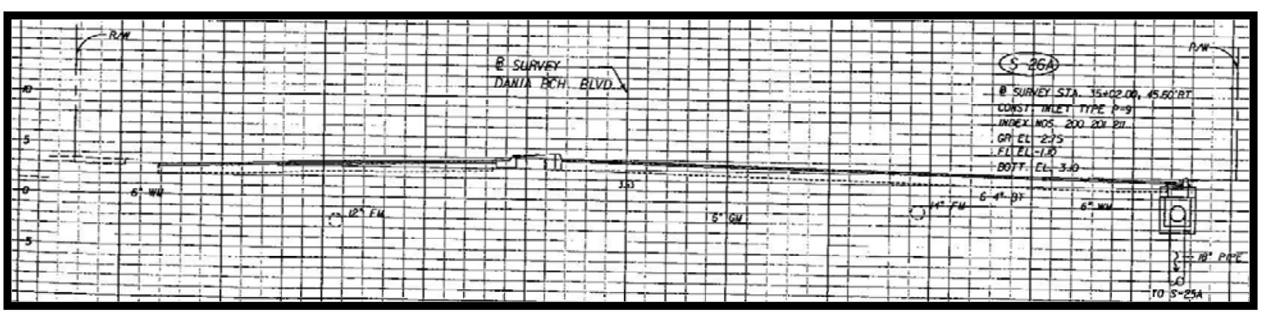


Figure 18: Illustration high resolution LiDAR data and OTG evaluation. As illustrated in the design drawing above, this evaluation comports with findings that the entire road is 3-4 ft elevation.

Method Illustration:
In this case, drawings acquired from FDOT were used to verify the elevation of Dania Beach Boulevard. Since FDOT Districts have plans for these roads, and since improvements will also have plans, the design and planning processes have a merge point. The results for each roadway, based on plan review, are shown in Table 8.

Table 8: Summary of Dania Beach Vulnerable Roads Based on Methodology (Evaluation 1-4)

State Road	Downscaling Evaluations				
	1		2	3	4
	W&O Map	Localized W&O Map (Blow Up)	Medium Resolution LiDAR	High Resolution LiDAR	OTG
US 1 (Federal Highway)	x				
US A1A (Dania Beach Blvd.)	x	x	x	x	x
Griffin Road	x	x	x	x	
Stirling Road	x	x	partial	partial	partial
Sheridan Street	x	x	partial	partial	partial

3. 2 Sketch Planning Tool

The downscaling approach and evaluation techniques were used to develop a framework for advancing a sketch planning tool that can be used to conduct a statewide assessment of state highways and SIS facilities that are most likely to be affected by frequent to continuous inundation due to SLR in the near term. This assessment is recommended for the planning horizons of 2030 and 2060.

The sketch planning tool would evaluate the high and low projections for 2030 and 2060 based on the USACE projection. As part of the framework development, the low end (3 inch) SLR for 2030 is not measurable, so this option was not run. The high projection (7 in) for 2030, the low 2060 (9 in) and high 2060 (24 in) were run and the results are shown in Figures 19-21 and summarized in Table 9. What these figures show is that, while the roadways are not inundated (black), the base may be (tan), which means structurally the roadway will fail. Table 9 shows how the 2030 and 2060 projection compare with the initial projection tool. The result is that an assessment of potentially vulnerable infrastructure for any SLR projection can be made at this level.

Table 9: Summary of Dania Beach Vulnerable Roads and Potential Impacts

State Road	Downscaling Evaluations			
	SLR Projection (Year, High/Low Bound and SLR)			
	2030 High 7 in	2060 Low <1 ft	2060 High 2 ft	2100 3 ft
US 1 (Federal Highway)	No impact	No impact	No impact	No impact
US A1A (Dania Beach Blvd.)	Base impact	Base impact	Part. Inundation	Flooded
Griffin Road	No impact	No impact	No impact	No impact
Stirling Road	Part. base	Part. base	Part. base	Part. base
Sheridan Street	No impact	No impact	Part. base	Part. base

Part. Base = base is wet in parts of the roadway, Part. Inundation = partially inundated in certain sections of the road

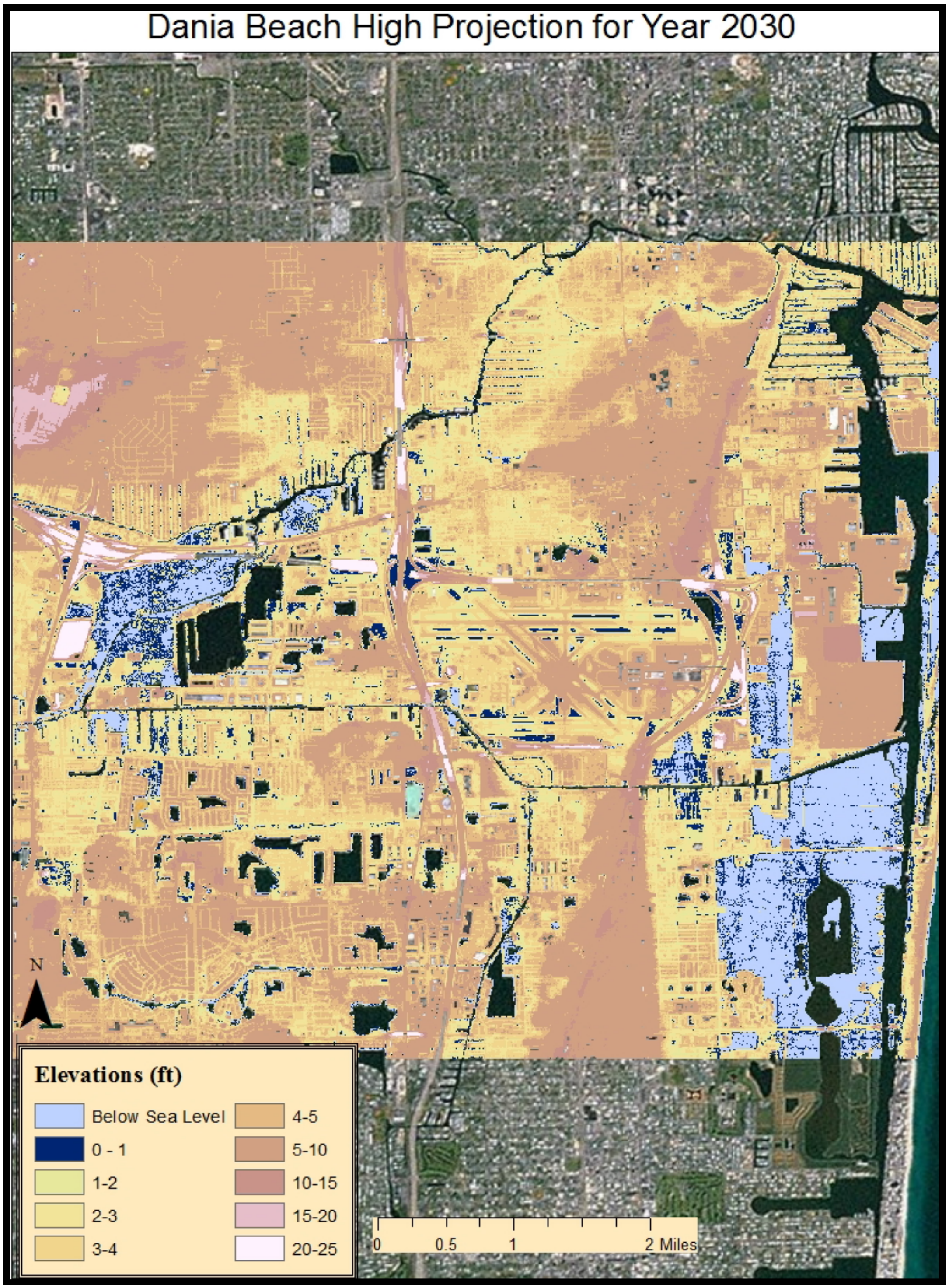


Figure 19: High projection (7 inches) SLR for the year 2030 for Dania Beach. The map shows many roads have wet bases (areas in tan color) but limited inundation.

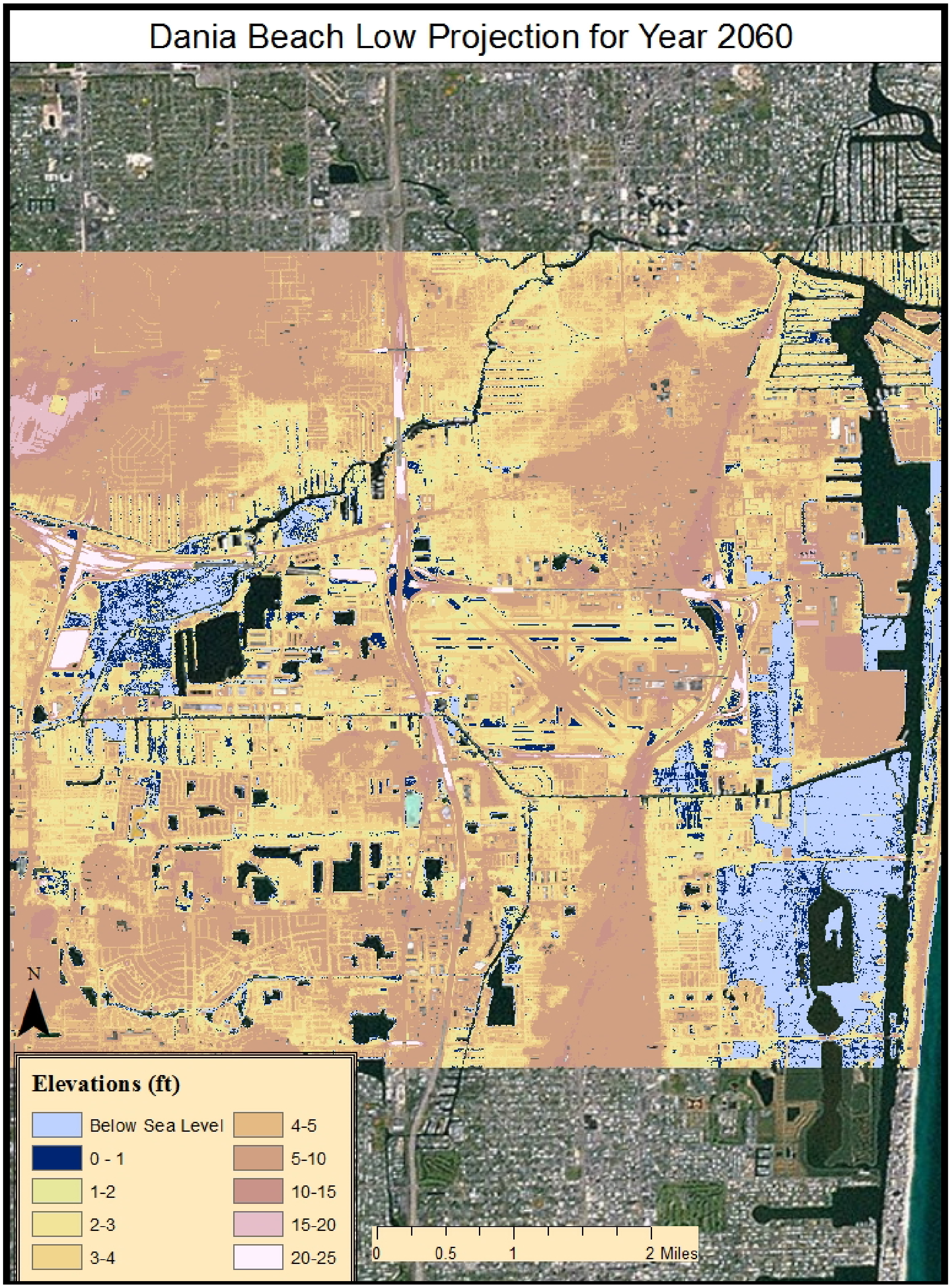


Figure 20: Low projection (<1 ft) SLR for the year 2060 for Dania Beach. The map shows eastern roads and many roads in the western area have wet bases (areas in tan color).

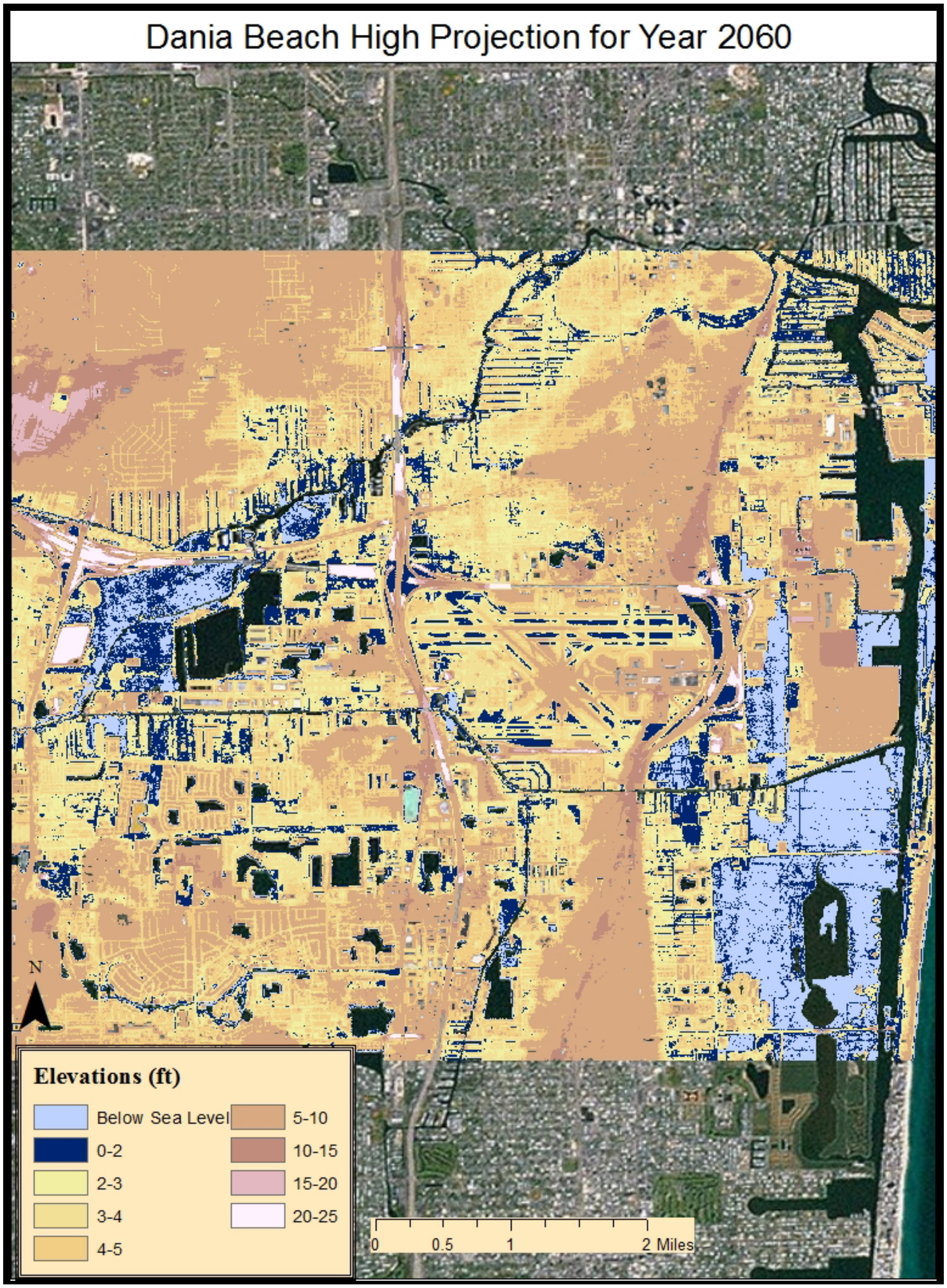


Figure 21: High projection (2 ft) SLR for the year 2060 for Dania Beach.The map shows many local roads in the east, and Dania Beach Blvd. and some western areas are inundated (areas in dark blue color).

3.3 Illustration of Applications of the Methodology

Example 1: Punta Gorda Area

The application of the downscaling evaluation to Dania Beach is described above. This was the initial verification of the protocol. Following the initial application of the evaluation techniques, the FAU research team decided to compare the results of its methods to those used in the work conducted by T. Chapin of the Punta Gorda Metropolitan Planning Organization in Punta Gorda (i.e., presented in the Florida Transportation Adapting to a Changing Climate Workshop held in October of 2010). Because of the hurricanes in 2004-2005, the Charlotte Harbor areas, which included Punta Gorda were concerned about SLR and storm surge, especially in the downtown area of Punta Gorda, one of two populated areas along the harbor. The focus here will be on SLR. Figure 22 illustrates the Weiss and Overpeck 1-meter map for the state, with the Punta Gorda area highlighted in yellow. The Weiss and Overpeck 1-meter map suggests that the area of Punta Gorda falls within the SLR zone. Figure 23 presents the map generated by Chapin, and areas in yellow and orange are included in the Weiss and Overpeck map. The three yellow square shapes in Figure 23 indicate the areas for focus of comparisons of the results.

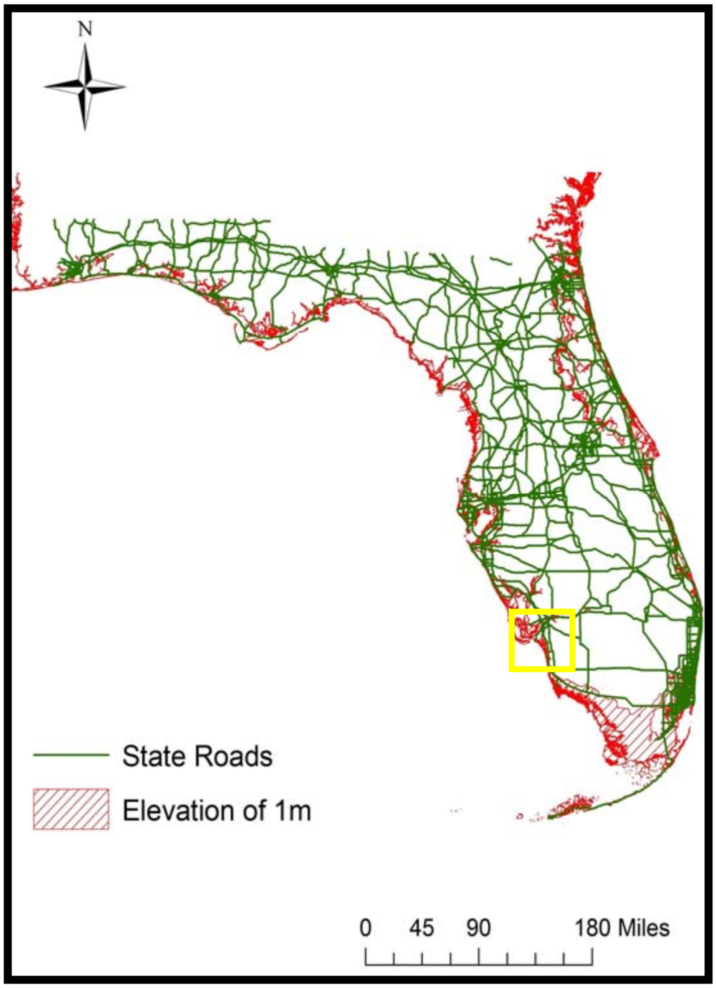


Figure 22: Weiss and Overpeck map showing location of Punta Gorda/Charlotte Harbor.

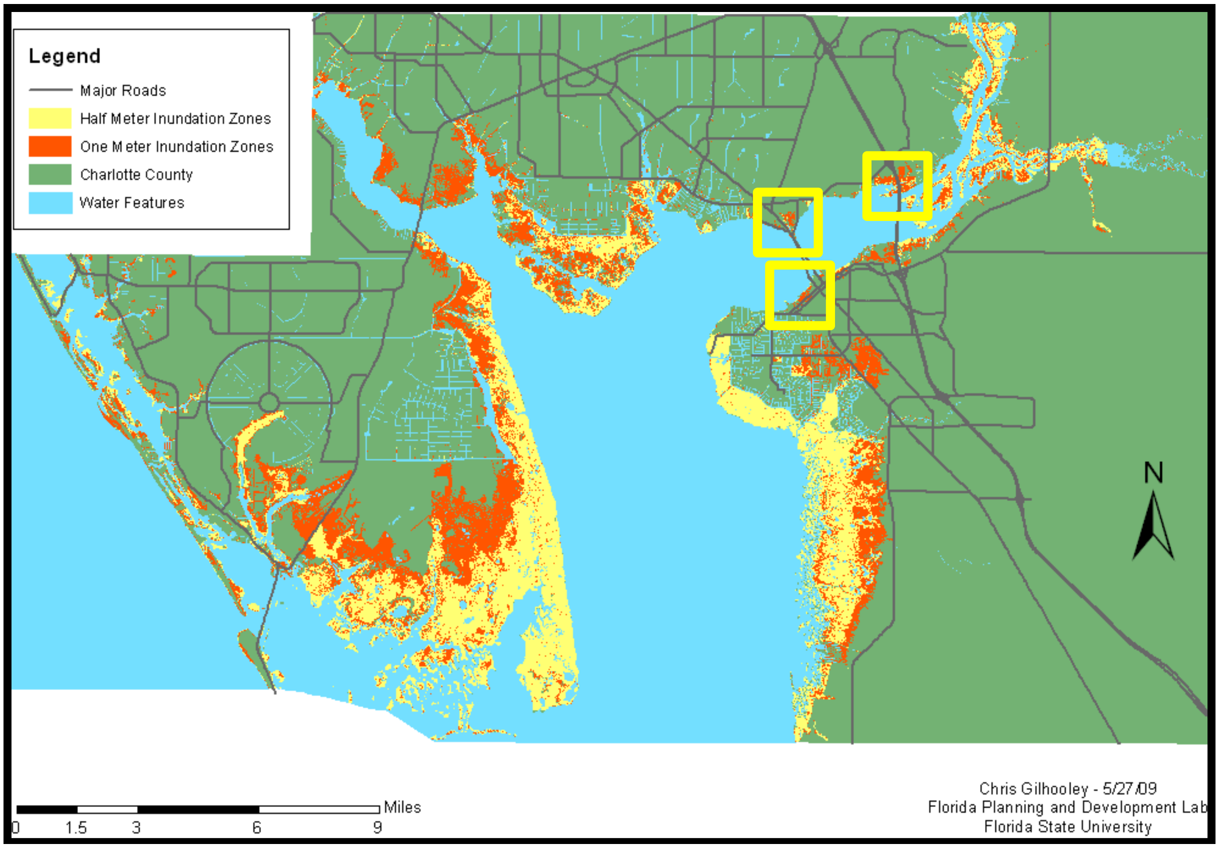


Figure 23: Map of Charlotte Harbor created by T. Chapin. Areas in yellow plus orange color represent elevations of 1-meter SLR. Areas of focus are highlighted in yellow boxes.

Figure 24 displays the crosshatched and enlarged area of Punta Gorda with yellow lines representing state roadways and focus areas highlighted by yellow squares. It shows both sides of the harbor as potentially vulnerable, including downtown Punta Gorda (south bank). Figure 25 superimposes the high resolution LiDAR on top of the Weiss and Overpeck map. It shows the downtown area as potentially vulnerable. A similar trend is depicted in Chapin's map. Moreover, Chapin drew the same conclusions. However, the Chapin and FAU LiDAR maps differ from the Weiss and Overpeck in the western part of the city, that is newer and built at a higher elevation to comply with FEMA flood requirements. The Chapin and FAU LiDAR maps appear to yield similar results.

The benefits of overlaying high resolution LiDAR data onto a base map is that it allows for the focusing on US 41 along the north side of the harbor. The road is potentially vulnerable according to Weiss and Overpeck, but the roadway itself appears to be elevated above the SLR of 1-meter. Thus, Figure 26 compares Chapin's map with the FAU LiDAR map on the north side of the harbor. According to the FAU LiDAR map, US41 is not classified as potentially vulnerable roadway. The elevation appears to be around 6 ft NAV 88. However, Edgewater Drive (the first intersection north of the bridge) is partially vulnerable in both maps. Chapin's photographs of the road show it to be a low-lying road, with private property at a higher elevation draining to it, which would concur with it being vulnerable to SLR.

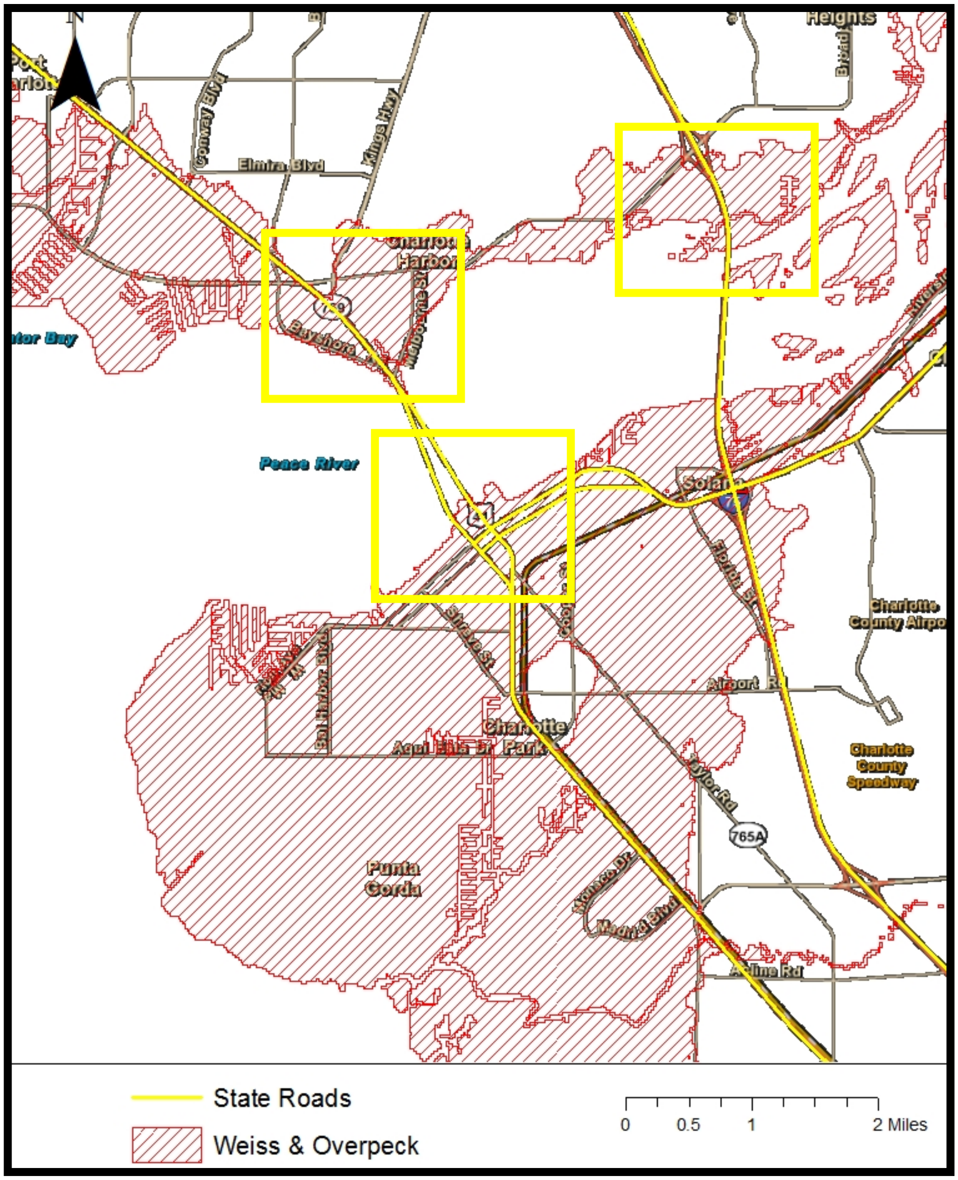


Figure 24: Weiss and Overpeck crosshatch of Punta Gorda. Red area indicates area with elevations of less than 1-meter, and yellow lines represent state roads. As depicted on the map most of the city is potentially vulnerable.

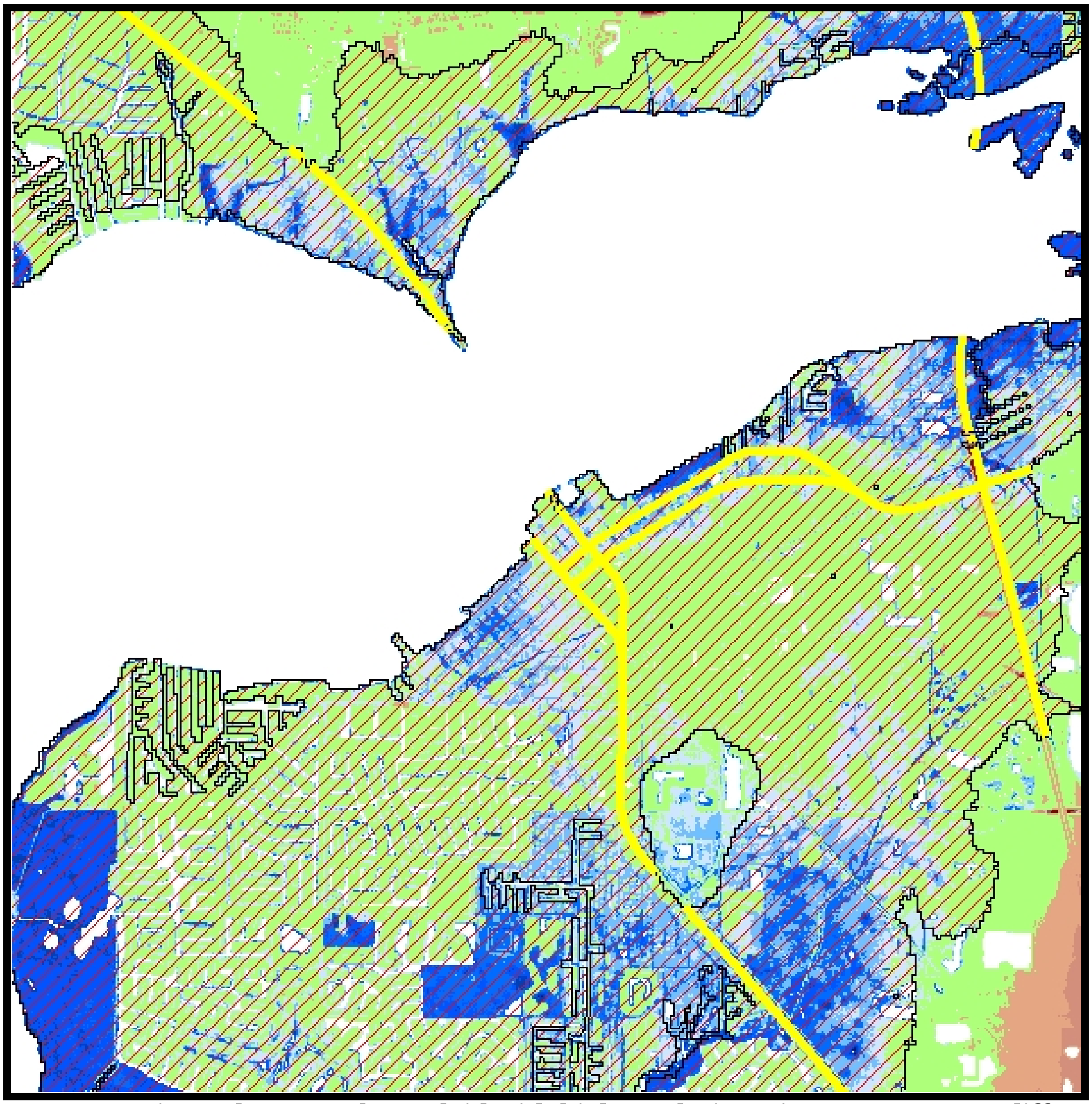


Figure 25: Weiss and Overpeck overlaid with high resolution LiDAR. Presents a different picture. It shows the old downtown areas along the harbor and the more inland portions south of downtown as potentially vulnerable areas. Western area (newer) is not within the SLR measure. However, bases of the road might be saturated.

