SOUTHEAST FLORIDA
REGIONAL COMPACT
CLIMATE CHANGE

Unified Sea Level Rise Projection
Southeast Florida

2019 UPDATE

Prepared by the

Southeast Florida Regional Climate Change Compact's
Sea Level Rise Ad Hoc Work Group

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Sea Level Rise Ad Hoc Work Group

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** Staff participation from federal agencies does not necessarily imply official review or opinions of their agencies.*

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Executive Summary

Early in the Southeast Florida Regional Climate Change Compact's ("the Compact") work together, Broward, Miami-Dade, Monroe, and Palm Beach counties recognized the need to unify a diversity of local sea level rise projections to create a single, regionally unified projection, ensuring consistency in adaptation planning and policy, and infrastructure siting and design in the Southeast Florida four-county region. The Compact published the first Regionally Unified Sea Level Rise Projection for Southeast Florida in 2011, and updated the projection in 2015. This document, the Compact's third Regionally Unified Sea Level Rise Projection, provides an update to the amount of anticipated sea level rise in Southeast Florida through 2120. These projections represent a consensus from a technical Work Group consisting of members from the academic community and federal agencies, with support from local government staff, and incorporates the most up-to-date, peer-reviewed literature, and climate modeling data. The Projection supports local government, regional entities, and other partners in understanding vulnerabilities associated with sea level rise and informs the development of science-based adaptation strategies, policies, and infrastructure design.

The 2019 Projection is based on projections of sea level rise developed by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014), as well as projections from the National Oceanic and Atmospheric Administration (NOAA) (Sweet et al., 2017), and accounts for regional effects, such as gravitational effects of ice melt, changes in ocean dynamics, vertical land movement, and thermal expansion from warming of the Florida Current that produce regional differences in Southeast Florida's rate of sea level rise compared to global projections.

Based on past and current emissions, all projection curves assume a growing greenhouse gas emission concentration scenario, in which emissions continue to increase until the end of the century, consistent with the IPCC Fifth Assessment Report's (AR5) Representative Concentration Pathways (RCP 8.5). Estimates of sea level rise are provided from a baseline year of 2000, and the planning horizon has been extended to 2120, in response to the release of climate scenarios extending beyond the year 2100 by federal agencies (NOAA and the U.S. Army Corps of Engineers) and the need for planning for infrastructure with design lives greater than 50 years.

In the short term, sea level rise is projected to be 10 to 17 inches by 2040 and 21 to 54 inches by 2070 (above the 2000 mean sea level in Key West, Florida). In the long term, sea level rise is projected to be 40 to 136 inches by 2120. Projected sea level rise, especially beyond 2070, has a significant range of variation as a result of uncertainty in future greenhouse gas emissions reduction efforts and resulting geophysical effects.

The 2019 Unified Sea Level Rise Projection includes three curves for application, in descending order, the NOAA High Curve, the NOAA Intermediate High Curve, and the curve corresponding to the median of the Intergovernmental Panel on Climate Change (IPCC) AR5 RCP 8.5 scenario. A fourth curve, the NOAA Extreme curve, is included for informational purposes, not for application, illustrating the possible upper limit of sea level rise in response to potential massive ice sheet collapse in the latter part of the century. This curve underscores that without imminent and substantial reductions in greenhouse gas emissions, much greater sea level rise is possible more than 100 years from now.

This guidance document describes the recommended application of the projection as it relates to both high- and low-risk projects and short- and long-term planning efforts. The Work Group recommends that this guidance be updated, at a minimum every five years to reflect the ongoing advances in scientific knowledge related to global climate change and potential impacts.

Introduction

IMPACTS ASSOCIATED WITH SEA LEVEL RISE FOR SOUTHEAST FLORIDA

The climate is changing, manifesting in significant impacts for the Southeast Florida region, including increasing average temperatures, more intense storm events, and rising sea levels. Sea level rise, caused by the thermal expansion of warming ocean water and melting land ice as the earth warms, is one of the most evident impacts in our region given Southeast Florida's low-lying elevation and porous geology.

The consequences associated with sea level rise are already apparent in Southeast Florida and pose an immediate and real threat to lives, livelihoods, economies, and the environment. Consequences include physical impacts such as coastal inundation and erosion, increased frequency of flooding in vulnerable coastal areas as well as inland areas due to impairment of the region's largely gravity-driven stormwater infrastructure system, reduced soil infiltration capacity, and saltwater intrusion of drinking-water supply. Moreover, the impacts of surge from tropical storms or hurricanes are exacerbated as a result of sea level rise. Increased pollution and contamination as a result of flooding degrades natural resources critical to the region's economy. Consequences also include cascading socio-economic impacts such as displacement, decrease in property values and tax base, increases in insurance costs, loss of services and impairment of infrastructure such as roads and septic systems. ***Appendix A: State of the Science***, describes the interconnected processes and resulting impacts of sea level rise in additional detail.

The extent of these impacts into the future is dependent upon the factors influencing the rate of sea level rise such as thermal expansion of oceans and increased rate of melting of land-based ice sheets due to global warming, the degree to which society limits greenhouse gas emissions in the near-term, and the decisions and investments made by communities to increase their climate resilience. One of the values of the Unified Sea Level Rise Projection is its application for scenario testing to better understand the potential impacts and timeline of sea level rise within the Southeast Florida community.

OBSERVED SEA LEVEL RISE IN SOUTHEAST FLORIDA

Global mean sea level (GMSL) during 2018 was the highest annual average in the satellite altimetry record (1993–2018), rising approximately 3 inches above the 1993 average (Thompson et al., 2019). Projections anticipate an increase in the acceleration of sea level rise regionally based on recent observations in response to changes in the speed and thermodynamics of the Florida Currents and Gulf Stream (Domingues et al., 2018; Sweet et al., 2017; Volkov et al., 2019). Based on the 5-year moving average, the observed sea level rise at the Key West tide gauge from 2000 to 2017 is 3.9 inches. Whether this rapid rise will be persistent into the future is unclear at this time.

HOW ARE GREENHOUSE GAS EMISSIONS AND SEA LEVEL RISE RELATED?

Since the beginning of the Industrial Revolution, human activities have caused significant increases in emissions of greenhouse gases in the atmosphere, such as carbon dioxide, methane, and nitrous oxides in addition to natural emissions of these gases due to the biome carbon and nitrogen cycles. Major sources of carbon dioxide are the burning of fossil fuels such as coal, petroleum-based liquid fuels, and natural gas for electric power generation, transportation, and industrial processes. These greenhouse gases trap heat from the sun in a natural process called the "greenhouse effect," which would otherwise be radiated back to space. Problematically, as the concentrations of these gases accumulate in the earth's atmosphere as a result of human activities, the earth's average temperature continues to rise. This process is called "global warming."

More than 90% of the warming that has happened on Earth over the past 50 years has been transferred to the ocean. Sea level rise is a result of both the expansion of seawater as the ocean temperature increases, as well as the melting of glaciers and ice sheets. As a result of continuing global warming, the rate of sea level rise accelerates with passing time.

FUTURE PROJECTIONS IF EMISSIONS ARE REDUCED

The rate of sea level rise projected, particularly in the latter half of the century, is dependent upon the amount of greenhouse gas emissions generated in the next decade and sustained in the coming decades. Rapid and immediate global, federal, state, local, and individual action will be necessary to limit the amount of sea level rise adaptation required. The four greenhouse gas concentration scenarios, known as the Representative Concentration Pathways (RCPs) are sets of scenarios for greenhouse gas emissions dependent upon reduction commitments, economic activity, energy sources, population, and land use trajectories, and other socio-economic factors. RCPs are input into climate models which yield sea level rise scenarios. The lowest concentration scenario, RCP 2.6, is viewed as the scenario necessary to keep global temperature increases below 2°C and slow the rate of sea level rise (van Vuuren et al 2011a). This scenario would require that greenhouse gas emissions peak around 2020 and decrease at 4% annually (van Vuuren et al., 2011a). Future global mean sea level would be significantly lower for RCP 2.6 compared to that of RCP 8.5 (IPCC, 2019). The types of reduction strategies necessary to reduce regional emissions can be found in the Compact's Regional Climate Action Plan (www.rcap2.org).

WHAT ARE RCPS?

The future impacts of climate depend not only on the response of our Earth system, but also on how global society responds through changes in technology, economy, policy, and lifestyle. These responses are uncertain, so future scenarios are used to explore the consequences of different options. Representative Concentration Pathways (RCPs) are possible future scenarios for greenhouse gas emissions, or concentration pathways, used within the IPCC AR5 and other complex climate modeling activities that simulate how the climate might change in the future. There are generally four of these scenarios used in climate modeling: RCP 8.5, RCP 6, RCP 4.5, and RCP 2.6. The numbers in each RCP refers to the amount of radiative forcing produced by greenhouse gases in 2100, which is a measure of the energy absorbed and retained by the lower atmosphere. For example, in RCP 8.5 the radiative forcing is 8.5 watts per meter squared (W/m²) in 2100.

RCPs start with atmospheric concentrations of greenhouse gases rather than socioeconomic processes (van Vuuren et al., 2011b). This is important because every modelling step from a socioeconomic scenario to climate change impacts adds uncertainty. That said, these concentration pathways are dependent upon reduction commitments, economic activity, energy sources, population, land use trajectories, and other socio-economic factors that could lead to a particular concentration pathway and magnitude of climate change.

