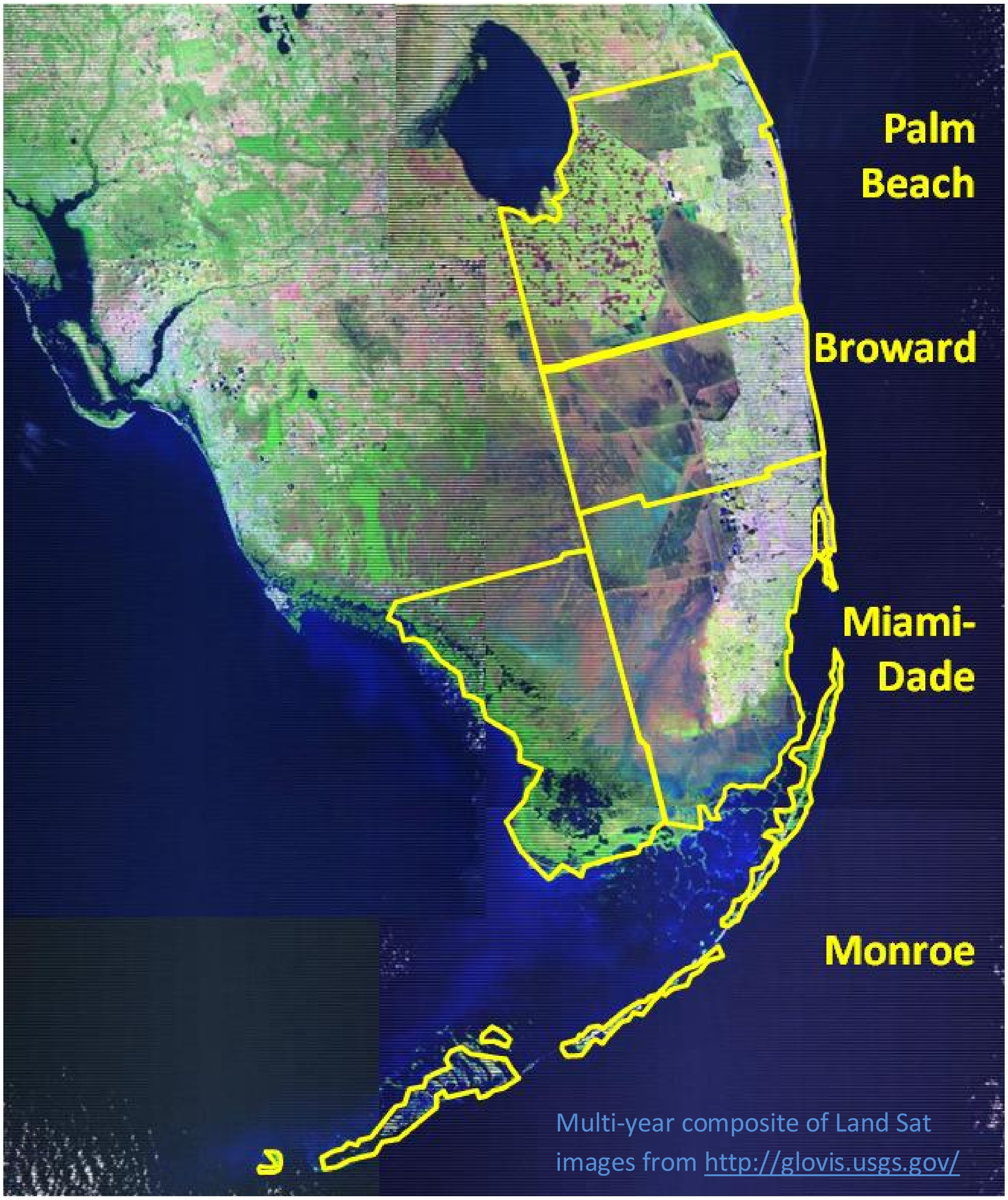
A Unified Sea Level Rise Projection for Southeast Florida

Southeast Florida Regional Climate Change Compact Counties



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Prepared by the Technical Ad hoc Work Group

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Executive Summary

Southeast Florida with its populous coastal counties, subtropical environment, porous geology and low topography is particularly vulnerable to the effects of climate change, especially sea level rise. At the October 23, 2009 Southeast Florida (SE FL) Regional Climate Leadership Summit, the local diversity in sea level rise (SLR) projections was highlighted as a concern and a barrier to achieving regionally consistent adaptation policies and to demonstrating a coordinated local effort to higher political levels. Following the summit, the four counties of Southeast Florida (Monroe, Miami-Dade, Broward and Palm Beach) entered into the SE FL Regional Climate Change Compact to work cooperatively to address climate concerns in the region. As expressed by the SE FL Compact Steering Committee, the Climate Compact Counties recognized the critical need to unify the existing local SLR projections to create a single regional SLR projection. Key participants in developing the existing projections and other local scientists specializing in the areas of sea level rise and climate change were invited to participate as the Regional Climate Change Compact Technical Ad hoc Work Group (Work Group). Their objective was to work toward developing a unified SLR projection for the SE Florida region for use by the SE FL Regional Climate Compact Counties and partners for planning purposes to aid in understanding potential vulnerabilities and to provide a basis for outlining adaptation strategies for the SE FL region.

Through a series of facilitated discussions, the Work Group reviewed the existing projections and the current scientific literature related to SLR with particular emphasis on the impact of accelerating ice melt on projections. The Work Group recommends that the SLR projection to be used for planning purposes in the SE FL region be based on the U.S. Army Corps of Engineers (USACE) July 2009 Guidance Document until more definitive information on future SLR is available. The projection uses Key West tidal data from 1913-1999 as the foundation of the calculation and references the year 2010 as the starting date of the projection. Two key planning horizons are highlighted: 2030 when SLR is projected to be 3-7 inches and 2060 when SLR is projected to be 9-24 inches (Figure E-1). Sea level is projected to rise one foot from the 2010 level between 2040 and 2070, but a two foot rise is possible by 2060. The historic tidal data for the past few decades is illustrated on the unified projection graphic to provide perspective on the projected rate of change of sea level. The historic rate extrapolated into the future is shown for comparison to the projected sea level rise curves but is not intended as a lower-limit projection. Due to the rapidly changing body of scientific literature on this topic, the Work Group recommends that the projection should be reviewed and possibly revised four years from final approval of this document by the SE FL Regional Climate Change Compact Steering Committee and after the release of United Nations Intergovernmental Panel on Climate Change Fifth Assessment Report.

The scientific evidence strongly supports that sea level is rising and, beyond 2060, will continue to rise even if mitigation efforts to reduce greenhouse gas (GHG) emissions are successful at stabilizing or reducing atmospheric GHG concentrations. A substantial increase in sea level rise within this century is likely and may occur in rapid pulses rather than gradually. However, precisely predicting future climate-induced sea level rise and associated rates of acceleration is difficult. Uncertainties exist because of natural variability, positive feedback mechanisms that accelerate select climate processes, the limitations of existing computer models and the inability to forecast the scope of human response in the near or long-range future to the need to limit greenhouse gas emissions and levels. Because of these limitations, a scientific narrative for beyond 2060 is provided to lend perspective on the potential for SLR toward the end of the century. Section E on "Sea Level Rise Projections Beyond 2060" describes (1) current global projections for the end of the century and (2) leading indicators and reinforcing feedback mechanisms of sea level rise, including continued emission of greenhouse gases, the impact of warm ocean water on glacial melt and ice sheets and open water impacts on pack ice.