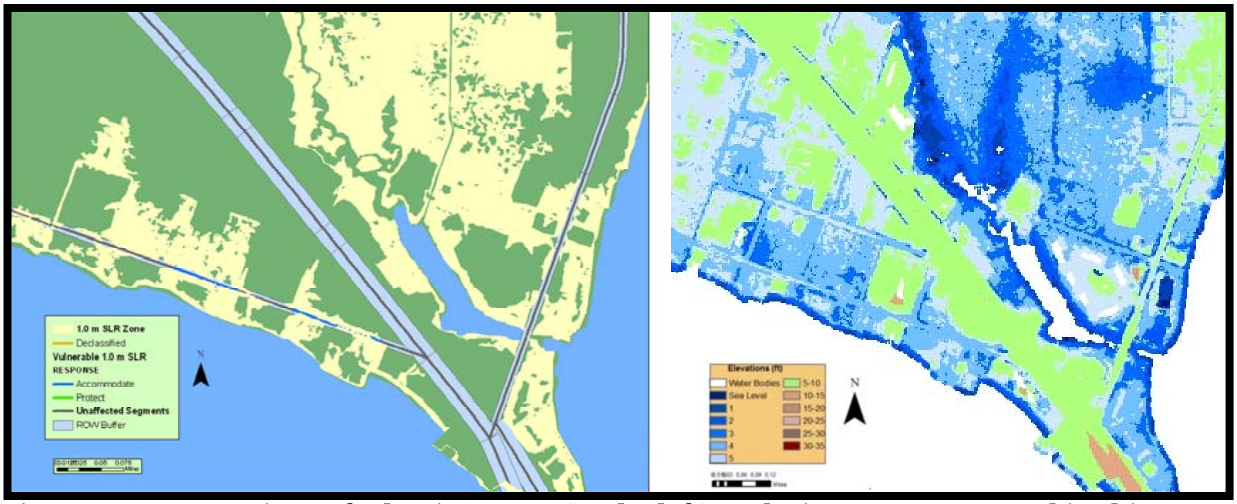


Figure 26: Comparison of Chapin's map (to the left) and LiDAR map created in this research (to the right) on the north side of Charlotte Harbor. According to the FAU LiDAR map, this road is not classified as potentially vulnerable. The result is unclear in Chapin's map.

Furthermore, Figure 27 shows the streets in the City of Punta Gorda downtown area in both the Chapin and FAU LiDAR maps. Both maps show a similar trend, identifying roughly the same downtown areas inundated. However, the FAU LiDAR map shows more detailed water levels than Chapin's map. Nevertheless, the FAU map shows that there are areas south of downtowns that are also vulnerable along the canals. Figure 28 shows the actual aerial photograph of the north end of the I-75 bridge. The aerial shows the low-lying mangrove areas aside the bridge. The ramp is well above the SLR projections. Note the bridge will show white like water bodies, because it is narrow in relation to the water – hence the LiDAR loses the surface.

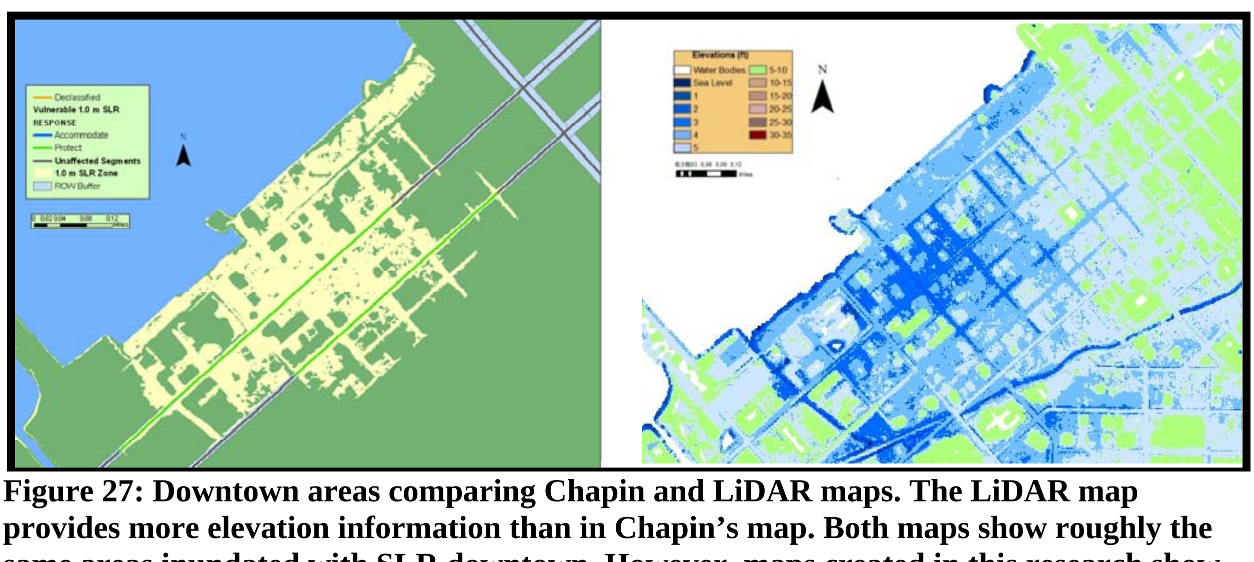


Figure 27: Downtown areas comparing Chapin and LiDAR maps. The LiDAR map provides more elevation information than in Chapin's map. Both maps show roughly the same areas inundated with SLR downtown. However, maps created in this research show that there are areas south of downtown that are also potentially vulnerable along the canals.

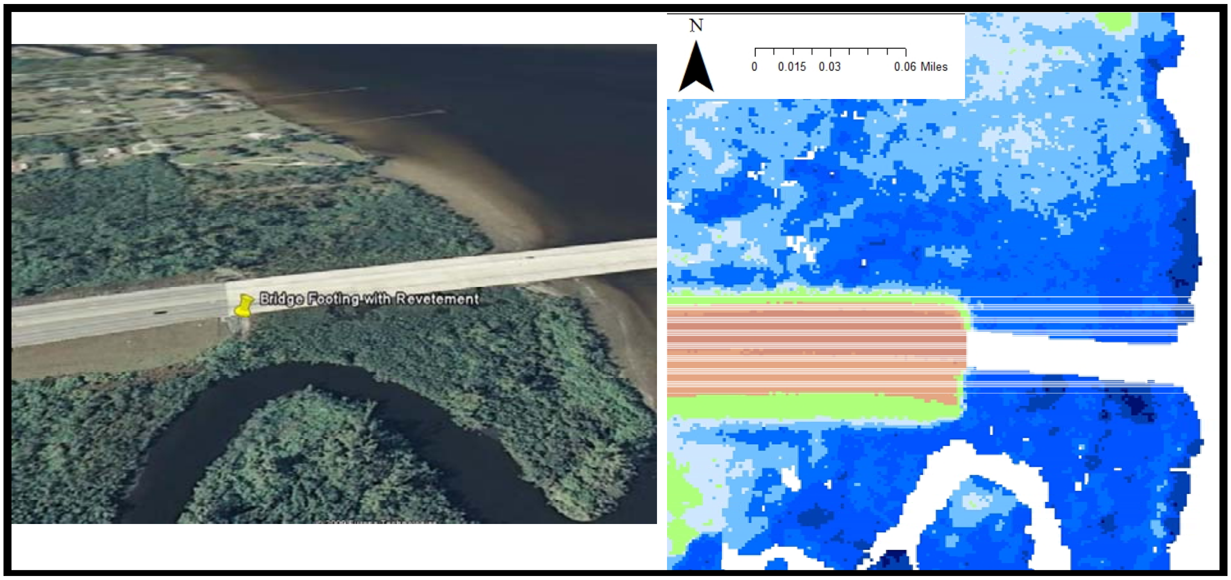


Figure 28: Aerial photograph of the north end of the I-75 bridge (to the left) and FAU LiDAR map (to the right). The aerial shows the low-lying mangrove areas aside the bridge. As shown in the FAU LiDAR map, the ramp is well above the SLR projections. Note the bridge will show white like water bodies, because it is narrow in relation to the bridge.

<u>Example 3: Florida Keys</u>

The research team also evaluated the known vulnerable area – the Florida Keys. US1 is the primary road in the Keys, and it is listed on the EXCEL spreadsheets as potentially vulnerable from the Weiss and Overpeck overlay (Figure 29). The question was how much of the roadway was actually vulnerable purely from a SLR perspective. The LiDAR image of the Keys confirms this vulnerability, although the bridge approaches in the lower Keys, and US1 on Key Largo are not submerged (Figure 30).

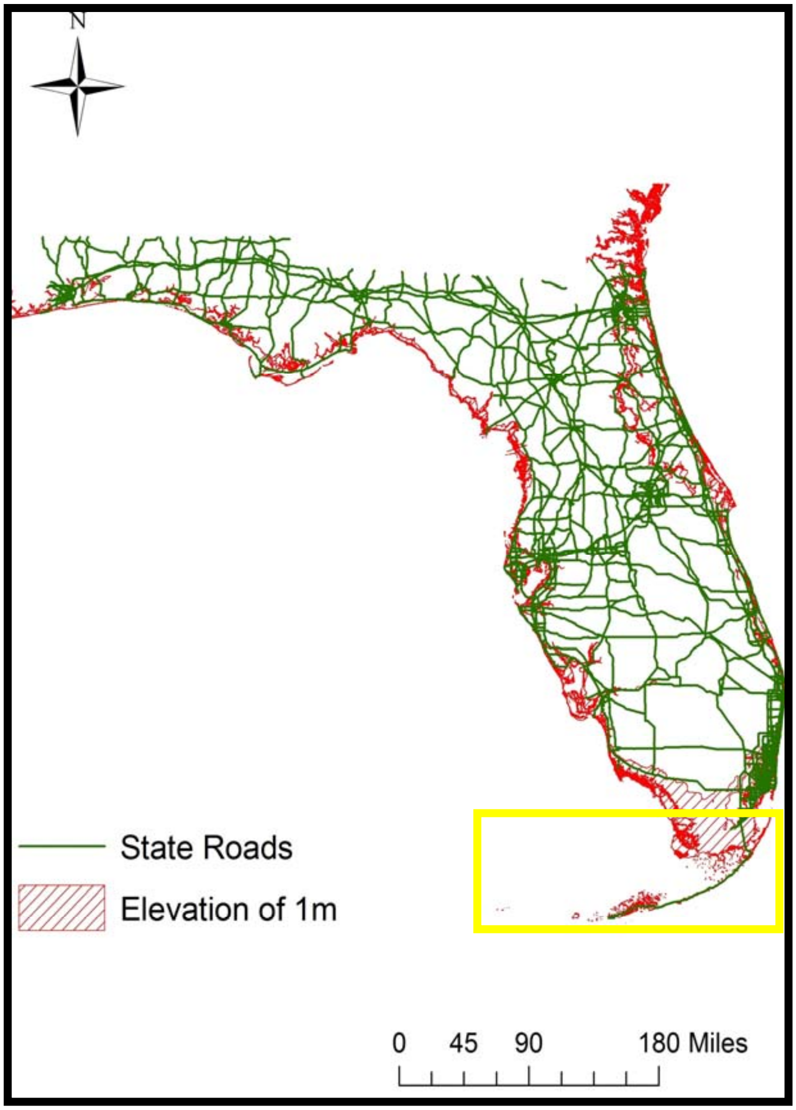


Figure 29: Weiss and Overpeck map shows the Florida Keys are inundated.

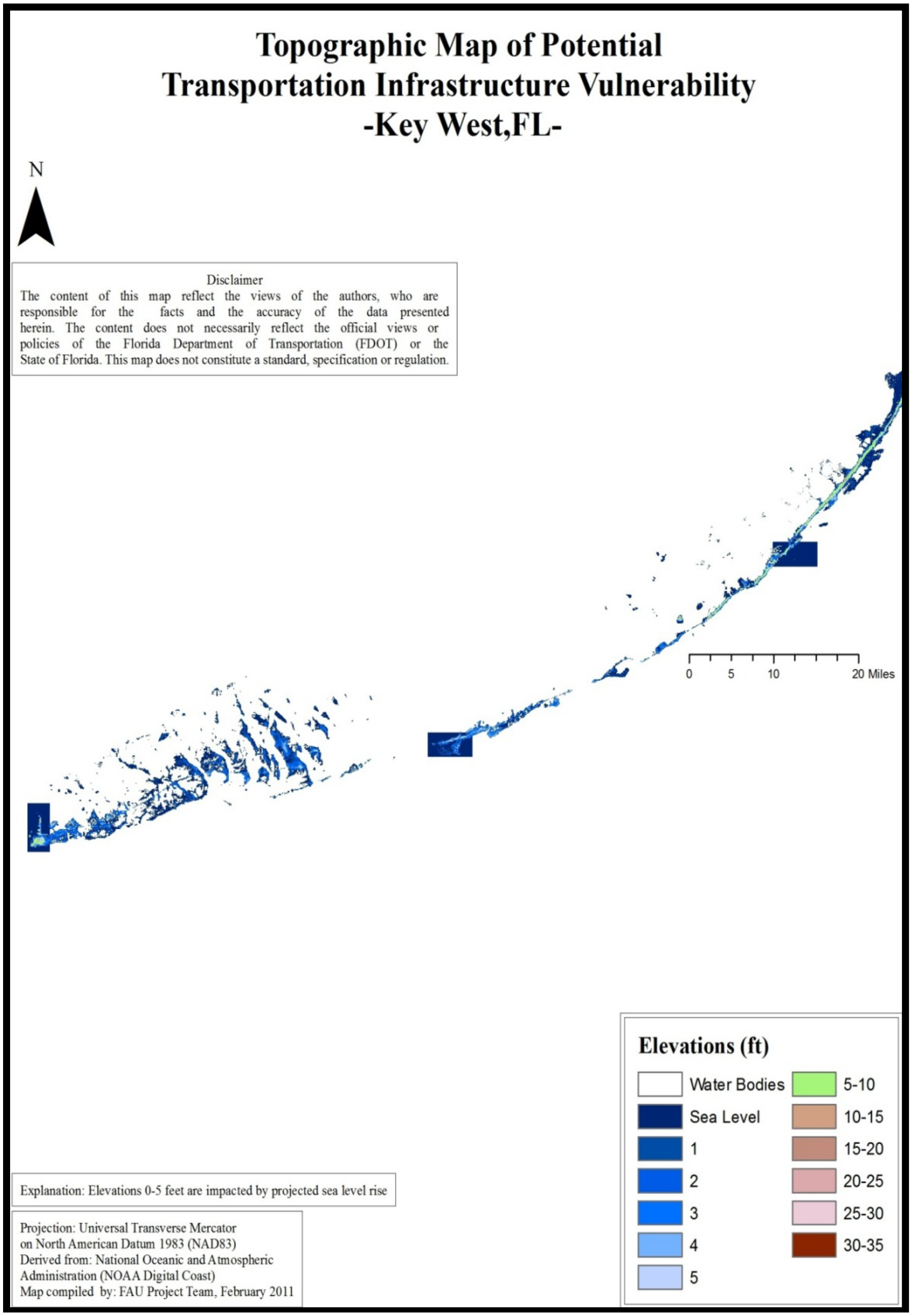


Figure 30: High resolution LiDAR image of the Florida Keys depicts that most of the Lower Keys are lost. Key Largo has US 1 on the high ground.

Focusing on Key Largo, the next step was to segment by year, not that the roadway section is now based on the 2100 period. The low end (3 inches) SLR for 2030 is not measurable, so this option was not run. The high projection (7 inches) for 2030, the low 2060 (9 inches), and high 2060 (24 inches) were run and are shown in Figures 31 – 33. What these figures show is that while the roadways are not inundated (black color), the base may be (areas in an color), which means structurally the roadway will fail.

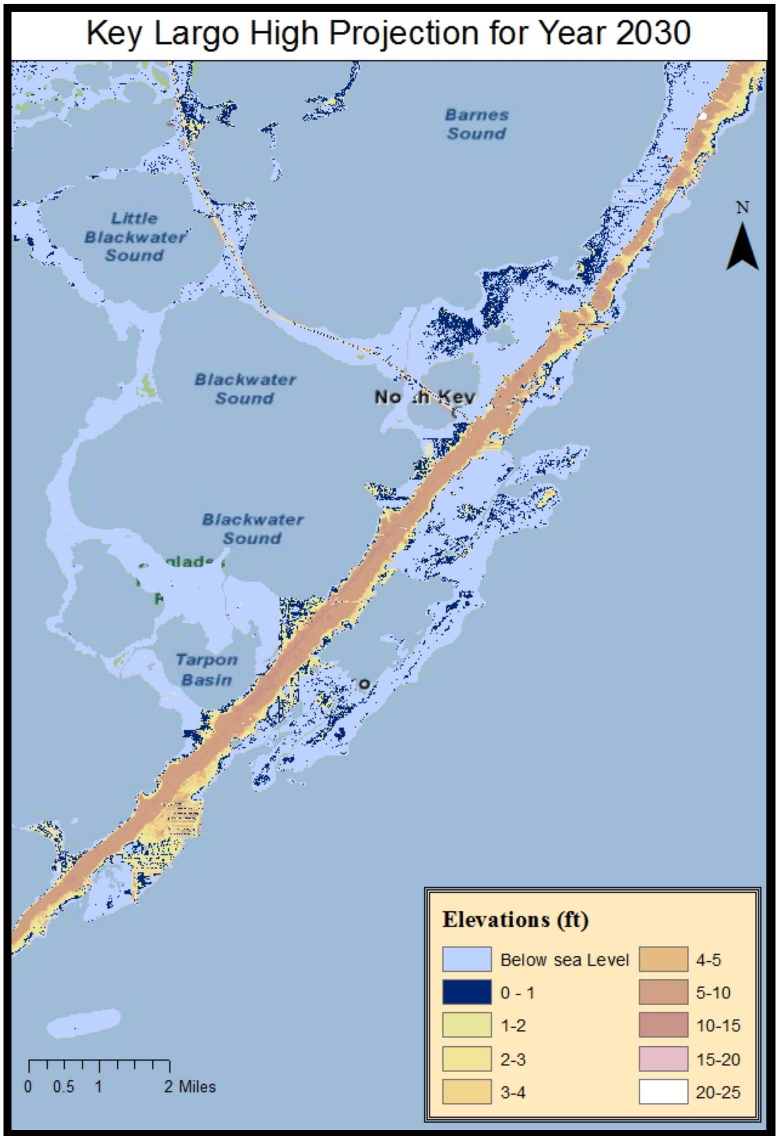


Figure 31: High projection (7 inches) SLR for the year 2030 for Key Largo. Island is decreasing to a spit, but much area remains. Much of the areas off US 1 have a wet road base (areas in tan color). Black areas are newly inundated.

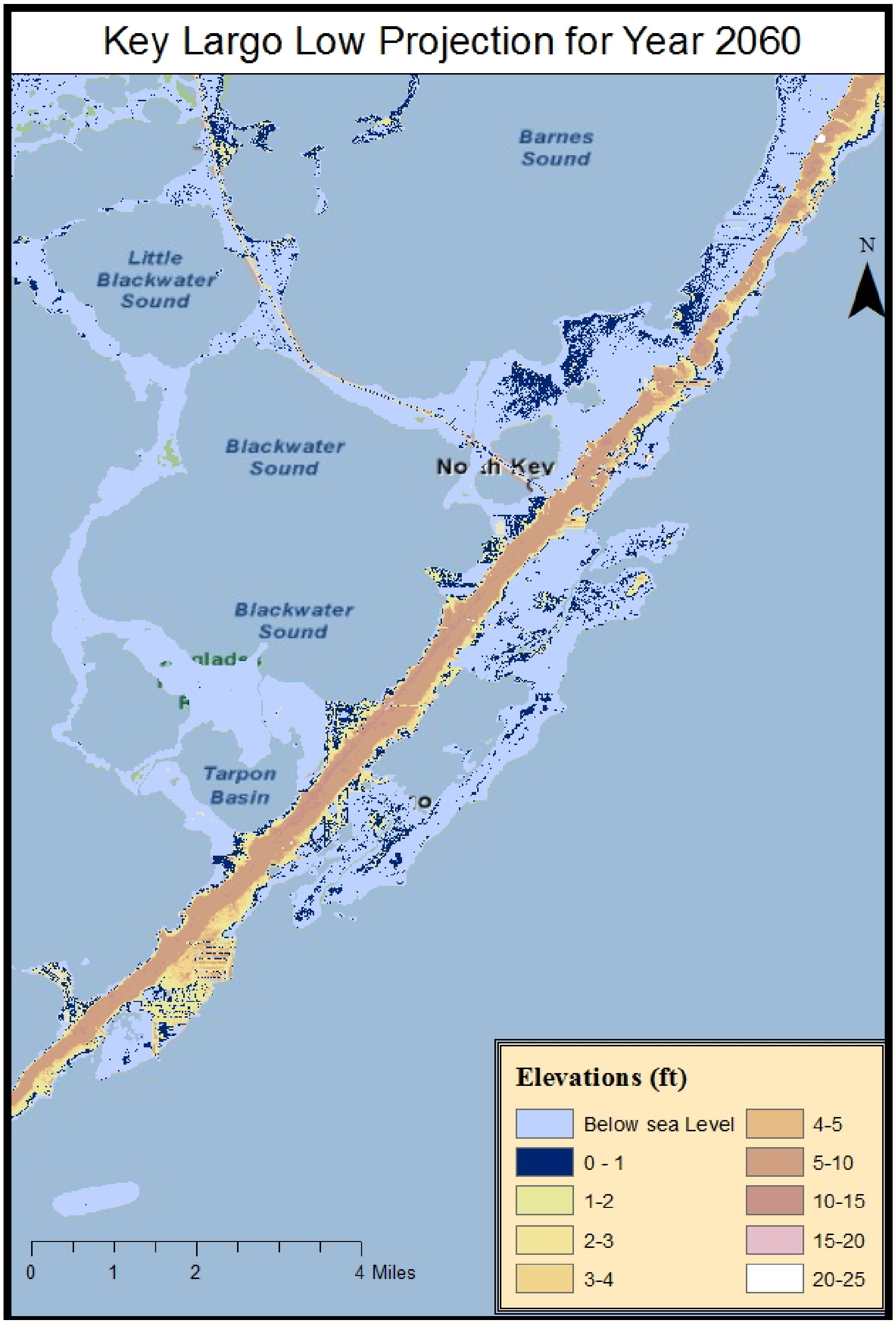


Figure 32: Low projection (< 1 ft) SLR for the year 2060 for Key Largo. Island is decreasing to a spit, but much area remains. Much of the areas off US 1 have a wet road base (areas in tan color). Areas closest to the water are inundated (black color). The difference with the high projection for the year 2030 is minimal.

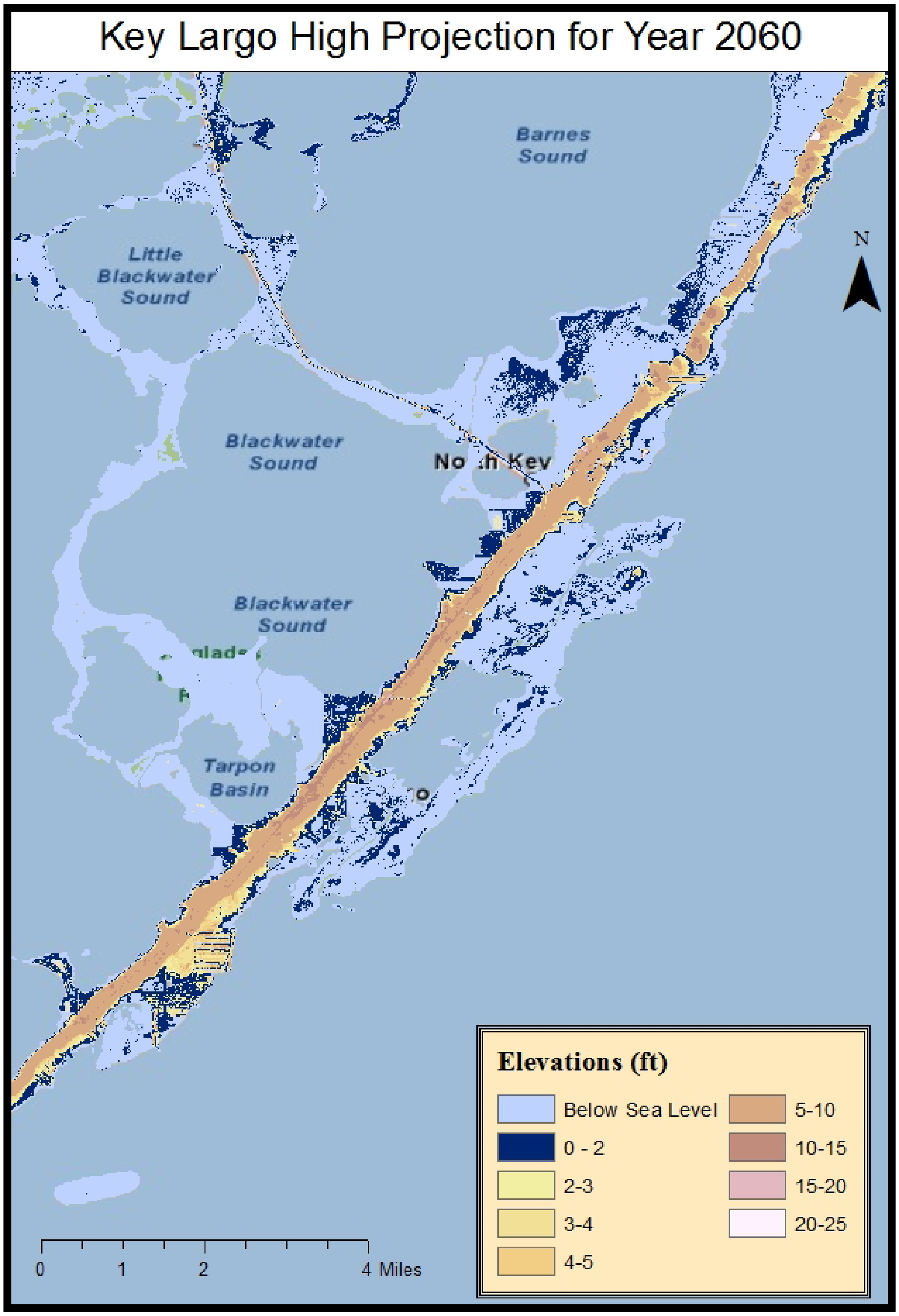


Figure 33: High projection (2 ft) SLR for the year 2060 for Key Largo. Island is decreasing to a spit. Much of the areas off US 1 have a wet road base (tan color) or inundated (black color).

Example 3: Airports

Airport data is provided by the state using latitude and longitude, not GIS coordinates. However the latitude/longitude data can readily be converted to aerial photography using Google Earth. This permits acquisition of LiDAR-specific maps for airports. FAU researchers looked specifically at the Fort Lauderdale-Hollywood International airport, just north of the Dania Beach which was studied using the same methods described above. Figure 34 shows the airport and drainage areas are vulnerable, but the runways are generally above projected ground water levels. Note that the airport is planning a 65 ft high runway, which would be well above any 100 year SLR projection. This is not a problem exclusive to Fort Lauderdale: other airports were also identified as vulnerable.

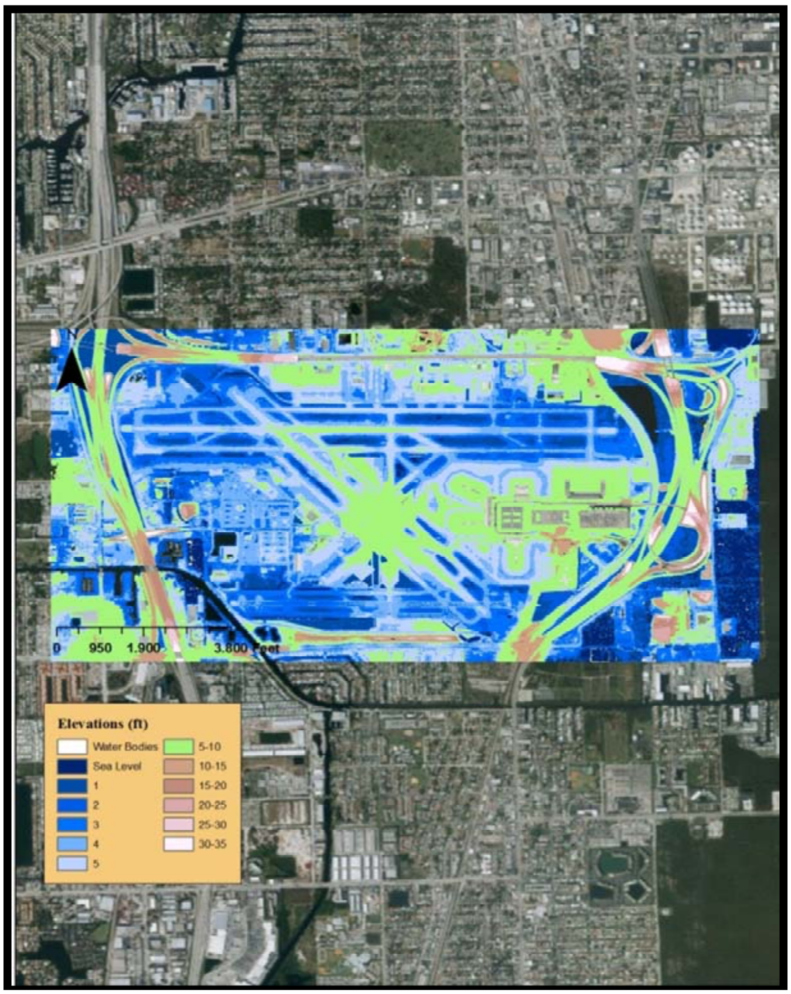


Figure 34: Illustration of Fort Lauderdale Hollywood International Airport. LiDAR map shows runways are currently above SLR projections; however drainage areas are not above SLR projections (areas in dark blue color are less than 1 ft SLR and medium blue color are less than 3 ft SLR)

Chapter 4: Discussion

4.1 Drainage Impacts

In southeast Florida, increased hydrostatic backpressure on the Biscayne Aquifer, the region's primary source of municipal water, is likely to increase saltwater intrusion and reduce groundwater flow to the ocean. Furthermore, sea level rise of as little as 3 to 9 inches within the next 10 to 30 years could decrease the capacity of existing coastal flood control structures (Obeysekera 2009) and may significantly compromise the region's stormwater drainage system, increasing the risk of flooding during heavy rainfall events. In other areas of the state, taking into consideration tidal fluctuations, below 5 ft NAV88, roads and roadway bases will by 2100 likely be inundated. In the interim, smaller sections of the roads will creep toward inundation, starting first with the road base. Compounding this problem, the intensity of torrential rain events and hurricanes, severe drought, and heat waves are expected to increase (IPCC 2007; Karl et al. 2009). These impacts are expected to worsen as SLR progresses.