SCENARIO COMPONENT	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Greenhouse gas emissions	Very low	Medium-low mitigation Very low baseline	Medium baseline; high mitigation	High baseline
Agricultural area	Medium for cropland and pasture	Very low for both cropland and pasture	Medium for cropland but very low for pasture (total low)	Medium for both cropland and pasture
Air pollution	Medium-Low	Medium	Medium	Medium-high

Main characteristics of each Representative Concentration Pathway (RCP). *Vuuren et.al., 2011*

RCP PRIMARY CHARACTERISTICS

>> **RCP 2.6** is representative of scenarios in the literature that lead to very low greenhouse gas concentration levels. It is a “peak-and-decline” scenario; its radiative forcing level first reaches a value of around 3.1 W/m^2 by mid-century, and returns to 2.6 W/m^2 by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially, over time (Van Vuuren et al. 2007a).

>> **RCP 4.5** is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009).

>> **RCP 6** is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions (Fujino et al. 2006; Hijioka et al. 2008).

>> **RCP 8.5** is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al. 2007).

(Characteristics quoted from van Vuuren et.al., 2011)

Purpose and Intended Use

WHO SHOULD USE THIS PROJECTION AND GUIDANCE DOCUMENT?

The Unified Sea Level Rise Projection for Southeast Florida and this guidance document are intended to assist decision-makers at both the local and regional levels in Southeast Florida to plan for and make decisions about sea level rise and associated vulnerabilities based on best-available science. The projection (Unified Sea Level Rise Projection for Southeast Florida) contains a graph and table describing the anticipated rise in sea level from 2000 through 2120. The projection can be used to estimate future potential sea level elevations in Southeast Florida and the relative change in sea level from today to a point in the future. The section, *Guidance for Application*, contains directions and specific examples of how the projection can be used by local governments, planners, designers, engineers, and developers. This regional projection is offered to ensure that all major infrastructure projects throughout the Southeast Florida region have the same basis for design and construction relative to future sea level.

WHO DEVELOPED THE UNIFIED SEA LEVEL RISE PROJECTION FOR SOUTHEAST FLORIDA?

In 2010, the Southeast Florida Regional Climate Change Compact first convened the Sea Level Rise Ad Hoc Work Group (Work Group) for the purpose of developing a Unified Sea Level Rise Projection for the region. The Work Group reviewed existing projections and scientific literature and developed a unified regional projection for the period from 2010 to 2060 (Compact, 2012), and recommended a review of the projection four years after its release in 2011.

In September 2014, the Sea Level Rise Work Group was reconvened to develop the second update of the Unified Sea Level Rise Projection, based on projections and scientific literature released since 2011, which was published by the Compact in October 2015 (Compact, 2015).

Based on guidance from the Work Group, and in response to emergent research since the publication of the 2015 report, the Compact reconvened the Work Group in 2019 to produce the third update. In particular, new research has indicated the potential for faster rates of melting of the Antarctic Ice Sheet, triggering the likelihood of higher rates of rise in the future. In addition, the Work Group opted to include the regional sea level rise rates as reported in the Fourth National Climate Assessment (Sweet et al., 2017).

The Ad Hoc Sea Level Rise Work Group consists of experts within the academic community and federal agencies, and is supported by individuals from local government and staff support to the Compact. Most of the 2019 Work Group members contributed to the previous Compact projections.

FREQUENCY OF FUTURE UPDATES

The Southeast Florida Regional Climate Change Compact is committed to updating the Unified Sea Level Rise Projection periodically, and at a minimum every five years, to incorporate the latest scientific understanding of climate change and sea level rise for Southeast Florida. Scientific understanding of sea level rise is rapidly advancing, generating new, peer-reviewed literature and modeling from a variety of key sources, including the Intergovernmental Panel on Climate Change (IPCC), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Army Corps of Engineers (USACE), among other recognized sources. By updating this document and the Unified Sea Level Rise Projection at least every five years, the Compact seeks to provide ongoing and current guidance for regionally consistent sea level rise planning and decision-making.

Unified Sea Level Rise Projection for Southeast Florida

2019 PROJECTION AND SUMMARY

This Unified Sea Level Rise Projection for Southeast Florida updated in 2019 projects the anticipated range of sea level rise for the region from 2000 to 2120 (Figure 1). The projection highlights three planning horizons:

1. **short term:** by 2040, sea level is projected to rise 10 to 17 inches above 2000 mean sea level.
2. **medium term:** by 2070, sea level is projected to rise 21 to 54 inches above 2000 mean sea level.
3. **long term:** by 2120, sea level is projected to rise 40 to 136 inches above 2000 mean sea level.

Details of the projection development methodology appear in the next section.

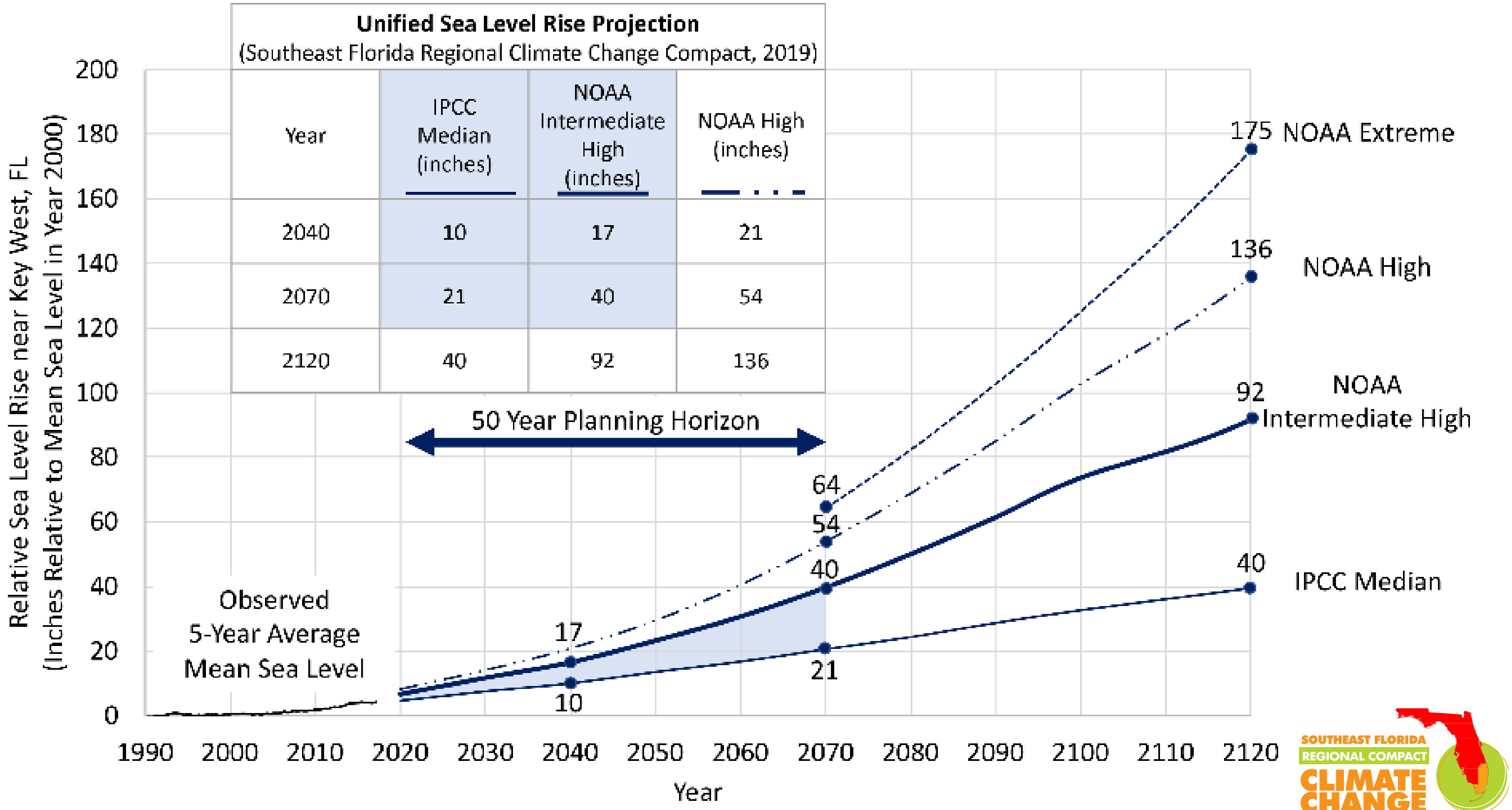
The Projection is recommended to be applied in the following manner:

- The blue shaded zone between the IPCC median curve and the NOAA Intermediate-High curve is recommended to be generally applied to most projects within a short-term planning horizon (up to 2070). The IPCC median curve represents the most likely average sea level before 2070, but is not representative of the realistic interannual and interdecadal variations that will occur with sea level rise values within the blue shaded zone. The IPCC median curve can be used for non-critical, low risk projects with short design lives (<50 years) that are adaptable, and have limited interdependencies with other infrastructure or services. All other projects with design lives that end before 2070 should consider values within the blue zone or along the NOAA Intermediate-High curve based on risk tolerance.
- For non-critical infrastructure in service during or after 2070, the NOAA Intermediate-High Curve is recommended. Sea level rise is unlikely to exceed the NOAA Intermediate-High Curve by 2100.
- The NOAA High curve of the projection, above the shaded zone, should be utilized for planning of critical, high risk projects in service after 2070 or for projects which are not easily replaceable or removable or are critically interdependent with other infrastructure or services. Examples are: major roads and bridges, water and wastewater utilities, power plants including nuclear, major urban developments, etc. Sea level rise is very unlikely to be higher than the NOAA High curve before 2100.
- The NOAA Extreme curve is displayed on the Unified Sea Level Rise Projection for informational purposes but is not recommended for design.