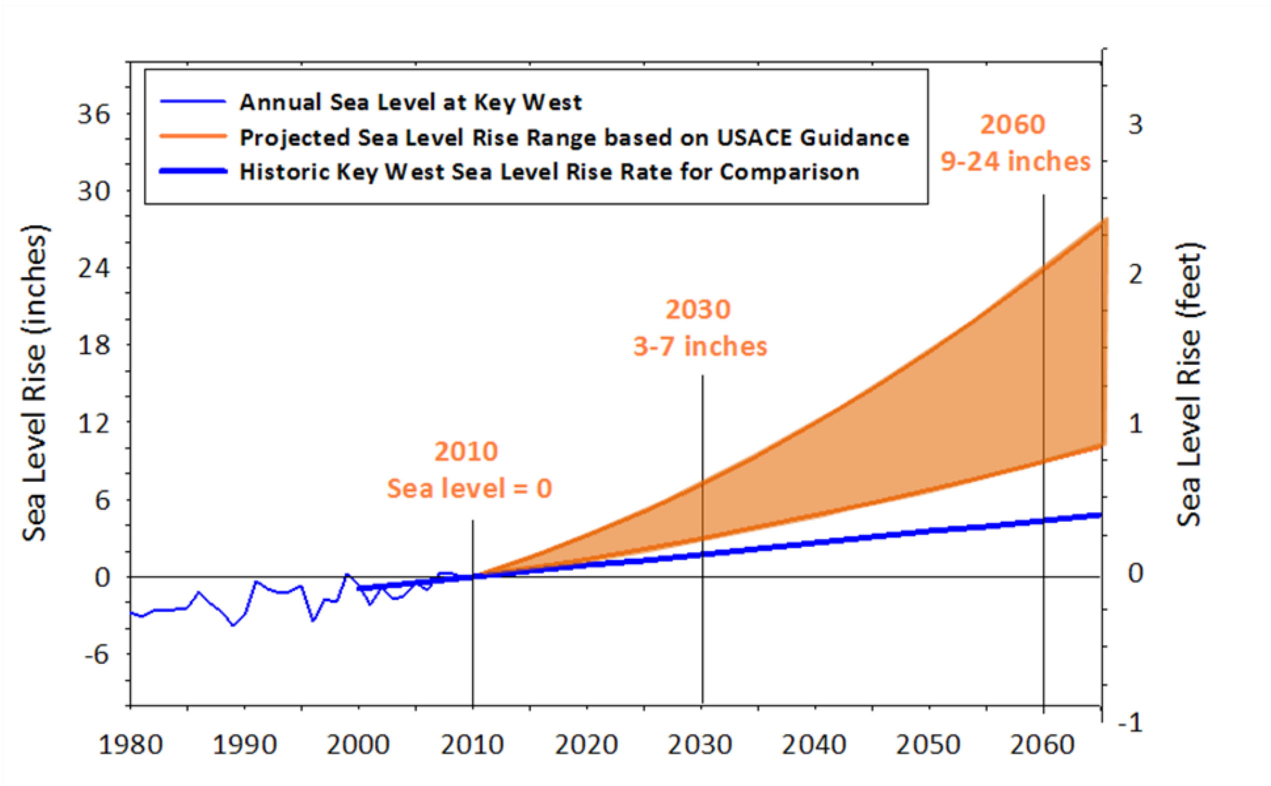


Figure E-1. Unified Southeast Florida Sea Level Rise Projection for Regional Planning Purposes. This projection uses historic tidal information from Key West and was calculated by Kristopher Esterson from the United States Army Corps of Engineers using USACE Guidance (USACE 2009) intermediate and high curves to represent the lower and upper bound for projected sea level rise in Southeast Florida. Sea level measured in Key West over the past several decades is shown. The rate of sea level rise from Key West over the period of 1913 to 1999 is extrapolated to show how the historic rate compares to projected rates.

Conclusions and Recommendations

The recommended projection provides guidance for the Compact Counties and their partners to initiate planning to address the potential impacts of SLR on the region. The shorter term planning horizons (through 2060) are critical to develop the SE FL Regional Climate Change Action Plan, to optimize the remaining economic life of existing infrastructure and to begin to consider adaptation strategies. As scientists develop a better understanding of the factors and reinforcing feedback mechanisms impacting sea level rise, SE FL community will need to adjust and adapt to the changing projections. Strategic longer term (beyond 2060) policy discussions will be needed to include development of guidelines for public and private investments which will help reduce community vulnerability to sea level rise impacts beyond 2060.

The following are recommendations of the Technical Ad hoc Work Group for consideration by the SE FL Regional Climate Compact Steering Committee to be used by the Compact Counties and their partners to develop the Regional Climate Change Action Plan.

a. The SE FL Unified SLR Projection should be based on the U.S. Army Corps of Engineers (USACE) July 2009 Guidance Document using Key West tidal data (1913-1999) as the foundation of the calculation and referencing the year 2010 as the starting date for sea level rise projections.

b. This projection should be used for planning purposes, with emphasis on the short and moderate term planning horizons of 2030 (USACE - 3-7 inches) and 2060 (USACE - 9-24 inches). The historical trend is provided only for comparison to the projected sea level rise curves.

c. A science-based narrative for 2060 and beyond provides context for the current state of scientific understanding and the potential issues which must be considered when looking toward the end of the 21st century and beyond.

d. The unified SE FL sea level rise projection will need to be reviewed as the scientific understanding of ice melt dynamics improves. The projection should be revised within four years of final approval of this document by the SE FL Regional Climate Change Compact Steering Committee. This timing is consistent with the release of Intergovernmental Panel on Climate Change Fifth Assessment Report which will provide a synthesis of the major findings in climate science to date.

e. Users of the projection should be aware that at any point of time, sea level rise is a continuing trend and not an endpoint.

f. The acceleration of sea level rise can be slowed and the magnitude reduced by actions to reduce greenhouse gas emissions. Substantial reduction in sustained long term emissions will result in a reduction in the cost of adaptation.

**This document was accepted by the SE FL Regional Climate Change Compact Staff Steering Committee on May 6, 2011 for use by the Regional Climate Change Work Groups in development of the SE FL Regional Climate Change Action Plan.*

A. Introduction

Local governments in Southeast Florida recognize that the region, with its populous coastal counties, subtropical environment, porous geology and low topography, is particularly vulnerable to the effects of climate change, especially sea level rise. Several advisory groups have been formed to make recommendations on mitigating greenhouse gases and other measures for adapting to the inevitable effects of climate change. While the 2007 report of the United Nations Intergovernmental Panel on Climate Change (IPCC 2007) proved to be a valuable source for the state of climate science for these advisory groups, the report warned that the sea level rise projections did not incorporate the contribution of land-based melting ice and therefore were probably low. Subsequent estimates that include the melting of grounded ice sheets confirm that the IPCC estimates are low and allow us to make more realistic projections (Horton et al 2008, Grinsted et al 2009, Pfeffer et al 2008, Siddall et al 2009, Vermeer and Rahmstorf 2009, and Jevrejeva et al 2010). Between 2008 and 2009, several entities developed SLR projections for the Southeast Florida (SE FL) area to incorporate the growing scientific evidence of accelerated melting of glaciers and ice sheets and to guide local climate change planning efforts (Table 1).

At the October 23, 2009 Southeast Florida (SE FL) Regional Climate Leadership Summit, the local diversity in sea level rise projections was highlighted as a concern and a barrier to achieving regionally consistent adaptation policies. Following the summit, the four county commissions of the region (Monroe, Miami-Dade, Broward and Palm Beach) signed the SE FL Regional Climate Change Compact to work together to address regional climate change issues. The SE FL Regional Climate Change Compact Steering Committee (Steering Committee), comprised of representatives of the four Climate Compact Counties and the South Florida Water Management District (SFWMD), recognized the critical need to unify the existing SE FL SLR projections creating a single sea level rise projection to use for regional planning purposes and to more effectively influence supportive policies at the state and federal levels.

Key participants in developing the existing projections and other local scientists knowledgeable about sea level rise and climate change were invited to participate on a Technical Ad hoc Work Group (Work Group) to jointly develop a unified sea level rise projection for use by the SE FL Regional Climate Compact Counties and partners. Work Group participants included representatives of the Miami-Dade County Climate Change Advisory Task Force (MDCCATF), the U.S. Army Corps of Engineers (USACE), Broward County Climate Change Task Force (BCCCTF), SFWMD, the University of Miami, National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory (NOAA-AOML), and Florida Atlantic University (FAU) (see the list of participants).

Prior to the first workshop, the Work Group and the Steering Committee participated in a survey to outline the policy implications of a unified sea level rise projection for Southeast Florida. More than half of the respondents agreed with the following reasons for needing a unified sea level rise projection:

- To create a single baseline for regional adaptation planning;
- To establish a foundation for the Regional Climate Change Action Plan;

- To ensure consistency in regional and local infrastructure planning and design;
- To strengthen advocacy for the Regional Climate Change Compact efforts by speaking with one voice on this topic; and
- To demonstrate regional cooperation and collaboration in technical matters.