4.2 Protecting Roadway/Transportation Systems

Over time, SLR could cause significant impacts on transportation infrastructure. The low-lying topography of some regions of Florida makes the transportation infrastructure along the coastline and low lying areas vulnerable to SLR. The vulnerability of transportation infrastructure will require the design of more resistant and adaptive infrastructure and network systems. This in turn, would involve the development of new performance measures for assessing the ability of transportation infrastructure (e.g., roadways, bridges, rail, seaports, airports) to respond to SLR; and enhanced design standards and guidelines for design and construction of resilient transportation facilities.

SLR could significantly reduce the effectiveness of flood control and stormwater drainage systems increasing the risk of severe flooding in Florida's low-lying terrain. As result of flooding, transportation infrastructures along the coastline can be adversely affected, for example, roads can be inundated and roadway beds can be damaged. With roadways, it is the base that is potentially damaged. The loss of drainage capacity due to SLR would reduce the availability of drainage storage and increase the water table in low-lying areas. The base will become saturated under this scenario. As a result, base failure could occur. In addition, since soil storage capacity is diminished, the potential to have water flood roadways or remain near the surface will damage pavements. Figure 35 is the typical representation of the problem before and after SLR. This diagram assumes a properly constructed roadway. Properly constructed FDOT roadways will flood, incur damage to roadway bases, and incur pavement failure, all while limiting emergency routes and impacting private property. Many local roads do not meet these standards so will be more vulnerable to failure.

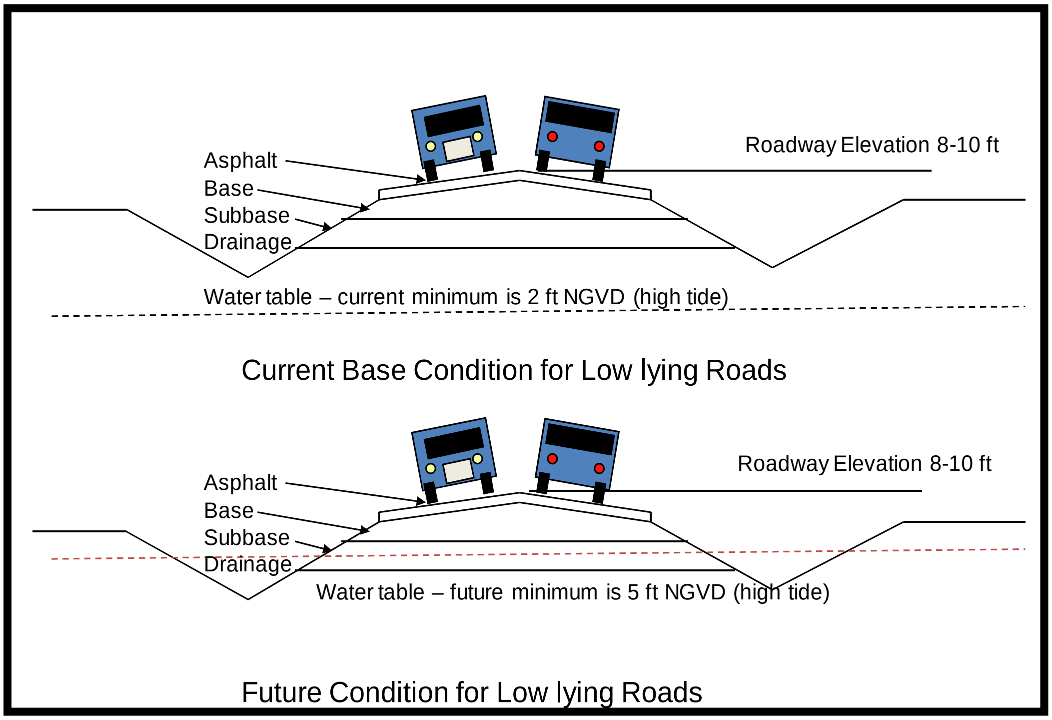


Figure 35: Impact to roadbeds – base gets saturated.

Furthermore, access to roads, bridges, rail and rail transit could be at risk of flooding. In this case, the effect of SLR might indirectly spread through the entire system affecting the overall system performance. For example, the flooding of a critical road or facility access can cause a shifting of traffic flow causing saturated conditions in other roadways. Since the roadway network is unable to carry the traffic demand, the system experiences operational failure; as a result causing high travel times and delays. Moreover, the inundation of a critical access could cause transportation connectivity problems by blocking access to other areas. Therefore, retrofitting, material protective measures, rehabilitation, and in some cases, relocation of the facility will be necessary to accommodate SLR impacts.

4.2.1 Roadway Base Protection

Because the base is the critical portion of the roadway to protect, it will need to have better drainage systems. At present, most base courses are installed above the water table. As long as the base stays dry, the roadway surface will remain stable. As soon as the base is saturated, the roadway can move. As the water table increases, the options must focus on base drainage. Additional stormwater systems will be useful in the short term, but this requires means to discharge the added stormwater. As sea level rises, wellpoint systems may need to be installed for more permanent drainage. Wellpoints are a series of small diameter wells spaced regularly along excavations of a project into the water table. Wellpoints are most commonly used in dewatering projects on construction sites. Wellpoint water is usually turbid, and may contain sand and other particles. The form of dewatering needs a discharge zone, which means offsite property will be required, much like what was needed for the I-595 improvements. Treatment areas to remove the particulates and sand will also be required, meaning additional area must be acquired for discharge purposes. Wellpoint pump stations will need to be regularly spaced along the affected roadway. As a result, a series of pump stations might be needed for every mile of roadway since typical dewatering systems are generally confined to areas less than 500 feet long. Wellpoints are useless in flood conditions, so steps must be taken to address wellpoint failure during heavy rainfall events, meaning additional drainage measures. Stormwater systems will need to be designed like sanitary sewers – tight piping, minimal allowances for infiltration and major pumping stations, which will also require permitted discharge points and associated treatment. The costs for this type of program could well exceed $1 million per lane mile (Bloetscher 2010).

FDOT and most municipalities rely heavily on exfiltration trenches or French drains. These systems work because the perforated piping is located above the water table. They cease to function if they are located in the water table. Exfiltration systems in low-lying areas will cease to work as they become submerged so this technology will be abandoned. Exfiltration trenches could be replaced by stormwater gravity wells or Class V injection wells. Stormwater gravity wells are a useful option where extensive saltwater underlies the surface. Drainage wells along the southeast coast can drain 1 million gallons per day (MGD) under certain conditions. However, as sea level rises, the potential differential may be altered since the saltwater wedge may migrate in because of surficial drainage efforts. Also, if head rises in the water table, this will alter pump characteristics. In some areas, these wells may work and in others they may not . This is a site-specific consideration. The wells are $150,000 each for a 24 inches diameter well. The well requires a splitter box and filter to remove solids. They also must be inspected regularly to insure they are not plugged and to insure they are not back flowing saltwater to the surface. Gravity wells require regular maintenance which will increase transportation system budgets. Permits remain a concern and it is likely the wells will need to be deeper than the current gravity wells.

Injection wells may be needed for other areas. A 24 inch Class V injection well would likely be up to 1,500 ft deep in some areas (like southeast Florida), or as little as 400 ft on the Gulf Coast. However, permitting Class V injection wells required consideration of the Underground Injection Control program under the Safe Drinking Water Act. Permitting and consistent monitoring of Class V wells is required. As a result, if Class V wells are used, the transportation entity will need to include ongoing stormwater efforts for Class V well compliance.

For low-lying roadways where transportation infrastructure is needed, elevating the road may be an option. However, this option comes with two significant issues: what elevation should the roadways be elevated to, and what impact will they have on adjacent properties. Such elevations on roadways may be well above adjacent properties (people will be looking at the side of the road from their windows) if the future conditions are designed for, and the roads will act as a dam to horizontal movement of water.

Local roadway elevations will be limited by the adjacent buildings. For example, in Dania Beach, the typical elevation of the floor in houses east of US1 is between 6 and 8 ft NGVD. It makes little sense to raise roadway elevations beyond the typical lowest elevation. Elevated roads will create "fishbowls" which have no outlet and will create prolonged flooding. Runoff will increase and runoff from private property to the right-of-way will cease. As a result, local neighborhoods will need extensive pumping to remove the stormwater that cannot flow to FDOT right-of-way nor escape the area on its own. Such an example exists in southeastern Dania Beach, there will be more of these situations as conditions continue to deteriorate and neighborhoods and communities will be disrupted.

In addition, sanitary sewers, water main and other utilities underlie these pavements. Elevating the roads would require the manholes to be reconstructed, water lines replaced, and most other underground utilities replaced.

Raising roadways is expected to exceed the cost of new roads. With the added improvements, additional right-of-way required and extensive fill, the cost has the potential to double. All adjacent properties would need pumps to remove their stormwater and prevent runoff from entering their property.

There are other impacts to residents that will predate the abandonment of local roads. The cost to install wellpoints and pump stations was discussed above. Aside from these being noisy operations, they require land for retention of runoff. In addition, elevated roadways will impact adjacent properties, causing water to remain on the sites. Adjacent properties are logical acquisition targets, but acquisition of property will be high since all the property is currently developed. These improvements will cause a displacement of current residents. Where these displaced residents go is uncertain, and migration and displacement of residents could create a domino effect.

4.2.2 Protection of Roadways Surfaces

The protection of roadways surfaces is intended to permit driving on the road. Areas of Dania Beach Boulevard (a state road) and many low-lying areas of the eastern cities in Broward County exist at elevations from 2 to 4 ft NGVD. Flooding of these roadways occurs during summer rains. Water on the asphalt damages the asphalt and base, creating more need for repairs and resurfacing. Roadways covered with water should not be driven on, although it happens regularly. Where roadways are consistently submerged, or where elevations are below projected mean high tides, the roadway surface will need one of two things – additional stormwater pumping to drain the surface (as well as all the surrounding property that contributed to the flooding) or higher roadway elevations. Alternatively, both, since the base course needs to be above mean high tide.

4.3 Increase Other Modes of Transportation

As sea level rises, populations at low elevations areas along Florida's coastline may move inland causing changes in travel patterns. As a result, re-routing of current transit, roadway, and non-motorized systems may be necessary, along with the relocation of pipelines, freight, seaports, and airport facilities. Travel pattern changes could potentially be adversely affected, including operational efficiency, capacity, and level of service of the current transportation systems. A significant increase of facility users on for example roadways, could exceed the operational capacity of facilities increasing user delays. Similarly, traffic delays will affect the reliability, efficiency and capacity of the transit systems. Transit passengers may experience longer travel times affecting the quality of service of the transit systems. These transportation issues will significantly affect the traffic safety and quality of life of the communities served by these transportation systems. Therefore, transit and other modes of transportation that are not single-occupant vehicle mode will need to be provided. Traffic safety plans that address the changes in environment conditions need to be developed and implemented. This should include a detailed route signing system. Emergency response plans need to be modified with new evacuation routes, accessibility, and mobility plans.

In view of the fact that the literature has stated there are many significant uncertainties with the forecasting SLR and, therefore, its impact on different transportation modes, the best course of action might be a no-regrets strategy and an adaptive process that can be easily modified for new SLR projections (Obeysekera 2009, Meyer 2006, Meyer et al. 2008, The National Academy of Sciences National Research Council 2010). A "no regrets" policy assumes that investments are made in infrastructure prior to the point in time when making the improvements comes too late to make meaningful improvements. Hence, you regret not making the decision sooner. When updates are made to statewide and modal plans, it is important that FDOT consider inclusion of verifiable data that analyzes SLR impacts and anticipated tidal fluctuations on transportations systems.

4.4 Planning

Over time, SLR and its associated tidal ranges and storm surge will have impacts on roads, rail, and other infrastructure. Detailed analysis and adaptation to these impacts is an important component of medium and long-range planning. As the USACE has specified, any coast or near-coast projects of the USACE must include consideration of SLR. Similarity, FDOT will need to build the impact of SLR into all planning horizons. It will also be important to incorporate adaptive management processes into the planning as more data becomes available.

The recommendation of this report is to use the USACE guidance document to develop statewide projections of sea level rise:

- Use intermediate and high curves to estimate lower to upper ranges of relative SLR
- Continue monitoring tidal data
- Develop statewide/regional projections for remaining tidal gauges in Florida
- Refine/test downscaling to identify potentially vulnerable transportation infrastructure

At some point, the additions to the process should include storm surge and tidal effects with SLR.

As part of FDOT project planning process, any major transportation improvement project in the Metropolitan Planning Organization (MPO) LRTP, SIS plans, and Statewide Bridge Replacement Program is evaluated through the ETDM process, which is supported by the FDOT's Project Development and Environment (PD&E) procedures. The ETDM process is conducted during the early stages of the planning process. It consists of following three phases (project delivery process): planning, programming, and project development. During the planning and programming screenings, which are part of the first two phases, important initial information that could be the basis for technical studies and engineering designs are analyzed. Based on the information gathered from agencies and local communities through the use of the Environmental Screening Tool (EST), the Class of Action for the proposed project is determined and summarized in the Programming Summary Report. This report discusses impacts of the proposed action and alternatives that should be recommended in either the Environmental Assessment (EA) or Environmental Impact Statement (EIS) in the PD&E process. Finally, the engineering and environmental studies recommended by either EA or EIS and required for the approval of the location and project design concepts are conducted during the project development.

4.4.1 Incorporation of No-Regrets and Gradual Adaptive Strategy

Since the project planning process consists of the ETDM procedures, it is recommended that as a part of the infrastructure prioritization processes and impact analyses in the planning and programming phases, SLR be considered. Coordination with local entities like the MPOs is suggested as those local agencies may be better able to identify and prioritize the local needs associated with SLR. Furthermore, to facilitate the FDOT decision making process and better understanding of the risks associated with project alternatives, probabilistic risk assessment analyses, infrastructure design and monitoring programs are recommended to be included in the project development phase.

Chapter 5: Recommendations

5.1 Summary Recommendations

The objectives of the research were: (1) provide an inventory and summary of existing studies for forecasting sea level in Florida; (2) analyze the advantages and disadvantages of different methods for forecasting SLR and the timing of the forecasts; (3) develop recommendations for which methodology for forecasting SLR and related impacts in Florida should be used by the FDOT; and 4) develop recommendations for how existing data sources could be integrated with other FDOT information systems for identifying infrastructure at risk from SLR.

The initial portion of the report provides an inventory and summary of existing studies for forecasting sea level in Florida. A summary table was created to facilitate the analysis of the advantages and disadvantages of different methods for forecasting SLR and the timing of the forecasts. The research team also considered the recommendations of the SLR scientific working group established by the Southeast Florida Regional Climate Change Compact. The recommendation is to use the USACE guidance for projecting SLR, incorporating low (historic), intermediate, and high results.

The next portion of the report was to develop recommendations for evaluating related impacts associated with SLR as well as for identifying potentially vulnerable transportation infrastructure in Florida. Such a methodology was developed using data from FDOT, USGS, NOAA, and other sources, that was then integrated with LiDAR, topographic and aerial photographic maps to identify potentially vulnerable roadway infrastructure across the state. Three case studies: Dania Beach, Punta Gorda, and Key Largo were used to demonstrate the effects. A series of solutions or a toolbox of options were identified for FDOT to consider.

The benefits of overlaying high resolution LiDAR data onto a base map are that it allows for the creation of mapping tools to evaluate potentially vulnerable infrastructure. The FAU team found this downscaling methodology to be effective and generally accurate, once correction factors were applied. In addition:

- The drill down/downscaling protocol is effective
- Results were accurate with data used
- Accuracy was validated by multiple sources
- The results provides excellent visual understanding of issues
- Vulnerable Infrastructure is easily identified and confirmed

However, the low resolution LiDAR does not have appropriate accuracy for this type of evaluation. The 1/9 arc maps have limited coverage, but are effective tools. The high resolution takes a lot of time to process, but gives high quality results.

Using these recommendations, a downscaling protocol was developed and tested on several low-lying areas of the state to determine the extent of FDOT roadway infrastructure vulnerability. LiDAR and ground-truthing was used to calibrate the protocol. Drill down efforts easily identified “potentially vulnerable” and thereafter “vulnerable” infrastructure. A series of matrices were developed on a county by county basis identifying the "potentially vulnerable" roadway infrastructure. A discussion of potential impacts and a series of options to address vulnerable infrastructure were identified that included options like elevating bridge approaches and causeways, rebuilding roads to 10 ft NAV88 or abandoning the infrastructure.

FAU performed this evaluation by acquiring LiDAR for the entire state of Florida. For coastal areas, FAU was able to massage LiDAR into 1 ft increments that are very useful for predicting potentially impacted infrastructure. Roadways sections were evaluated first because the LIDAR mapping provides immediate information that can be added to GIS mapping systems. Given the high degree of accuracy with the 7.5 inches vertical imaging (high resolution), this data layer is of sufficient accuracy to support more site-specific design efforts for right-of-way acquisition, new roadways routes, and bridge, airport, and port infrastructure. The LiDAR can help FDOT avoid low-lying areas, provide alternate routing that can sustain long term traffic without the potential for inundation, locational needs for stormwater pumping or storage, and for addressing vulnerable bridge approaches, etc.

The team initiated an evaluation of other infrastructure besides roads. The team found that for airports, the methodology applies but is site-specific. This is a phase II endeavor. Bridge navigation was evaluated but this was less valuable. Specific buildings (like FDOT structures) must be evaluated on a case-by-case basis. The methodology works, but a GIS location of the infrastructure to be evaluated is needed.

Finally, the report outlines recommendations for how existing data sources could be integrated with other FDOT information systems for identifying infrastructure at risk from SLR. This report reviews some of the impacts and also identifies critical data gaps which, when filled, will enable more precise identification of at-risk infrastructure and predictions of impacts on physical infrastructure and on communities. Roadways are designed for 50 to100-years service life, while continually refurbished and maintained. As a result, FDOT would likely want the roadway base above the mean high water table. Such roads would likely have surface elevations well above the current levels in the future.

Short-term and long-term actions are recommended for incorporating SLR into the FDOT planning process.

Short-term actions include:

- **Apply the USACE methodology to develop statewide and regional projections of SLR.**

SLR projections for 2030 and 2060 are being revised upwards in most scientific literature. New data suggests that current projections underestimate the impact of ice melt and, therefore, the upper end of the estimates should be used. In addition, a more refined analysis of regional variation in SLR should be included in next steps. The USACE derived statewide projections should be revisited in 2013 when both new USACE guidelines and IPCC projections will be available and as additional tidal stations in Florida become USACE compliant.

- **Develop a sketch planning tool to identify potentially vulnerable infrastructure.**

Based on the framework proposed for downscaling and evaluation, FDOT should develop a GIS sketch planning tool that integrates SLR projections with FDOT data sources to assess vulnerable infrastructure. The researchers recommend that tidal effects combined with SLR be used to assess potentially vulnerable infrastructure. This report developed a drill down protocol to integrate currently available data from different sources to evaluate infrastructure vulnerability easily and visually. The recommended sketch planning tool will allow the initial identification of areas of the state most vulnerable which appear to be southeast Florida, the Keys and areas of the southwest coast of Florida. More refined regional and localized analyzes of potentially vulnerable areas can be developed to further verify infrastructure vulnerability.

In addition, the matrices created as a part of this project identify potentially vulnerable roadways sections to a SLR of about 3 ft by 2100. The sketch planning tool should include a 2030 and 2060 analysis of potentially vulnerable roadways sections and options for constructing resiliency. Ultimately, the use of LiDAR and on-the-ground surveys should supplement FDOT's ETDM/EST database where transportation project sponsors and Environmental Technical Advisory Team (ETAT) members could discuss potential impacts or concerns as part of the corridor/planning screening of project proposals and be another consideration in the evaluation of reasonable alternatives.

Long-term actions include:

- **Develop a no-regrets and gradual adaptation strategy in the planning, design, construction, and maintenance of transportation infrastructure.**

The adaptation strategy should prioritize infrastructure that are most vulnerable to SLR impacts. Adaptation should be grounded in the best available scientific understanding of the risks, impacts, and vulnerabilities. Adaptation actions should not be delayed to wait for a complete understanding of the impacts, as there will always be some uncertainty (USDOT 2011). Since the impact of SLR and combined effects vary over time, it might be preferred to adopt an adaptive and gradual strategy that allows for the design facilities with shorter service life (Meyer 2006, Meyer et al. 2008, The National Academy of Sciences National Research Council 2010). The implementation of effective monitoring and maintenance programs would allow for gradual and adaptation process. The incremental changes will highly depend on the facility performance data and new SLR predictions. Risk assessment analysis will need to be conducted to evaluate different alternatives. The latter, will enable FDOT to analyze the cost and performance failure risks associated when incorporating the SLR uncertainties in the design of a transportation facility.

- **Develop guidance for how best to incorporate SLR in long term transportation planning processes including project prioritization processes of FDOT and its partners (e.g. SIS Strategic Plans, MPO, LRTP) and in project development processes (e.g. EDTM and PD&E).**

Incorporating SLR considerations in planning processes and in project development would include the following (but not limited to): probabilistic risk assessment analyses, infrastructure prioritization procedures, SLR impact assessment analysis, and monitoring programs. This should be implemented at the early stages of the ETDM planning process so FDOT's transportation project sponsors and ETAT members could discuss potential impacts. SLR consideration should also be incorporated in the PD&E manual. Within the FDOT PD&E manual, SLR impacts should have their own chapter under Part 2. SLR best falls under the Environmental Assessment Impact section and it might fit within a current impact category, but considering that SLR can have social/economic, cultural/historical, and natural/physical impacts it would be best to consider SLR impacts within the impact section of EA, in its own sub-section.

SLR considerations could also be incorporated in infrastructure prioritization as part of long term planning. In this process, critical elements of the transportation infrastructure would be identified and an inventory would be created. These are the key elements of the system that if failing would cause an overall system failure. For example, the flooding of emergency evacuation routes or road entries would propagate the effect through the network causing a performance failure. Priority should be given to projects that avoid, reduce or mitigate such impacts.

- **Evaluate potential areas of integration for assessing regional and localized impacts of SLR and coordinate with external partners both state and federal (e.g. the Florida Department of Environmental Protection, Florida water management districts, USGS, Florida Department of Emergency Management etc.) to integrate SLR with other models/tools to better assess storm surge, surface, and groundwater impacts to transportation infrastructure and modes.**

Chapter 4 discussed in detail the issues associated with the need to better assess the surface and groundwater impacts of SLR on transportation infrastructure. In addition, under next steps, a detailed discussion of further integration and coordination related to storm surge impacts is discussed. This will be an area for further research and study.

- **Develop a performance and monitoring program consisting of performance assessment and SLR data assessment.**

The adaptation strategy should include performance measures to continuously assess whether adaptive actions are achieving the desired outcomes. The process should flexible enough to accommodate uncertainty and change and should consist of performance assessment and SLR data assessment. In *performance assessment*, FDOT would apply approaches for assessing facility performance under current conditions and the ability to accommodate future SLR, associated flooding from tides and storm surge with adaptive actions. This will facilitate the project prioritization process, risk assessment analysis, and decision-making process.

In *SLR data assessment*, FDOT would continue to monitor SLR scientific data and models, and methods of prediction. This is essential for the incorporation of SLR uncertainties into planning, design, construction, monitoring, and maintenance process. SLR data should be monitored and revised on a frequent basis (at least every 2 years – when new data and technologies become available). Importantly, the implementation and efficient management of a monitoring program would provide more accurate impact assessments facilitating a better and no-regrets decision-making process.

5.2 Next Steps

FDOT contracted with FAU to develop a protocol to identify transportation infrastructure vulnerable to static flooding from rain events or other natural occurrences. The first piece was to assume a planning number for SLR. The 2030, 2060 and 2100 timeframes were taken into consideration FAU does not recommend changing the SLR projection for areas of the state beyond the Panama City area, which needs further investigation into geologic activity in the area. The differences in Panama City from the rest of the state are significant and suggest that SLR is offset by upheavals and subsidence issues in the area. The rest of the state incurs very similar SLR results and very similar to the global averages as well. These results appear acceptable for planning purposes, just as the USACE found them to be applicable for their guidance manual.

There are several areas that were not evaluated in detail in this report. SLR is a permanent, static condition. Storm surge is a localized, temporal condition, but very destructive. Storm surge will affect roadways and bridge infrastructure as a result of washouts. Since horizontal movements are typical of storm events and can create considerable damage to the transportation network, there is a need to identify infrastructure that might be overtopped, thereby destroying pavement, or subject to horizontal forces for which the (bridge) structures were not designed. As noted in the appendices, SLOSH models are fraught with uncertainty and can never really be applied in practice because storms will never hit at the magnitude, direction, tide, or speed modeled. There is always uncertainty, and the roughness of the topography creates a significant barrier to the bathtub SLOSH model approach. Suggested additions to the process include evaluation of impacts of SLR in tandem with increased storm intensity and rainfall in generally. Two methods could be used for this. The first is a crude mass-balance approach that looks at rainfall, soil capacity and the increase in water accumulated above the future mean high tide. This would identify those areas in the 5-6 ft NAV88 range that would most likely flood in heavy rainstorms.

A better method would be to apply HEC-HMS or HEC RAS, depending on the situation to model stormwater flow in a given basin. Such a proposed project has been submitted to NOAA by Broward County and FAU. The FAU team would suggest applying both approaches to the Dania Beach example for comparisons to determine which provides more useful data, but these type of projects are manpower intensive and can be costly. The results are specific to a set of conditions, and therefore may not mimic any potential event, or only one of limited probability. If such an approach is desired, the Dania Beach example has significant amounts of known data, was used in this report and has several potentially vulnerable transportation modes present (air, rail, port, and roadways), so would minimize the work effort to gather data for the model.

A simpler concept might be to inventory prior hurricane data to identify most likely east coast, west coast and Panhandle events. One side always has more surge than the other, so a mass balance approach could be developed along with the concepts of fluid momentum combined with high resolution LiDAR to identify the most likely scenarios for several areas of the state. The concept would be to inventory these areas for infrastructure vulnerable to dynamic overtopping or horizontal forces (bridges). The concept, once honed, could be slid along the coasts in specific intervals to identify "hot-spots" where significant hardening might need to be considered. Such a process would also utilize a bridge and roadway infrastructure database to estimate costs of the upgrades, so that FDOT could prioritize funding needs to maximize response to hardening needs concurrently. It is suggested that data on airports, railroads, and port access be added to the roadway infrastructure component. The rail and airport databases are not nearly as well developed as the roadway database. Both of these modeling tools are suggested concepts to evaluate in a Phase II project. Doing both in the same area would provide useful information on the value for detailed drill-down data.

Gauging local response to FDOT's options with respect to this infrastructure is a major need. Combining all these system changes would be an easy step forward from this point. The results would yield useful data that would help the MPOs, local governments, and FDOT set priorities to infrastructure upgrades to harden facilities from dynamic natural events. Such a scenario is illustrated in Figure 36. The Southeast Florida Regional Climate Change Compact and a number of the communities in the southeast are keenly interested in the effects of natural system changes on the built environment. Southeast Florida would be an interested partner, but ongoing input from FDOT-Tallahassee is needed.

A future concept would be to consider the use of probabilistic risk assessment analysis techniques for planning, design, construction, and maintenance of transportation infrastructure **(**see Meyer 2006, Meyer et al. 2008, The National Academy of Sciences National Research Council 2010). The use of reliable SLR probabilistic distributions (projections) along with storm surge probabilities may help FDOT harden coastal vulnerable infrastructure. More data is needed to pursue this option, but it has the potential to be useful in the assessment and a design of a more resilient infrastructure able to withstand increased SLR conditions and maintain a desired performance level.

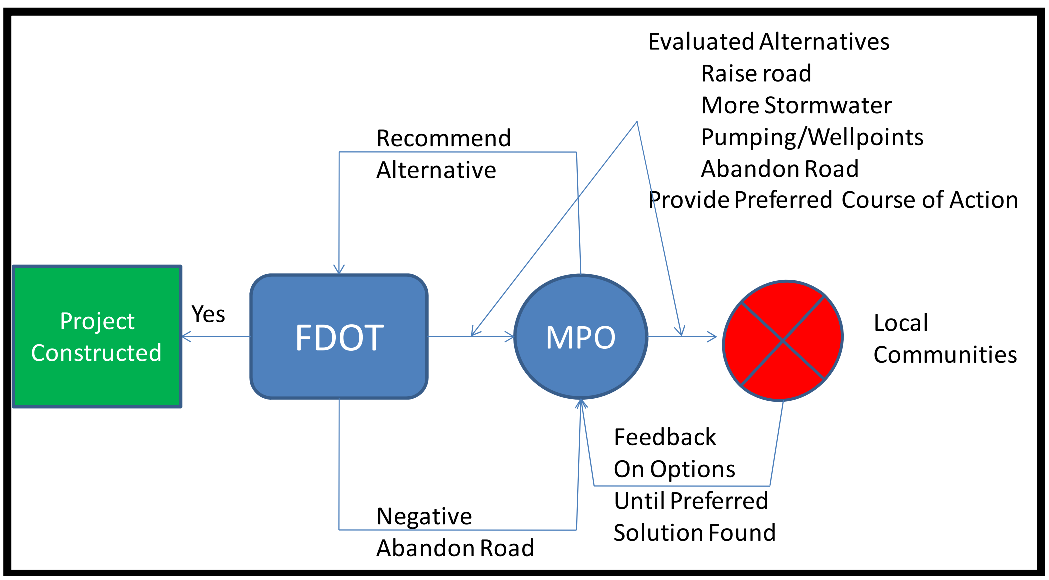


Figure 36: Decision tool for reaching solutions to SLR impacts of specific roadways.

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Appendix A: Quadratic Acceleration Equation

Predicting Interim Sea Level Rise Using a Quadratic Acceleration Equation (Heimlich, *et al* 2010 and others)

Historically, as shown in Figure A-1, sea levels were much lower during the last ice age and rose rapidly during the Holocene period until about 2400 years ago, when sea level rise slowed significantly to a rate of about 30 mm (1 ¼”) per century, approximately 10% of the current rate.

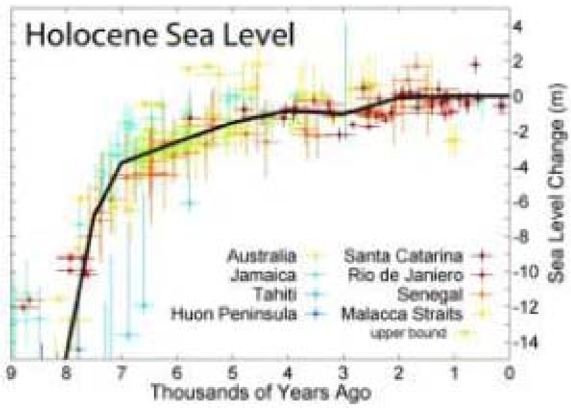

Figure A-1: Holocene sea level.