TABLE 1: Sea Level Rise Projection data by decadal intervals

DATUM: FEET 2000 MSL			
YEAR	IPCC MED 50%	NOAA2017	NOAA2017
		INT-HIGH	HIGH
2000	0.00	0	0
2010	0.19	0.3	0.33
2020	0.39	0.56	0.69
2030	0.63	0.98	1.18
2040	0.84	1.38	1.74
2050	1.13	1.94	2.46
2060	1.40	2.56	3.38
2070	1.72	3.31	4.49
2080	2.03	4.17	5.74
2090	2.40	5.12	7.09
2100	2.72	6.14	8.56
2120	3.29	7.64	11.32

DATUM: FEET NAVD			
YEAR	IPCC MED 50%	NOAA2017	NOAA2017
		INT-HIGH	HIGH
2000	-0.80	-0.78	-0.78
2010	-0.61	-0.49	-0.45
2020	-0.42	-0.22	-0.09
2030	-0.17	0.2	0.4
2040	0.04	0.6	0.96
2050	0.33	1.15	1.68
2060	0.60	1.78	2.6
2070	0.91	2.53	3.71
2080	1.23	3.38	4.96
2090	1.59	4.34	6.3
2100	1.92	5.35	7.78
2120	2.49	6.86	10.54



Unified Sea Level Rise Projection
(Southeast Florida Regional Climate Change Compact, 2019)

Year	IPCC Median (inches)	NOAA Intermediate High (inches)	NOAA High (inches)
2040	10	17	21
2070	21	40	54
2120	40	92	136

FIGURE 1: Unified Sea Level Rise Projection

These projections start from zero in year 2000 and are referenced to mean sea level at the Key West tide gauge. Based on the 5-year average of mean sea level, approximately 3.9 inches of sea level rise has occurred from 2000 to 2017 (see historic sea level section of guidance document). The projection includes global curves adapted for regional application: the median of the IPCC AR5 RCP 8.5 scenario (Growing Emissions Scenario) as the lowest boundary (solid thin curve), the NOAA Intermediate High curve as the upper boundary for short-term use until 2070 (solid thick line), the NOAA High curve as the upper boundary for medium and long-term use (dash dot curve). The shaded zone between the IPCC AR5 RCP 8.5 median curve and the NOAA Intermediate High is recommended to be generally applied to most projects within a short-term planning horizon. Beyond 2070, the adaptability, interdependencies, and costs of the infrastructure should be weighed to select a projection value between the IPCC Median and the NOAA High curves. The NOAA Extreme curve (dash curve) brackets the published upper range of possible sea level rise under an accelerated ice melt scenario. Emissions reductions could reduce the rate of sea level rise significantly.

Projection Development Methodology

PROJECTION UPDATE

The key components of the methodology used to develop the Unified Sea Level Rise Projection are as follows:

Starting in 2000: The year 2000 has been selected as the initial year of the projection because of its use as the reference year for the latest regional sea level projections published by NOAA (Sweet et al., 2017), which is the primary source of the data used in this report. The previous projection started in 1992, based on the midpoint of the tidal epoch from 1983 to 2001 which defined the previous elevation of mean sea level. Defining mean sea level by a timeframe is necessary because sea level is constantly changing. A fixed elevation is necessary to serve as a baseline for which to add sea level rise projections and to convert to elevations in other datums. NOAA has determined a new mean sea level for 2000, the midpoint of the tidal epoch from 1991 to 2009. A comparison of the 2015 and 2019 Unified Sea Level Rise Projection is presented in the next section.

Updated Planning Horizons: To align with a 20-year planning horizon for land use and a 50-year planning horizon for infrastructure, the sea level rise values displayed were moved to 2040 and 2070, respectively.

Planning Horizon of 2120: In response to the release of climate scenarios extending beyond 2100 by federal agencies including the US Army Corps of Engineers (USACE) and the National Oceanographic and Atmospheric Administration (NOAA) and the need for planning for infrastructure with design lives greater than 50 years, the Unified Sea Level Rise Projection time scale has been extended to 2120.

Tide Gauge Selection: The Key West gauge (NOAA Station ID 8724580) was maintained as the reference gauge for calculation of the regional projection, consistent with all previous projections. In addition, appropriate conversion calculations are provided in Section 4: Guidance for Application, in order to reference the projection to the Miami Beach gauge (NOAA Station ID 8723170), the South Port Everglades gauge (NOAA Station ID 8722956) or the Lake Worth Pier gauge (NOAA Station ID 8722670). The Key West gauge has recorded tidal elevations since 1913. Tidal records from Miami Beach, South Port Everglades and Lake Worth Pier are available since 2003, 2018 and 1996, respectively.

Updated Historic Data: Observed data from the Key West tide gauge was plotted from 1992 to 2017 based on the mean sea level, averaged over 5-year intervals. These data were obtained from the USACE Sea Level Tracker, https://climate.sec.usace.army.mil/slr_app/.

Selection of NOAA (2017) Regional Projections and Update of IPCC Median Curve: The regional sea level projections available from NOAA (Sweet et al., 2017) replaced two of the three previously used curves. The selected curves are regional projections rather than previously used global projections. The NOAA Intermediate High regional projection was selected as the upper short term boundary for typical infrastructure because of its IPCC determination to be very likely under the RCP 8.5 emissions pathway, which aligns with current global emissions trends. The NOAA Intermediate High regional projection also approximates the previously used USACE High curve. The NOAA High curve was updated with its regional projection. The third curve, the IPCC Median, was reprojected for the region (Key West) rather than global scale, using the NOAA (Sweet et al., 2017) methodology.

Reference to NOAA Extreme Curve: The NOAA Extreme curve is displayed on the Unified Sea Level Rise Projection for informational purposes but is not recommended for design.

COMPARISON WITH PREVIOUS PROJECTIONS

Table 2 compares values from the 2015 and 2019 Unified Sea Level Rise Projections at the planning horizons referenced in the 2015 projection. The numeric values have been rounded for simplicity. The difference in the reference elevation for the two projections is less than 1 inch (1992 mean sea level compared to 2000 mean sea level) and was considered to be included in the rounding error to allow this comparison. The lowest curve, the IPCC median, increased by 2 to 3 inches in the 2019 projection. The upper boundary of the short term projection increased by 2 to 5 inches (for planning horizons before 2060). The NOAA High curve used for critical infrastructure or planning horizons after 2060 increased 7 to 22 inches, the most significant change between projections.

TABLE 2: Comparison of Unified Projection in 2015 and 2019 at Key West

UNIFIED SEA LEVEL RISE PROJECTION COMPARISON						
Year	**High Adaptability**		↔		**Low Adaptability**	
	2015	**2019**	**2015**	**2019**	**2015**	**2019**
	IPCC Median Global (inches)	IPCC Median Regional (inches)	USACE High (inches)	NOAA Inermediate High (inches)	NOAA High (inches)	NOAA High (inches)
2030	6	8	10	12	12	14
2060	14	17	26	31	34	41
2100	31	33	61	74	81	103

Note: The NOAA Extreme curve values are not included in the table because there was not a comparable curve in the 2015 projection.

Guidance for Application

GUIDANCE IN APPLYING THE PROJECTIONS

Audiences

The Unified Sea Level Rise Projection for Southeast Florida is intended to be used for planning purposes by a variety of audiences and disciplines when considering sea level rise in reference to both short- and long-term planning horizons as well as infrastructure siting and design in the Southeast Florida area. Potential audiences for the projections include, but are not limited to, elected officials, urban planners, architects, engineers, developers, resource managers, and public works professionals.

One of the key values of the projection is the ability to associate specific sea level rise scenarios with timelines. When used in conjunction with vulnerability assessments, these projections inform the user of the potential magnitude and extent of sea level rise impact at a general timeframe in the future. The blue shaded portion of the projection provides a likely range for sea level rise values at specific planning horizons. Providing a range instead of a single value may present a challenge to users such as engineers who are looking to provide a design with precise specifications. Public works professionals and urban planners need to work with the engineers and with policymakers to apply the projection to each project based on the nature, value, interconnectedness, and life cycle of the infrastructure proposed.

Finally, elected officials should use the projections to inform decision-making regarding adaptation policies, budget impacts associated with design features that address future sea level rise, capital improvement projects associated with drainage and shoreline protection, and land use decisions.

Applying Projection Curves to Infrastructure Siting And Design

When determining how to apply the projection curves, the user needs to consider the nature, value, interconnectedness, and lifespan of the existing or proposed infrastructure. An understanding of the risks that critical infrastructure will be exposed to throughout its life cycle such as sea level rise inundation, storm surge, and nuisance flooding and a plan for adaptation must be established early in the conceptual phase. A determination must be made on whether or not threats can be addressed mid-life cycle via incremental adaptation measures, such as raising the height of a sluice gate on a drainage canal. If incremental adaptation is not possible for the infrastructure proposed and inundation is likely, designing to accommodate the projected sea level rise at conception or selection of an alternate site should be considered. Forward thinking risk management is critical to avoiding loss of service, loss of asset value, and most importantly loss of life or irrecoverable resources. The guidance in the following paragraphs can be considered for selection of curves from the projection for project applications.