The majority of respondents expected a local sea level rise projection to influence the understanding of regional risk to property, the design of public infrastructure and a variety of public policies. While this information was presented to the Work Group to provide context for their efforts, their main objective was to use available scientific literature to develop a unified SLR projection that will guide future policy decisions.

Table 1. Sea Level Rise Projections for Southeast Florida. Sea level rise (SLR) ranges are shown in inches rounded to the nearest half inch, for four planning horizons. The reference year represents the time point at which sea level equals zero.

Projection	Year Developed	Reference Year	SLR range			
			2030	**2050**	**2060**	**2100**
Historic-Key West (1920-2000) ‡		2000	2.5	4.5	5	9
Miami-Dade Climate Change Advisory Task Force (Miami-Dade 2008)	2007	2000	-	>18	-	36-60
Broward County Climate Change Task Force (Broward County 2010)	2009	2000	3-9	-	10-20	24-48
South Florida Water Management District (SFWMD 2009)	2009	1990	-	-	5-20	-
U.S. Army Corps of Engineers July 2009 Guidance Document*	2009	2010	3-7	7.0-17.5	9-24	19.5-57
Florida Atlantic University – Resilient Waters**	2009	2000	4.5-7	9-15	11.5-20	24-48

‡ Key West rate for 1910-2010 – 2.24 ± 0.16 mm/yr (NOAA) = 8.8 inches/century, calculated as a linear rate

*Calculations using Key West tide stations showing the intermediate to high range guidance equations (USACE 2009)

** FAU Resilient Waters – Quadratic Equation using 2-4 feet as the 2100 projection (Heimlich et al 2009)

The existing local projections varied not only in the range of values for SLR but in most other components as well (Table 1). The initial review revealed that they were developed at different times and incorporated different scientific literature in their synthesis. They also differed in the reference year, which represents a baseline for current sea level, making comparisons of magnitude across the projections difficult. The local projects also used different planning horizons. Also while some were based on ranges of SLR for a given year, others used complex formulas to determine the values.

From August – December 2010, the Work Group reviewed the existing projections, discussed the current scientific literature and developed the set of recommendations contained in this document for presentation to and approval by the Steering Committee.

This document is organized into three main sections. The first, Section B, is a discussion of the current state of SLR science. The second section (C) discusses planning projections through 2060, and (D) outlines the Work Group's recommendation for a unified SLR projection for the SE FL region. The final section (E) looks beyond 2060 to lend perspective on the potential for continued acceleration of SLR through the end of the century. Section E describes (1) current global projections for the end of the century, and (2) leading indicators of future sea level rise. As scientists develop a better understanding of the factors and reinforcing feedback mechanisms, the SE FL community will need to adjust and adapt future plans to the changes in the projected rates of sea level rise.

B. Scientific Summary

B.1 Factors influencing sea level rise

During a period of warming climate, the volume of water in the ocean is primarily impacted by thermal expansion and volume added from land-based sources of melting ice and groundwater depletion. According to the IPCC, thermal expansion of the ocean from the warming of ocean water accounted for 13-31% of the observed rate of sea level rise for the period of 1961-2003 (Bindoff et al 2007). For the period of 1993-2007, approximately 30% of the rate was due to ocean thermal expansion (Cazenave and Llovel 2010). Ice loss from mountain glaciers and the Greenland and Antarctic Ice Sheets accounted for approximately another 55%. Since 2003, the rate of ocean thermal expansion has slowed slightly while sea level has continued to rise. Melting land ice is estimated to have contributed 80% of observed sea level rise in the past five years (Cazenave and Llovel 2010). Acceleration of ice sheet loss since 1993 has been three times larger than that for mountain glaciers and ice caps and if it continues then melting of ice sheets will dominate sea level rise in the 21st century (Rignot et al 2011).

Relative sea level takes into account cumulative changes in the level of ocean waters plus local changes in the elevation of the land caused by uplift or subsidence, glacial rebound, and erosion of the coast. For example, parts of the Earth's surface are still undergoing adjustment due to the deglaciation event following the last Quartenary ice age (Cazenave and Llovel 2010). Preliminary results from the Continuously Operating Reference (COR) Stations, a network of permanent Global Positioning System receivers that monitor vertical and horizontal land motion, suggest the land elevation in Key West is rising slightly at 0.24 mm/yr (~1 inch/century) while the average of 5 other COR sites show that Florida may be sinking at a rate of 2 inches/century (Maul 2008). These land contributions account for most of the differences in the rates of sea level rise among Florida's tide gauge stations. However, South Florida coastal land elevations are considered to be relatively stable meaning that the land mass is experiencing neither significant uplift nor subsidence.

Ocean temperature, salinity, and atmospheric circulation patterns also influence oceans currents and sea level rise. The Gulf Stream will eventually be impacted by (1) changes in the Arctic atmospheric front, and (2) Atlantic circulation caused by ocean warming and freshwater fluxes in northern high latitudes. A slowing of the Florida Current and the Gulf Stream could result in rapid sea level rise primarily along the northeast coast of North America (Yin et al 2009). By 2100, these circulation changes could contribute an extra 8 inches of sea level rise in New York and 2 inches in Miami (Yin et al 2009).

B.2 Sea level rise in geological time

On geologic time scales, sea level has been both significantly higher and lower than today's level. Changing planetary conditions such as tectonics, volcanism, and orbital variations; as well as climate oscillations, solar dynamics, and anthropogenic forcing ensure that both local and global sea levels are dynamic. Reconstruction of paleoclimates (Siddall et al 2003) indicates that during glacial/interglacial cycles over the past several hundred millennia, sea level has varied from about 420 feet (120m) below to about 50 feet (15 m) above current levels (see Figure 1).

The rate of sea level rise has also been variable through geologic history, with reported extreme values of more than one foot of rise per decade. Since the last Glacial Maximum about 18,000 years ago, rates of sea level rise are reported at 26 mm/yr (~10 inches/decade) (Stanford et al 2010) to over 40 mm/yr (~16 inches/decade) (Fairbanks 1989, Stanford et al 2006). Sea level rose in a series of rapid 3-30 footsteps separated by periods of relative stability (Anderson and Thomas 1991; Anderson et al 2004; Bard et al 2010; Blanchon and Jones 1995; Dominguez and Wanless 1991; Florea and Vacher 2006; Jarrett et al 2004; Locker et al 1996; Rodriguez et al 2000).

Global temperature and sea level are strongly correlated. This can be established by comparing paleoclimatic temperature reconstructions with changes in sea level. Figure 1 shows an overlay of roughly 400,000 years of global temperature based on Lake Vostok ice cores (Petit et al 1999), and sea level from Red Sea sediment cores (Siddall et al 2003), and provides two obvious conclusions: 1) As air temperatures rise and fall, so does sea level; and, 2) Rapid and large changes in sea level have occurred in the past and are possible in the future.

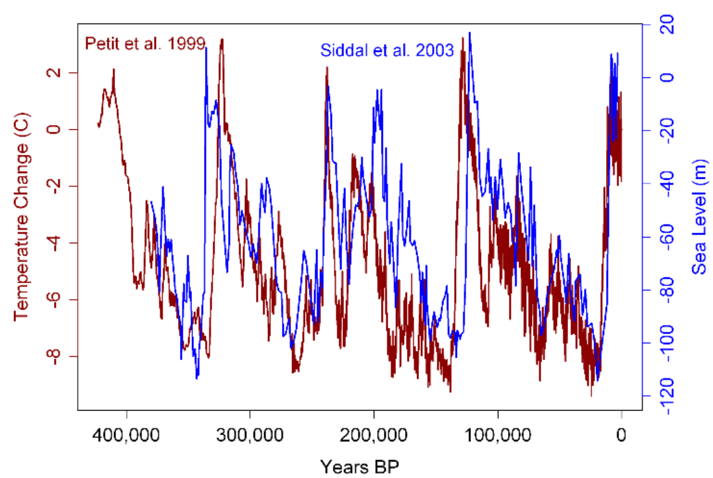


Figure 1. 400,000 Years of Reconstructed Temperature and Sea Level. Over geologic time, temperature (red) and sea level (blue) are well correlated (Siddall et al 2003).