Approximately 100 years ago, early in the Industrial Revolution, sea level rise began to accelerate, averaging about 2.0 mm/yr during the 20th century (IPCC AR4, 2007) and 3.1 mm/yr since 1993 based on satellite altimetry (Cazenave, Lombard, & Llovel, 2008). A Florida Institute of Technology Report (Maul, 2008) shows an average rate of sea level rise of 2.24 ± 0.04 mm per year from 1915 to 2005 based upon tide gauge readings in Key West, which has the Western Hemisphere’s longest sea level record. Sea level has risen by approximately 200 mm (~8”) during the past century (IPCC AR4, 2007). A January 2009 report of the U.S. Climate Change Science Program (US EPA, 2009) cites the average rates for South Florida. Global rates are listed for comparison. There does not appear to have been a significant difference between sea level rise during the 20th Century between Florida and globally.

A recent paper from Florida State University evaluated the effect of climate change on the Atlantic meridional overturning circulation (AMOC), the major oceanic current that includes the Gulf Stream and Atlantic Current that flows north along the east coast of the United States and across to the British Isles and Europe. This report predicts a significant reduction of AMOC flow that will cause regional variation in sea level rise, especially in the northeast coast of the United States and the coasts of the British Isles, where dynamic increments of 15-21 cm (6-8 inches) for New York City and 5- 20 cm (2-8 inches) for London. The Florida State University Nested Regional Spectral Model forms a core part of the regional climate modeling system and regional climate model studies have found the dynamical downscaling approach successful for the southeast region of the United States (Cocke et al, 2007). Cocke et al (2007) conclude that the southeast United States has long been known to have potential predictability during winter because of its strong teleconnection to tropical Pacific sea surface temperatures driving El Nino - Southern Oscillation (ENSO) events. Sea level rise is expected to continue for centuries even if greenhouse gas emissions are sharply reduced in the near future because substantial energy has already been absorbed in the oceans. Substantial sea level rise that will impact Southeast Florida during the 21st Century is inevitable and adaptation will be required.

Heimlich, *et al.,* 2010 is FAU's most recent publication related to climate change, with a focus on the effects of sea level rise on water supplies and stormwater. The document, entitled *Southeast Florida's Resilient Water Resources: Adaptation to Sea Level Rise and Other Impacts of Climate Change*, outlines the knowledge of the climate change issues and draws upon a specific evaluation of a utility system. Among the major findings of this report are that sea level rise will lead to significant loss of soil storage capacity, which will lead to the potential flooding of large areas after relatively minimal storm events. This creates a potential disruption of transportation as well as potential damage to roadway beds as a result of soil saturation. The study is a follow-up to Murley, et al., (2008) which evaluated the state policy framework for adaptation to climate change. Both were funded by the National Commission on Energy Policy. Further, much of the water resources work builds on prior work for the Florida Section of the American Water Works Association related to statewide impacts of climate change on water supplies, which are difficult to separate from stormwater events in many cases. The same loss of soil capacity is noted in those studies (Bloetscher, 2008, 2008a, 2009, 2009a).

Adaptation planning requires estimated timeframes for sea level rise thresholds throughout the 21st Century. Recently the U.S. Army Corps of Engineers published guidelines for predicting sea level rise that employs a similar method (USACE, 2009). Much of the literature on sea level rise focuses on predictions for 2100, with predictions from 2 to 6 feet as likely sea level rise projections. To attain sea level rise values ranging from 2 to 6 feet by 2100, sea level rise would have to accelerate considerably, as a result, the empirical method for predicting sea level rise throughout the 21st Century assumes sea level rise will assumed to accelerate as melt rates increase in proportion to rising temperatures in Greenland and Antarctica in addition to thermal expansion of the ocean, the major projection in the IPCC report. This approach is supported by Church & White (2006), which demonstrates that sea level rise during the 20th Century can be correlated with an acceleration model. Church and White (2006) demonstrated that sea level rise data could be correlated using an acceleration model described by Quadratic Acceleration Equation A1:

$$\Delta S = +v_o(t - t_o) + \frac{a(t - t_o)^2}{2} \qquad \text{Equation A1}$$

Data for 1870 to 1990 was well correlated with an acceleration, *a*, of 0.013 mm/yr^2 and a velocity, v_o, of 2.0 mm/yr. The resulting acceleration equation predicts sea level rise of 295 mm (0.97 feet) in 2100, which agrees with the median IPCC (2007) prediction as shown in Figure A2.

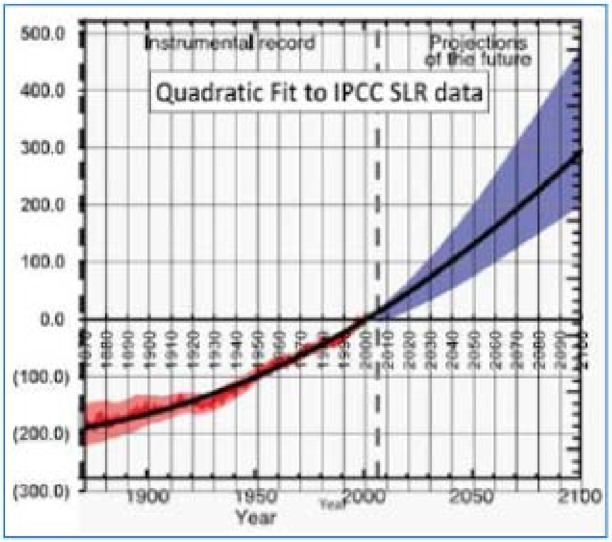

Figure A-2: IPCC 2007 sea level predictions.

To provide a method of forecasting intermediate values of sea level rise corresponding to sea level rise in 2100, ΔS_{2100}, of 2 through 4 feet, a series of curves based on the Quadratic Acceleration Equation shown in Equation I was generated to derive sea level rise values. For any given value of sea level rise in 2100, ΔS_{2100}, velocity v_o, for year t_o = 2000, acceleration, a, can be calculated according to Equation A2.

$$\Delta S_{2100} = \frac{2(\Delta S - v_o(t - t_o))}{(t - t_o)^2} = \frac{2(\Delta S_{2100} - 3.1(100))}{(100)^2} \qquad \text{Equation A2}$$

The rate of sea level rise for base year 2000 is assumed to be 3.1 mm/yr, i.e. the average rate from 1993 to 2003 as determined from satellite measurements (Cazenave, Lombard, & Llovel, 2008). The initial velocity, v_o, in 2000 was set at 3.1 mm/yr, the latest rate estimate based on satellite data (Cazenave, Lombard, & Llovel, 2008). Figure 2 of this report shows estimated values of sea level rise through 2100 based on this equation. Superimposed on Figure 2 are horizontal timelines for sea level rise values at 0.5 foot intervals. Since topographical maps are developed at increments of elevation, usually 1 foot, it is useful for planning purposes to define timeframes for specific event horizons. For example, the planner would want to know the range of times when a given sea level might be reached. If a topographical map is available at 1 foot increments, the planner can determine the projected consequences at 1, 2 or 3 foot sea level rise with precision, but not for 1.3 feet, the approximate median value for 2060 in Figure 30. The projected years, t at which any given amount of sea level rise might occur can be calculated using Equation III if one knows the initial velocity, v_o, and acceleration, a corresponding to the projected sea level rise in 2100, ΔS_{2100} calculated using Equation II,

$$T = 2000 + \frac{-v_o \sqrt{v_o^{\,2} + 2 \cdot \Delta S \cdot a_{\Delta S_{2100}}}}{a_{\Delta S_{2100}}}$$

A1 provides projected range of sea level rise values at 10-year intervals throughout the 21st Century. Table A1shows dates for the indicated sea level rise thresholds corresponding to a 2100 sea level rise of 4, 3, and 2 feet. For planning purposes, it is recommended that a more conservative approach of using projected date ranges corresponding to 3 and 4 feet of sea level rise in 2100 be utilized. These values appear as the horizontal red bars in Figure 2. For example, for a projected sea level rise of 1.0 feet, it is recommended that the planner use a date range of 2043-2050 from Table A1. From Table A1, a 0.5 foot sea level rise is forecasted for 2027-2031, i.e. 18 to 22 years from 2009.

Year	Sea level rise since 2000, feet		
2000	0.00	-	0.00
2010	0.11	-	0.12
2020	0.24	-	0.32
2030	0.39	-	0.57
2040	0.56	-	0.88
2050	0.75	-	1.25
2060	0.96	-	1.68
2070	1.19	-	2.17
2080	1.44	-	2.72
2090	1.71	-	3.33
2100	2.00	-	4.00

Sea level rise since 2000, feet	Projected date ranges Sea level rise in 2100: 4ft Early	3ft Mid	2ft Late
0.00	2000	2000	2000
0.25	2017	2018	2021
0.50	2027	2031	2036
0.75	2036	2041	2050
1.00	2043	2050	2062
1.50	2056	2065	2082
2.00	2067	2078	2100
2.50	2076	2090	2116
3.00	2085	2100	2130
3.50	2093	2110	2144
4.00	2100	2119	2157

Table A-1: Projected Sea Level Rise Date Ranges

It is significant that the acceleration would have to increase more than 4-fold during the 21st Century over the historical acceleration reported by Church and White (2006) to obtain a result of 2 feet in 2100 and acceleration factors of 9-fold and 14-fold are required to obtain results of 3 feet and 4 feet respectively in 2100. That sea level rise could accelerate by as much as 4-, 9- or 14-fold seems surprising. Nonetheless, it is a fact that Greenland and Antarctica have more than enough ice to raise sea levels by many times these amounts and that glacial melt appears to be increasing significantly and there is a question for how rapidly the ice sheets can melt or disintegrate and that answer cannot be determined with precision at this time. There is significant concern among the science community that a threshold could be reached at an uncertain time in the future when glaciers and ice sheets could suddenly collapse causing a dramatic increase in sea level rise. Sea level rise in year 2100 is assumed to range from 2 through 4 feet based on Karl, et al (Karl, *et al*, USCCSP, & NOAA, 2009).

Appendix B: NOAA Graphs Illustrating Sea Level Change in Florida

The graphs below display sea level trends that have been measured by NOAA tide stations, using data on "ocean fluctuations and vertical motion of the land" at any given station (NOAA 2008). The sea level trends were calculated using monthly data through the end of 2006 and all of the stations had data from a span of 30 years or more (NOAA 2008). For ease the graphs have been sorted according to the FDOT district to which they correspond. The tide stations were all built and have operated for different lengths of times. The USACE Engineering Circular 1165-2-221 suggests that only Compliant Tide Station data should be used in any measurement/projection reports (USACE 2009). A station that is currently being monitored and has 40 years of continuous prior period is considered a Compliant Tide Station. Using these guidelines, only 9 of Florida's 14 stations are considered compliant: Key West, Vaca Key, Naples, St. Petersburg, Cedar Key, Apalachicola, Pensacola, Mayport and Fernandina Beach. Figures B1-15 outline the results of the tidal stations. What is clear from these graphs is that every station shows a consistent increase in sea level rise, averaging just over 2 mm/yr, which corresponds well with the worldwide average.

FDOT District 1

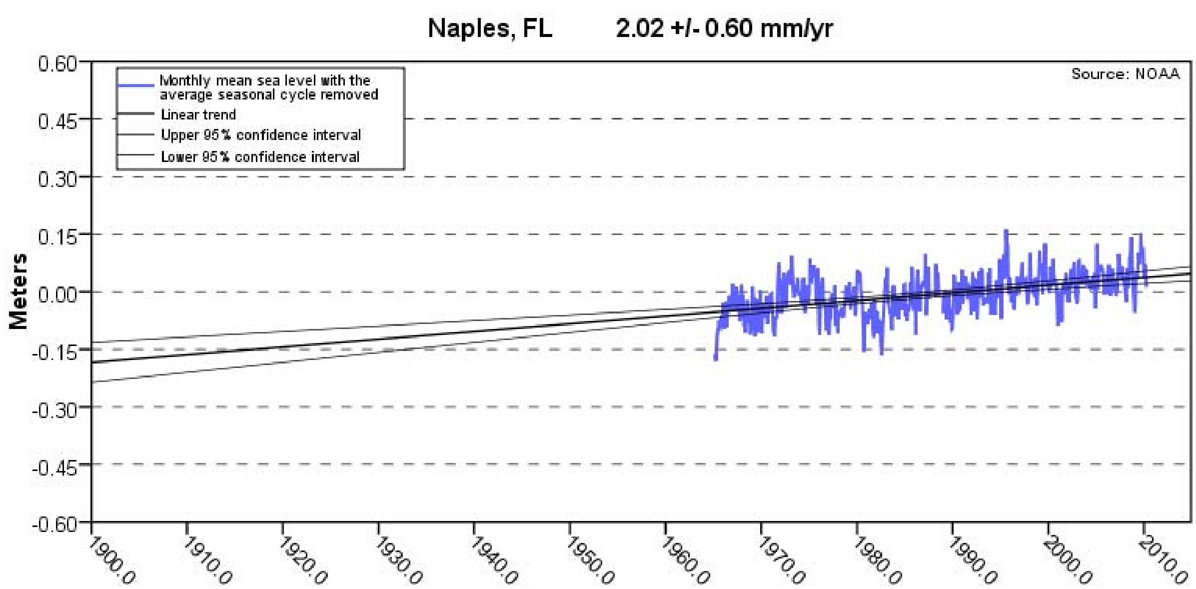

Figure B-1: Naples, FL - The mean sea level trend is 2.02 millimeters/year with a 95% confidence interval of +/- 0.60 mm/yr based on monthly mean sea level data from 1965 to 2006, equivalent to a change of 0.66 feet in 100 years.

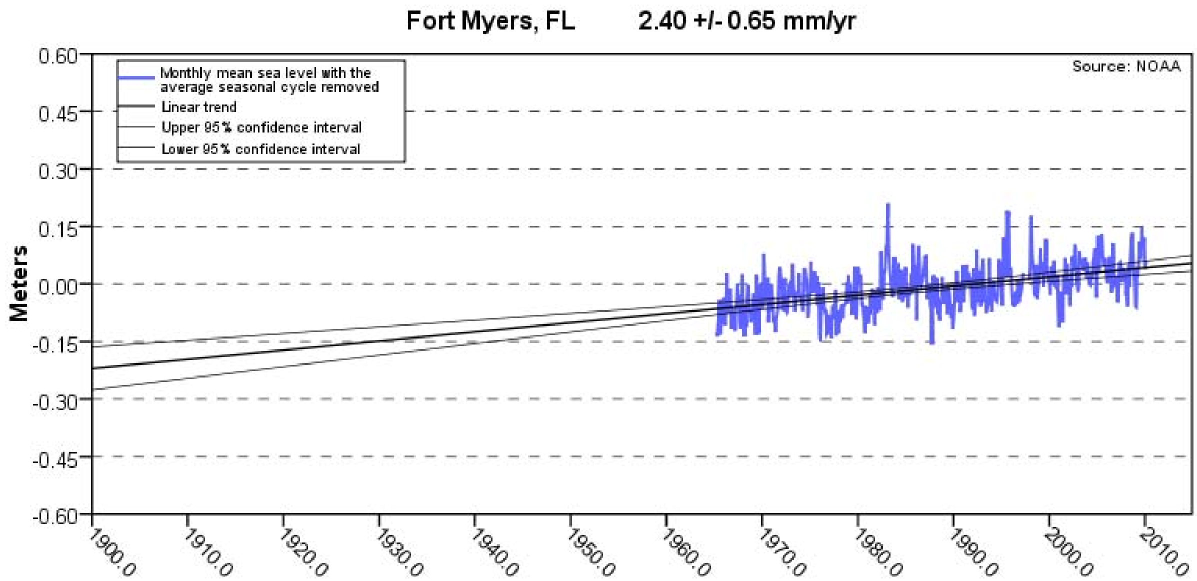

Figure B-2: Fort Myers, FL – The mean sea level trend is 2.40 millimeters/year with a 95% confidence interval of +/- 0.65 mm/yr based on monthly mean sea level data from 1965 to 2006, equivalent to a change of 0.79 feet in 100 years.

FDOT District 2 East

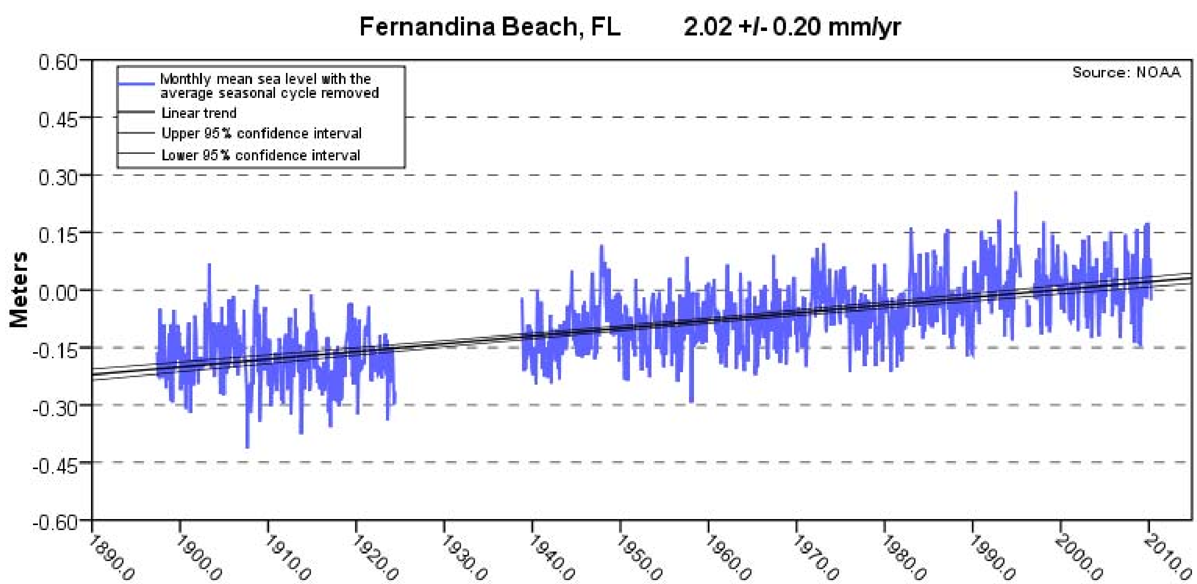

Figure B-3: Fernandina Beach, FL – The mean sea level trend is 2.02 millimeters/year with a 95% confidence interval of +/- 0.20 mm/yr based on monthly mean sea level data from 1897 to 2006, equivalent to a change of 0.66 feet in 100 years.

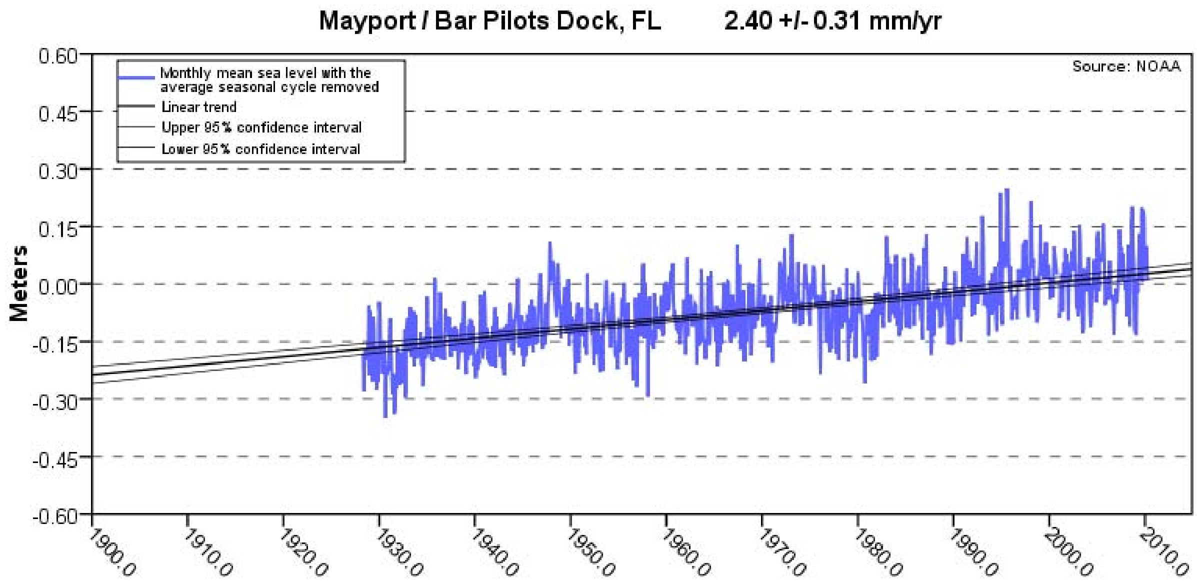

Figure B-4: Mayport/Bar Pilots Dock, FL – The mean sea level trend is 2.40 millimeters/year with a 95% confidence interval of +/- 0.31 mm/yr based on monthly mean sea level data from 1928 to 2006, equivalent to a change of 0.79 feet in 100 years.

FDOT District 2 West

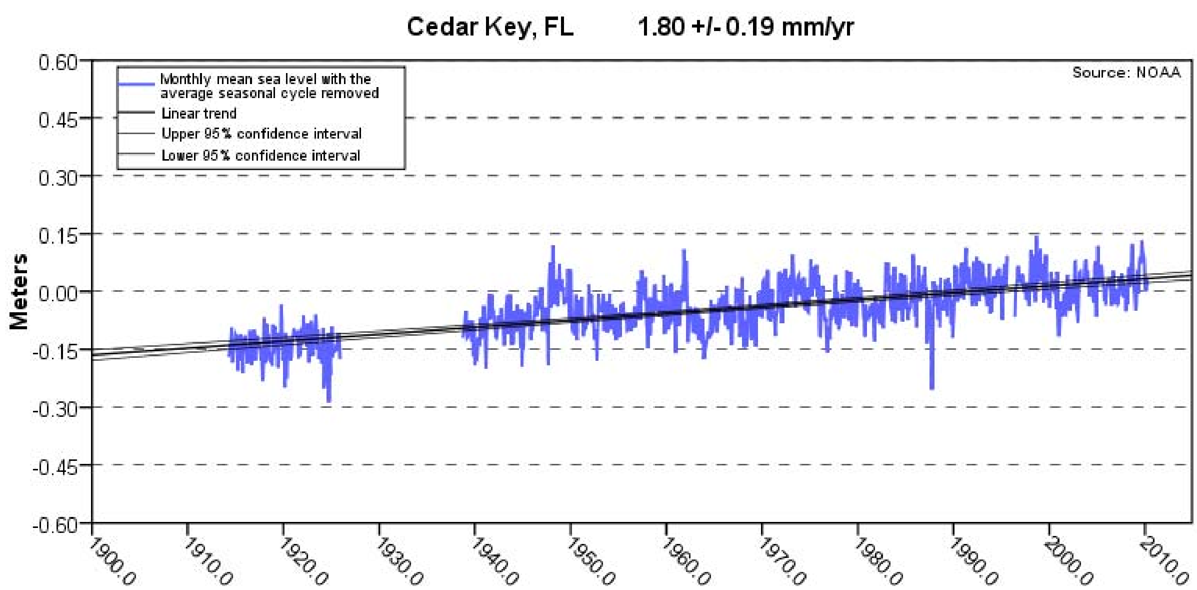

Figure B-5: Cedar Key, FL – The mean sea level trend is 1.80 millimeters/year with a 95% confidence interval of +/- 0.19 mm/yr based on monthly mean sea level data from 1914 to 2006, equivalent to a change of 0.59 feet in 100 years.

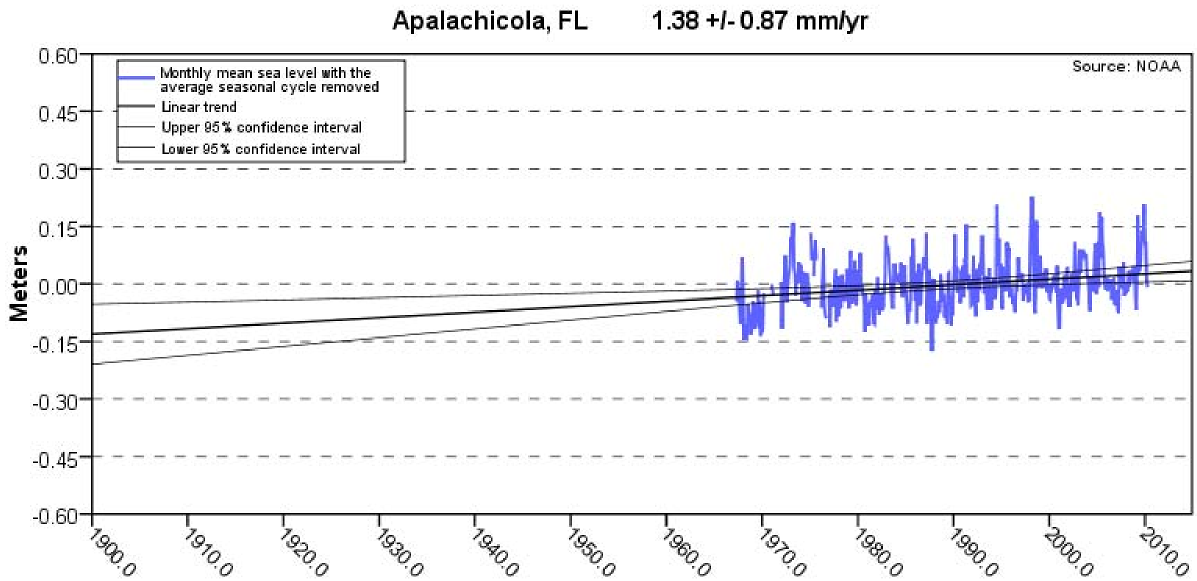

Figure B-6: Apalachicola, FL – The mean sea level trend is 1.38 millimeters/year with a 95% confidence interval of +/- 0.87 mm/yr based on monthly mean sea level data from 1967 to 2006, equivalent to a change of 0.45 feet in 100 years.

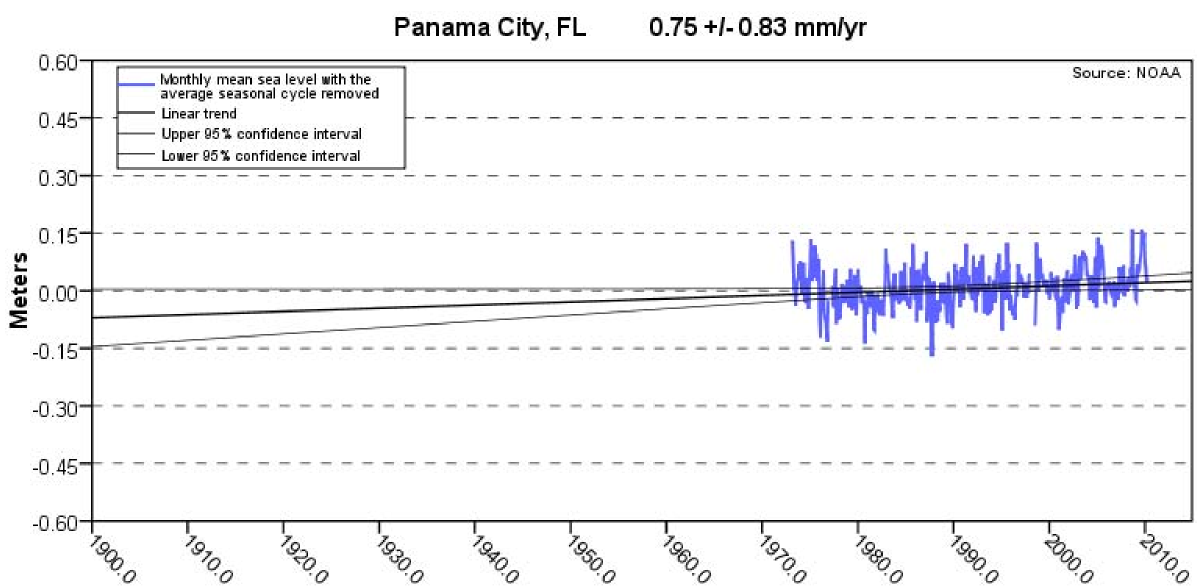

Figure B-7: Panama City, FL – The mean sea level trend is 0.75 millimeters/year with a 95% confidence interval of +/- 0.83 mm/yr based on monthly mean sea level data from 1973 to 2006, equivalent to a change of 0.25 feet in 100 years.

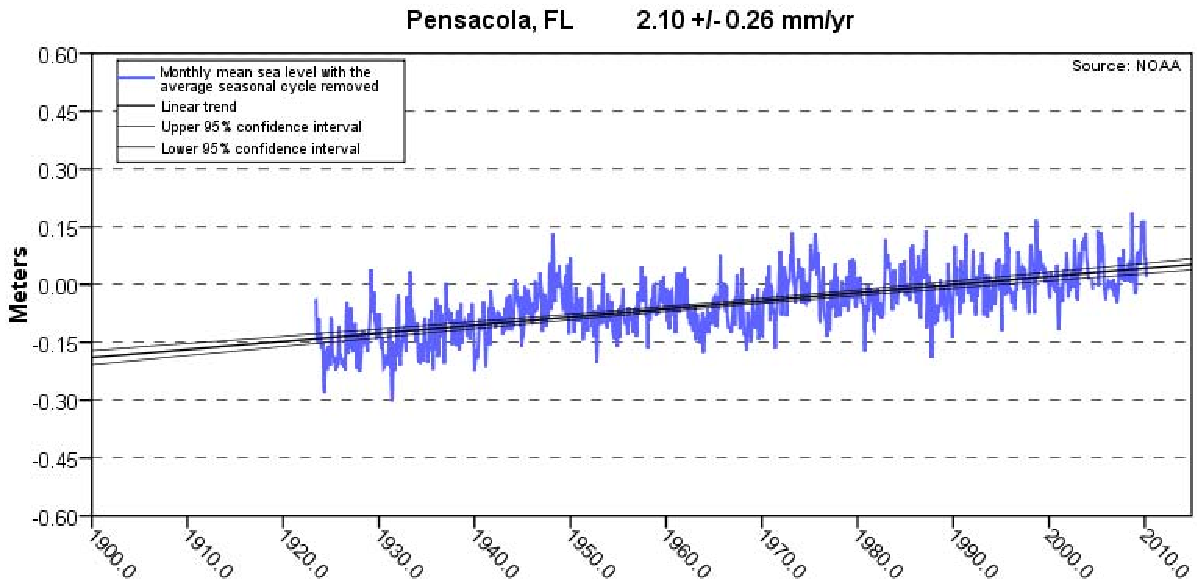

Figure B-8: Pensacola, FL – The mean sea level trend is 2.10 millimeters/year with a 95% confidence interval of +/- 0.26 mm/yr based on monthly mean sea level data from 1923 to 2006, equivalent to a change of 0.69 feet in 100 years.