>> Application of the IPCC Median Curve

The IPCC Median or lower blue shaded portion of the projection can be applied to most infrastructure projects before 2070 or projects whose failure would result in limited consequences to others. An example low risk projects may be a small culvert in an isolated area. The designer of a type of infrastructure that is easily replaced, has a short lifespan, is adaptable, and has limited interdependencies with other infrastructure or services must weigh the potential benefit of designing for higher sea level rise with the additional costs. Should the designer opt for specifying the lower curve, she/he must consider the consequences of under-designing for the potential likely sea level condition. Such consequences may include premature infrastructure failure.

>> Application of the NOAA Intermediate High Curve

Projects in need of a greater factor of safety related to potential inundation should consider designing for the NOAA Intermediate High Curve. Examples of such projects may include evacuation routes planned for reconstruction, communications and energy infrastructure, and critical government and financial facilities or infrastructure that may stay in place beyond a design life of 50 years.

>> Application of the NOAA High Curve

Due to the community's fundamental reliance on major infrastructure, existing and proposed critical infrastructure should be evaluated using the NOAA High curve. Critical projects include those projects which are not easily replaceable or removable, have a long design life (more than 50 years), and are interdependent with other infrastructure or services. If failure of the critical infrastructure would have catastrophic impacts, it is considered to be high risk. Due to the community's critical reliance on major infrastructure, existing and proposed high risk infrastructure should be evaluated using the NOAA High curve. Examples of high risk critical infrastructure include nuclear power plants, wastewater treatment facilities, levees or impoundments, bridges along major evacuation routes, airports, seaports, railroads, and major highways.

Projection Referenced to the North American Vertical Datum

The Unified Sea Level Rise Projection referenced to the North American Vertical Datum (NAVD) is shown in Figure 2 and summarized in Table 3. Each NOAA tide gauge in the region has published datums that can be used for conversions between elevations (https://tidesandcurrents.noaa.gov/datums.html?id=8724580).

FIGURE 2: **Unified Sea Level Rise Referenced to NAVD**

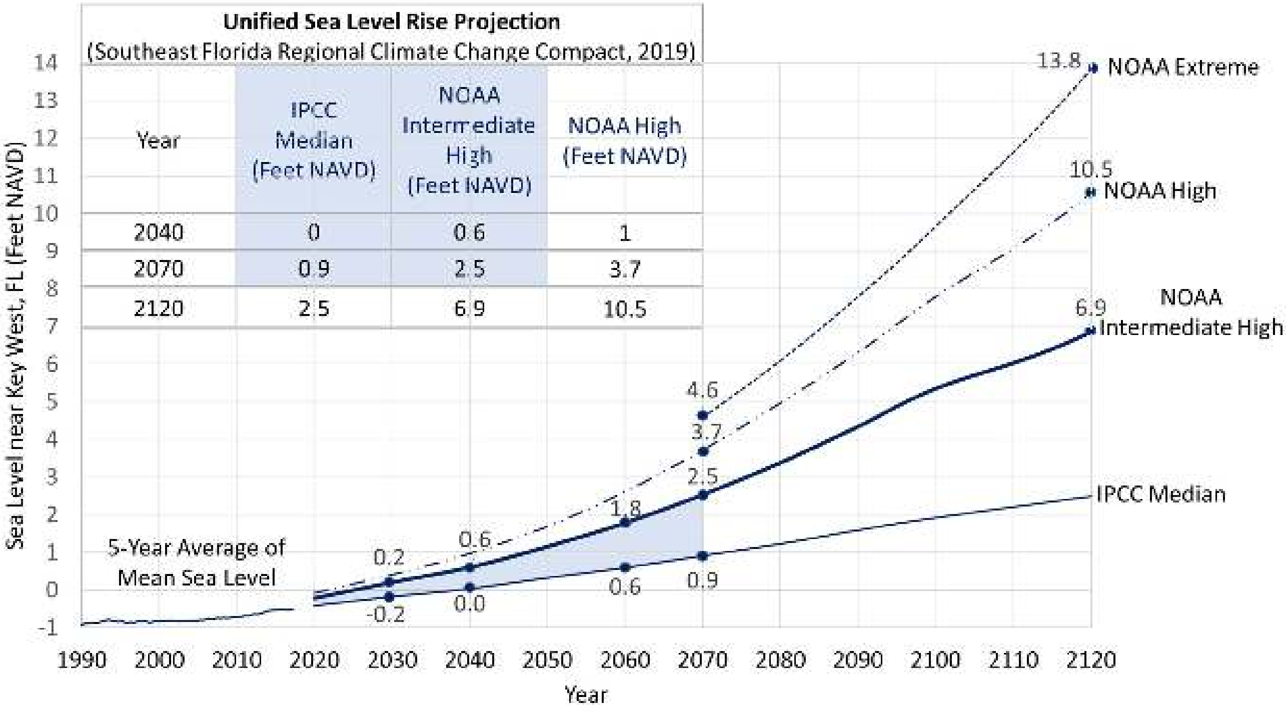


TABLE 3: **Unified Sea Level Rise Projection Referenced to NAVD**

UNIFIED SEA LEVEL RISE PROJECTION (Southeast Florida Regional Climate Change Compact, 2019)			
Year	IPCC Median (Feet NAVD)	NOAA Intermediate High (Feet NAVD)	NOAA High (Feet NAVD)
2040	0	0.6	1
2070	0.9	2.5	3.7
2120	2.5	6.9	10.5

Referencing to Today's Sea Levels

Based on the 5-year average of mean sea level at Key West, sea level rose approximately 3.9 inches from 2000 to 2017 (NOAA, 2020). This value of 3.9 inches can be subtracted from the rise projected in Table 1 to obtain an estimate of how much sea level will rise from the 2017 mean sea level. Note the availability of computed values for the 5-year average of mean sea level will always be delayed as a function of needing to have 2.5 years data past the date in order to compute the average.

To compute the rise expected from any future date relative to the existing sea level, the linear trend should be computed and its slope should be multiplied by the number of years that have passed since 2000. Based on a linear trend analysis of the historic record at Key West, sea level has risen at a rate of approximately 0.1 inches per year. Note this linear trend will change as more data are collected by the tide gauge. Also, when the slope of the linear trendline changes, the computed amount of rise will change. Care should be taken to consider the computation methodology before comparing statements of relative sea level rise for a distinct time period.

TOOLS AVAILABLE TO VISUALIZE SEA LEVEL RISE

The observed data and NOAA curves included in the projection can be reproduced using the USACE Sea Level Rise calculator http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html and USACE Sea Level Tracker https://climate.sec.usace.army.mil/slr_app/. Inundation from sea level rise can be visualized by using the Florida Sea Level Sketch Planning Tool https://sls.geoplan.ufl.edu/beta/viewer/.

Summary

The Work Group recommends the use of the NOAA High curve, the NOAA Intermediate High curve, and the median of the IPCC AR5 RCP 8.5 scenario (IPCC, 2013) as the basis for a Southeast Florida sea level rise projection for the 2040, 2070 and 2120 planning horizons. In the short term, mean sea level rise is projected to be 10 to 17 inches by 2040, and 21 to 54 inches by 2070 (above the 2000 mean sea level).

Both mean and annual average of sea level exhibit significant variability over time and that should be considered when using the projections. Annual average of sea level at the Key West gauge has risen approximately 3.9 inches from 2000 to 2017 (which is much larger than the linear trend-derived rate of rise reported by NOAA). Whether this rapid rise will be persistent into the future is unclear at this time.

In the long term, sea level rise is projected to be 40 to 136 inches by 2120. The IPCC Median or lower blue shaded portion of the projection can be applied to most infrastructure projects before 2070 or projects whose failure would result in limited consequences to others. Projects in need of a greater factor of safety related to potential inundation should consider designing for the NOAA Intermediate High Curve. For critical infrastructure projects with design lives in excess of 50 years, use of the NOAA High curve is recommended with planning values of 54 inches in 2070 and 136 inches in 2120. Sea level will continue to rise even if global mitigation efforts to reduce greenhouse gas emissions are successful at stabilizing or reducing atmospheric CO2 concentrations; however, emissions mitigation is essential to moderate the severity of potential impacts in the future. 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 sea level rise in the region. The shorter-term planning horizons (through 2070) are critical to implementation of the Southeast Florida 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, the Southeast Florida community will need to adjust the projections accordingly 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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Appendix A: State of Science Update

REGIONAL AND GLOBAL SEA LEVEL RISE OBSERVATIONS

Historic Sea Level Rise in Southeast Florida

Based on the 5-year average of mean sea level, approximately 3.9 inches of sea level rise has occurred from 2000 to 2017. Figure A-1 shows the rise of sea level as observed in Key West for the time period from 1913 to 2020 and includes the monthly mean sea level data, the 5-year average of mean sea level and a linear trendline through the monthly mean sea level. The linear trend does not match the monthly mean sea level data well. The linear trend suggests sea level rose only 2 inches from 2000 to 2019, which is less than the 5-year average trend analysis from 2000 to 2017 shown (NOAA, 2020). The 5-year average of the monthly mean sea level illustrates the variability in sea level throughout the time period and highlights the continued increase in sea level above the linear trend in the last decade.