B.3 Sea level rise in modern times

Following a small rapid sea level rise 2,500 to 2,400 years ago (Dominguez and Wanless 1991), global sea level change has been slow. Since this rapid pulse, the relative sea level in Florida has risen very slowly permitting a long period of stabilization – and even seaward expansion – of our coastal environments. However, tide gauge and satellite measurements show that the global rate of sea level rise has been increasing since about 1930 (Bindoff et al 2007, figure 5.13). Early estimates of this rate averaged over the entire 20th century found 1.7 ± 0.3 mm/yr (6.7 ± 1.2 inches/century) (Church and White 2006). More recent assessments over the period 1993 to 2003 find a rate of 3.1 ± 0.7 mm/yr (12.2 ± 2.75 inches/century) (Cazenave and Nerem 2004) and 3.2 ± 0.4 mm/yr (12.6± 1.6 inches/century) over the time frame 1993 – 2007 (Merrifield et al 2009). It can therefore be concluded that the rate of sea level rise has been increasing over the past 80 years. A rate that increases over time is a positive acceleration. The magnitude of this acceleration is one of the fundamental drivers that will determine the future rates and heights of sea level.

B.4 Acceleration of sea level rise

Contemporary SLR projections are based on (1) global and local sea level measurements which document an accelerating rate of sea level rise, (2) the preponderance of scientific evidence that recent land-based ice loss is increasing and (3) global climate models that conclude the rate of sea level rise will continue to accelerate. This is a critical point in developing projections that vary from the measured historical rate of sea level rise. Determining an accurate acceleration rate is dependent upon the spatial and temporal variability of the ocean, long term records, and precise observational sampling and accuracies.

The most comprehensive review of global accelerations was provided by Woodworth et al (2009) noting that analyses of accelerations over the late 19th and 20th centuries by several authors are in general agreement. An analysis spanning the period from 1870 through 2004 found a small positive globally averaged acceleration (Church and White 2006). More recent studies by Merrifield et al (2009) over the period 1955-2007 found a positive acceleration since the late 1970's, and analysis of Greenland and Antarctic ice loss from GRACE satellite data over the period 2002-2009 allowed Velicogna (2009) to estimate a global acceleration. Results of these analyses are shown in Table 2. Consistent with the foregoing observation of an increase in the rate of sea level rise since the mid 20th century, Table 2 shows an increase in acceleration in more recent periods.

Woodworth et al (2009) noted that climate phenomenon occurring in one part of the globe influence other parts of the globe. These so called "teleconnections" have a significant impact on the reported differences in acceleration rates and influence a variety of parameters from ocean temperature to atmospheric pressures and circulation patterns. This type of natural multi-decadal climate variability can complicate the analysis of short and long term trends in climate data and contributes to the challenge of predicting future SLR. However, Merrifield et al (2009) provided evidence of acceleration in the rate of sea level rise distinct from the decadal climate variability.

Table 2. Estimates of Global Sea Level Acceleration. An increase in the rate of sea level rise since the mid 20th century shows an increase in acceleration during more recent periods.			
Period	**Acceleration** (mm/yr^2)	**Acceleration** (inches/yr^2)	**Author**
2002 - 2009	0.17 ± 0.05	6.7 x10^{-3} ± 0.05	Velicogna 2009*
1990 - 2009	0.12	4.7 x10^{-3}	Merrifield et al 2009
1978 - 2009	0.09	3.5 x10^{-3}	Merrifield et al 2009
1901 - 2000	0.013 ± 0.006	0.5 x10^{-3}± 0.01	Church and White 2006

* Based on ice sheet melt contribution

C. Planning Projections Through 2060

C.1 Unifying Existing Local Projections

The development of the unified SE FL SLR projection for regional planning purposes was a process requiring facilitated discussions over several meetings. At the first meeting of the Work Group, the pre-workshop survey results were reviewed, focusing on the need for and application of, a unified SE FL SLR projection. Each of the existing local SLR projections was introduced revealing the method for development and the literature upon which it was based. After defining the key characteristics of a SLR projection, the Work Group identified points of agreement related to existing projections and discussed planning horizons. The participants then worked toward a projected SLR range for 2030 and 2060. The group recommended additional discussion on the 2100 planning horizon, and recommended that the final projection be reviewed, and possibly revised, four years from final approval of this document by the SE FL Regional Climate Change Compact Steering Committee and after the release of IPCC AR5.

After thorough review and debate, the Work Group Members agreed that the U.S. Army Corps of Engineers Guidance Document curves (USACE 2009) offered a reasonable and defensible projection to use in the 2030 and 2060 time frames (Figure 2). The Work Group agreed that the curves should be illustrated through 2060, with the historical tidal data and extrapolation of the historical SLR rate to provide perspective. Based on the unified projection, Compact Counties must consider that sea level is projected to rise one foot from the 2010 level sometime between 2040 and 2070, but with a two foot rise possible by 2060. Table 3 shows the projected change in the rate of rise of sea level by decade, illustrating the acceleration of the rate with time. The average rate of rise of sea level at the Key West tidal station from 1913-1999 was 0.88 inches/decade. By 2060, sea level is projected to be rising by two to six inches per decade.

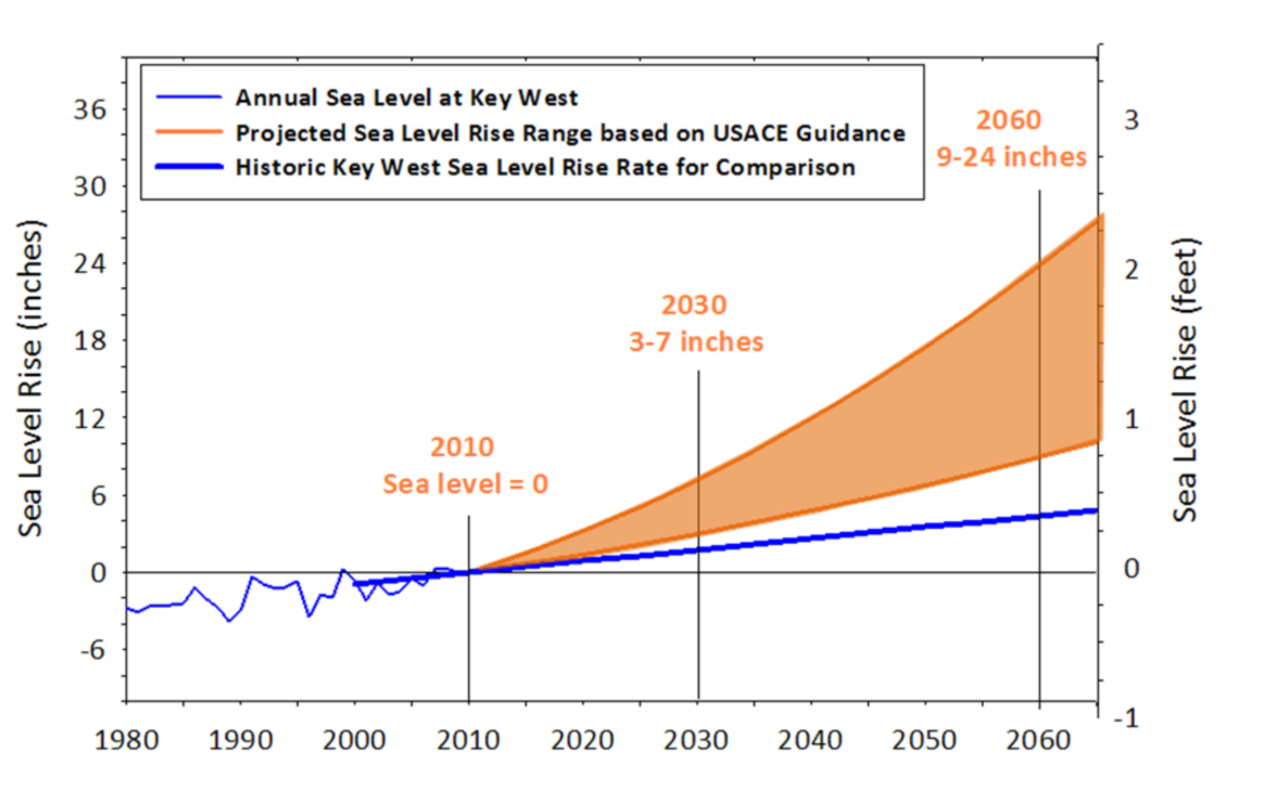


Figure 2. Unified Southeast Florida Sea Level Rise Projection for Regional Planning Purposes. This projection uses historic tidal information from Key West and was calculated by Kristopher Esterson from the United States Army Corps of Engineers using USACE Guidance (USACE 2009) intermediate and high curves to represent the lower and upper bound for projected sea level rise in Southeast Florida. Sea level measured in Key West over the past several decades is shown. The rate of sea level rise from Key West over the period of 1913 to 1999 is extrapolated to show how the historic rate compares to projected rates.