(FDOT District 4 (N/A))
FDOT District 5

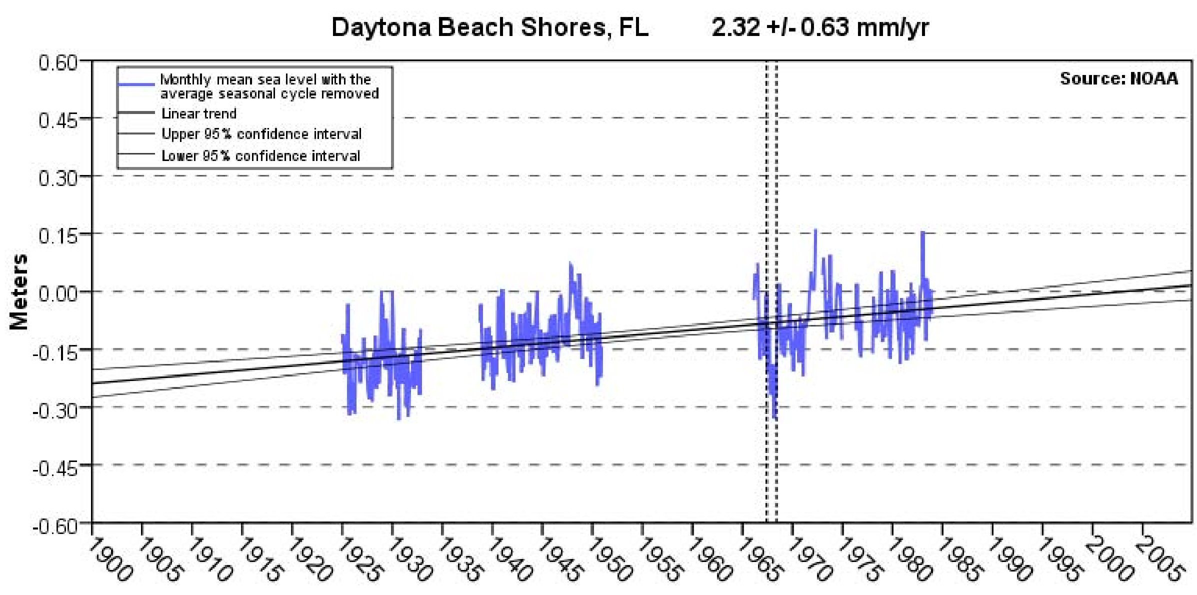

Figure B-9: Daytona Beach Shores, FL – The mean sea level trend is 2.32 millimeters/year with a 95% confidence interval of +/- 0.63 mm/yr based on monthly mean sea level data from 1925 to 1983, equivalent to a change of 0.76 feet in 100 years. Note: dashed vertical lines bracket any periods of questionable data.

FDOT District 6

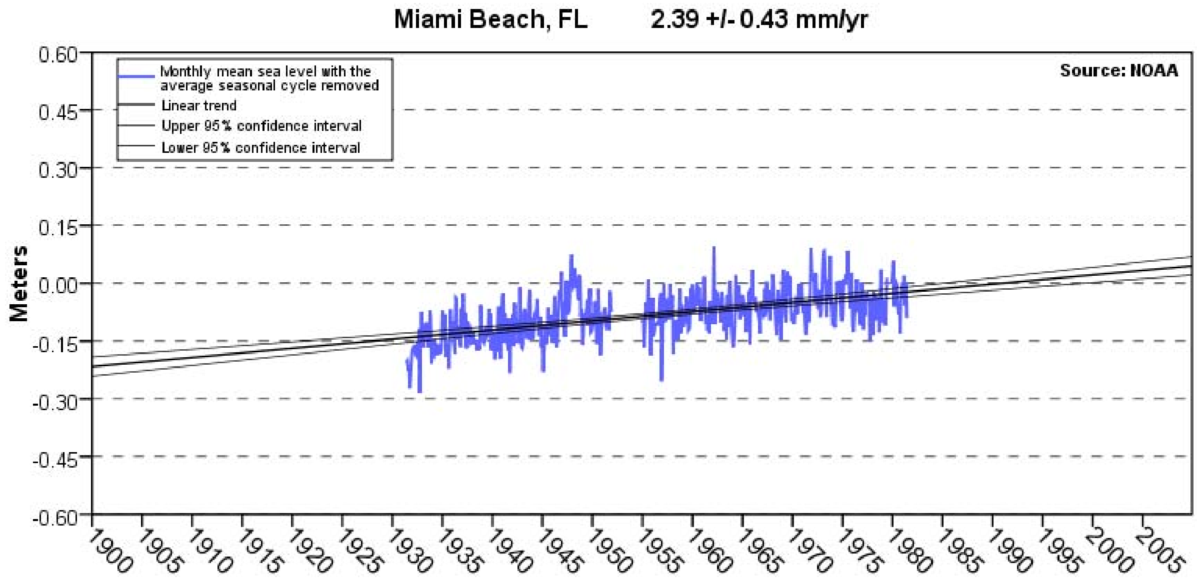

Figure B-10: Miami Beach, FL – The mean sea level trend is 2.39 millimeters/year with a 95% confidence interval of +/- 0.43 mm/yr based on monthly mean sea level data from 1931 to 1981, equivalent to a change of 0.78 feet in 100 years.

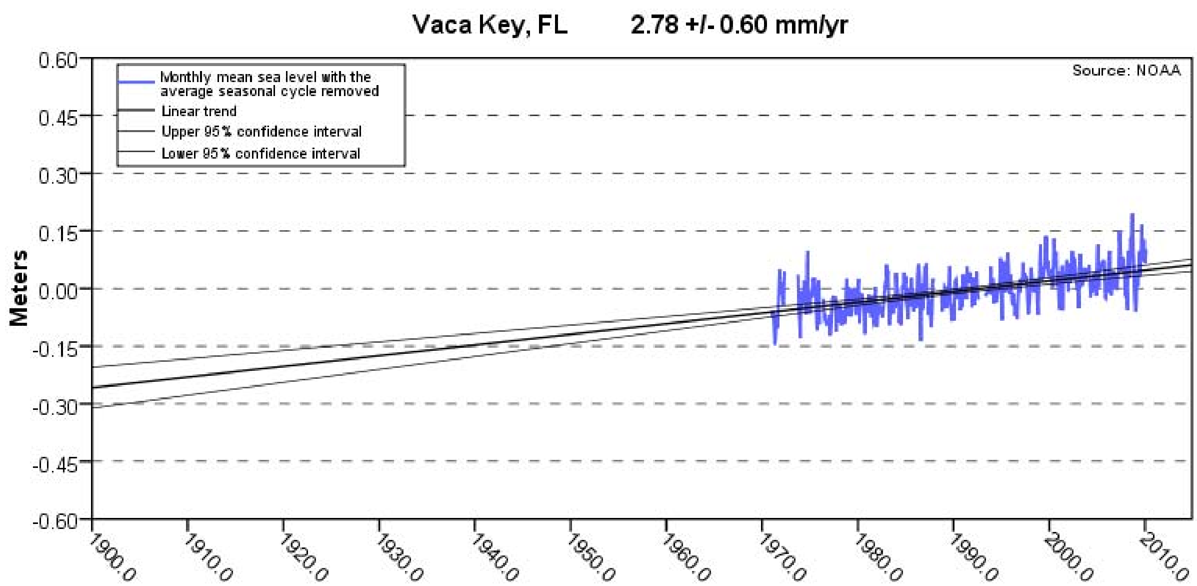

Figure B-11: Vaca Key, FL – The mean sea level trend is 2.78 millimeters/year with a 95% confidence interval of +/- 0.60 mm/yr based on monthly mean sea level data from 1971 to 2006, equivalent to a change of 0.91 feet in 100 years.

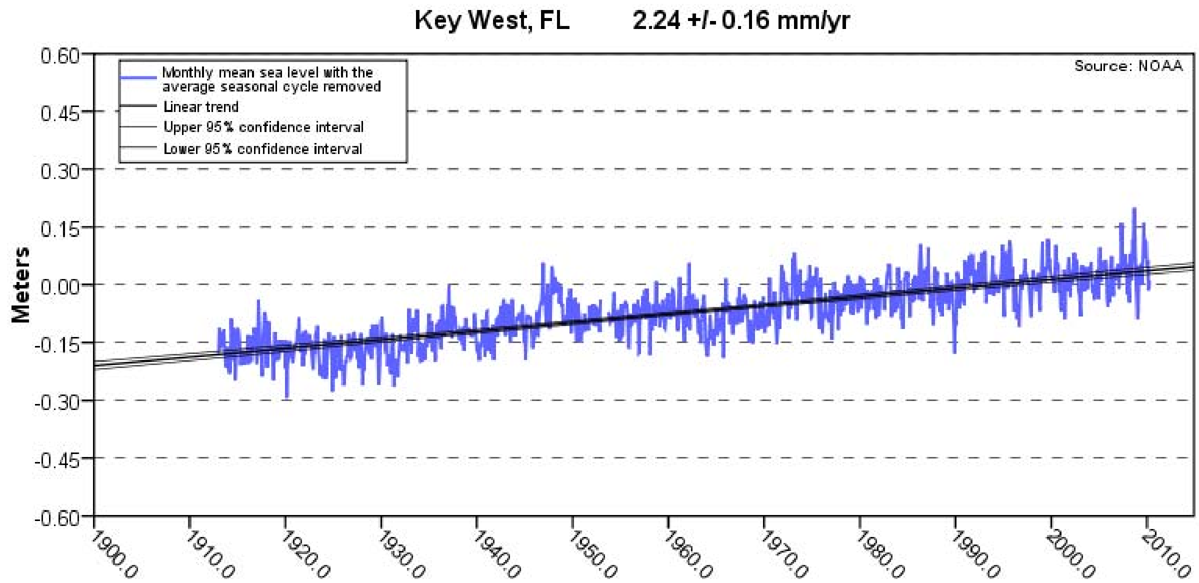

Figure B-12: Key West, FL – The mean sea level trend is 2.24 millimeters/year with a 95% confidence interval of +/- 0.16 mm/yr based on monthly mean sea level data from 1913 to 2006, equivalent to a change of 0.73 feet in 100 years.

FDOT District 7

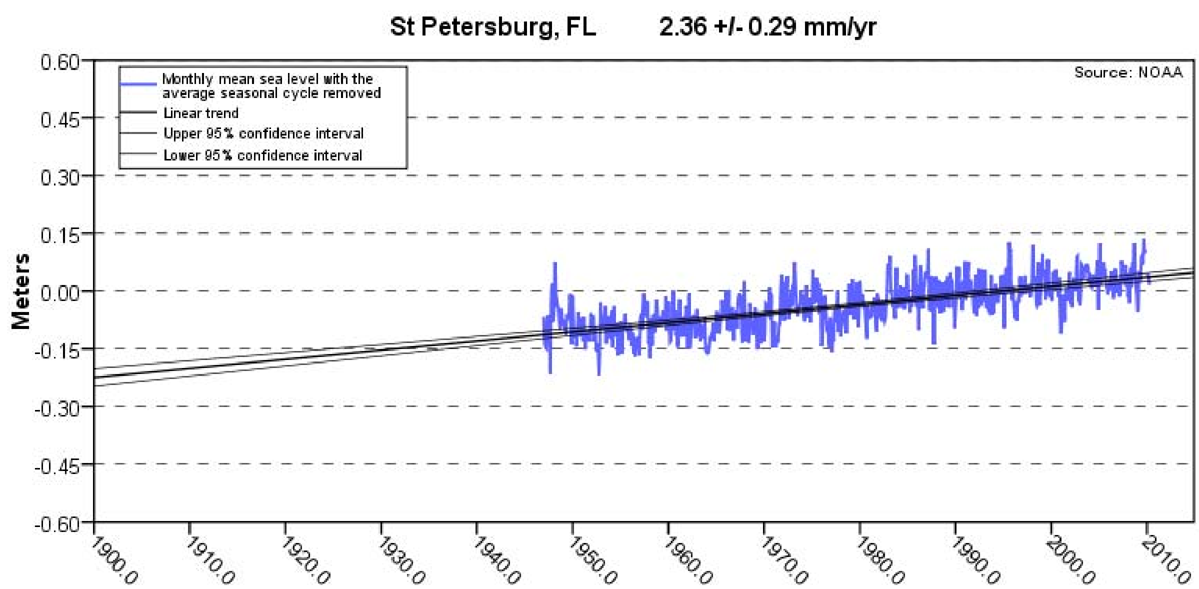

Figure B-13: St. Petersburg, FL – The mean sea level trend is 2.36 millimeters/year with a 95% confidence interval of +/- 0.29 mm/yr based on monthly mean sea level data from 1947 to 2006, equivalent to a change of 0.77 feet in 100 years.

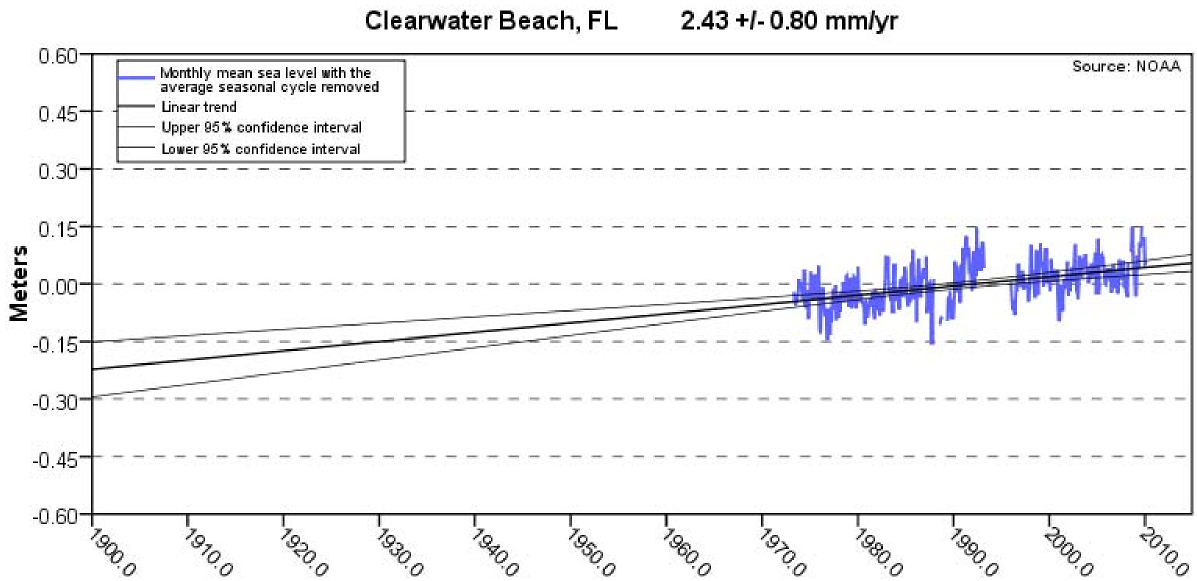

Figure B-14: Clearwater Beach, FL – The mean sea level trend is 2.43 millimeters/year with a 95% confidence interval of +/- 0.80 mm/yr based on monthly mean sea level data from 1973 to 2006, equivalent to a change of 0.80 feet in 100 years.

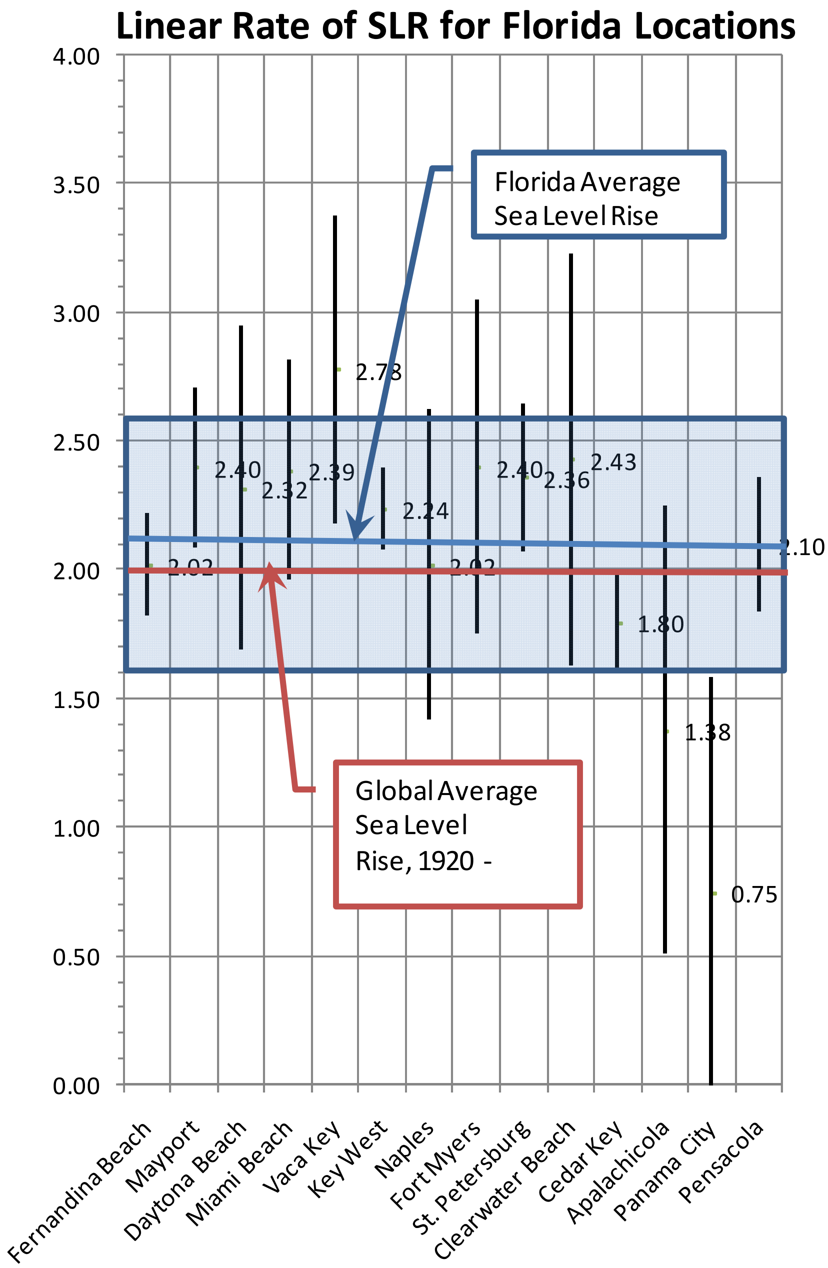

Figure B-15: Shows the results of analysis of the 14 stations in Florida. The Florida average sea level rise is 2.10 ±0.49 mm/yr.

Appendix C: Sea Level Rise: Projection, Impact and Application Models

Numerous researchers are modeling sea level rise projections. Listed below are just a few of these sea level rise models. Many of the models focused on in this report stem from sea level rise research based in Florida. However, other national and global sea level rise models are also described below. The newest reports come from the Greater Everglades Ecosystem Restoration (GEER) conference, July 2010. The models are split into three types of models that look at sea level rise projections, storm surge and applications. The projection models are reports that determine future sea level rise. Storm surge models are those methods which look at the impact of sea level rise on storms and flooding, such as the SLOSH model. The application models are reports that use sea level rise rates from another source as a component of a larger sea level rise study.

1. Projections & Models

1.1 Selected Global Projections & Models

IPCC 4th Assessment Report (AR4)

The IPCC 4th assessment report (AR4) is a consensus document that incorporates a variety of opinions concerning global warming, sea level rises and the role of greenhouse gases. Many simple levels of climate models exist. A simple general circulation model (SGCM) consists of a dynamical core that relates material properties such as temperature, to dynamical properties such as pressure and velocity. More sophisticated GCM models may include representations of the carbon cycle, but all are generally limited to studying the atmosphere. Three-dimensional (more properly four-dimensional) GCMs discretize the equations for fluid motion and integrate these forward in time. Simple models may contain simplified parameters for processes like convection, which occur on scales too small to be resolved directly. A GCM contains a number of prognostic equations that are stepped forward in time (typically winds, temperature, moisture, and surface pressure) together with a number of diagnostic equations that are evaluated from the simultaneous values of the variables. Chemical transport models can be used to predict changes induced by carbon dioxide additions to the atmosphere.

Atmospheric GCMs (AGCMs) model the atmosphere, with reference to a land-surface model, and sea surface temperatures (SSTs). AGCMs consist of a dynamical core which integrates the equations of fluid motion for (IPCC 2007):

- surface pressure
- horizontal velocity in atmospheric layers
- temperature and water vapor in atmospheric layers

Oceanic GCMs (OGCMs) model the ocean (with fluxes from the atmosphere imposed) and may or may not contain a sea ice model. Coupled atmosphere-ocean GCMs (AOGCMs) (e.g., HadCM3, GFDL CM2.X) combines the two models. They thus have the advantage of removing the need to specify fluxes across the interface of the ocean surface. These models are the basis for sophisticated model predictions of future climate in the IPCC reports. 23 AOGCMs are used in the IPCC report and projections.

Estimates derive sea level rise using a hierarchy of models, which encompass a simple climate model, a large number of Atmosphere-Ocean General Circulation Models (AOGCMs) and several Earth System Models of Intermediate Complexity. The models are used to project global average sea level rise at the end of the 21st century (2090–2099). The model scenarios each have a midpoint range within 10% of the TAR (Third Assessment Report) model average for 2090–2099. IPCC and other climate and sea level forecasts assume gradual linear responses and changes, not sudden tipping points, switches to new states, rapidly reinforcing feedbacks, and rapid rises. But when stressed and destabilized, climate, polar ice and sea level will, at some point, reach a tipping point and undergo rapid change towards a new state (IPCC 2007).

These models do not assess the probability of sea level rise, nor offer a best estimate/upper bound for the projections since the IPCC feels that knowledge of the effects driving sea level rise are too limited. The full effects of changes in ice sheet flow or uncertainties in climate–carbon cycle feedbacks are also not included.

AOGCMs represent the only current tools that could provide detailed regional predictions of future climate change but most remain under development. Each year improvements are made such as the dynamical cores (advection, etc.), more processes have been incorporated into the models like land surface and sea ice processes and parametrizations of physical processes. The horizontal and vertical resolutions of many models have been improved, but the models still show significant errors at smaller scales. The ultimate source of most of these errors is that many important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with larger-scale features. Examples are the El Niño-Southern and Madden-Julian Oscillations. Improvements in computing power, scientific understanding or detailed observations of some physical processes, and the resulting cloud responses will improve down-scaling in the future.

For use in Florida, all climate models have the same limitations. The grid spacing for climate models is roughly half the size of the state at the highest resolution, and requires input of terrestrial and water features. Florida is so flat that differentiation between the two makes drill down especially difficult. As a result, the IPCC models, like most global climate models, are limited by its lack of drill down abilities for the state (IPCC 2007; Bates et al. 2008).

International Alliance of Research Universities (IARU) Report

The United Nations Framework Convention on Climate Change in Copenhagen was held in 2009 with the purpose to *"develop a global response to the threat of climate change caused by human activities"* (International Alliance of Research Universities 2009). The IARU report presents an up-to-date (at the time) overview of a broad range of research relevant to climate change. Topics included in the report expand beyond fundamental climate science to include the impacts of a changing climate on society and environment. The basis of climate projections assume the climate is largely controlled by the flows of heat entering and leaving the planet from the sun and that sunspot activity may impact heating and cooling variation noted in the record. As an example, it was stated that 2008 *"was comparatively cooler than the immediately preceding years, primarily because there was a minimum in the cycle of the sun's magnetic activity (sun spot cycle) and a La Niña event in 2007/2008."*

Components included in the analysis are the ocean, land, atmosphere and snow/ice pack. A fundamental assumption is that the heat flux into the ocean *"proceeds more slowly than into the atmosphere,"* which they believe causes the ocean to store so much heat that a change in ocean temperature is a better indicator of change in the climate than changes in air temperature. For example, they pointed out that the ocean has warmed significantly in recent years; about 50% greater than had been previously reported by the IPCC which may portend a higher rate of sea level rise than the IPCC report indicates. They also noted the long-term trend of increasing temperature in the atmosphere is proceeding within the range of IPCC projections which indicates that most of the sea level rise from 1930-1990 can be attributed to thermal expansion of the ocean. However, the acceleration after 1990 may be due to the growing contribution of ice loss from Greenland.

The IARU report is new compared to the IPCC and older reports and thus reflects newer data. It forecasts sea level rise as a result of thermal expansion based on Rahmstorf 2007, using a linear regression of sea level versus time. However Rahmstorf 2007 has been superseded by a newer correlation of Vermeer and Rahmstorf in 2009, which includes both linear and second-order term and leads to quadratic acceleration models. They also note that models of the behavior of polar ice sheets are still in their infancy, so projections of sea level rise to year 2100 based on such *"process models"* are highly uncertain. They suggest an alternative approach is to base projections on the observed relationship between global average temperature rise and sea level rise over the past 120 years, assuming that this observed relationship will continue into the future. New estimates based on this approach suggest a sea level rise of around a meter or more by the year 2100. The IARU model has the advantage of UN peer review and is a consensus model, but the Vermeer and Rahmstorf 2009 result updates the IARU model. Vermeer and Rahmstorf (2009) is the preferred consensus.

(Available at http://climatecongress.ku.dk/pdf/synthesisreport)

Inverse Statistical Model

This project builds on Grinsted's prior work and incorporates a new addition to the climate scenario forcing – volcanic contributions. An inverse statistical model was used in this article to examine possible changes in sea level due to the differences in anthropogenic and natural forcings by the year 2100 (Jevrejeva, Moore, & Grinsted, 2010). They utilized the central estimates of radiative forcing projections from six IPCC Special Report on Emission Scenarios (SRES) scenarios: A1B, A1Fi, A1T, A2, B1, B2 (Meehl et al. 2007). These scenarios combine anthropogenic and natural forcings. However, the anthropogenic forcing projections vary widely due to wide variations in emissions forecasts for greenhouse gases (CO_2, CH_4 and SO_2). The model is semi-empirical (relies to some extent on observation/experimentation) and uses global tide gauge sea level records as a constraint. They estimated sea level rise of 0.6–1.6 m, with confidence limits of 0.59 m and 1.8 m. In the scenarios only a maximum 5% of total sea level rise is attributed to solar and volcanic radiative forcings, with anthropogenic greenhouse gasses being the dominant forcing. Even the most intense century of volcanic forcing from the past 1000 years would result in only a 10–15 cm potential reduction of sea level rise. The result of the model is that mean global sea level becomes a measurement of global response, independent of global temperature. (Jevrejeva, Moore, & Grinsted 2010). This is a global model has the same disadvantages as the IPCC models since it is based on AR4 (Jevrejeva, Moore, & Grinsted 2010). The model is not transferable to Florida nor does it permit drilldown.

(Avaliable at http://www.agu.org/journals/ABS/2010/2010GL042947.shtml)

Glaciations Synthesis

This global model is a synthesis of current results which update the IPCC 2007 report (Meier et al 2007). The model focuses primarily on a means to predict the ice contribution to sea level rise. They believe that the *"primary driver of recent ice loss is the rapid retreat and thinning of marine-terminating glaciers, which are susceptible to a nonlinear dynamic instability when their beds are below sea level"* (Meier et al. 2007). They estimate that 60% of the ice loss is from glaciers and ice caps by comparing the contribution of glaciers and ice caps to ice sheets, as well as stressing the importance of terrestrial ice being transported to the sea The contribution of these smaller glaciers has accelerated over the past decade and develop a whole glacier continuity equation to predict ice melt contributions over the next century. They indicate that *"ice wastage contributions to sea level rise will likely continue to increase in the future as warming of cold polar and subpolar glaciers continues and dynamically forced responses continue to occur"* (Meier et al. 2007). The final result of this model provides plots for accelerated glacier melt, which may cause additional 0.2 to 0.5 m of sea level rise by the year 2100 associated solely with ice melt (resulting in 3-4ft rise).

This model addresses a major drawback of the IPCC 2007 report and IARU models which did not account for actual and potential glacier and ice cap melt. This partially remedies that omission and forecasts higher sea level rise by the year 2100. However, both the Meier (1990) and IPCC (1990) report the results of committees that agreed to an upper bound SLR scenario in which the Antarctic contribution to sea level rise is zero. The committees did not, however, decide whether "*no Antarctic contribution*" represents a worst-case scenario or a scenario with some chance of being exceeded (Meier et al. 2007).

(Available at http://www.sciencemag.org/content/317/5841/1064.abstract)

UNEP 2009 Compendium

This compendium combines research from other reports to create sea level rise projections for the year 2100 (McMullen & Jabbour 2009). Estimates for how much regional and global sea levels will rise are based on the IPCC AR4 model, but focuses on the dynamic ice changes that were excluded from AR4 estimates because no consensus could be reached based on published literature available at that time (Solomon et al. 2009). The new work uses data similar to Wanless for Miami-Dade County with the same caveats (Wanless 2009). The model assumes thermal expansion of warming ocean water will generate a sea level rise of 1.6 mm/yr, plus an increase of 1.2 mm/yr of new water from the ice sheets of Greenland, Antarctica, glaciers and ice caps, for a total runoff totaling 2.8 mm/yr at present (+/- 0.72 mm/yr). The researchers stress that all contributions result from sources that are currently undergoing changes of anthropogenic origin. The graphical representations for total global average sea level rise are derived from Pfeffer's work (Pfeffer, Harper, & O'Neel 2008). This is an important update of the IPCC 2007 report (McMullen & Jabbour 2009). The relative importance of thermal expansion and ice melt contributing to global average sea level rise has varied for the year 2100 (Jevrejeva, Moore, & Grinsted 2010; Church 2008; Lettenmaier & Milly 2009; WCRP 2009).

Sea level rise is discussed on a global scale both historically and projected. They note that sea level rise has been measured directly by tide gauge records since the 1870s and by satellite altimetry since the 1990s. According to Rohling et al. (2009) the sea level changes over longer periods of time, thousands to millions of years, are inferred from geologic evidence. Their average rate of global mean sea level rise over the 20th century matches the IPCC 2007 Sea Level Change plot (Figure C1). They note that *"regional sea level is affected by isostatic responses to the unloading of burden from bedrock, by coastal subsidence in response to removal of materials or to new loads, and by gravitational and ocean current effects causing the ocean surface to deviate from a consistent elevation"* (Pfeffer, Harper, & O'Neel 2008; Milne et al. 2009; Lettenmaier & Milly 2009; Bamber et al. 2009).