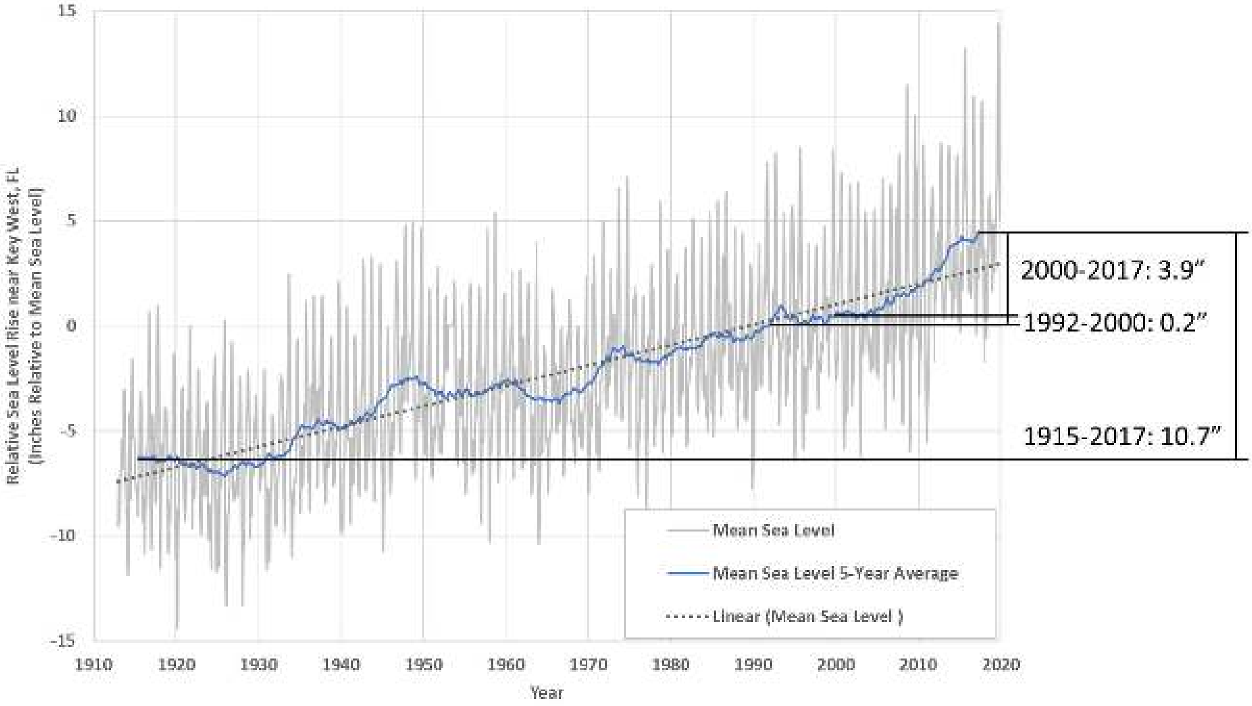

FIGURE A-1. Relative Sea Level Rise in Key West, Florida (NOAA Station ID 8724580) presented as monthly mean sea level, 5-year average of monthly mean sea level and linear trend of monthly mean sea level. Annotated measurements on right of figure are computed by subtracting the 5-year average mean sea levels for the years listed. Sea level rise computed based on the linear trend will differ from the 5-year mean sea level trend shown.

As discussed in the following sections describing the factors influencing sea level rise, the changing climate will drive new nonlinear trends in sea level that deviate from historic trends, hence the need for the Unified Projection. Although significant changes in sea level trends are anticipated over the coming decades, a preliminary comparison of the Unified Projection and the available measured data is presented in Figure A-2. The 5-year average mean sea level was observed to track between the IPCC Median and NOAA Intermediate High curves from 2013 to 2017 (2017 was the last year of computable 5-year average at the time of publication).

Monthly mean sea level was observed to exceed the NOAA Intermediate High curve in almost every tidal cycle since 2000. For additional context, the linear trend based on historic data included in Figure A-1 remains below the IPCC Median curve from 2007 onward and below the 5-year average of mean sea level from 2010 onward.

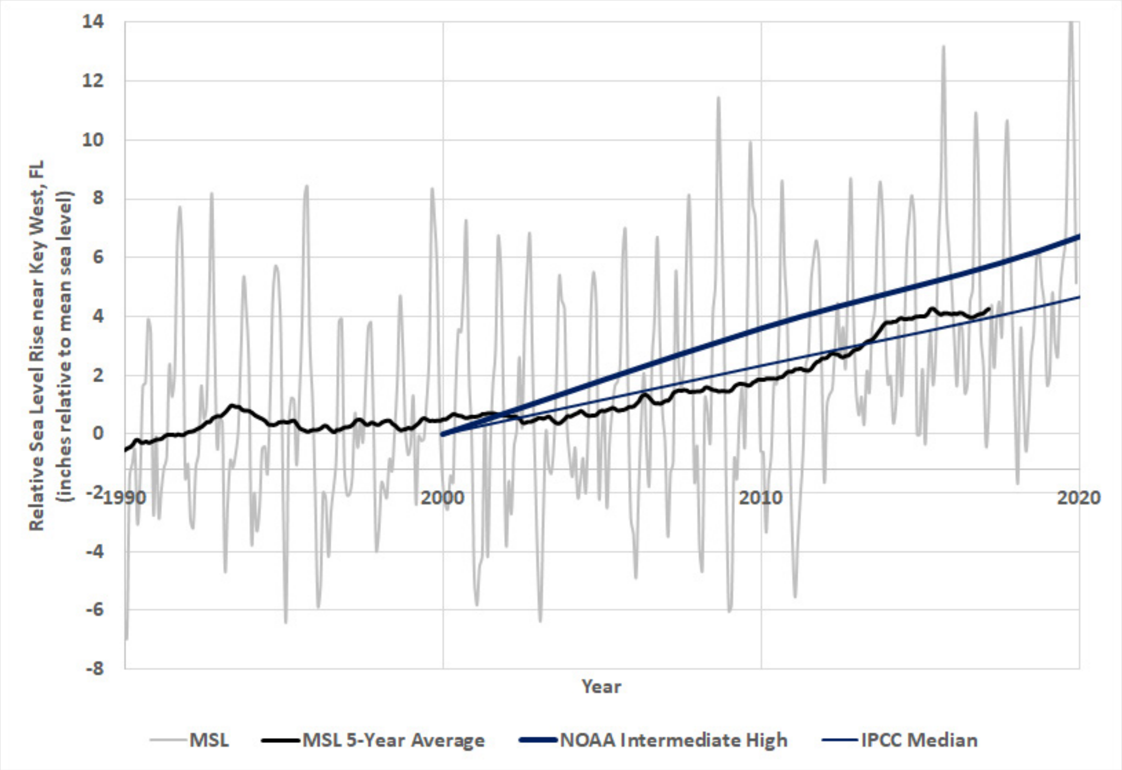

FIGURE A-2. Comparison of the Unified Sea Level Rise Projection from 2000 to 2020 and Relative Sea Level Rise in Key West, Florida from 1990 to 2020. Monthly mean sea level and the 5-year average of monthly mean sea level are based on measurements from NOAA Station ID 8724580.

ACCELERATION OF SEA LEVEL RISE

Dangendorf et al., (2017) produced a global mean sea level reconstruction for the 21st century incorporating up-to-date observations of vertical land motion and corrections for local gravitational changes resulting from ice melting and terrestrial freshwater storage. Their results provided a global sea level rise rate of 1.1 ± 0.3 millimeter per year before 1990 that is below previous estimates, and a rate of 3.1 ± 1.4 millimeter per year from 1993 to 2012 that is consistent with independent estimates from satellite altimetry.

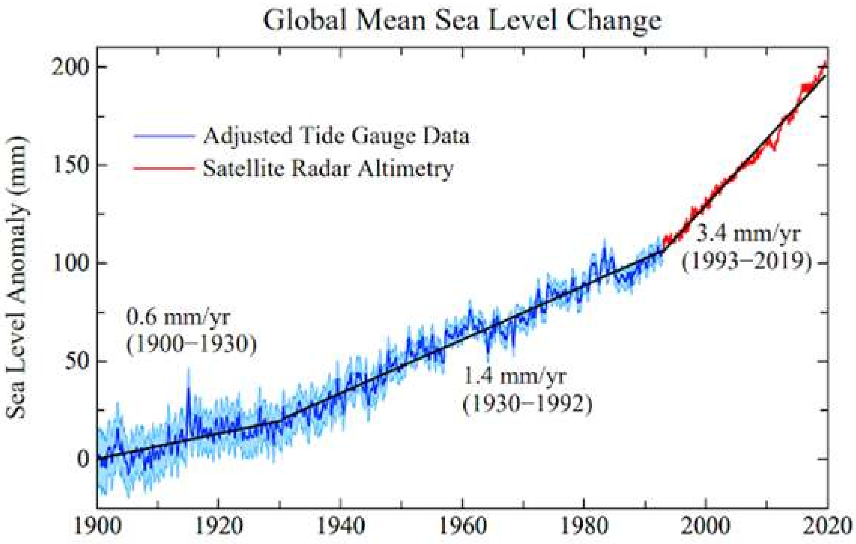

FIGURE A-3. **Global mean sea level change from 1900 to 2019 and increasing acceleration rates** (modified by Hansen et al., (2015) from Church and White (2011) and Hay et al., (2014). 1993 to 2019 data distributed by AVISO+ (https://www.aviso.altimetry.fr) with support from CNES.