Table 3. Projected Rate of Sea Level Rise by Decade. This table shows how the rate of sea level rise (SLR) is projected to accelerate with time. The average rate of rise of sea level at the Key West tidal station from 1913-1999 was 0.88 inches/decade. By 2060, sea level is projected to be rising by more than two to six inches per decade. Values for the projected rise are rounded to the nearest 0.5 inch.

Time Range		Decadal Rate of Rise	
	Projected Rise (Inches)	Historic (Inches/Decade)	Projected Rate of Sea Level Rise (Inches/Decade)
		0.82-0.94	
2010-2020	1.5 - 3.0		1.4 – 3.2
2020-2030	3.0 - 7.0		1.6 - 4.0
2030-2040	5.0 – 12.0		1.8 - 4.8
2040-2050	7.0 - 17.5		2.0 - 5.6
2050-2060	9.0 – 24.0		2.2 - 6.3

C.2 Sea Level Change Projections Using USACE Methodology

The U.S. Army Corps of Engineers (USACE) sea level change projections are produced in a multiple scenario format with three projections: a high rate projection, an intermediate projection, and a projection of the historically measured rate as a baseline comparison. The methodology is applicable to all USACE Civil Works activities except Regulatory actions. Potential relative sea-level change must be considered in every USACE coastal activity as far inland as the extent of estimated tidal influence.

The USACE sea level change projection methodology is summarized in Engineering Circular (EC) 1165-2-211 and was derived from *Responding to Changes in Sea Level: Engineering Implications* (National Research Council 1987). The EC contains the following changes from the NRC (1987) projections:

1.) Changes in the formula to allow the user to select a specific origin year (allows flexibility to start the projection on a given year).

2.) The EC uses only two out of the three original NRC curves. NRC curve III (highest rate) and curve I (lowest rate) are retained while curve II, an intermediate rate, is dropped. The EC added a new projection, continuation of historic rate, to form the lowest of their three projections. (The unified SE FL SLR projection differs from the EC projection by using the lowest and highest rates to form the projected curve and includes the historic rate for comparison purposes only.)

3.) Changes in the formula to allow the user to specify the historic relative sea level rise rate appropriate for the user's area of interest. In the NRC's (1987) original work, the rate of sea level rise was fixed at 1.4 mm/year (.055 inches/year).

C.2.1 Projection Format

USACE considers the entire range of possible future rates of sea-level change for planning studies and engineering designs. The EC is built on the assumption that the range of possible future rates of sea level rise is bracketed by the historic and upper rate projections.

Upper - The upper rate projection assumes that in addition to the historic rate of sea level rise, there is a major acceleration in the rate over the 21st century. This high rate exceeds the upper bounds of IPCC estimates from both 2001 and 2007, which many scientists agree did not adequately address the potential rapid loss of ice from Antarctica and Greenland.

Lower - The lower rate projection assumes that in addition to the historic rate of sea level rise, there is a moderate acceleration in the rate over the next century. The lower projection is not a "most probable" projection. In fact, the projections are not probabilistic in nature and are all assumed to be plausible.

Historic - The historic projection uses a locally derived historic rate of sea level rise (Key West 1913-1999) that is extrapolated into the future without any change in the existing rate of sea level rise. For the purposes of the SE FL Compact, the historical rate is used only as a reference and is not intended to indicate a likely lower bound.

C.2.2 Data Inputs

The only data required for calculation of a projection using EC 1165-2-211 is the relative sea level change rate at the location of the desired projection. For the purposes of the SE FL unified SLR projection, the relative sea level rise rate at Key West (2.24 mm/year, NOAA 2010) was used.

C.3 SLR Projection Use by the Compact Counties and Partners

The ranges of SLR presented in this section for the 20 and 50 year planning horizons (Figure 2) are based on the USACE guidance document equations using Key West tidal data. The projection is intended to be used for planning purposes to guide future policy and adaptation strategies on transportation, the built environment and land and natural systems. The individual Compact Counties and partners will have to consider to what extent to use the projection for the development of regulations, permitting or engineering specifications in their own jurisdictions. The current unified projection will allow the SE FL Regional Climate Change Compact Counties and their partners to immediately explore adaptation planning scenarios which may be included in the SE FL Regional Climate Change Action Plan. Prior to the development of engineering solutions, the Work Group will be able to revisit the scientific literature and update the projection as appropriate.

The USACE Sea Level Rise Guidance document, Engineering Circular (EC) 1165-2-211, expires in July 2011 and will be replaced with a new EC at that time. No change is expected in the guidance with regard to development of local sea level rise projections, but some additional guidance may be provided regarding evaluation of potential impacts. The Work Group recommends review of the unified projection four years from final approval of this document by the SE FL Regional Climate Change Compact Steering Committee and after the release of the EC and IPCC AR5.

D. Recommendations for a Unified Sea Level Rise Projection

The following are recommendations of the Technical Ad hoc Work Group for consideration by the SE FL Regional Climate Compact Steering Committee to be used by the Compact Counties and their partners to develop the Regional Climate Change Action Plan.

a. The SE FL Unified SLR Projection should be based on the U.S. Army Corps of Engineers (USACE) July 2009 Guidance Document using Key West tidal data (1913-1999) as the foundation of the calculation and referencing the year 2010 as the starting date for sea level rise projections.

b. This projection should be used for planning purposes, with emphasis on the short and moderate term planning horizons of 2030 (USACE - 3-7 inches) and 2060 (USACE - 9-24 inches). The historical trend is provided only for comparison to the projected sea level rise curves.

c. A science-based narrative for 2060 and beyond provides context for the current state of scientific understanding and the potential issues which must be considered when looking toward the end of the 21st century and beyond.

d. The unified SE FL sea level rise projection will need to be reviewed as the scientific understanding of ice melt dynamics improves. The projection should be revised within four years of final approval of this document by the SE FL Regional Climate Change Compact Steering Committee. This timing is consistent with the release of Intergovernmental Panel on Climate Change Fifth Assessment Report which will provide a synthesis of the major findings in climate science to date.

e. Users of the projection should be aware that at any point of time, sea level rise is a continuing trend and not an endpoint.

f. The acceleration of sea level rise can be slowed and the magnitude reduced by actions to reduce greenhouse gas emissions. Substantial reduction in sustained long term emissions will result in a reduction in the cost of adaptation.

E. Sea Level Rise Projections Beyond 2060

In general, SLR projections are presented as a range of values to capture natural variability, the potential impacts and uncertainty of human actions/inaction on climate change as well as to represent the emerging progression of natural processes contributing to sea level rise. Climate mitigation of greenhouse gases has yet to start in a globally concerted and meaningful way. Current and future mitigation of greenhouse gases through policy actions, behavioral and cultural change and reduction of the burning of fossil fuels will alter the impacts of climate change. In addition, the emerging understanding of reinforcing climate-change feedback loops will influence scientific monitoring, climate modeling and predictive tools into the future. The questions remain about how soon significant sea level rise will become disruptive to Southeast Florida communities, and how much faster might sea level be expected to rise toward the end of this century. This section describes (1) current global projections for the end of the century and (2) emerging science on leading indicators and reinforcing feedback mechanisms.