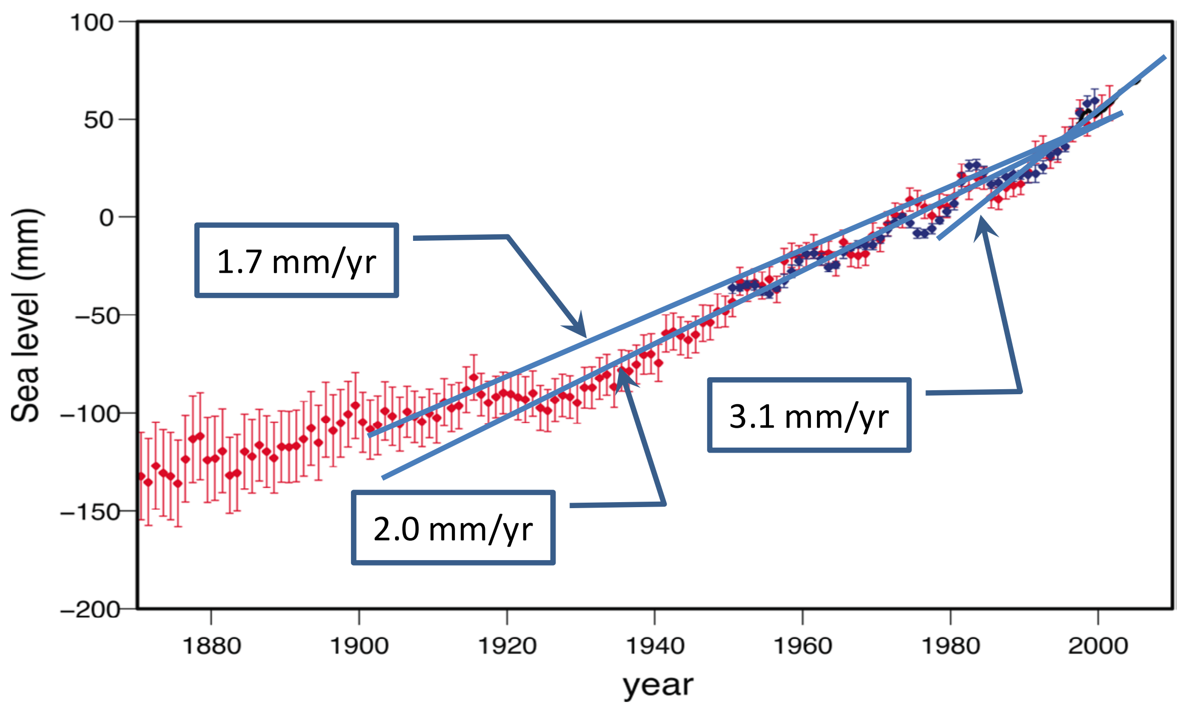

Figure C-1: Sea level change 19th Century to Present (IPCC 2007), modified to use here.

The report goes well beyond sea level and climate change science because it intends to act as a blueprint for counties to deal with potential issues associated with climate change. For example, this report introduces the concepts behind storm surge during increased the severity of storm events. The impacts they identify include *"increased frequency and severity of flooding in low-lying areas, erosion of beaches, and damage to infrastructure and the environment, including wetlands and inter-tidal zones, and mangroves, with significant impacts on biodiversity and ecosystem function"* (McMullen & Jabbour 2009). As noted by Meier et al., impacts will last for hundreds of years (2007).

The major limitation of this report is that it does not assess the probability of sea level rise, nor does it offer a solution to regional predictions. However, it states that there are no robust methods for modeling future dynamic glacier and ice cap or ice sheet contributions to sea level, but suggests limiting values for the next century. The Researchers calculate that a combined sea level rise in excess of 1.15 m from Greenland and Antarctica is physically unlikely due to limitations in the rates of discharge from ice melt and from iceberg fluxes required to drain ice through existing marine outlets. Similarly, they suggest that glaciers and ice caps are limited to no more than about 0.55 m of global mean SLR by the year 2100.

(Available at http://www.unep.org/compendium2009/)

Semiempirical Method (R07) & the Dual Model

Vermeer and Rahmstorf presented an updated version of their global sea level rise projection model in 2009. The method proposes a simple relationship linking global mean temperature to global sea level variations on large time scales (decades to centuries). This relationship is tested with data from a global climate model for the past millennium and the next century. To develop the model the authors use "*the semi-empirical method*" (R07). Since the equation from the semi-empirical method represents two time scales it is called the dual model.

Rahmstorf originally proposed that the initial rate of sea level rise in response to a large, rapid warming could be approximated by thermal expansion only, based on the temperature at which sea level is in equilibrium with climate, so that the rate of rise of sea level, dH/dt, is proportional to the warming above this base temperature (2009). The approach matches the approach commonly used in ice modeling, where the rate of mass loss is assumed to be proportional to the temperature increase.

This model (RO7) was criticized for not performing well in a model test under conditions of past natural variability, dominated by the response to volcanic eruptions, although R07 by design was not applicable to such conditions. The newer version simulates past millennium, where *"the climate model was forced by solar variability, volcanic activity, changes in greenhouse gas concentration, and tropospheric sulfate aerosols"* (Vemeer & Rahmstorf, 2009). This simulation, along with the forcing and a range of other models, was published in the IPCC Fourth Assessment Report (2) (AR4; Figure 6.14). The goal of this method is to present a reasonable approximation of the future sea level response to global warming (Vemeer & Rahmstorf, 2009).

The results provide a close link between global temperature and the rate of sea level rise for 1880–2000. In particular, it shows that the rate of sea level rise increased up to 1940 in line with rising temperatures, then stagnated up to the late 1970s while global temperature also remained nearly level, followed by another rise that continues until today. This result leads to slightly different temperatures (and hence rates of sea level rise) in 1990, greater warming and greater sea level rise for the 21st centuries. Overall, sea level projections range from 75 to 190 cm for the period 1990–2100. The model averages for all emission scenarios are close together, mostly because *"sea-level rise integrates the temperature rise over time, so that a temperature increment in 1999 has 100 times the effect on final sea level compared with the same increment in 2099"* (Vemeer & Rahmstorf, 2009).

Assuming this method presents a reasonable approximation of the future sea level response to global warming, sea level could rise three times as much by the year 2100 as the projections of the IPCC AR4 (2) suggest. But, uncertainties remain. While the thermal expansion response has been tested on simulated data, it is less clear whether the information contained in the 120 years of observational data about the ice response is sufficient to describe the future ice-melt contribution out to the year 2100.

(Avaliable at http://www.pnas.org/content/early/2009/12/04/0907765106.full.pdf+html)

MIT Integrated Global Systems Model (IGSM)

MIT created the Integrated Global System Model (IGSM), which is used to make projection probabilities of climate change from 1861-2250. The year 1861 was chosen as a based "*because of the large inertia of the ocean and carbon reservoirs*" (Sokolov et al. 2009). After the year 2100 the projections assume that anthropogenic emissions rates stay constant. This model includes sub-models of the relevant aspects in human activity and the natural earth system.

The projection uses no empirical data as is it a Bayesian Monte Carlo approach based on expert opinion solicited via a Delphi methodology (Sokolov et al. 2009). The basic method they employed for uncertainty analysis was a Monte Carlo simulation, in which multiple input sets are sampled from probability distributions representing uncertainty in input parameters from the Delphi questionnaires. Large groups of experts are required (400 were used). The Delphi is assumed to correlate toward consensus to derive distributions that can be sampled. The random sampling typically requires many thousands of samples to converge to a stable distribution of the model output. The sampling strategy used in the model to stabilize the output was a Latin Hypercube Sampling (LHS) method (Iman & Helton 1988). LHS divides each parameter distribution into *n* segments of equal probability, where *n* is the number of samples to be generated.

The intent was to arrive at consensus on up to 35 variables, noting that only three properties are commonly recognized as being major contributors to the uncertainty in simulations of future climate change: the effective climate sensitivity of the system (S), the rate at which heat is mixed into the deep ocean (Kv), and the strength of the aerosol forcing associated with a given aerosol loading (Faer) (Meehl et al. 2007). All are issues Vermeer and Rahmsdorf identified in their model (above). Uncertainties in each significantly affect 20th century simulations, so principle estimates of these properties and their uncertainties were derived from simulations in which these properties are varied to determine which give simulations consistent with observed 20th century changes. Rather than sampling high or low growth rates that applied to the 100 year horizon as has been done previously in most Monte Carlo studies of emissions, they created stochastic growth paths characterized as a random walk.

With regard to sea level rise, the research team notes that *"uncertainties in the sea level rise due to thermal expansion of the deep ocean are primarily associated with the uncertainties in the climate parameters,"* by incorporating the IRAU concepts on thermal inertia of the ocean, which significantly delays its response to changes in radiative forcing, although simulations by Sokolov et al. (2007) showed that thermal sea level rise has practically no dependence on forcing through the year 2050, a major deviation from the other models (Sokolov et al. 2009). Components of the model include models of human activities and emissions, a Natural Emissions Model (NEM), a mixed layer/anomaly diffusing ocean model (ADOM), a land system model combined with the Terrestrial Ecosystem Model (TEM), an atmospheric dynamics, physics and chemistry model and the Community Land Model (CLM). The combined components describe global, water and energy budgets and ecosystem processes (Sokolov et al. 2009). To address these issues, the probability distribution functions (pdfs) derived by Forest et al. (2008) were used in the IGSM and a large ensemble (~600) of simulations of 20th century climate was carried out. By combining the likelihood distributions estimated from each diagnostic using Bayes' Theorem, a *posterior* probability distribution was obtained. As with other estimates of probability distributions using Bayesian methods, *priors* on the three parameters are required. The simulations were compared against observations of surface, upper air, and deep-ocean temperature changes.

The combined components describe global, water and energy budgets and ecosystem processes. The advantage of the approach is that is provides an unusual long time perspective and the additive of specific sub models. It is complex and will need revision as new understanding of ocean and atmospheric dynamics evolve (Sokolov et al. 2009). Because the method uses no data, it cannot be down-scaled. It applies to a global scale of professional opinion. Such a process could be suggested for Florida at a later date.

Of interest, they note that at the end of the 21st century sea level rise is more sensitive to changes in characteristics of the climate system than in emissions. Such behavior was also observed in simulations with the version of the IGSM2 in which a 3D ocean GCM was used instead of a 2D anomaly diffusing ocean model.

(Avaliable at http://dspace.mit.edu/handle/1721.1/44627)

1.2 Down-scaling-National/Florida Based Projections & Models

Climate Change Models are typically for the whole globe, as the atmosphere is a unit at the global level as are the oceans. These models provide a general picture of the total global system on ocean, air, and land interactions and, of necessity, do not take into account more regional and local conditions and the different feedbacks that occur at smaller scales.

For regional and more local assessment of the potential impacts of climate change, local models consistent with the global picture that add capabilities smaller scale, localized phenomena need to be developed. The problem is the cost to prepare such models which are far more complex than the current global models.

Florida is a particular case because of its peninsula-like nature and the fact that on global scale models, the smallest unit for the area is mostly sea. So down-scaling is particularly difficult and more specific models need to be developed. For example, the pattern of land and sea breezes is important for rainfall dynamics in much of Florida. The literature review describes a number of ongoing modeling projects related to Florida.

USACE – EC 1165-2-211/EC 1165-2-212 Sea Level Rise Projection Guidelines

In the preparation of this document, the USACE has relied entirely on climate change science performed and published by agencies and entities external to USACE because conducting studies as to the causes, potential scenarios, and consequences of climate change is not within the USACE mission. The USACE is a user of the currently accepted community consensus on the state of climate science knowledge. USACE policies are expected to be periodically reviewed and revised as the accepted consensus changes. The goal of this report is to provide guidance on how all civil works projects will incorporate sea level rise considerations. The circular stipulates that "impacts to coastal and estuarine zones caused by sea level change must be considered in all phases of Civil Works programs" (USACE 2009, 2011).

The USACE model on sea level rise projections is a projection based on historic tide gauge data from NOAA and an updated equation from a National Research Council (NRC) report in 1987. Only tide gauges with over 40 years of record are utilized. Global mean sea level (GMSL) over the past several million years has varied principally in response to global climate change (National Research Council 1987; IPCC 2007).

The projection model provides three alternatives of future sea level change rates: "*low*," "*intermediate*," and "*high*." The "*low*" sea level rate is based on historic sea level change rates. The "*intermediate*" rate is determined using the modified Curve I and equations 2 and 3 from NRC 1987. IPCC's recent projections, the modified NRC projections and local rates of vertical land movement were considered in estimating intermediate rates of MSL. The "*high*" rates for the projections are estimated using the modified Curve III and equations 2 and 3 from NRC 1987. Final estimates are created using modified projection equations added to the local rate of vertical land movement. By accommodating accelerated glacier loss, the high rates exceed the upper bounds of the IPCC 2007 estimates. The current three scenarios proposed by the NRC result in global sea level rise values, by the year 2100, of 0.5 meters, 1.0 meters, and 1.5 meters. The NRC committee recommended *"projections be updated approximately every decade to incorporate additional data"* (1987). At the time the NRC report was prepared, the estimate of global mean sea level change was approximately 1.2 mm/year. Using the current estimate of 1.7 mm/year for global mean sea level change, as presented by the IPCC (IPCC 2007), results in this equation being modified.

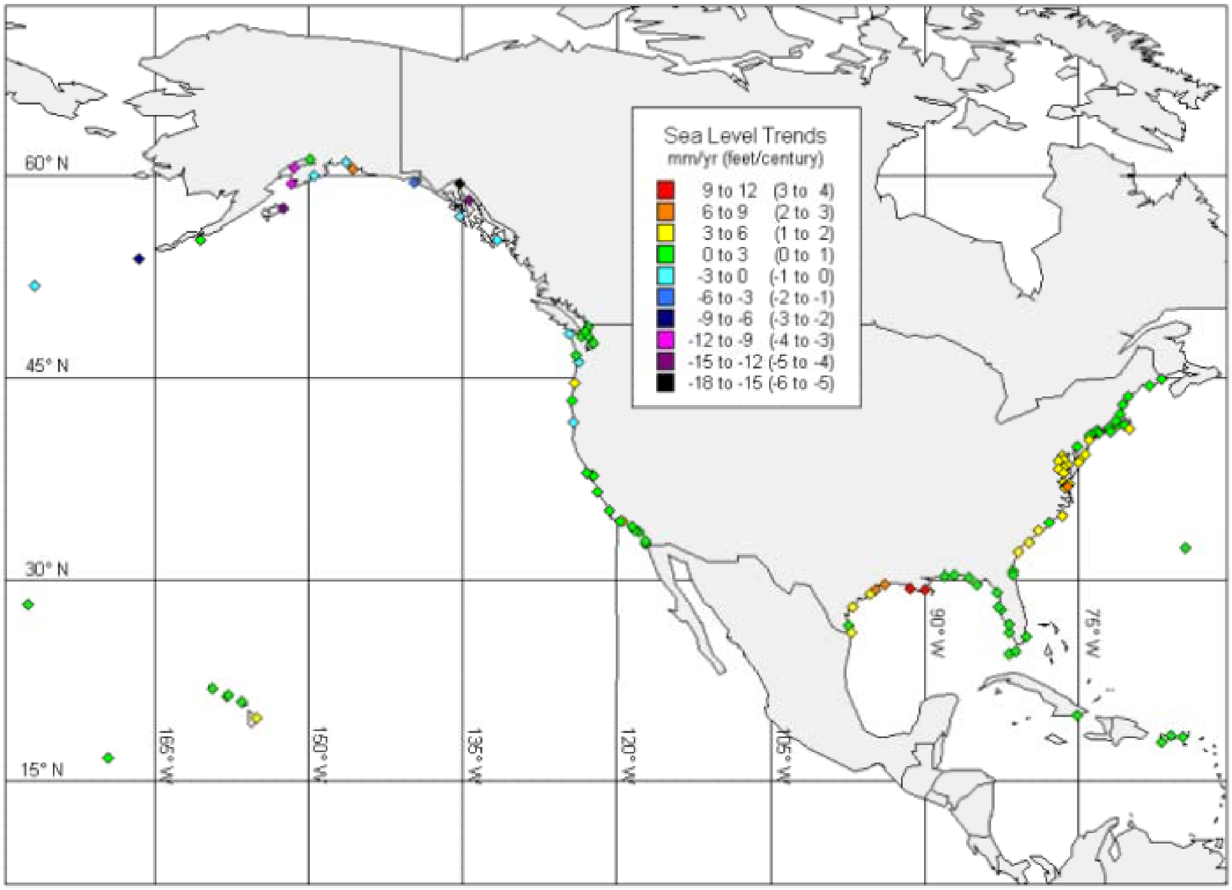

Figure C-2: USACE mean sea level trends for U.S. Tide Stations.

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Quadratic Acceleration Equation

Heimlich, along with co-authors from FAU, wrote a study on climate change and Florida's coasts in the report Southeast Florida's Resilient Water Resources. The goals of this project were to get a better understanding of the impacts sea level rise will have on Southeast Florida's water supply, ground and surface waters and wastewater reuse alternatives. These goals were attained though literature research, consultations with experts and a water utility case study in the City of Pompano Beach. This report predicts interim sea level rise throughout the 21st century using a quadratic acceleration equation. The assumption is that sea level rise will accelerate in proportion to melt rates due to rising temperatures in Antarctica and Greenland. This equation is an empirical method for predicting sea level rise based on physical results from thermal warming as in IARU (Bloetscher & Heimlich 2010; Heimlich et al. 2009).

This model uses an average of data in available literatures, relying heavily on the most recent literature. It builds on contributions from outside just thermal expansion of the ocean and has ties to basic thermal chemical equations for the expansion of fluids. It appears to correlate well with a number of other models. This model has been published and discussed extensively in SE Florida. It is one of the most recently published sea level rise projections related to Florida specific water issues. Developed by engineers who are looking at adaptation issues and timing it deals with timing and probability which most of the other projections do not. As a disadvantage, it assumes climate conditions throughout the world will be as projected in literature (although note that the Florida sea level rise data matches the global sea level rise so this may not be a disadvantage). The model is not site specific, may be conservative and was not developed by meteorological people. It suggests that 3 feet is an appropriate planning value for a year 2100 planning horizon. It is the only estimate that shows time variations for planning purposes (see Figure C3). The point of the time variations is to allow officials who must address the issues a window of opportunity so that funds are not spent too early, but that improvements can be made before they are in crisis.

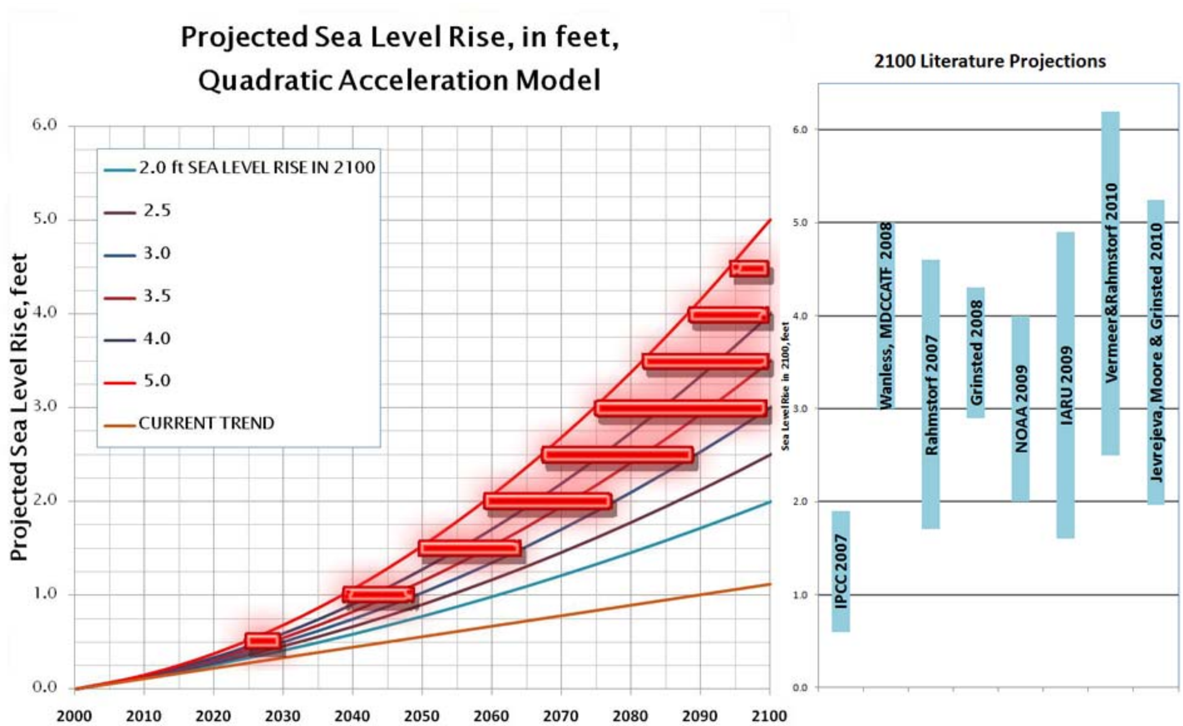

Figure C-3: Quadratic Acceleration Model (Heimlich et al. 2009).

Miami-Dade County Climate Change Projection

In response to climate change research, Miami-Dade County has created a sea level rise projection model to assess the risks and impacts sea level rise may have on the county from a group of experts led by Harold Wanless at the University of Miami (see later discussion). The goal was to get the county to reconsider aspects of county management, zoning, infrastructure, and planning in light of this new research. The project noted that since 1932, south Florida has had about a 9 inch relative rise of sea level, which is 1 foot per century or about 8 times the average rate over the past 2,500 years. Much of this accelerated rise is the result of warming (and expansion) of water in the western North Atlantic Ocean is suggested to be in response to global warming. The model looks at the effect that 1-5 ft sea level rise would have, and suggests that *"Miami-Dade County will not be able to defend against such a rise and must begin a responsible and serious re-evaluation of all aspects of its present laws and approaches to growth, development, permitting, zoning, infrastructure, waste disposal and pollution, adaptation, and natural area preservation"* (Miami-Dade County Climate Advisory Task Force 2008).

The report uses detailed information about infrastructure in the area to determine potential risks. The project is not a model but an application of the IPCC AR4 projections for the coming century, with some of the assumptions altered. The Miami-Dade report changes the assumptions which deal with the thermal expansion of oceans, non-ice sheet glacial melt, Greenland melt and Antarctica. The altered assumptions change projected sea level rise to 3-5 ft of global sea level rise by the year 2100. (Miami-Dade County Climate Advisory Task Force 2008) One of the main advantages of this work is the assesment of potential risks to infrastructure.

South West Florida Regional Planning Council Assessment

The Southwest Florida Regional Planning Council (SWFRPC) and the Charlotte Harbor National Estuary Program have worked together to create a sea level rise projection model. This model uses scenario levels based on a report by the Environmental Protection Agency (Titus & Narayanan 1995) and Stanton and Ackerman (2007). The EPA project uses three climate change probability of occurrence scenarios; 1) Lower: a condition that involves a future in which significant mitigative actions are undertaken to reduce the human influence on climate change, 2) Intermediate: a scenario which falls within various forecasts, and 3) Upper: a future in which few actions are taken to address climate change and the most recent projections of more significant impacts are used, including those related to glacial ice melting. These three projections are created by using documented sea level rise, multiplied by the number of years, plus "normalized" sea level rise projections. From the Stanton and Ackerman report (2007), the model uses the rapid stabilization case and the business-as-usual case to create two additional probability levels, which represent opposite extremes of sea level rise probability. The time frame for this model was set through the year 2100 in the Charlotte Harbor report (2010). This is basically a bathtub model that was prepared to address storm surge to identify vulnerable property in Charlotte County, as well as the probability of sea level impacts. As a result the focus is more oriented to flooding from storm surge with sea level impacts as a byproduct. (Beever et al 2009; Charlotte Harbor National Estuary Program and the Southwest Florida Regional Planning Council 2010; Stanton & Ackerman 2007; Titus & Narayanan 1995). These scenarios along with the Sea, Lake and Overland Surges from Hurricanes (SLOSH) Model were used to project storm surge and to identify vulnerable property in the Southwest Florida area.

SimCLIM

A CH2MHill developed model, SimCLIM is an adaptation and sustainability model that is used for assessing the impacts and adaptations to climate change. The model is the only available down-scaling model. It takes global data and projects the information to local levels. This program uses observed data (tides), emission scenarios and GCM results to project temperature/precipitation, local daily/monthly/annual projections and precipitation intensities related to climate change. SimCLIM assesses climate change impacts geographically and over time. This model is a method of quantifying the likelihood of climate impacts at a local scale (Tak 2010). It attempts to assess impacts of climate change geographically and over time using a combination of GCM output and GHG scenarios to project temperature, precipitation and sea level rise. It uses climate change model projections for the years 2050 and 2100. The model aslo evaluates the changing extremes and impact on hydrologic design.

The model is a commercial tool developed by CH2MHill for its clients and as a business development tool. Descriptions for the model are limited so full evaluation of veracity is not possible. While the model has been applied in a number of areas, there is no peer review and no verification that the drill down results provides any degree of accuracy. Additions to this model are planned in the future which deal with sustainable water management infrastructure.

(Available at http://coaps.fsu.edu/fcikickoff/presentations/20101116vandertak.pdf)

1.3 Projects in Progress

North Florida – Gulf Coast Alliance Project

This project is currently in progress. In 2004 a partnership was initiated between the states of Alabama, Florida, Louisiana, Mississippi, and Texas called the Gulf of Mexico Alliance. The intent of the alliance was to enhance the economic and ecological health of the Gulf of Mexico. Within the alliance there are six priority areas: water quality; habitat conservation and restoration; ecosystem integration and assessment; nutrients and nutrient impacts; coastal community resilience; and environmental education. Coastal community resilience partly deals with climate change and sea level rise issues. This project builds on a report released in 2006, the *Governors' Action Plan for Health and Resilient Coasts*. This was a three year project that identified the regionally significant issues. The *Governors' Action Plan II* is a five year plan that does more research on the issues previously identified.

There are three steps within "*coastal community resilience*" issues. The first step in the coastal community resilience section is a risk and resilience assessment. The second step is risk and resilience management toolbox and the third step is risk and resilience communication. Step one provides tools for communities to understand the risks/impacts associated with hazards like climate change. The second step prepares an inventory of tools which address coastal hazards, identify gaps and develop new methods to aid resilience. The last step is to inform communities about the risks and to supply access to any tools which will improve resilience. This is an ongoing study and the tools developed from this study for assessment and communication may be useful as adaptive measures, but it provides no sea level rise modeling as planned.

The Gulf coast of Florida is not included in the project - the study area is short of the Florida coast. This project is intended as a guidance document with suggested measures to improve infrastructure and reduce risk, not project sea level. However, the GOMA approach will permit Florida to leverage data collection and other activities with the other four Gulf of Mexico states. In addition, Florida and GOMA will be participants in the Gulf of Mexico Restoration Council, part of the recovery from the Gulf oil spill. Florida and GOMA are also applying to administer a NOAA grant to produce a regional coastal and marine spatial plan of the offshore state and federal waters of the Gulf. The effort is under the leadership of the National Ocean Council. The GOMA based activities reflect a federal approach of dividing Florida into east and west coastal and ocean regional areas. A similar approach is followed for fisheries management, coastal and ocean observations and offshore energy activities. This geographic division makes it difficult for limited staff to monitor separate regional activities and insure consistency from the state of Florida perspective. (Northern Gulf Institute 2010; Gulf of Mexico Alliance 2006-2009; Gulf of Mexico Alliance 2009-2014)

2. Storm Surge Models

Storm surge models are methodologies and systems used to predict storm surge events not sea level rise. Some of these models may suggest sea level impacts, but their goal is temporal in nature, while sea level rise is a permanent condition. These models vary according to location and each cover different aspects of storm surge.

2.1 Selected State Impact Models

Northwest Alternative to SLOSH Model

This model is useful to identify vulnerable bridge infrastructure that might be damaged by wave velocity and for flood insurance purposes and routing. Unfortunately SLOSH Models are basically bathtub models. The topography distinguished the probability of flooding based on incidental events that have a very low probability of occurring. An example of this would be that the bathtub model shows low lying areas far inland being flooded during a storm surge even though they are not hydrological connected to the sea. The model also does not relate to permanent sea level rise since groundwater effects are ignored. Another limitation of the model is that the size, direction, and timing of waves cannot be accurately outlined. In general this model is not appropriate for sea level rise.

ADCIRC Coastal Circulation and Storm Surge Model

ADCIRC is a system of computer programs for solving time dependent, free surface circulation, and transport problems in two and three dimensions (University of North Carolina at Chapel Hill 2010). The model's computer programs use a finite element method in space to allow for unstructured, flexible grids. Typical ADCIRC applications have included: (i) modeling tides and wind driven circulation, (ii) analysis of hurricane storm surge and flooding, (iii) dredging feasibility and material disposal studies, (iv) larval transport studies, (v) near shore marine operations and feasibility studies (University of North Carolina at Chapel Hill 2010). Users of the ADCIRC model include: USACE, LNEC, NOAA, NRL, Seahorse Coastal and PSU Glacier Bay Tidal Modeling.

The ADCIRC model can be used for assessment of flooding associated with higher seas and for identification of vulnerable bridge infrastructure that might be damaged by wave velocity. It may also be useful for flood insurance purposes and routing. Because it is searching for a free surface circulation, it defaults to a bathtub model that relies on topographic data. The topographic data limits it application. Available GIS and other mapping is also a limiting feature. Storm surge models are designed to relate to temporal flooding events from storm surge, not permanent conditions. Another limitation of the model is that the size, direction and timing of waves cannot be accurately outlined. It is not appropriate nor does it portend to be appropriate to assess sea level rise impacts.

(Available at http://adcirc.org/)

SLAMM Model

The Sea Level Rise Affecting Marshes Model (SLAMM) model was developed using EPA funding by Park et al. in 1986 (Park, Armentano, & Cloonan 1986). This model simulates wetland conversion processes and shoreline changes during long-term sea level rise. Maps from this model are created under accelerated sea level rise conditions (Warren Pinnacle Consulting, Inc., 2010). The model can be used for any location, just by using the appropriate (location specific) data. Within SLAMM there are five processes that affect wetlands under different sea level rise scenarios: inundation, erosion, overwash, saturation, and accretion (Warren Pinnacle Consulting Inc 2010).

SLAMM simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise. A complex decision tree incorporates geometric and qualitative relationships to represent transfers among 30 x 30 m coastal finite element modules looking at interaction of open water, wetlands and dry land - requiring all three plus topography. The five issues considered include:

- **Inundation:** Calculated based on the minimum elevation and slope of the cell.
- **Erosion:** Triggered given a maximum fetch threshold and proximity of the marsh to estuarine water or open ocean.
- **Overwash:** Barrier islands undergo overwash at a fixed storm interval. Beach migration and transport of sediments are calculated.
- **Saturation:** Migration of coastal swamps and fresh marshes onto adjacent uplands--response of the water table to rising sea level.
- **Accretion:** Vertical rise of marsh due to buildup of organic and inorganic matter on the marsh surface. Rate differs by marsh-type.

When a threshold of 9 km is exceeded, horizontal erosion rates are implemented based on visual inspection of maps

SLAMM estimates (fresh) water table from the elevation nearby swamps or fresh-water wetlands. As sea levels rise, this applies pressure to fresh water table (within 4 km of open saltwater). The model incorporates IPCC Projections as well as fixed rates of SLR-based on Figure C4. It assumes that long-term differential between eustatic and Local SLR will remain constant during period of projection.

The model has the potential to overestimate soil saturation due to a "perched water table." Marsh-type is more highly correlated to salinity than elevation when fresh-water flow is significant. The model is not a mechanistic model and does not account for peat collapse, but can be visualized in Figure C4. Note this is not intended to address urban areas or large regions. It is specific to wetland impacts. Applications of this model to sea level rise effects are not available in literature(**http://warrenpinnacle.com/prof/SLAMM/**).