Recent analyses of tide gauge records acquired along the United States Atlantic coast indicate year-to-year acceleration in the rate of sea level rise (Sweet et al., 2017). During 2010-2015, accelerated sea level rise at rates five times the global average was observed between Key West and Cape Hatteras (Valle-Levinson, 2017), and is attributed to the warming of the Florida Current (Domingues et al., 2018). Locally, Wdowinski et al. (2016) analyzed the Virginia Key tide gauge record (near Miami) and found a significant acceleration in the rate of sea level rise since 2006. The average rate of regional sea level rise since 2006 was 9±4 millimeters per year, significantly higher than the global average rate, which has been estimated to be in the range of 4-5 millimeters per year for the post-2006 period (WMO, 2019). The global and regional processes driving sea level rise and its acceleration are discussed in the following sections.

NOAA Sea Level Rise Scenarios

For the Compact 2019 projections, the workgroup referenced the technical information provided in the NOAA report (Sweet et al., 2017) which was also used as input to the sea level rise chapter of the National Climate Assessment (NCA) (https://science2017.globalchange.gov/chapter/12/). The sea level projections in the NOAA report were developed by a Federal Interagency Sea Level Rise Task Force and they included six scenarios (Table A-1 below) using a risk-based framing approach to deal with uncertainties. The scenario approach is similar to the regional sea level rise scenarios produced by Hall et al. (2016) and they are linked to the greenhouse gas emission scenarios, RCP 2.6, 4.5, and 8.5 as shown in Table A-1. The NOAA 2017 report includes the best available research since the production of the Compact 2015 report and is considered to be a reliable source of data from the national effort on sea level rise projections. More importantly, the projections are available regionally and that allowed the work group to customize 2019 projections using the Key West gauge as was done for the 2015 projections.

TABLE A-1: Interpretations of the Interagency Global Mean Sea Level (GMSL) rise scenarios (National Climate Assessment (NCA), Chapter 12)

SCENARIO	INTERPRETATION
Low	Continuing current rate of GMSL rise, as calculated since 1993 Low end of *very likely* range under RCP 2.6
Intermediate-Low	Modest increase in rate Middle of *likely* range under RCP 2.6 Low end of *likely* range under RCP 4.5 Low end of *very likely* range under RCP 8.5
Intermediate	High end of *very likely* range under RCP 4.5 High end of *likely* range under RCP 8.5 Middle of *likely* range under RCP 4.5 when accounting for possible ice cliff instabilities
Intermediate-High	Slightly above high end of *very likely* range under RCP 8.5 Middle of *likely* range under RCP 8.5 when accounting for possible ice cliff instabilities
High	High end of *very likely* range under RCP 8.5 when accounting for possible ice cliff instabilities
Extreme	Consistent with estimates of physically possible “worst case”

In general, the global sea level rise pathways for different emission scenarios are not very different until about the mid-century after which they deviate significantly (e.g. Figure 4.2, IPCC 2019). The broad range of sea level rise projection during the latter part of the century reflects the significant uncertainty in predicting the contributions of individual sea level rise components, attributable primarily to ice cliff instability. Driven by the desire to capture the potential for larger sea level rise resulting from rapid melting from the ice sheets towards the latter part of the century, the work group made a decision to select higher scenarios that are also consistent with the growing emission scenario, RCP 8.5. Recent sea level rise guidance from the Tampa Bay Region recommended the use of RCP 8.5 “*...until the private and public sectors make meaningful efforts to reduce greenhouse gas emissions.*” Consequently, the Intermediate High, and High scenarios (Table A-1) were included in the 2019 scenarios set. Consistent with the 2015 projections, IPCC Median scenario for RCP 8.5 was added to define the lower boundary of the range. The IPCC Median (with a Global Mean Sea Level, GMSL, rise of 0.73 meters) lies between Intermediate Low (0.5 meter of GMSL) and Intermediate (1 meter GMSL) scenarios in the NOAA 2017 set (Table A-1). The Work Group also included the NOAA 2017 Extreme Scenario as an estimate of the upper bound of what could happen as a result of a catastrophic ice sheet collapse and the primary intent of this inclusion was to emphasize what could happen to GMSL if the emissions were allowed to continue without mitigation.Inclusion of such an extreme scenario is not unprecedented. For instance, New York City (Gornitz et al., 2019) included a new, physically plausible, upper-end scenario dubbed ARIM (Antarctic Rapid Ice Melt) scenario for this purpose. The California guidance also includes a similar scenario, called H++ which reflects extreme sea level but with unknown probability.

FACTORS INFLUENCING FUTURE SEA LEVEL RISE

Global Processes

Thermal expansion

Warming of oceans leads to a lower density and as a consequence volume per unit mass increases. The ocean has absorbed more than 90% of the heat that is generated by heat trapping greenhouse gasses making the thermal expansion a significant component of the observed sea level rise. Thermal expansion is expected to increase, but its contribution to the global sea level rise may be exceeded by the increased contributions from melting land-based ice sheets.

Acceleration of Ice Melt

Accelerated melting of glaciers and ice sheets of Greenland and Antarctica has become the predominant factor affecting sea level rise acceleration (Oppenheimer et al., 2019). Melting is caused by anthropogenic forcing leading to increasing temperatures and warming of the atmosphere, warm currents moving along the coast of Greenland, and warm ocean water moving under and up into ice sheets through deep outlet glacial fjords in Greenland and Antarctica in response to meteorologic changes. The rate of melt of the Greenland Ice Sheet was relatively stable in the 1990s and has increased since then to a rate seven times greater than in 1992 (IMBIE, 2019; Chen et al., 2017). The rate of acceleration peaked in 2011, slowed in response to cooler conditions until 2016, but has begun increasing again. Although all of the ice melt processes are not fully represented in the climate projection models, studies suggest contributions from ice melt are likely to match the estimates of melt from the IPCC AR5 RCP 8.5 scenario (Oppenheimer et al., 2019).

Based on geologic records from the last two pre-historical periods that the Greenland and Antarctica ice sheets melted, global mean sea level likely rose 18 to 27 feet in response, but potentially as much as 75 feet. Models and analyses cannot yet confirm if similar rates of pre-historic rise will occur in response to melt in the future (Oppenheimer et al., 2019). The possibility of such extreme rise in response to ice melt prompted the inclusion of the NOAA Extreme curve for reference in the Unified Sea Level Rise Projection and to highlight the importance of greenhouse gas mitigation. Although unlikely and not appropriate for infrastructure planning, the Work Group wanted to acknowledge the evolving science in projecting accelerating ice melt and bracket the uncertainty in rise at the end of the century based on the most recent observations and models.

Thawing Permafrost

Frozen soils are both a major source of emissions today, and a major sink for carbon during past ice ages. Permafrost is permanently frozen soil, which holds vast amounts of organic material in a suspended state of decay. It is found in vast, remote and inaccessible places: under tundra's covered active layer (seasonally melted mud), underwater, and under sea ice and/or snow. It is the least understood, but potentially one of the most important climate change drivers. Satellite remote sensing is less useful in its direct observation of permafrost, compared to other phenomena important to sea level rise. But the high atmospheric methane concentration in the atmosphere above the northern polar region stands out above other regions on earth. Russian, Alaskan and other scientists from around the world are actively investigating the potential for significant additional emissions of carbon dioxide and methane from thawing permafrost (Shakova et al., 2019). Prior to the last three decades, heavy multi-year sea ice protected solid frozen permafrost, and the methane sequestered within it as massive subaqueous methane hydrate deposits. Release of this methane could constitute a powerful tipping point for atmospheric warming, and the glacial melting to follow. It is unknown when such a tipping point is likely to occur, but the continued acceleration of global warming with business as usual, RCP 8.5, puts us on a dangerous trajectory.

Regional/ Local Processes

Distinct rates of sea level rise recorded along the U.S. East Coast are currently largely modulated by the effect of various regional and local processes (Piecuch et al., 2018). The long-term regional sea level rise projections employed in this report are primarily based on the recent scenarios convened by the Sea Level Rise and Coastal Flood Hazard Interagency Task Force (Sweet et al., 2017), which explicitly consider these effects from regional drivers. As an example, regional drivers may account for an additional 37 centimeters of sea level rise by 2100 in Key West under the assumptions linked with the NOAA Intermediate-High scenario, totaling 1.87 meters of sea level rise compared with 1.5 meters globally. The following section describes the most important regional drivers that can affect rates of sea level rise in Southeast Florida.

Vertical Land Movement

Vertical earth movements (subsidence or uplift), which regionally and locally modify the averaged rate of sea level change, result in a relative rate of change that varies from one location to another. These land movements are inferred from historical tide data and geodesic measurements. When added to projected rates of mean sea level rise, the vertical land movement results in a perceived rates of sea level rise change ranging from increased rise in regions of subsidence (e.g., New Orleans) to falling sea levels where the land is being uplifted (e.g., along the northern border of the Gulf of Alaska). Sea level rise in geologically stable regions have only small differences with respect to the global rate of rise. Some of the processes leading to vertical land movement include the post-glacial rebound (known as Glacial Isostatic Adjustment — GIA), sediment compaction, dam retention, and groundwater and oil withdrawal.