E.1 Global sea level rise projections for 2100 and beyond

The United Nations Intergovernmental Panel on Climate Change (IPCC 2007) published the IPCC Fourth Assessment Report (AR4) in 2007 providing a comprehensive summary of scientific literature regarding sea level change mechanisms and projections (Bindoff et al 2007). The AR4 report predicted a nonlinear acceleration of sea level over the 21st century. However, concern that increased meltwater contributions from Greenland and Antarctica were not included directly in the projections, coupled with observations that sea level rise rates are already trending along the higher end of the 2007 IPCC estimates (Rahmstorf et al 2007, Jevrejeva et al 2008) has lead to the view of many investigators that these projections are too low and that glacial meltwater will increase levels and rates of SLR well above the IPCC projections. At the national level, the National Science and Technology Council and U.S. Climate Change Science Program (CCSP) submitted a report to the Environmental Protection Agency (EPA) recommending "Thoughtful precaution suggests that a global sea-level rise of 1 m (3.3 ft) to the year 2100 should be considered for future planning and policy discussions" (CCSP 2009). However, the report noted that large uncertainties in the glacial meltwater contributions required further scientific scrutiny.

Subsequent to the 2007 IPCC projections, the scientific community has continued to model and project sea level rise. Attention has focused on the glacial meltwater issue and in general, most contemporary projections are higher than the IPCC AR4 values. Table 4 lists projections at year 2100 from recent peer-reviewed publications indicating a movement towards increased acceleration of SLR. Figure 3 is the U.S. Army Corps of Engineers projection for the South Florida region to 2110. Table 5 lists the estimated time frames for 1-3 foot sea level rise scenarios based on the projection in Figure 3.

Table 4. Global Sea Level Rise Projections in Feet at 2100 From Recent Peer-Reviewed Scientific Publications. Projections range from 0.23-6.56 ft.

Author	Min (ft) @ 2100	Max (ft) @ 2100
Jevrejeva et al 2010	1.97	5.25
Grinsted et al 2009	2.95	4.27
Siddall et al 2009	0.23	2.69
Vermeer and Rahmstorf 2009	2.46	6.23
Pfeffer et al 2008	2.62	6.56
Horton et al 2008	1.54	3.28

Table 5. Estimated Timeframes for a 1-3 Foot Rise in Sea Level in Southeast Florida from the 2010 Level. The time estimates are based on the USACE projection in Figure 3.

Projected Sea Level Rise	Estimated Time Occurrence
1 foot	2040-2070
2 feet	2060 - 2115
3 feet	2078 - 2150

E.2 Leading indicators and reinforcing feedback mechanisms

Increasing concentration of greenhouse gases and rising global air and oceanic water temperatures precede and contribute to sea level rise. This section of the report discusses select measurable changes to physical and climatic parameters and reinforcing feedback mechanisms which could contribute to accelerated sea level rise. A more extensive coverage of metrics that can give advance warning of climate-related changes has been developed by the National Research Council (2010).

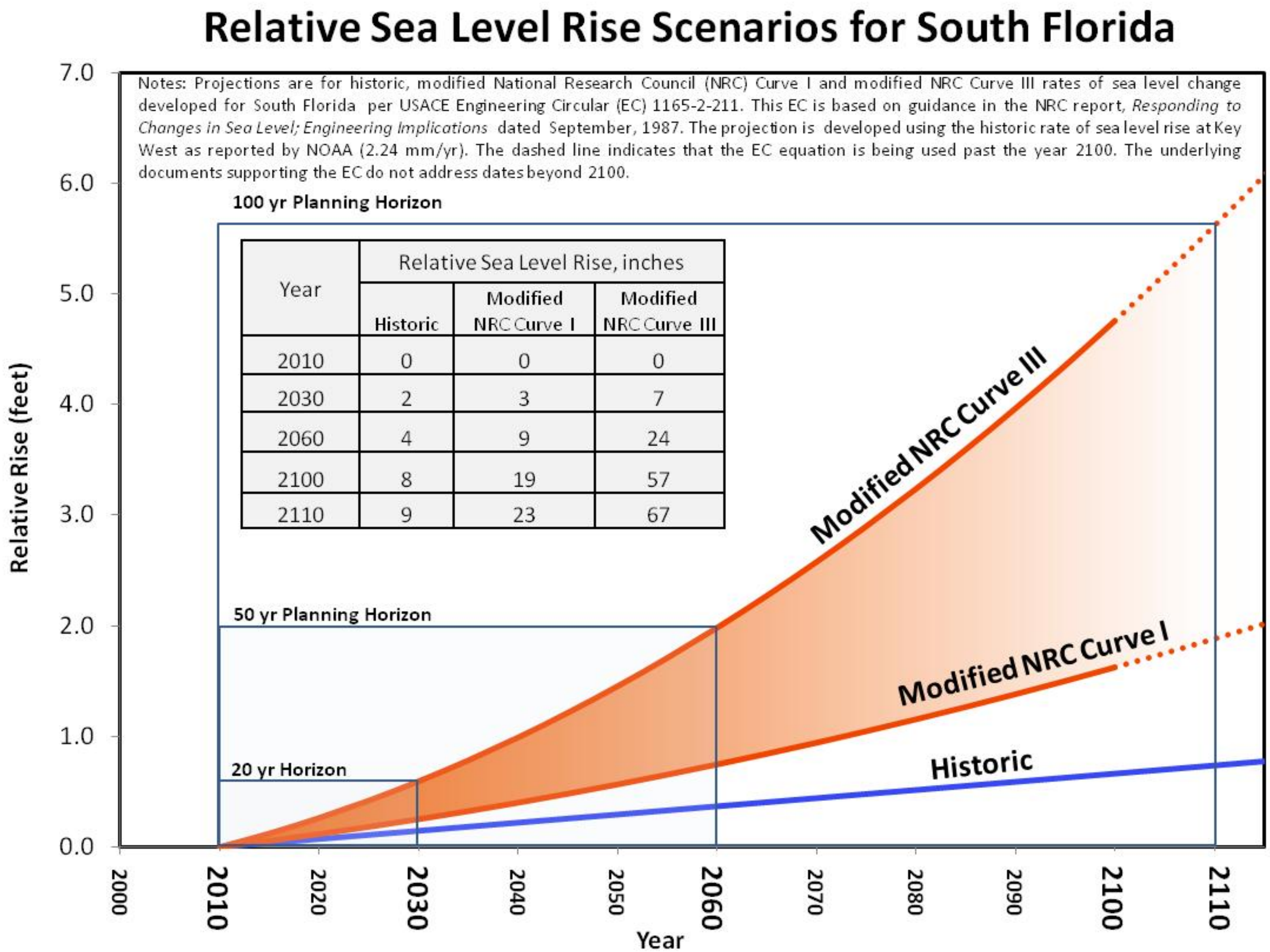
E.2.1 Continuing and persistent greenhouse gas emissions

The earth's climate system has an inherent buffering capacity that helps maintain relative atmospheric stability over long periods of time. Current greenhouse gases concentrations are beyond historic levels preventing us from using past records to predict the outcome of the substantial inertia in the earth's climate system caused by greenhouse gases, such as carbon dioxide (CO_2), with long residence times. Carbon dioxide concentrations in March 2011 (392 ppm, NOAA Earth System Research Laboratory 2011) are 110ppm higher than the pre-industrial maximums. The equilibrium temperatures in the past interglacial periods were thus achieved with much lower greenhouse gas concentrations. Higher equilibrium temperatures can reasonably be expected after the climate system has finally adjusted to the much higher greenhouse gas concentrations of today. The exact timeframe of reaching that equilibrium is not known with certainty. CO_2 has an atmospheric residence time of hundreds of years so the carbon burned by the last few generations is mostly still at work in the atmosphere (Archer 2005; Caldeira and Wickett 2005). The effects of the current generation's greenhouse gas emissions on the global climate system will be manifested now and in the future and will include increasing sea level rise.