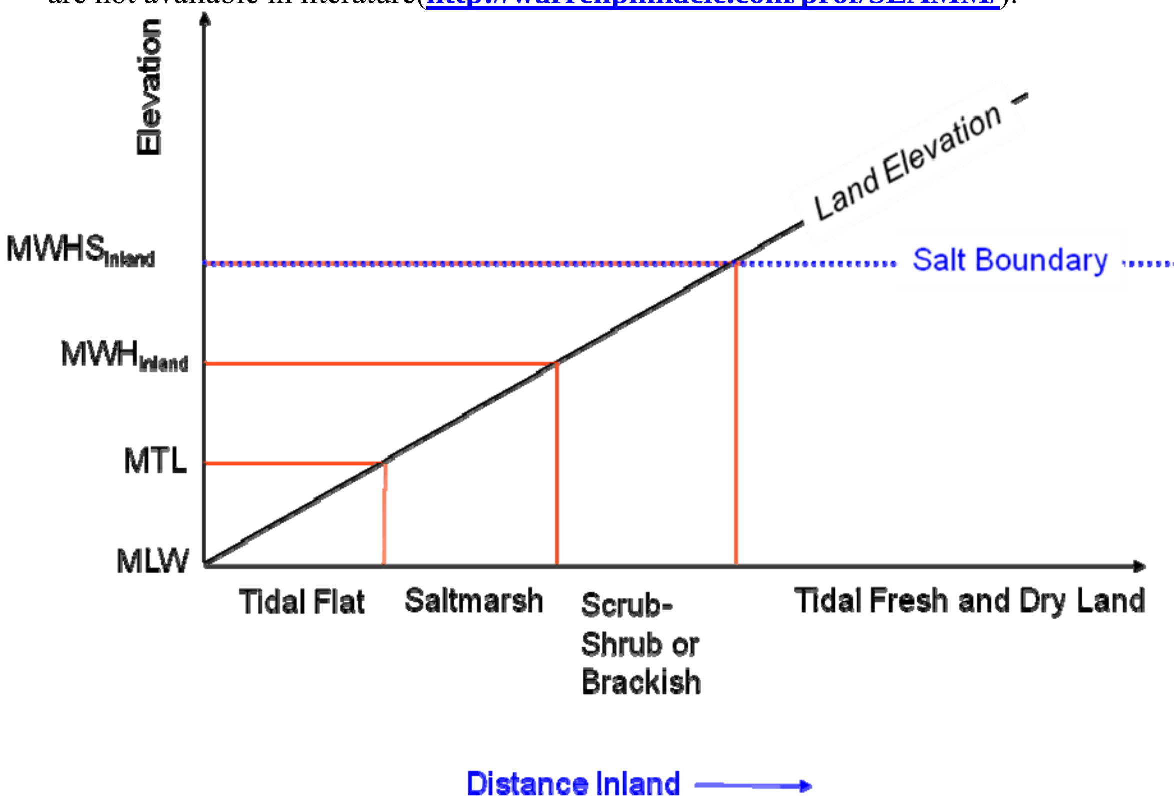

Figure C-4: Application of SLAMM model.

SLOSH Model

The SLOSH model stands for "*Sea, Lake and Overland Surges from Hurricanes*" (NOAA/National Weather Service 2010). This is a computerized storm surge model run by the National Hurricane Center (NOAA) with the purpose of measuring storm surge heights/winds from historical, hypothetical, or predicted hurricanes. SLOSH consists of physical equations that are applied to the shoreline of a specific location and incorporates unique bay/river configurations, bridges, levees, water depths, roads, and other physical features (NOAA/National Weather Service 2010). The output map for the model uses the National Geodetic Vertical Datum as its elevation reference point. The accuracy of SLOSH is within ±20% of the actual results. The SLOSH model is "*best used for defining the potential maximum surge for a location*" (NOAA/National Weather Service 2010). The point of a hurricane's landfall is crucial to determining which areas will be inundated by the storm surge. Where the hurricane forecast track is inaccurate, SLOSH model results will be inaccurate. The SLOSH model, therefore, is best used for defining the potential maximum surge for a location.

The model has potential for application in sea level rise studies to incorporate episodic events. This model is also useful for identifying vulnerable bridge infrastructure that might be damaged by wave velocity and for flood insurance purposes and routing. Unfortunately SLOSH Models are basically bathtub models. The topography distinguishes the probability of flooding based on incidental events that have a very low probability of occurring. A limitation of the model is that the size, direction and timing of waves cannot be accurately predicted because all storm events varying probability of occurrence and the effect of climate change on this occurrence is not well understood. This model can be used with sea level rise projections to describe storm surge conditions in particular areas.

(Available at http://www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml)

CH3D-SSMS Storm Surge Model

CH3D-SSMS is a storm surge and coastal flooding model used for forecasting topical and extratropical storms. The system combines the CH3D (curvilinear-grid hydrodynamic) storm surge and coastal flooding model with the SWAN (shallow water wave model) into a high resolution model grid. The CH3D model uses a horizontally boundary-fitted curvilinear grid and a vertically sigma grid, so is suitable for application to coastal and nearshore waters with complex shoreline and bathymetry. The non-orthogonal grid enables CH3D to more accurately represent the complex geometry than the orthogonal grid, which is used by most other ocean circulation models. Recent applications have used horizontal grid on the order of 10-20 meters over a 200km x 50km area. A fully integrated modeling system CH3D-IMS has been developed and applied to several estuarine systems including the Indian River Lagoon, Tampa Bay, and Charlotte Harbor.

The model uses boundary conditions of surge and wave from a global basin-scale surge model (ADCIRC) and a global basin-scale wave model (WAVEWATCH-III). These two models include coverage of the Gulf of Mexico and Western Atlantic. In Florida grids have be created for the East Florida Coast, Tampa Bay and Charlotte Harbor, Florida Panhandle, and Chesapeake Bay. Wind and atmospheric pressures are provided by NAM (North Atlantic Mesoscale) and GFDL-Hurricane model. Based on wind forecast CH3D-SSMS creates an 84-hour water level forecast with wave height/period/direction, flow field, and maximum of maximum water level and inundation every 6 hours. CH3D-SSMS has been used for hurricanes Isabel (2003) Frances and Ivan (2004). (Sheng et al. 2005; Sheng 2006).

This model is useful for identifying vulnerable property that might be impacted for flood insurance purposes and routing, and for emergency planning. Unfortunately storm surge models are basically bathtub models. The topography distinguished the probability of flooding based on incidental events that have a very low probability of occurring. The model also does not relate to permanent sea level rise since groundwater effects are ignored. Another limitation of the model is that the size, direction, and timing of waves cannot be accurately outlined. In general this model is not appropriate for sea level rise.

(Available at http://ch3d.coastal.ufl.edu/)

CH3D-SSMS Modeling in Virginia

This is not a model but an application of the CH3D-SSMS model discussed above. This model is based on inundation in the Outer Banks and Chesapeake Bay during Hurricane Isabel in 2003. The CH3D-SSMS model looks at the effects of waves on storm surge, currents, and inundation by comparing observed wind, wave, surge, and inundation data. CH3D-SSMS includes both coastal and basin-scale storm surge wave models. Results of this model showed clear effects of waves on storm surge. It was determined that wave-induced stress and radiation stress (outside the estuaries) is more important for affecting water level then wave-induced bottom stress (Sheng, Alymov, & Paramygin 2010).

Exhaustive application of this model for projected effects of sea level rise needs to be evaluated. This model might also useful for identifying infrastructure that might be vulnerable to inundation, for flood insurance purposes, and routing for emergency planning. The topography distinguishes the probability of flooding based on incidental events that have a very low probability of occurring. The model is used for short duration events which mean that this model is not appropriate for sea level rise.

(Available at http://www.agu.org/journals/ABS/2010/2009JC005402.shtml)

PL4 –Priority Level Forecast System

This is an application of the CH3D model noted above by incorporating probabilistic elements. Using this method as many simulations as possible are performed in order to have highest levels of confidence in the results. By combining CH3D, "*the Southeastern Universities Research Association Coastal Ocean Observing and Prediction Program's forecasting systems*" a priority level forecast system is created (Davis et al. 2010). The forecast model is focused on the application of storm surge forecasts in a limited-resource environment. The probability density functions in the ensemble sets are grouped into priority levels, which rely on previous calculations, and have increasing confidence levels. PL4 (27 members) is "*sufficient to resolve 90% of the inundation within the domain*" and has the best accuracy and timeliness balance. PL4 completes its analysis in 83 min for a 5-day forecast (Davis et al. 2010).

This model might also useful for identifying infrastructure that might be vulnerable to inundation, for flood insurance purposes, and routing for emergency planning. The topography distinguishes the probability of flooding based on incidental events that have a very low probability of occurring. The model is used for short duration events, which means that this model is not appropriate for sea level rise.

Gulf Coast Study: Sea Level Rise Rectification Program (SLRRP) Model & CoastClim V.1

The study was designed by US DOT to "*increase the knowledge base regarding the risks and sensitivities of all modes of transportation infrastructure to climate variability and change, the significance of these risks, and the range of adaptation strategies that can be considered to ensure a robust and reliable transportation network*" (Potter, Burkett, & Savonis 2008). Climate changes anticipated during the next 50 to 100 years for the central Gulf Coast include warming temperatures, changes in precipitation patterns, and increased storm intensity. As a result, the study assessed the impact of sea level rise (SLR) on transportation infrastructure based on sea level rises of 61 cm and 122 cm (2 and 4 ft). Historical trends and future climate scenarios were used to establish a context for examining the potential effects of climate change on all major transportation modes within the region. As discussed above, actual SLR may be higher or somewhat lower than these levels. Findings include that warming temperatures are likely to increase the costs of transportation construction, maintenance, and operations. More frequent extreme precipitation events may disrupt transportation networks with flooding and visibility problems. The study indicates that substantial portions of the transportation infrastructure in the region are at risk: *"27 percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports are at or below 122 cm (4 ft) in elevation, although portions of the infrastructure are guarded by protective structures such as levees and dikes"* (Potter, Burkett, & Savonis 2008). The effects of sea level rise in most central Gulf Coast counties will be exacerbated by the sinking of the land surface, which is accounted for in this assessment. More than half of the area's major highways (64 percent of Interstates; 57 percent of arterials), almost half of the rail miles, 29 airports, and virtually all of the ports are below 7 m (23 ft) in elevation and subject to flooding and possible damage due to hurricane storm surge.

Geographically this project covers the Gulf Coast, stopping before it reaches Florida. A Gulf Coast study by the U.S. Climate Change Science Program developed the sea level rise rectification program SLRRP (Potter, Burkett, & Savonis 2008). SLRRP is a software package designed to have a user-friendly interface, that is used to generate sea level rise projections using scenario outputs from IPCC 2001 and various GCM models. This is a storm surge model that was used with relative sea level rise projections. The relative sea level rise projections were selected using region-based tide stations, a Special Report on Emissions Scenarios (SRES) emission scenario and a GCM model. SLRRP projections are set through the year 2100 and use historic monthly mean sea levels as part of the projection equation. This model uses the global model and narrows the projections to a particular region. The CoastClim model produces approximates for relative sea level rise under climate scenarios (Potter, Burkett, & Savonis 2008).

There are several issues with this model. First, it stops short of the coast where the impacts will likely be. It uses the 2001 IPCC projections which are well out of date. It is a storm surge model that might be useful for identifying vulnerable bridge infrastructure that might be damaged by wave velocity and for flood insurance purposes and routing, but because it is a bathtub model, it is not appropriate for sea level rise which is a permanent condition. Groundwater effects are ignored.

(Available at http://www.climatescience.gov/Library/sap/sap4-7/final-report/)

3. Illustrative Applications

The application models below are selected models from reports in Florida. These models take sea level rise projection numbers from other studies, or use general sea level rise numbers and apply them to illustrative impact studies. Some researchers both create a sea level rise projection and then apply the projection to an application model. Miami-Dade County would be an example of a location which has created projections and applied sea level rise to maps.

3.1 Florida Applications

Big Pine Key – Nature Conservancy

This project is an application of LiDAR to an assumed future sea level. This report uses 2007 Digital Elevation Models derived from LiDAR data for Big Pine Key. Using this data, projections of future shoreline locations and major habitat distribution was projected to the year 2100. The sea level rise projection scenarios were determined from scientific literature (IPCC 2007 & Rahmstorf et al. 2007 scenarios). The IPCC scenarios of sea level rise used for the projections in this research included scenario B_1 (best-case scenario), A_1B (rapid growth with balanced energy sources scenario), A_1F_1 (rapid growth with intense fossil fuel use). The Rahmstorf projections used were the high and low end projections of sea level rise by the year 2100. Once the projections were mapped, the report determined the estimated property value losses for Big Pine Key based on year 2100 sea level rise projections using 2008 values. The best case scenario was 7in of sea level rise, which equals 1,840 acres (34%) of inundation on Big Pine Key. The highest sea level rise model was 4.6ft and equals 5,950 acres (96%) inundation on Big Pine Key. (Bergh 2009). This model is basically a bathtub model using LiDAR. It is much more helpful than many because, with good quality LiDAR data, the specific topography can be distinguished. It is basically an earlier version of the work FAU is doing, but FAU has better quality LiDAR data.

(Available at http://frrp.org/SLR%20documents/FINAL%20-%20Aug%2021%20-WITH%20COVER.pdf)

Broward County Climate Change Task Force SLR Assessment

The Broward County Climate Change Task Force has been charged with the duty to project sea level rise in Broward County and to model the effects this projection would have on the area. The Subcommittee determined that based upon the review of the best available technical data and scientific modeling, a projection of 3-to-9 inches of sea level rise from the 2000 level by the year 2030 should be utilized in the development of immediate and short term recommendations. They further determined that a projection of 10-20 inches of sea level rise from the year 2000 level by the year 2060 and a projection of 24-48 inches of sea level rise by the year 2100 should be utilized in the development of mid and long term recommendations. No modeling was done. These projections were overlaid with LiDAR data that has a vertical precision of about 6 inches. The resulting illustrations show the potential impacts of sea level rise on Broward County at 1ft, 2ft and 3ft sea level rise. It was determined that in Broward County 1ft of sea level rise would impact 1,934 households (4,151 residents), 182 businesses, property loss˜ $469M, 4 major roads, and libraries/parks/natural areas (Broward County Climate Change Task Force, 2010). The assumed sea level rise projected based on available literature is used and assigned to LiDAR mapping. Because this is not a model, but an application of data, it may useful for comparative purposes. Recognition of the Task Force suggestions is needed in dealing with Broward County officials.

(Available at http://www.broward.org/NaturalResources/ClimateChange/Documents/FinalCCActionPlan_forBCBCCappdxB.pdf)

EPA Mapping Technique

This report presents the methods and results of a two-part effort to estimate the probability distribution of future sea level rise implied by the expectations of approximately twenty climate researchers. In the first phase, we developed a simplified model for estimating sea level rise as a function of thirty-five major uncertainties, derived probability distributions for each parameter from the existing literature, and conducted a Monte Carlo experiment using 10,000 simulations, then applied it to maps. The report, by James Titus and Vijay K. Narayanan of the Environmental Protection Agency, projected sea level rise against DEM data to illustrate the effects of sea level rise (1995). The digital elevation data used is the USGS 1-degree elevation series and NOAA shoreline data. The mapping methodology does not use sea level rise projections to illustrate impacts, but instead, shows what land falls below 1.5 and 3.5 meter contours. Three different scales were used to show the potential impacts of sea level rise: the entire Atlantic/Gulf Coast, only the Gulf Coast, and at the state level (from New York to Texas) (Titus & Narayanan 1995). The estimates of sea level rise are somewhat lower than those published by previous IPCC assessments, primarily because of lower temperature projections. This report estimates that global temperatures are most likely to rise 1°C by the year 2050 and 2°C by the year 2100, that there is a 10 percent chance that temperatures will rise more than 4°C in the next century, and a 90 percent chance that they will rise by at least the 0.6°C warming of the last century. By contrast, IPCC (1992) estimated that a warming of 2.8°C was most likely. The temperature estimates are lower *"because (a) we assume lower concentrations of carbon dioxide; (b) we include the cooling effects of sulfates and stratospheric ozone depletion; and(c) our panel of experts included a scientist who doubts that greenhouse gases will substantially increase global temperatures"* (EPA 1995).

This is not a model but an application of a bathtub approach. There is useful topographic input and the maps provide useful information for the probability of sea level rise in coastal areas. It is oriented to sea level rise, but does not incorporate groundwater conditions that need to be known to outline flooding potential. Corrections are also needed for LIDAR data. In this model the resolution is not good enough for low lying coastal vulnerability assessments.

(Available at http://repositories.tdl.org/tamug-ir/bitstream/handle/1969.3/25952/8881-Probability%20of%20Sea%20Level%20Rise.pdf?sequence=1)

Brevard/Volusia County Sea Level Rise Maps

The East Central Florida Regional Planning Council created a set of maps visualizing the potential impacts of sea level rise on Brevard and Volusia County. These maps are based on 5 ft of sea level rise and show which areas are more likely to be protected from erosion, inundation, and flooding. The protection scenarios are ranked into four categories: protection almost certain, protection reasonably likely, protection unlikely and right to protect but protection unlikely. Also overlaid on the maps is the location of critical facilities and streets. The maps are focused on 240 square miles and uses 10-ftt (NGVD) contours as benchmarks. 10-ft contours were chosen because tidal influences can extend to the 5-foot contour and the 10-ft contour approximates the highest elevation that may be effected with 5 ft of sea level rise over the next few hundred years. Although there is some LiDAR data for this region, the best topographic maps for some areas are the 5-, 10-, 15- and 20-ft contours, which is why the planning council decided to use the 5- and 10-ft contours for the maps. (East Central Florida Regional Planning Council 2004)

This project is the first detailed study to examine the potential effects of sea level rise on East Central Florida. Local governments, county government, and property owners are presented with possible solutions for protecting the valuable coastline of the region as well as the impacts a possible five foot rise of sea level may cause. This is an application of a bathtub model. LiDAR quality is unclear but is likely 1 arc medium resolution which may not be good enough for detailed studies. This model has useful topographic input and provides useful information for coastal areas. Groundwater conditions need to be known to outline flooding potential. Corrections are also needed for LIDAR data.

Southwest Florida Regional Planning Council Sea Level Rise Maps

The primary focus of this project is the vulnerability of coastal regions to climate change in the Charlotte Harbor National Estuary Program (CHNEP) and the SWFRPC. This project includes an assessment of significant potential effects of climate change on the human and native ecosystems of the southwest Florida portion of the Charlotte Harbor National Estuary Program study area, including consequences for human and natural resources resulting from and related to sea level rise, aquatic and atmospheric temperature rise, changes in rainfall patterns, increased storm intensity, waterbody acidification, and general weather instability.

The Southwest Florida Regional Planning Council created maps of potential sea level rise impacts on the counties within the planning council (Beever et al. 2009; Beever et al. 2010). The maps created cover Sarasota County, Charlotte County, Lee County, and Collier County. All of the maps are set for 5-ft of sea level rise and show the likelihood of protection into four categories: shore protection almost certain, shore protection likely, shore protection unlikely, and no shore protection. This project was funded by the EPA for six of the planning councils in Florida. Since the project was in conjunction with the 6 other planning councils, the elevation data used was the 5-, 10-, 15- and 20-ft NGVD contours because the all of the studies needed to use the same data for the whole state. This project lays the groundwork for the development of conceptual models of climate change effects, habitat succession predictive tools, and local government guidance resolutions.

This is not a model but an application of bathtub model to the region. It used medium 1 arc LiDAR, which is not sufficient for detailed studies. However the project has useful topographic input and provides useful information for coastal areas. It does not address groundwater conditions which need to be known to outline flooding potential. Corrections are also needed for LIDAR data.

Water Management District Comprehensive Presentation of SLR

This presentation given by the South Florida Water Management District provides an overview of sea level rise and its potential impacts on Florida. Within this presentation the SFWMD provides a map of flood inundation tools, a digital elevation maps project. These maps use 2007-2008 FDEM LiDAR data, with vertical accuracies of +/- 0.6ft for open terrain and +/- 1.19ft for other land covers, with a confidence level of 95%. The elevations for the map are in 1 foot increments from ≤-1 to <14 feet. The geographic location of this map covers all of Florida from the northern edge of Palm Beach County to Key West (Shugar & Obeysekera 2010). This is one of latest efforts of the SFWMD to evaluate the impacts of SLR using most recent topographic data. This is an application, not a model. It applies a bathtub model result with all the implications of same. However this project has useful topographic input and provides useful information for coastal areas. A disadvantage is that groundwater conditions need to be known to outline flooding potential. Corrections are also needed for LIDAR data.

Charlotte Harbor Climate Ready Estuary Program

The Charlotte Harbor Climate Estuary Program created a set of sea level rise maps that showed potential impacts to the Charlotte Harbor area at three projected sea level rise rates. The three projections were the low (0.6ft), intermediate (1.7ft), and upper levels (3.9ft) of sea level rise predictions determined using a combination of literature sources to develop sea level rise scenarios over varing time horizons: Stanton and Ackerman 2007, USACE and Southwest Florida Regional Planning Council. (Charlotte Harbor National Estuary Program and the Southwest Florida Regional Planning Council 2010).

This is not a model but an application of a bathtub model to the region. It used medium 1 arc LiDAR, which is not sufficient for detailed studies. However the project has useful topographic input and provides useful information for coastal areas. It does not address groundwater conditions which need to be known to outline flooding potential.

Weiss and Overpeck Sea Level Rise Maps

The sea level rise maps created by these scientists use USGS digital elevation models to calculate areas that may be affected by sea level rise. These susceptible areas are *"based solely on elevation and adjacency to the sea for regions around the globe"* (Weiss & Overpeck 2006). The resulting maps can be overlaid with information such as airports, cities, highways, railroads, rivers, etc. For the Florida based maps sea level is graphically shown at current levels and increments of 1-meter, up to 6 meters.

This model is useful for high level evaluation of potential vulnerability, which is what FAU has used it for. However, it is not detailed enough for site specific vulnerability as it is basically a bathtub model. The model is topography based and outlines all land below a certain elevation. The model ignores groundwater impacts and does not deal with the probability of timing of changes which is necessary for policy discussions.

Coastal Services Center in NOAA

This is not a model but a website that provides an inventory viewer that shows what topographic and bathymetric data is available or any one location (NOAA Coastal Services Center 2009). The regional inventory for the southeast was completed in 2009, and the Gulf of Mexico inventory was competed in 2007. There is also a tool called the risk and vulnerability assessment tool (RVAT) within the coastal services center; however, it is only for Brevard and Volusia Counties. This tool uses information about increasing flood protection, reducing flood risk, reducing insurance premiums, and storm surge inundation. (NOAA Coastal Services Center 2010). An advantage of this data is that is uses high resolution bathymetric data only. A negative is that RVAT is not useful for this project and that this model is not a sea level rise prediction tool.

USGS Future Impacts of Sea Level Rise on Coastal Habitats and Species (FISCITS)

The FISCITS is a new modeling effort to integrate ecological and hydrological models with the intent to assess the impacts of sea level rise in the Greater Everglades. FISCITS stands for "*Future Impacts of Sea Level Rise on Coastal Habitats and Species*" (Langtimm et al. 2010). Started in March 2009, this is an integrated bathtub application to predict sea level rise effects for resource management by combining hydrological and biological models. This model is also based on previous USGS models and research from the Comprehensive Everglades Restoration Plan (Langtimm et al. 2010). This model is location specific and does not relate to global models.

USGS South Florida Ecosystem Portfolio Model (EMP)

The USGS South Florida Ecosystem Portfolio Model (EMP) is a regional web tool that is GIS-based, decision-supported, and uses multi-criteria. This prototype model has been created with the intent to evaluate proposed land cover/land use changes and land use plans. With the EPM model, land-use scenarios are evaluated based on land cost, economic benefits and ecological metrics. Future evaluations will include integrated land-use/sea level rise scenarios, based on vulnerability and quality-of-life metrics. Between ecological/environmental and economic modeling approaches, EPM represents a methodological middle ground. This model has the potential to be used for sea level rise scenarios (Labiosa et al. 2009). This model is location specific and does not relate to global models.

USGS Tides and Inflows in the Mangroves of the Everglades (TIME)

TIME is a USGS model which simulates salinity variations and major hydrologic processes on localized temporal and spatial scales in order to evaluate hydrologic changes in different sea level rise scenarios. The goal of the TIME model is to provide reliable hydrologic information about the response of the Everglades to sea level rise and provide scenarios to represent sea level rise with water-management schemes (Bahm et al. 2010). This model is location specific and does not relate to global models.

USGS Internet-based Modeling, Mapping, and Analysis for the Greater Everglades (IMMAGE)

The prototype model "*Internet-Based Mapping, Modeling, and Analysis for the Greater Everglades*" or IMMAGE is being developed by the USGS. Eventually this model will serve as a web interface for four different sea level rise impact assessment models. The goal is for IMMAGE improve the "*usability*" of these four key models. The four models which IMMAGE will create interfaces for include: BISECT (Biscayne and Southern Everglades Coastal Transport), habitat distribution models which use output from BISECT (developed by Everglades National Park), the National Land Change Community Model and the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model (Hearn et al. 2010). This model is location specific and does not relate to global models.

USGS Biscayne and Southern Everglades Coastal Transport Model (BISECT)

BISECT or Biscayne and Southern Everglades Coastal Transport is a spatially-extensive model which predicts hydrologic responses to natural and man-made events. BISECT was also developed to evaluate the Comprehensive Everglades Restoration Plan (CERP) ecosystem restoration and the effects of sea level rise on water flow and solute transport. The model was created by linking the USGS TIME model (Tides and Inflows in the Marshes of the Everglades) with a ground/surface water model of Biscayne Bay, the existing conditions simulated within the model fall in the time period 1996-2004 and the grid size of the model is 500 x 500 meters.(Lohmann, Swain, & Decker 2010). This model is location specific and does not relate to global models.

MIT USGS Science Impact Collaborative (MIT MUSIC) Everglades Project

In the MIT MUSIC program (MIT USGS Science Impact Collaborative) there is a Florida based project which looks at conservation and climate change responses. This scenario-based research investigation aims to better illustrate the challenges and future conditions decision-makers may need to consider in developing conservation strategies. The study investigates a number of possible trajectories of future land use/change scenarios with respect to climate change, shifts in planning approaches and regulations, population change, and variations in financial resources. Through a systematic exploration at the landscape-scale, this research aims to identify some of the major challenges to future conservation efforts. The project seeks to emphasize connecting/buffering habitats through land acquisition and creating a national climate change adaptation strategy. The US Fish and Wildlife Service hired MIT to help with this task. MIT uses a systematic scenario-based approach in their methods. The model does not predict change, but rather creates a plausible range of conditions. The time frame for the spatially-explicit scenarios is 2050-2100.

The methodology for the model starts with a literature review and manager survey. Then the assumptions, rules, and constraints from the first part are packaged into scenarios. MIT works with partners like USGS to simulate the scenarios. Scenarios are conceived not as blueprints for the future, but as learning tools for the management of uncertainty. The scenarios are internally-consistent bundles of assumptions with a number of dimensions. Each scenario is projected into the future using a computer simulation technique that creates land use visualizations called "*Alternative Futures*" (AF). The last step is to consider potential impacts from the land and hydrologic changes derived from the scenarios. The model uses GIS to organize data and represent complex processes. The result is a set of scenarios which bind current uncertainties like climate change (MIT - USGS Science Impact Collaborative 2010). Inclusion of climate change uncertianties and perceptions of managers with a modeling framework is one of the unique advantages of this project and has high relavance to Florida. It is not a sea level rise program. The projections are limited to 50 year horizon. This model is not location specific and does not relate to global models.

Miami-Dade County Wanless Maps

Harold Wanless of the University of Miami is on the Miami-Dade County Climate Change Task Force. The maps and projections from Wanless portray potential impacts of climate change on the Miami-Dade region. The sea level rise projections are based on the IPCC 2007 projections, but note that Global sea level rise (based on tide gauge and satellite data) have been following the highest end of the 2001 IPCC sea level projection. The project attempts to capture thermal expansion (1.6 mm/yr), plus glacial retreat (1.2 mm/yr). Thermal expansion is projected to contribute more than half of the average rise, but land ice will lose mass increasingly rapidly as the century progresses. The study noted that *"an important uncertainty relates to whether discharge of ice from the ice sheets will continue to increase as a consequence of accelerated ice floC5w, as has been observed in recent years.* (Wanless 2009). Dr Wanless' maps include projections altered to include glacial processes that were not included in the IPCC projections. Sea level rise impact maps are created using satellite altimeter data for the sea level rise. Figure 23 shows the satellite comparison to the published sea level rise maps. What this shows is that sea level rise appears to be tracking the high rate estimates (5+feet) (Wanless 2009). The Science Committee's Statement on Sea Level can be used by the County in the Coming Century to guide future climate change adaptation policy.

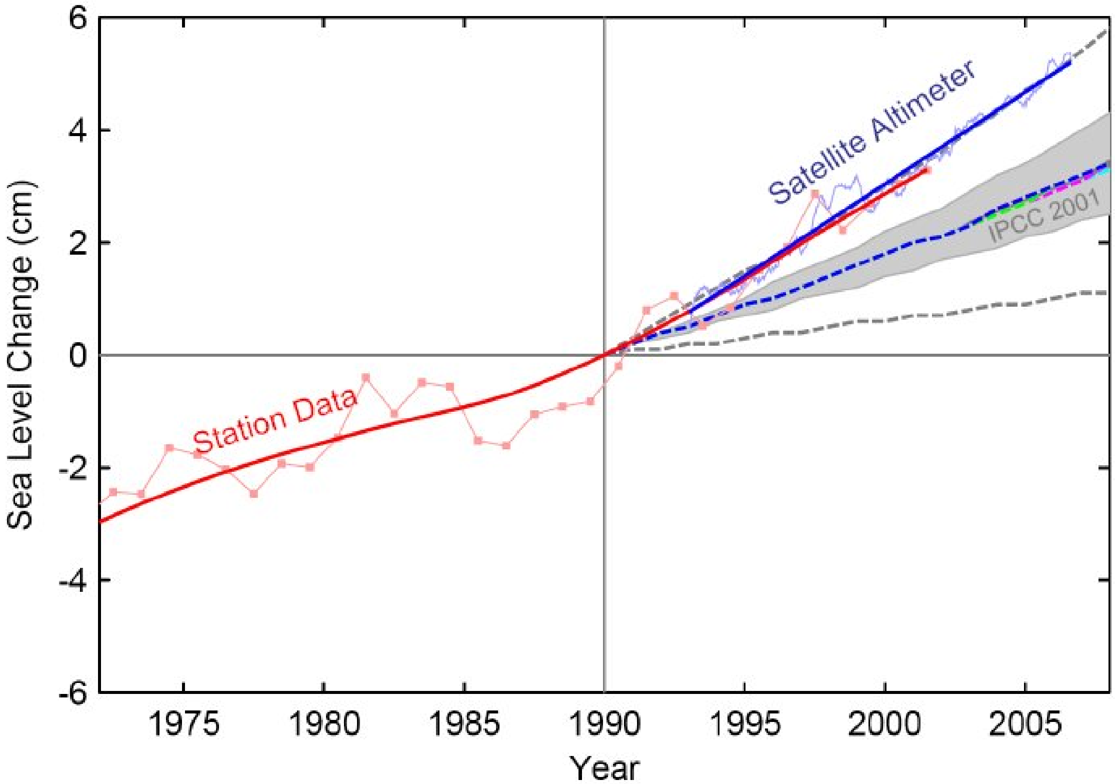

Figure C-5: Satellite altimeter projection compared to published maps.