A robust method for estimating vertical land movements is based on continuous GPS measurements conducted at selected locations. Over the past two decades, more than 60 continuous GPS stations were constructed and operated in Florida by federal and state institutes, including the Continuously Operating Reference (COR) network, US Coast Guard, Florida Department of Transportation, and others. The length of record in these stations vary from one to fourteen years, reflecting the difficulties in maintaining smooth operation of a continuous GPS station. The continuous GPS measurements indicate that vertical land movements in Florida are fairly small; they vary in the range of ±4 millimeters/year. In South Florida, in general, coastal land elevations are considered relatively stable—meaning that the land is not experiencing significant uplift or subsidence. Therefore, the processes listed above are likely not playing a major role on the current sea level rise rates observed in Southeast Florida. It is important to note, however, that the vertical land movement that is occurring is non-uniform across South Florida, and movement measured at specific monitoring stations sites may not reflect vertical land movement in adjacent areas.

Ocean Dynamics, Gulfstream/ Circulation

Regional patterns of sea level change are partly due to trends in ocean currents, redistribution of temperature and salinity, and atmospheric pressure. The reasons for changes in “Ocean Dynamics” are well known (Hall et al., 2016). Thermal expansion changes the elevation of the sea surface non-uniformly and to balance the resulting pressure gradient, ocean mass will flow from areas of large water depths into shallower continental shelf areas (Hall et al. 2016; Yin et al. 2009). Long-term changes in ocean dynamics still represent one of the largest sources of uncertainty for long-term projections of sea level rise (Kopp et al., 2014; Chen et al., 2019), and current observations show only a modest decline in the strength of the Florida Current flow.

Ocean circulation has changed little during the current period of scientific observation, but in the future it may considerably alter the relative rate of sea level rise in some regions, including Southeast Florida. The potential slowing of the Florida Current and Gulf Stream could result in a more rapid sea level rise along the east coast of North America. By 2100, these circulation changes could contribute an extra eight inches of sea level rise in

New York and three inches in Miami according to Yin et al. (2009). Most of the global climate models used by the IPCC (IPCC, 1913 project a 20-30% weakening of the Atlantic Meridional Overturning Circulation (AMOC), of which the Gulf Stream and Florida Current are a part, a response to warming caused by increasing greenhouse gases. Measurements of the AMOC have yet to conclusively detect the beginning of this change, however there has been a report of a recent decline in AMOC strength by Smeed et al. (2014) that coincides with the mid-Atlantic hotspot of sea level rise reported by Ezer et al. (2013) and Rahmstorf et al. (2015). Recent analysis of the Florida Current transport has detected only a slight decrease in circulation over the last decades. Assuming the long-term slowdown of the AMOC does occur, sea level rise along the Florida east coast could conceivably be as much as twenty centimeters (eight inches) greater than the global value by 2100. Given that changes in ocean dynamics, such as these changes projected for the AMOC, are still one of the main sources of uncertainty for long-term regional sea level rise scenarios (e.g. Kopp et al., 2014; Piecuch et al., 2018), longer records of the Florida Current and Gulf Stream transport are required to confirm if the long-term decline in the strength of the flow persists, or if it is associated with interannual/decadal natural variations. Recent regional sea level rise scenarios for the U.S. coasts have been made available by the Sea Level Rise and Coastal Flood Hazard Interagency Task Force (Sweet et al., 2017), and explicitly consider regional effects of changes in ocean dynamics and other local contributors, as described above.

Regional Ocean Heat Content Changes

Recent studies revealed accelerated rates of year-to-year changes in regional sea level variability along the U.S. East Coast (Valle-Levinson et al., 2017). Even though these variations are not necessarily linked with long-term sea level rise trends, these accelerated changes currently contribute to flooding conditions often observed at Southeast Florida communities. Analysis showed that accelerated sea level rise recently observed for Southeast Florida from 2010 to 2015 were in fact associated with thermal expansion from warming of the Florida Current during the same time period, as reported in Domingues et al., (2018). Further analysis (Volkov et al., 2019) revealed that such warming was linked to large-scale heat convergence within the North Atlantic subtropical gyre caused by changes in the Atlantic Meridional Overturning Circulation (AMOC). While current findings indicate that these effects occur mostly on year-to-year timescales, under a long-term scenario that includes the decline in the AMOC circulation (as suggested by IPCC 2013), it is likely that amplified sea level rise rates may be observed along Southeast Florida through similar mechanisms.

Sea level fingerprinting (Gravitational Effects)

Melting ice sheets in polar regions is one of the main processes contributing to sea level rise, but not in a spatially uniform manner, because of gravitational forces. Melting ice sheets reduces the mass of water stored in polar regions and, consequently, reduce the gravitational attraction of continental ice sheets. As a result, the volume of ocean water near the melting ice sheet decreases, leading to reduction in sea level height near the polar regions, and an increase in sea level further away. This process is termed sea level fingerprinting (Mitrovica et al., 2011, 2009). It suggests a counterintuitive change in regional patterns of sea level changes, in which sea level height decreases near the source of fresh water supply to the ocean.

A sea level fingerprinting study by Hay et al. (2014) suggest that melting of the Greenland Ice Sheet results in a slightly lower rate of sea level rise along the Florida shorelines with respect to the global mean rate. The calculated change is 20% of the total contribution of the Greenland Ice Sheet to the global mean rate, which is currently estimated as 1-1.5 millimeters/year. According to Hay et al. (2014), melting of the West Antarctic Ice Sheet increases the rate of sea level rise along the Florida coast by 20% with respect to the total contribution of the West Antarctic Ice Sheet to the global mean rate, which is so far about 0.75-1 millimeters/year. Thus far, the contribution of sea level fingerprinting in southeast Florida had been fairly small, about 0.2-0.3 millimeters/year.

However, in the future with increasing rate of polar ice melt, the effect of sea level fingerprinting can increase, especially if the Antarctic Ice Sheet will melt significantly faster than the Greenland Ice Sheet. It should be noted that the NOAA (2017) scenarios used for the current projections explicitly account for regional fingerprinting.

EFFECTS OF GREENHOUSE GAS EMISSIONS

The Intergovernmental Panel on Climate Change based the climate projections of their Fifth Assessment Report on four greenhouse gas concentration scenarios, known as the Representative Concentration Pathways (RCPs) (IPCC, 2014). These RCPs are sets of scenarios for greenhouse gas emission, greenhouse gas concentration, and land use trajectories; their primary product is greenhouse gas concentration scenarios for use as inputs into climate models (van Vuuren et al., 2011a). The number in the name of each RCP is the end-of-century radiative forcing in W/m^{-2} caused by the greenhouse gas concentrations in 2100.

The lowest concentration scenario, RCP 2.6, is viewed as the scenario necessary to keep global temperature increases below 2°C (van Vuuren et al 2011a). This scenario would require that greenhouse gas emissions peak around 2020 and decrease at 4% annually (van Vuuren et al. 2011a). The highest concentration scenario, RCP 8.5, assumes a greatly increased population with low economic and efficiency gains by 2100, along with a strong dependence on fossil fuels, including a ten-fold increase in coal use by the end of the century (Riahi et al., 2011).

RCP 4.5 and RCP 6.0 are concentration scenarios sitting between these two extremes. In the RCP 4.5 scenario, emissions valuation policies, reaching $85 per ton of carbon dioxide by 2100, drive alternatives in energy production and land use changes to reduce emissions. It assumes use of bioenergy production coupled with carbon capture and storage to produce energy with net-negative carbon emissions. RCP 6.0 assumes cost-effective reduction of emissions through a global emissions permit market, and includes a shift from coal-fired to gas-fired energy production and more than 30% non-fossil fuel energy production by 2100 (Masui et al., 2011).

Beyond these four concentration pathways, the IPCC recently released a report outlining the emissions scenarios required to limit global warming to 1.5°C (IPCC, 2018). In this model pathway, global net anthropogenic carbon dioxide emissions decline by about 45% from 2010 levels by 2030, reaching net zero around 2050. The report also contains an emissions projection to limit global warming to 2.0°C; in this scenario, carbon dioxide emissions decline by about 25% by 2030, and reach net zero around 2070.

Prior to 2050, different emission scenarios produce minor differences in sea level rise projections, however, they diverge significantly past mid century. After 2050, the sea level rise projections increasingly depend on the trajectory of greenhouse gas emissions, underscoring the critical need for urgent and ambitious decarbonization policies and efforts.

Seasonal Cycle of Sea Level and Interannual Variability

There is a strong seasonality to average sea level variation with any given year. This is primarily driven by seasonal oceanographic and atmospheric processes such as fluctuations in coastal ocean temperature, salinity, winds, atmospheric pressure, and ocean currents. In Southeast Florida, the sea level driven by astronomical tides exhibits a strong seasonality with higher than average values during the months of September to November with a peak during the month of October (Figure A-4). The seasonal high in October may be as much as 5-6 inches above the average. The high values during September to November, superimposed on the mean sea level curve and diurnal and semidiurnal tides further exacerbates the recurrent flooding that has been increasing in recent years.

In addition to the seasonal fluctuations, sea level may also exhibit interannual variability due to fluctuations in oceanographic and atmospheric processes (Figure A-4). Such fluctuations may further increase the mean annual sea level above the average seasonal cycle shown in Figure A-4 and they may persist at a higher or lower level for several years. For example, Figure A-5 shows that the annual fluctuation since about 2012 has been largely positive until 2019, a pattern that is not characteristic of annual variability since 1990. It is possible that such a persistence may be due to a systematic trend in ocean currents and/or other atmospheric-oceanographic process but it is too early to make such an attribution.