E.2.2 Increasing concentrations of water vapor

Water vapor increases the greenhouse effect and a warmer atmosphere will hold more water. The Earth's atmosphere continues to warm with a 2-10°F (1.1-6.4°C) increase in average global temperature predicted by the end of the century (IPCC 2007). For each degree C of global warming, the atmosphere can hold an additional 7.5% of water vapor (Horváth and Soden 2008). Growing concentrations of water vapor will result in a 2% increase in global precipitation (Held and Soden 2006). The current warmer atmosphere has nearly 5% more water vapor compared to pre-industrial levels. The eruption of Mt. Pinatubo in 1991 produced the last transient global cooling (-0.5 degree C) and drying event. The water vapor reduction was responsible for a significant portion of the global cooling observed, which validated the water vapor feedback mechanism as a contributor to climate impacts in Global Climate Models.

Figure 3. USACE Sea Level Rise Projection for the South Florida Region through 2110. Unlike the SE FL unified sea level rise projection developed by the Work Group shown in Figure 2, this graphic is developed directly according to the USACE Guidance document and illustrates the projection beyond 2100. With time, the projection increasingly diverges from the historic rate of rise.



Year	Relative Sea Level Rise, inches		
	Historic	Modified NRC Curve I	Modified NRC Curve III
2010	0	0	0
2030	2	3	7
2060	4	9	24
2100	8	19	57
2110	9	23	67

E.2.3 Changes in Cloudiness

Clouds provide important regulators of the energy flow at the top of the atmosphere. On the one hand, clouds reflect sunlight back to space which has a cooling effect on the planet, while on the other hand clouds absorb infrared radiation which has a warming effect. As the climate warms from increasing greenhouse gases, clouds will also change. Current model projections indicate that the changes in cloud properties act to amplify the initial warming from increases greenhouse gases (Soden and Held 2006), although the magnitude of this amplification varies substantially from model to model. Comparisons with observations (Bony and Dufresne 2005, Clement et al 2009) suggest that the observed amplifying effects of clouds are as strong or possibly stronger the current model predictions. This suggests that the surface warming for any given emission scenario will be closer to the upper end of the model projections. To the extent that sea level rise is directly correlated to surface warming; the changes in cloud properties would also be expected to amplify sea level rise.

E.2.4 Heat storage in oceanic waters

Due to greenhouse gases in the atmosphere, the Earth is absorbing more energy than it is emitting back to space resulting in an energy imbalance. While air temperatures have increased resulting in melting snow and ice, much of the excess energy has been absorbed as heat in the ocean; raising the oceanic temperature as well. The oceanic heat storage is a leading indicator as an additional 1.08°F (0.6°C) in average global temperatures will result from this additional heat without further change in the concentration of greenhouse gases (Hansen et al 2005). Increased global heat storage in the upper 2,000 meters (6000 feet) of ocean was documented during 2003-2008 using data from the ARGO oceanic probes (von Schuckmann et al 2009). The climate system's lag in responding to heat storage implies the need to anticipate additional temperature shifts and to consider impacts related to ice sheet disintegration and sea level rise (Hansen et al 2005).

E.2.5 Warm water impact on glaciers, pack ice, and glacial earthquakes

Since the mid 1990s, ice sheet melt in Greenland has accelerated as a result of warming atmospheric conditions (Zwally et al 2002). Over the past decade, scientists have begun to fully appreciate that much of the rapidly accelerating melt on the Greenland and Antarctic Ice Sheets is the result of warmed ocean water coming from the north and the south. A layer of salty water that was originally observed under the Arctic Ocean pack ice in the 1890s (as documented by Fridtjof Nansen using temperature profiles) has moved south along the Greenland coast and warmed to 39°F (+4°C). In 2007, the TARA transpolar ice drift repeated Nansen's experiment and determined that this layer had thickened by 100m (328 feet) and warmed by an additional 0.9°F (Gascard et al 2008). This warmed, salty ocean water has now moved from the Atlantic and into Sermilik Fjord by way of the Irminger current just offshore (Nettles and Ekstrom 2010).

For the past century and most dramatically since the 1980s, the layer of warm salty subsurface North Atlantic water has been warming, further, thickening and moving northward into the Arctic and along Greenland's coasts. This warmed subsurface ocean water continues to penetrate the Arctic Ocean accelerating summer pack ice melt from below and entering fjords, causing rapid melting beneath the outlet glaciers of the Greenland Ice Sheet (Holland et al 2008). Accelerated melting has coincided with warm salty water at the Jakobshavn Fjord on the west coast of Greenland (Holland et al 2008) and at the Helheim Glacier into East Greenland's Sermilik Fjord (Straneo et al 2011).

Glacial earthquakes were discovered in 2003 (Nettles and Ekstrom 2010) and are caused by intensified movement at glacial outlet fjords. Lamont-Doherty Earth Observatory scientists' review of the phenomenon shows the locations of 13 repeated glacial earthquake sites in the major glacial outlet fjords on both coasts of Greenland (Figure 2 in Nettles and Ekstrom 2010). They present convincing connections between the calving events at Helheim Glacier and ensuing glacial earthquakes generated by subsequent rapid seaward glacial movements. Nettles and Ekstrom show the locations of 14 teleseismic detections along the Antarctic coast (Figure 9 in Nettles and Ekstrom 2010). These earthquakes are well removed from tectonically active plate boundaries and likely correspond to glacial earthquakes at the glacial ice outlets along the Antarctic coast.

E.2.6 The role of ice shelves in stabilizing glaciers

Following the Larsen Ice Shelf collapse on the Antarctica Peninsula in 1995, several glaciers were no longer buttressed. This resulted in active surging in the Boydell, Sjögren, Edgeworth, Bombardier, and Drygalski glaciers (De Angelis and Skvarca 2003). Pine Island glacial outlet to the West Antarctic Ice Sheet is now thinning rapidly and is of special concern. This phenomenon of "uncorking" a glacier may indicate a mechanism triggering rapid pulses in sea level rise during periods of de-glaciation. Recent studies of sediment cores under the West Antarctic Ice Shelf have documented pre-Pleistocene disintegrations of the west Antarctic region that must have caused large increases in global sea levels (McKay et al 2009).

E.2.7 Open water, wind and sun impacts on Arctic pack ice

Since 1990, there has been a dramatic reduction in the areal extent, thickness and thus the volume of summer pack ice in the Arctic Ocean, according to data posted on the National Snow and Ice Data Center (NSIDC) website (http://nsidc.org/). These expanding areas of open water are also impacting the pack ice. Thinner ice is more easily broken up by waves, which crest larger in the expanded fetch across widening areas of open water. Thin ice is easily rafted, with one floe slipping on top of another, which in turn creates more open water.

Winter storm tracks, which used to cross the North Atlantic from Southern Greenland to the Norwegian Coast, are now tracking farther northward and growing more intense. Meteorologists have coined a name for this new class of fast developing, intense winter storms called "Arctic Bombs". New wind patterns are emerging, such as the "Arctic Dipole" pattern (Wu et al 2006), which may account for the diminishing pack ice in the East Greenland Current

As the thickness and extent of Arctic Pack Ice has diminished, a radical change in albedo from 70 to 90% reflection of solar energy (depending on snow cover) on an ice-covered ocean to the 80 to 90% heat absorption by an ice-free ocean has increased the surface temperature of the Arctic Ocean dramatically from -1°C to 4-5°C (below freezing to 39-41°F) during the summer months (NSIDC). This warmed Arctic Ocean water is now accelerating melt of the remaining pack ice and adding to the warmth of the East Greenland Current, which is penetrating Greenland's fjords and accelerating melt of outlet glaciers.

E.2.8 Melting permafrost

Schuur et al. (2008) state "Thawing permafrost and the resulting microbial decomposition of previously frozen organic carbon (C) is one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere in a changing climate." Simulation models show that the loss of Arctic ice can result in significant ground level warming and permafrost melt (Lawrence et al 2008). Because Arctic soils may hold 30% or more of all the carbon stored in soils worldwide, thawing could initiate significant additional emissions of carbon dioxide or the more potent greenhouse gas, methane. These gases, in the form of methane hydrates, have been trapped in the permafrost since the last ice age. Additional methane hydrates are found on the broad continental shelves at shallow depths, where they are also being released as they are melted by the warming Arctic Ocean as described by the NSIDC website (nsidc.org). The release of these ancient gas stores and the melting of permafrost are not processes which could be reversed in the short term and will be important future contributors to climate change.