Appendix D: Data Gaps Identified by Research Groups

There were a series of gaps identified by research groups. These gaps cover needs surrounding sea level rise projections and impacts.

For the Florida Keys the following gaps were identified:

- Improved National Elevation Dataset(NED)-based SLR modeling focused on future shorelines, dominance of generalized habitat types, and property values (The Nature Conservancy 2009)

- Improved analysis and mapping capabilities for identifying areas at risk that are vulnerable to sea level rise by utilizing the most recent LiDAR data (Broward County Climate Change Task Force 2010)

- LIDAR data for entire Florida Keys

- Complete Sea Level Affecting Marshes Model (SLAMM) or similar analysis of select areas of the Keys to improve predictions of future habitat distributions with and without modeled shoreline hardening as a variable to help determine if large scale shoreline hardening is a viable response to SLR and what the ecological consequences of that response would be (The Nature Conservancy 2009)

- Development of a working understanding of future marine habitat distribution driven by SLR (The Nature Conservancy 2009)

- Remaping of the freshwater lenses of Big Pine Key to determine if SLR has had a measurable impact on the lenses in the twenty years since the last lens mapping study and install a network of permanent groundwater monitoring wells to help track future SLR-driven changes in lens distribution and water quality (The Nature Conservancy 2009)

- Better projections for sea level rise. Without more regional-specific and firm projections, it is difficult to accurately predict the potential effect and develop adaptation strategies of sea level rise on District mission elements (SFWMD Interdepartmental Climate Change Group 2009)

The South Florida Water Management District identified the following gaps on rainfall and flood control:

- Significant gaps in the information needed to project rainfall accurately, especially changes in timing, amounts, and distribution

- Due to the amount of uncertainty of rainfall projections, the need for changes in the flood control system is currently unknown (SFWMD Interdepartmental Climate Change Group 2009)

- Develop strategies for retrofitting flood control gates for sea level rise (Broward County Climate Change Task Force 2010)

- Develop collaboration with international climate scientists, to refine climate predictions for Florida in partnership with federal agencies, international efforts, and Florida universities to (Broward County Climate Change Task Force 2010):

    - Undertake review of current studies and models
    - Consider undertaking updating model development to more precisely forecast Florida's changes in weather patterns
    - Undertake specific analysis of uncertainties and contingencies in climate Scenarios for Florida

Broward County Task Force concluded:

- Develop strategies, cost/benefit analyses, and schedules for raising or relocating railroad tracks in anticipation of accelerated sea level rise and other potential effects of climate change (Broward County Climate Change Task Force 2010)

The National Academy of Sciences:

- Expand and maintain comprehensive and sustained climate observations. Regular and sustained observations of climate variables are needed to provide real time information about climate change to monitor the progress of climate change, inform climate-related decision making, and to monitor the effectiveness of actions taken to respond to climate change (The National Academy of Sciences National Research Council 2010)

- Continued research on the mechanisms and manifestations of natural climate variability in the atmosphere and oceans on a wide range of space and timescales, including events in the distant past. Improved understanding of regional variability modes is also critical for improving regional climate projections (The National Academy of Sciences National Research Council 2010)

- Develop more informative and comprehensive scenarios of drivers of future climate forcing and socioeconomic vulnerability and adaptive capacity. The development of scenarios allows better understanding of the dynamics of the interconnected human-environment system and, in particular, how the dynamics will change depending on the choices we make (The National Academy of Sciences National Research Council 2010)

- Increased understanding of climate system forcing, feedbacks, and sensitivity. Continued research on the basic mechanisms and processes of climate change can be expected to yield additional progress. Some critical areas for further study include the following: (The National Academy of Sciences National Research Council 2010)

- Continued research to improve estimates of climate sensitivity, including theoretical, modeling, and observationally based approaches
  - Improved understanding of cloud processes, aerosols and other short-lived forcing agents, and their interactions, especially in the context of radiative forcing, climate feedbacks, and precipitation processes
  - Continued theoretical and experimental research on carbon cycle processes in the context of climate change, especially as they relate to strategies for limiting climate change (CCSP 2007; The National Academy of Sciences National Research Council 2010)
  - Improve understanding of the relationship between climate change and other biogeochemical changes, especially acidification of the ocean
  - Improve understanding of the hydrologic cycle, especially changes in precipitation
  - Improved understanding of the mechanisms, causes, and dynamics of changes in the cryosphere, especially changes in major ice sheets and sea ice

- Improve regional climate modeling, observations, and assessments. Given the importance of local and regional information to decision makers, and the fact that it might take decades to develop global models with sufficient resolution to resolve local-scale processes, it is essential to continue improving regional climate information, including observations and assessments of regional climate and climate-related changes as well as models that can project inter-annual, decadal, and multi-decadal climate change, including extreme events, at regional-to-local scales across a range of future global climate change scenarios (The National Academy of Sciences National Research Council 2010)

- Greater understanding of thresholds, abrupt changes, and other climate "surprises." Some of the largest potential risks associated with future climate change come not from the relatively smooth changes in average climate conditions that are reasonably well understood and resolved in current climate models, but from extreme events, abrupt changes, and surprises that might occur when thresholds in the climate system (or related human or environmental systems) are crossed (The National Academy of Sciences National Research Council 2010)

- Foster adaptive coastal management actions with a long-term, systemic perspective while avoiding the worst economic, social, and ecological consequences for coastal areas (The National Academy of Sciences National Research Council 2010)

- Develop tools to assess local vulnerability to sea level rise in the context of multiple stresses, such as increased storm surge or rainfall rates, and the feasibility and acceptability of various adaptation options

- Reduce scientific uncertainties associated with ice sheet changes. Comprehensive, simultaneous, and sustained measurements of ice mass and volume changes and ice velocities are needed, along with measurements of ice thickness and bed conditions, both to quantify the current contributions of ice sheets to sea level rise and to constrain and inform ice sheet model development for future assessments (The National Academy of Sciences National Research Council 2010)

- Improve understanding of ocean dynamics and regional rates of sea level rise. Direct, long term monitoring of sea level and related oceanographic properties via tide gauges, ocean altimetry measurements from satellites, and an expanded network of *in situ* measurements of temperature and salinity through the full depth of the ocean water column are needed to quantify the rate and spatial variability of sea level change and to understand the ocean dynamics that control global and local rates of sea level rise (The National Academy of Sciences National Research Council 2010)

- Develop tools and approaches for understanding and predicting the vulnerability to, and impacts of, sea level rise on coastal ecosystems and coastal infrastructure, as well as for impacts of sea level rise on infrastructure, including ports, roads, cities, dikes, levees, and freshwater aquifers and storage facilities, should take into account potential shifts in storm patterns, rainfall rates, and other climate changes (The National Academy of Sciences National Research Council 2010)

- Expand the ability to identify and assess vulnerable coastal regions and populations and to develop and assess adaptation strategies to reduce their vulnerability (The National Academy of Sciences National Research Council 2010)

- Develop decision support capabilities for all levels of governance. Methods for identifying preferences and weighing alternative adaptive responses will be needed as environmental and social conditions change with climate change (The National Academy of Sciences National Research Council 2010)

Appendix E: Planning Implementation Tools for Adaptation

The planning implementation tools for adaptation below are an extension of the tools discussed in section 6. When regional planners were asked what resources might be made available from the state that would enhance the ability to account for the potential impacts of sea level rise in long-range planning, the planners listed the following (n being the number of responses):

1. Credible predictions of sea level rise scenarios for which planning would be appropriate coupled with information about likely impacts and best practices for adaptation (n=18);

2. Public education that can serve to raise public awareness of the importance of dealing with potential sea level rise impacts now (n=3);

3. Policy direction as to how local governments should address sea level rise in comprehensive plans (n=5); and

4. Funding to help defray the costs of conducting local vulnerability studies and assessments of practical adaptation options. (Deyle, Bailey, & Matheny 2007)

5. Maps of current and proposed wildlife corridors and potential coastal ecosystem land acquisition sites to facilitate permitting and benefit both natural and infrastructure SLR adaptations.

Coastal managers from all levels of government are concerned about current and future risks to coastal areas. In order to develop adequate responses to the risks posed by climate change and sea level rise, they require answers to questions such as:

- How much will sea level rise in the future and on what time scales?

- How will sea level rise and changing storm patterns translate into local problems such as erosion, flooding, damage to infrastructure, and loss of ecosystems?

- What coastal protection measures are physically and economically feasible and socially and environmentally acceptable in different locations, and how much time do we have to start implementing these measures?

- At what point is it more cost effective to retreat from the shoreline than to defend coastal land uses in place?

- How uncertain is the information about sea level rise and other coastal (physical, ecological, and socioeconomic) processes, and what are the implications of these uncertainties for decision making? (The National Academy of Sciences National Research Council 2010)

On the national level, mainstreaming adaptation across the federal government in response to unavoidable climate change will require a coordinated federal response, one that could take the following approach, recommended by the Pew Center on Global Climate Change (Smith et al. 2010):

1. Establish a National Adaptation Program:
   - Create a multiagency Adaptation Coordinating Committee to manage and oversee the program, including the development of strategic planning guidance, national adaptation policies, and the coordination and integration of federal adaptation activities

   - Create Sector Working Groups chaired by lead agencies that represent the major cross-cutting substantive issues for each sector impacted by climate change

   - Create an Adaptation Program Office in the Executive Office of The President to support the Adaptation Coordinating Committee and the National Adaptation Program

2. Develop Adaptation Strategic Plans:
   - Create strategic planning guidance that establishes national adaptation goals, objectives, and priorities as well as substantive and procedural expectations for strategic plans

   - Require the development of federal agency adaptation strategic plans by all agencies with significant responsibility for federal programs or resources either vulnerable to climate change or necessary to promote adaptation

   - Call for sector adaptation strategic plans to be developed by multiagency Sector Working Groups for key U.S. sectors vulnerable to climate change

   - Develop a national adaptation strategic plan that supports national adaptation goals, objectives, and priorities, and provides a clear focus on the resolution of multiagency issues for specific impacts and sectors as well as overall barriers to and recommendations for national adaptation efforts

   - Provide direction and technical support for state adaptation strategic plans

   - Establish a multiagency National Climate Service to provide demand-driven and usable climate information, guidance, and other technical resources to end users across sectors, regions, and political jurisdictions. The interagency service would be coordinated by NOAA and report to the Adaptation Coordinating Committee. Sector Working Groups reporting to the Adaptation Coordinating Committee, but led by other federal agencies with sector expertise, should involve stakeholders in identifying end-user needs and developing appropriate decision support products and services as a core element of the National Climate Service

   - Direct the U.S. Global Change Research Program to evaluate and expand its current research agenda to include adaptation research needs within an Adaptation Research Program. The Adaptation Program Office would prepare a bi-annual report to the U.S. Global Change Research Program Integration and Coordination Office and the Subcommittee on Global Change Research on research needs identified through the

Adaptation Strategic Planning Initiative and the National Climate Service

- Convene an interagency task force reporting to the Adaptation Coordinating Committee to develop guidance, recommendations, and draft regulations for considering the environmental impacts of climate change on major federal actions in EISs as required under NEPA (Smith et al. 2010)

The White House Interagency Report provides a national approach to climate change adaptation, outlining the role of the Federal Government (White House Council on Environmental Quality 2010).

The White House Council on Environmental Quality principles for adaptation:

- Adopt Integrated Approaches: Adaptation should be incorporated into core policies, planning, practices, and programs whenever possible
- Prioritize the Most Vulnerable: Adaptation plans should prioritize helping people, places and infrastructure that are most vulnerable to climate impacts and be designed and implemented with meaningful involvement from all parts of society
- Use best Available Science: Adaptation should be grounded in the best-abvaialable scientific understanding of climate change risks, impacts, and vulnerabilities
- Build Strong Partnerships: Adaptation requires coordination across multiple sectors and scales and should build on the existing efforts and knowledge of a wide range of public and private stakeholders
- Apply Risk Management Methods and Tools: Adaptation planning should incorporate risk management methods and tools to help identify, assess, and prioritize options to reduce vulnerability to potential environmental, social, and economic implications of climate change
- Apply Ecosystem-based Approaches: Adaptation should, where relevant, take into account strategies to increase ecosystem resilience and protect critical ecosystem services on which humans depend to reduce vulnerability of human and natural systems to climate change
- Maximize Mutual Benefits: Adaptation should, where possible, use strategies that complement or directly support other related climate or environmental initiatives, such as efforts to improve disaster preparedness, promote sustainable resource management and reduce greenhouse gas emission, including the development of cost effective technologies,
- Continuously Evaluate Performance: Adaptation plans should include measureable goals and performance metrics to continuously assess whether adaptive actions are achieving desired outcomes

The White House Council on Environmental Quality recommended policy goals and actions for the Federal Government:

1. Encourage and Mainstream Adaptation Planning across the Federal Government – Climate change will challenge the mission, operations, and programs of nearly every Federal

agency. Ensuring that the Federal Government has the capacity to execute its missions and maintain important services in the face of climate change is essential.

- Implement adaptation planning within Federal agencies
- Employ a flexible framework for agency adaptation planning
- Use a phased and coordinated approach to implement agency adaptation

2. Improve Integration of Science into Decision Making – Access to integrated, interdisciplinary science is critical to understanding potential climate change impacts, and informing the development, implementation and evaluation of response strategies.

- Create a "roadmap" of existing Federal science efforts that inform and support adaptation
- Prioritize activities that address science gaps important to adaptation decisions and policies
- Build science translation capacity to improve the communication and application of science to meet the needs of decision makers
- Explore approaches to develop an online data and information clearinghouse for adaptation

3. Address Key Cross-Cutting Issues – The breadth of certain climate change impacts creates challenges that cut across the jurisdictions and missions of individual Federal agencies. Addressing these issues will require a collaborative approach along with coordination and partnerships at the local, state, Tribal, and regional levels. The Task Force focused on an initial set of cross-cutting issues and recommends the following actions:

<u>Improve water resource management in a changing climate</u>

- Strengthen data and information systems for understanding climate change impacts on water
- Improve water-use efficiency to reduce climate change impacts
- Develop a national action plan to strengthen climate change adaptation for freshwater resources

<u>Protect human health by addressing climate change in public health activities</u>

- Enhance the ability of Federal decision makers to incorporate health considerations into adaptation planning
- Build integrated public health surveillance and early warning systems to improve detection of climate change health risks
- Promote resilience of individuals and communities to climate-related health risks
- Build resilience to climate change in communities
- Ensure relevant Federal regulations, policies, and guidance demonstrate leadership on community adaptation

- Integrate adaptation considerations into Federal programs that affect communities
- Facilitate the incorporation of climate change risks into insurance mechanisms
- Explore a public/private partnership to produce an open-source risk assessment model

<u>Address additional cross-cutting issues</u>

- Develop a strategic action plan focused on strengthening the resilience of coastal, ocean, and Great Lakes communities and ecosystems to climate change

4. Enhance Efforts to Lead and Support International Adaptation – Climate change poses risks and opportunities that are important to many of the U.S. Government's international development, security, and diplomatic priorities. Climate change adaptation should be a core consideration in the design and implementation of U.S. foreign assistance activities. Agencies should enhance collaboration to support international adaptation objectives.

- Develop a Government-wide strategy to support multilateral and bilateral adaptation activities and integrate adaptation into relevant U.S. foreign assistance programs
- Enhance collaboration on adaptation among international development, national security, and technical support agencies
- Engage global development partners and the private sector to promote knowledge sharing and coordinate investments

5. Coordinate Capabilities of the Federal Government to Support Adaptation – The Federal Government should improve coordination of its science, services, and assessments to better support stakeholders.

- Build and maintain strong partnerships to increase responsiveness of Federal Government activities to support local, state, and Tribal needs
- Develop regional climate change adaptation consortia among Federal agencies
- Establish performance metrics for evaluating Federal adaptation efforts

Appendix F: Approaches to Incorporate Climate/Transportation Information

The approaches that may be taken when incorporating climate change and transportation information include scenario planning, timeframes, risk assessment, integrated projections, risk analysis tools, region based analysis, interdisciplinary research, identification of vulnerable assets, identification of opportunities for adaptation, understanding changes in facility life span, and understanding the consequences of failure and assessing the risks, costs, and benefits of adaptation.

Scenario Planning

Scenario development is a different kind of modeling approach. Typically, scenarios attempt to outline possible features in relation to changes in two or more parameters. One or more parameters are considered as driving forces which result in a potential array of changes in dependent variables. For example, if population growth is considered a prime driving force, then the possible impact on other factors such as land use, highway development, water disposal, etc. can be analyzed. A recent scenario for Florida projected the potential impact of the combined growth management plans of each county and municipality with a substantive impact on other parameters.

Scenario Development has been used in the Greater Everglades Region by the MUSIC group from MIT to depict the possible impacts of climate change on landscape transformation in the face of climate change. Scenarios do not predict the future: they illustrate possible futures to encourage decision making that will enhance desirable futures and prevent less desirable ones.

MUSIC is a two-year initiative funded by USGS and the U.S. Fish and Wildlife Service, with the goal of “addressing the challenge of climate change in the Greater Everglades Landscape” (Vargas-Moreno et al. 2010). The resulting management-relevant scenarios derived from the project are learning tools which show potential projections for the years 2020, 2040, and 2060 (Vargas-Moreno et al. 2010). The “alternative futures” scenarios are visualizations of landscape transformations such as inundation (Vargas-Moreno et al. 2010). Partnerships may be created as a result of managers using these scenarios as a learning tool to “understand the cumulative impacts of possible decisions across a range of scales” (Vargas-Moreno et al. 2010).

Planning Timeframes

The timeframes generally used for the Federal transportation planning process (20 to 30 years) are short compared to the multi-decadal period over which climate changes and other environmental processes occur. While the current timeframe is realistic for investment planning, agencies need to consider incorporating longer-term climate change effects into their visioning and scenario planning processes that inform their long-range plans (Potter, Burkett, & Savonis 2008)**.**

Risk Assessment Approach

Given the complexities of climate modeling and the inherent uncertainties regarding the magnitude and timing of impacts of climate factors, the deterministic methods currently used to support decisions cannot fully address the range of potential environmental conditions that transportation managers need to consider. Adopting an iterative risk management approach would provide transportation decision makers, public officials, and the public a more robust picture of the risks to, and level of resilience of, various components of the transportation network (Potter, Burkett, & Savonis 2008).

The recommended conceptual framework for consideration of climate factors proposed incorporates four key factors that are critical to understanding how climate change may impact transportation (Potter, Burkett, & Savonis 2008):

1. *Exposure:* What is the magnitude of stress associated with a climate factor (sea level rise, temperature change, severe storms, and precipitation) and the probability that this stress will affect a transportation segment or facility?

2. *Vulnerability:* Based on the structural strength and integrity of the infrastructure, what is the potential for damage and disruption in transportation services from this exposure?

3. *Resilience:* What is the current capacity of a system to absorb disturbances and retain transportation performance?

4. *Adaptation:* What response(s) can be taken to increase resilience at both the facility (e.g., a specific bridge) and system levels?

The U.S. Climate Change Science Program has identified the following keys areas of research opportunities relevant to transportation decision-makers:

Integrated Climate Data and Projections

It would be useful to the transportation community if climatologists could continue to develop more specific data on future impacts. Higher resolution of climate models for regional and sub-regional studies would support the integration of region-specific data with transportation infrastructure information (Potter, Burkett, & Savonis 2008).

Risk Analysis Tools

Transportation planners need new methodological tools to address the uncertainties that are inherent in projections of climate phenomena. Such methods are likely to be based on probability and statistics as much as on engineering and materials science. The approaches taken to address risk in earthquake-prone areas may provide a model for developing such tools (Potter, Burkett, & Savonis 2008).

Region-based Analysis

Transportation in northern climates will face much different challenges than those in the south, as coastal areas will similarly face different challenges than interior portions of the country. Further, additional analysis on demographic responses to climate change, land use interactions, and secondary and national economic impacts would help elucidate what impacts climate will have on the people and the Nation as a whole, should critical transportation services in the region be lost (Potter, Burkett, & Savonis 2008).

Interdisciplinary Research

Collaboration between the transportation and climate research communities will benefit both disciplines in building methodologies and conducting analyses to inform the Nation's efforts to address the implications of climate change (Potter, Burkett, & Savonis 2008).

In 2008, the Transportation Research Board of the National Academies Committee on Climate Change and U.S. Transportation published recommendations for both research and actions that can be taken to prepare the U.S. transportation infrastructure for climate change (Transportation Research Board of the National Academies 2008):

- Transportation officials at all levels of government and in the private sector should inventory potentially vulnerable critical assets

- Transportation officials should incorporate climate change into their long-range plans for new facilities and maintenance

- Transportation officials should rely on more probabilistic techniques to guide decisions that weigh the cost of upgrading or protecting assets against the risk and consequences of failure

- Research programs should invest in developing monitoring technologies that can measure stresses and strains on key infrastructure assets and provide warning of pending failures

- Transportation professional associations should develop procedures to identify and share best practices in managing assets

The committee also laid out a decision framework for transportation professionals to use in addressing impacts of climate change on U.S. transportation infrastructure (Transportation Research Board of the National Academies 2008). The steps include: assess climate changes, inventory transportation infrastructure, analyze adaptation options and consider monitoring as an option, determine investment priorities, develop/implement a program of adaptation strategies for the near and long terms, and periodically assess the effectiveness of adaptation strategies.

In 2009, The Transportation Research Board of the National Academies Committee for Study on Transportation Research Programs to Address Energy and Climate Change recommended the following with regard to policies and strategies relating to the use of the transportation system and to assist infrastructure owners in adapting to climate change, based on the recommendations of the Transportation Research Board of the National Academies Committee on Climate Change and U.S. Transportation:

Identification of Vulnerable Assets and Locations

The task is more difficult than may be perceived because the severity of impact can be increased by a confluence of events. In the Gulf Coast region, for example, storm surges will be compounded by the land subsidence already occurring, increased wind speeds from more intense storms, and heavier precipitation. These interacting effects require careful and extensive analysis, as illustrated by the Global Change Research Program study of Gulf Coast infrastructure vulnerability (Savonis et al. 2008; Transportation Research Board of the National Academies 2009).

Identification of Opportunities for Adaptation of Specific Facilities

Once vulnerable assets have been identified, policy makers will need a range of options for responding which entails the conduct of a comprehensive review of policy, engineering, and other options for addressing risk. The objective would be to develop a database of options for specific facilities and regions that transportation officials could draw on (Transportation Research Board of the National Academies 2009).

Understanding Changes in the Life Span of Facilities Caused by Climate Change

The expected life span of facilities can be changed by climate influences such as heat, drought, wind loading, and flooding (Transportation Research Board of the National Academies 2009).

Understanding the Modes and Consequences of Failure

Better understanding of potential modes of failure and its consequences is crucial to informing the evaluation of options. Failure in this sense is not necessarily a catastrophic failure; it could be structural, functional, or economic. This research would summarize available understanding, both experiential and theoretical, to provide guidance on what transportation officials would need to prepare for (Transportation Research Board of the National Academies 2009).

Assessing the Risks, Costs, and Benefits of Adaptation

Once assets have been identified as vulnerable to climate change, possible effects on their future performance have been assessed, and options for responding to risk have been arrayed, policy makers need guidance on the costs and benefits of the various options. The objective of this research area would be to develop a framework for producing and refining estimates of costs and benefits. Such estimates may have to rely on judgment initially, but they should be refined with experience and research (Transportation Research Board of the National Academies 2009). The Committee also addressed the need for the development of models and tools to support decision-making, monitoring and sensing tools, and stakeholder involvement.

Appendix G: Summary of Projected Impacts on Transportation Infrastructure

Table 2 illustrates potential adaptation measures for the protection of transportation infrastructure, the importance of each of these will vary with location and community structure.

Table G-1: Tools for Protection of Transportation Infrastructure from Sea Level Rise Impacts

Transportation Resource Adaptation Alternatives
Protect Roadway Base • Increase stormwater drainage system capacity • Increase the number of pumping stations specifically installed to drain roadway right-of-ways • Identify offsite stormwater retention areas to divert excess stormwater • Eliminate exfiltration trenches as a drainage solution • Install wellpoint dewatering technology for permanent use • Raise roadway elevations
Protection of Roadway Surfaces • Increase roadway stormwater activity • Elevate roadways surfaces 5 feet above mean high tide (to a minimum of 10 ft NAV88) (will cause consequential stormwater runoff to adjacent properties) • Relocation of critical roadways • Re-route traffic, freight and transit routes
Abandon Roadways • Abandon roadways too low and with neighboring areas too low to elevate without private property impacts • Abandon state roadways and rights-of-way to local governments
Stormwater Management

Transportation Resource Adaptation Alternatives
• Reengineering canal systems, control structures and pumping stations
Provide Different Modes of Transportations **Transit** • Provide urban and intercity transit services • Provide accessibility and connectivity to and from transit centers • Increase transit route coverage and frequency • Promote transit patronage **Freight** • Evaluate logistic and schedule • Re-route existing freight routes • Institute short sea slipping among ports to decrease traffic load on local infrastructure. **Other** • Promote use of non-motorized vehicles • Provide connected bicycle and pedestrian paths • Promotion of rail and other transit methods • Promotion of alternative fuel and fueling infrastructure? • Provide special attention to adaptation on critical evacuation routes • Increased use of the canal network for transportation

This section is about a report by the National Research Council which shows the impacts that sea level rise can have on transportation infrastructure. Sea level rise is shown to have definite linkages with urban infrastructure through research like that of the Transportation Research Board. The links between sea level rise and infrastructure may lead to impacts on transportation. These potential transportation infrastructure impacts were analyzed in a recent study by the National Research Council of the National Academies (Adapting to the Impacts of Climate Change 2010). Below is a modified version of the findings that relate to sea level rise impacts on Florida:

Table G-2: Transportation Adaptation
Examples of ideas about specific options for facilitating transportation sector adaptation to climate change and identification of entities best poised to implement each option. Most adaptations are local and need to be tailored to local conditions. The suitability of each adaptation must therefore be evaluated in the context of local conditions. Where possible, the table refers to assessments and syntheses that consider multiple adaptation options and provide reference to specific studies. (The National Academy of Sciences National Research Council 2010)

Climate change	Impact	Possible adaptation action	Federal	State	Local govt.	Private sector	NGO/Indiv.
Long-term sea level rise	Permanent flooding of coastal land	Build or enhance levees/dikes for protection	□	□	□	□	
		Elevate critical infrastructure that is at risk for sea level rise	□	□	□	□	
		Abandon/move threatened facilities to higher elevations	□	□	□	□	
	Loss of barrier islands	Protect and/or relocate newly exposed railroads, highways, bridges	□	□	□	□	
		Switch to alternate shipping methods if waterborne transport cannot use the Intracoastal Waterway or other shipping channels				□	
	Impacts on infrastructure such as bridges or harbors (RFP-PI)[a]	Raise bridge heights and reinforce or relocate harbor infrastructure Establish adaptive standards to implement during regular maintenance and rebuilding of facilities	□	□	□		
New patterns of prevailing winds	Existing airport runways may become less efficient. Time of travel on long distance flights and transoceanic shipping may be affected	Increase airport runway lengths	□	□	□	□	
	Time of travel on long distance flights and transoceanic shipping may be affected.	Evaluate effects on logistics, adjust schedules				□	□
More intense precipitation	Change in hydrology	Revise hydrologic flood frequency models	□				
		Revise computational models for storm return frequencies					□
	Change to hydraulics	Revise design standards for hydraulic structures - culvers, drainage channels, highway underpasses	□	□			
		Reinforce at-risk structures with particular attention on bridge pier scouring	□	□	□		

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Examples of ideas about specific options for facilitating transportation sector adaptation to climate change and identification of entities best poised to implement each option. Most adaptations are local and need to be tailored to local conditions. The suitability of each adaptation must therefore be evaluated in the context of local conditions. Where possible, the table refers to assessments and syntheses that consider multiple adaptation options and provide reference to specific studies. (The National Academy of Sciences National Research Council 2010)

		Review hydraulic structures for deficiencies - culverts, drainage channels		□	□	□	
	More frequent flooding	Provide federal incentives to avoid development in flood plains	□				
		institute better land use planning for flood plain development including prohibition in some instances			□		
		Recognize the inherent cost to society of construction in flood prone areas				□	
		Elevate structures where possible; reconstruct to higher standards		□	□		
		Replace vulnerable bridges and other facilities		□	□		
		Harden infrastructure and port facilities		□	□	□	
	Changes in efficiency of some transportation modes; change in safety (or perception of safety) in some transportation modes	Shift transportation preferences among air, rail, ship, or highway routing as appropriate	□	□	□	□	□
Warmer temperatures and heat waves	Stress on pavements and road decks	Research on new pavement materials and bridge decking materials more resistant to heat stress and degradation	□				□
		Establish standards for and use heat resistant pavements		□	□		
		Replace vulnerable pavement, outdated expansion joints, or runways as needed		□	□		
		Revisit OSHA[b] standards for construction workers in light of higher temperatures and other climate stresses	□	□			
		Implement more nighttime construction		□	□	□	
	Railway buckling	Research on stresses in rails leading to buckling	□				□
		Implement changes in rail design to accommodate higher temperatures to prevent rail buckling				□	
	Lower air density	Increase airport runway lengths	□	□	□	□	

Table G-2: Transportation Adaptation

Examples of ideas about specific options for facilitating transportation sector adaptation to climate change and identification of entities best poised to implement each option. Most adaptations are local and need to be tailored to local conditions. The suitability of each adaptation must therefore be evaluated in the context of local conditions. Where possible, the table refers to assessments and syntheses that consider multiple adaptation options and provide reference to specific studies. (The National Academy of Sciences National Research Council 2010)

	Changes to engine fuel efficiency	Changes (+/-) to the amount of fuel needed in all forms of motorized transport	□			□	□
		Reevaluate airport runway lengths required to take off	□	□	□	□	□
Greater coastal storm strength with sea level rise	More extreme, or more frequent coastal flooding	Analyze transportation system vulnerabilities in light of storm surge potential	□	□	□		
		Revise anticipated future climate changes (e.g., precipitation intensity and duration curves) and require their use as a condition for federal investments in infrastructure and incorporate climate	□	□	□		
		Require climate change assessments in long range transportation planning in floodplains, and in land use planning in flood prone coastal areas	□	□	□		
		Include climate considerations in planning within metropolitan planning organizations (MPO's)			□		
		Indentify and take constructive action to provide and protect emergency evacuation routes	□	□	□		
		Revise FEMA flood maps	□				
		Strengthen port facilities to temporarily withstand flooding and surges	□	□	□	□	
		Elevate structures and resources	□	□	□	□	
		Build or raise seawalls/levees/dikes for protection	□	□	□	□	
		Surge barriers to protect vulnerable rives and adjacent infrastructure	□	□	□		
		Retrofit to strengthen - tie down bridge decks, protect piers against scour	□		□		
		Protect critical components - tunnels, electrical system		□	□		
		Abandon, relocate, or more infrastructure and facilities		□	□	□	

[a] Sources were abbreviated in the tables to conserve space. The abbreviations refer to the following publications: RFF-PI = Neumann & Price, 2009

[b] Occupational Safety and Health Administration