E.2.9 Planning considerations for 2060 and beyond

The recent observations noted above emphasize the likelihood of accelerated ice melting and SLR rise for 2060 and beyond. The realities of the SE FL topography make the region highly vulnerable to the impacts of sea level rise and short term extreme events such as storm surge (Figure 4). As sea level rises, a disproportionate percentage of land in the lower lying counties will be impacted within the first several feet of rise (Table 8). Based on the current topography, some sea level rise increments will produce a larger percent of land loss than others (Table 8). This makes longer range adaptation planning especially important in SE FL. The evidence for reinforcing feedback mechanisms is increasing, resulting in environmental conditions which are irreversible in the short term. Uncertainties about the timing and magnitude of future long term sea level rise should not be a reason for inaction. The sustainability of the select economic drivers such as beaches, the Everglades and tourism in the short term and the evolution of the SE FL community in the long term depend on developing appropriate adaptation strategies today.

The prospect of intense positive feedback mechanisms is an even greater incentive for taking steps to mitigate the drivers of climate change. Even if CO_2 production was totally halted today, the world would be committed to many decades of future climate change and sea level rise. The projections should be used as guidance tied to the appropriate expected lifetimes of planned projects. Sea level rise concerns

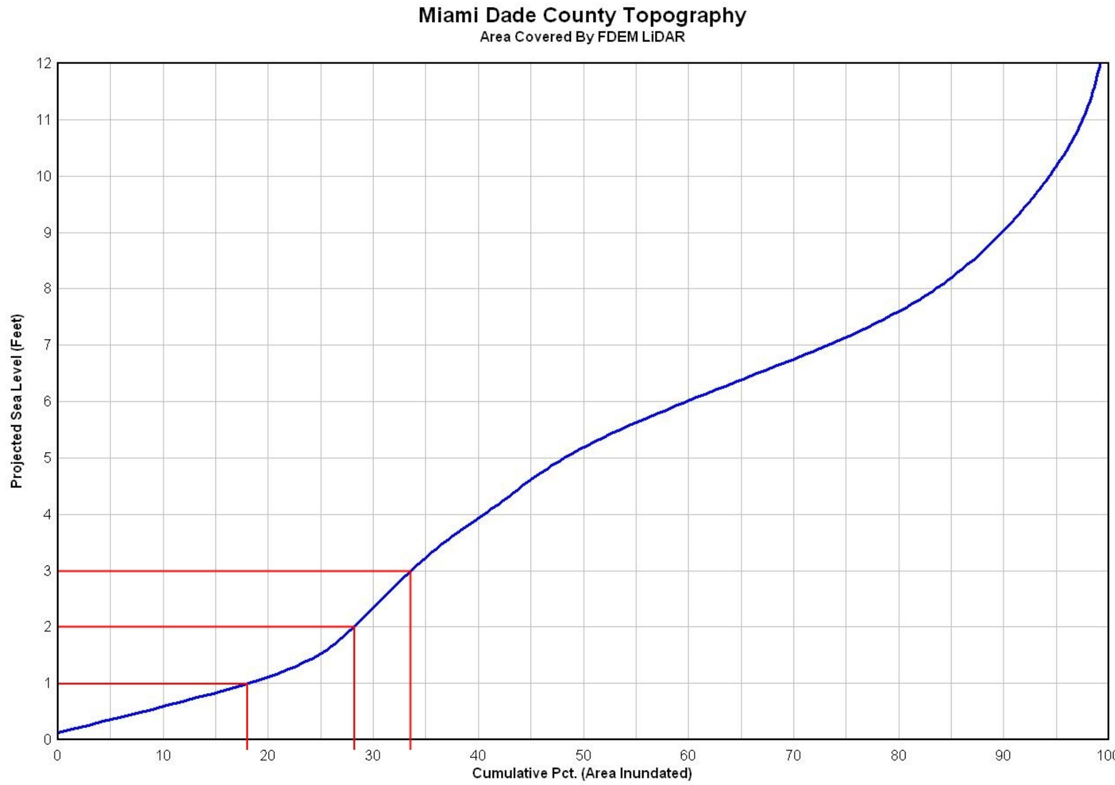


Figure 4. Hypsographic (hypsometric) Curve Showing the Distribution of Land Elevation for Urban Miami-Dade County. This chart illustrates the percentage of the eastern two-thirds of Miami-Dade County's land area that would be below sea level for any given sea level rise scenario based on LIDAR elevation data. The red lines connect the percentage of land for each foot of rise up to 3 feet (see Table 8). Just as sea level rise this century is expected to be non-linear, so will the percentage of land impacted at each sea level rise increment. Certain specific sea level rise horizons will require greater adaptation efforts than others. The Everglades portion of the County (about 1/3 of the total County area) was not covered by the LiDAR data source but adding it would make the left half of the curve lower and significantly increase the percentage of land impacted in the early part of sea level rise (Source: P. W. Harlem, Florida International University – by permission).

Table 8. The Percent of Land with Elevations Below Sea Level for the Urban Portion of Miami-Dade County for 1-3 Foot Sea Level Rise Scenarios. This table is derived from the hypsographic curve (Fig. 4). Note that each foot of rise produces a different percent of land area at elevations below sea level. This non-linearity through time is an important concept to apply to adaptation planning.

SLR Rise (Feet)	Land with Elevations Below Sea Level (%)	Change (%)
1	18.2	-18.2
2	28.2	-10.0
3	33.6	-5.4

will require implementation of measures to proactively reduce future uncertainties and community risks. This will be particularly appropriate for assessing the viability of public and private investments in vulnerable areas which involve significant costs, long implementation times and support or encourage additional investments and development. Examples include key components of transportation, power, water supply, water treatment and flood/storm damage reduction systems.

F. Conclusions

The Work Group agreed to use the USACE Guidance (USACE 2009) as the basis for a Southeast Florida sea level rise projection for the 2030 and 2060 planning horizons. A one foot rise in sea level above the 2010 levels is projected to occur in the 2040-2070 time period with a two foot rise possible by 2060. Uncertainties exist in precisely predicting future climate-induced sea level rise rates and acceleration beyond 2060. They are related to feedback mechanisms which accelerate a variety of climatic and ice melt processes, the limitations of current computer models to incorporate these feedbacks, and the inability to determine the scope of human response to the need to limit greenhouse gas emissions and levels in the near or long-term future. However, the scientific evidence supports that the planet is warming in response to increasing levels of greenhouse gases and, as a consequence, ice melt is increasing, sea level is rising, and reinforcing positive feedbacks are coming into play. Sea level will continue to rise even if mitigation efforts to reduce greenhouse gas emissions are successful at stabilizing or reducing atmospheric CO_2 concentrations. A substantial increase in sea level rise within this century is likely and may occur in rapid pulses rather than gradually.

The recommended projection provides guidance for the Compact Counties and their partners to initiate planning to address the potential impacts of SLR on the region. The shorter term planning horizons (through 2060) are critical to develop the SE FL Regional Climate Change Action Plan, to optimize the remaining economic life of existing infrastructure and to begin to consider adaptation strategies. As scientists develop a better understanding of the factors and reinforcing feedback mechanisms impacting sea level rise, SE FL community will need to adjust and adapt to the changing conditions. To ensure public safety and economic viability in the long run, strategic policy decisions will be needed to develop guidelines to direct future public and private investments to areas less vulnerable to future sea level rise impacts.

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Back Cover Figure: A coastal South Florida home is shown under current sea level conditions and inundated during a seasonal extreme high tide event. Exceptional astronomical tides (approximately 10 inches above average high tide for the year) such as the one pictured in the lower photo occur seasonally and can be made more extreme by north and northeasterly winds. In addition, sea level has risen 4-5 inches since the 1950-60s when many homes were built in coastal South Florida. Annual inundation events illustrate the potential challenges and risks of future sea level rise to the South Florida communities and underscore the need to develop appropriate adaptation strategies. The Unified Sea Level Rise Projection for Southeast Florida provides an estimate of the magnitude and timing of sea level rise through 2060 and a discussion of the risks beyond 2060 (photo credit: Paul Krashefski).