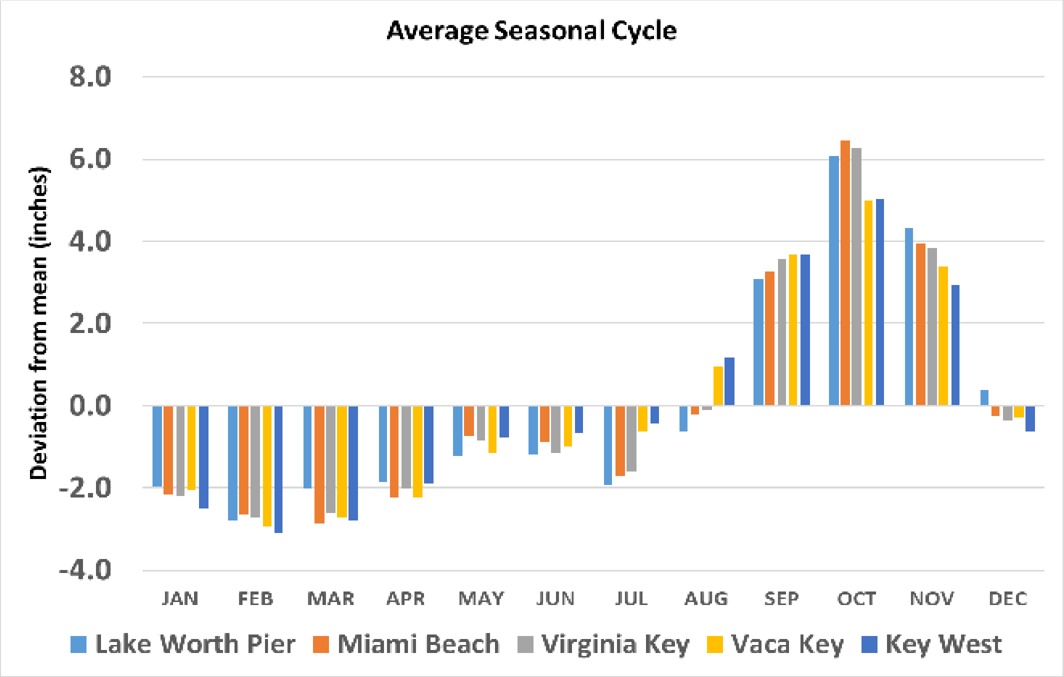

FIGURE A-4: Tidal water elevations in the Southeast Florida area average 5 to 6 inches higher at the end of the summer (NOAA, 2020b). This increases the risk of recurrent high tide street flooding and more severe storm surge impacts, particularly during periods of astronomical high tides (i.e. king tides). Ongoing and accelerating local sea level rise will just make this problem worse.

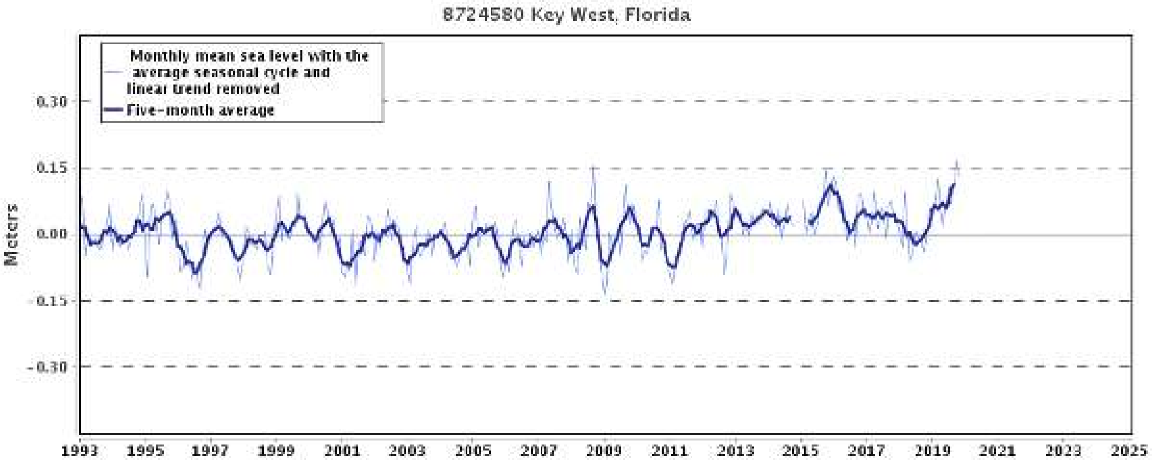

FIGURE A-5: The plot shows the interannual variation of monthly mean sea level and the 5-month running average. The average seasonal cycle and linear sea level trend have been removed (Retrieved from NOAA Tides and Currents website (https://tidesandcurrents.noaa.gov/)

Increase in Recurrent Tidal Flooding

Accelerating rates of sea level rise, due to both global and regional processes, have resulted in increased flooding frequency in several coastal communities along the US Atlantic coast, including the Southeast Florida region (Ezer et al., 2013; Ezer and Atkinson, 2014; Kirshen et al., 2008; Kleinosky et al., 2006; Sweet et al., 2018; Wdowinski et al., 2016; 2019; Valle-Levinson et al., 2017). These recurrent flood events, often termed "nuisance flooding," occur during high tide conditions, with or without heavy inland rainfall. When flooding events occur due to high tide flooding alone, they are also termed "king tides", or "sunny-day flooding." Recurrent tidal flooding results in inundation, impedes access, impairs stormwater drainage infrastructure, and damages vulnerable systems. With sea level rise, the frequency of tidal flooding will increase, leading to chronic flooding approaching permanent inundation.

An analysis of flooding frequency from 1998 to 2013 in Miami Beach revealed that recurrent tidal flooding events quadrupled, from two events during the eight years from 1998-2005, to 8 to 16 total events in the following eight years from 2006-2013 (Wdowinski et al., 2016). In 2005, 2015, 2016, and 2017, compound flooding induced by hurricanes led to the highest observed numbers of annual flood days on record (Ezer and Atkinson, 2017; Ezer et al., 2017; Wdowinski, 2019). From 2006 to 2012, recurrent tidal flooding occurred approximately every other year, typically during the fall (September through November). Since 2010, higher than normal tides have also been observed in the winter and spring seasons (Figure A-6, Wdowinski et al., 2019). In 2019, unprecedented flooding occurred in Key Largo, where a neighborhood was flooded continuously for more than four months.

How will flooding frequency evolve over time?

On the national scale, NOAA (2014) published an assessment of nuisance flooding finding that the duration and frequency of these events are intensifying around the United States. Subsequently, Park and Sweet (2015) demonstrated that coastal areas are experiencing an increased frequency of flood events (an acceleration) over the last few decades, and that this acceleration in flood occurrence will continue regardless of the specific rate of sea level rise. The recent assessment published by NOAA (Sweet et al., 2018) in fact shows that the number of high-tide flooding days has been increasing at a nonlinear rate for locations along the U.S. East Coast, including Southeast Florida. Results from this assessment indicate that under the NOAA Intermediate scenario, Miami will likely experience approximately 60 days of high-tide flooding per year by 2050, while under the NOAA Intermediate-High scenario this number may exceed 150 days per year (Figure A-7, personal communication, Sweet et al., 2018).

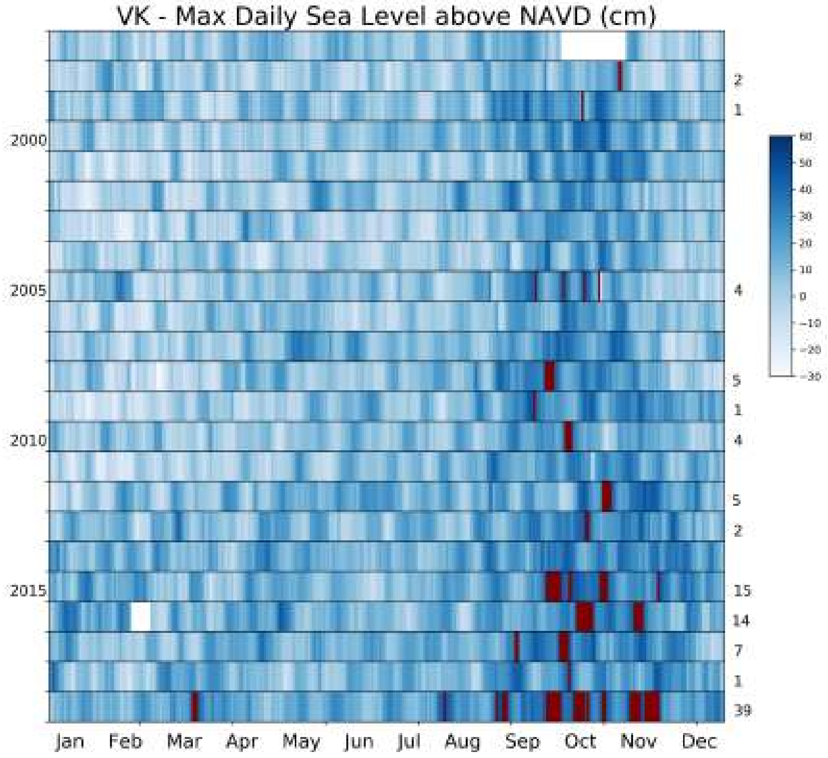

FIGURE A-6. Frequency of tidal flooding in Miami Beach, based on Virginia Key tide gauge. Higher than normal tides shown as red bars in figure. Number of events in a given year listed in right margin of graphic (Wdowinski, 2019).

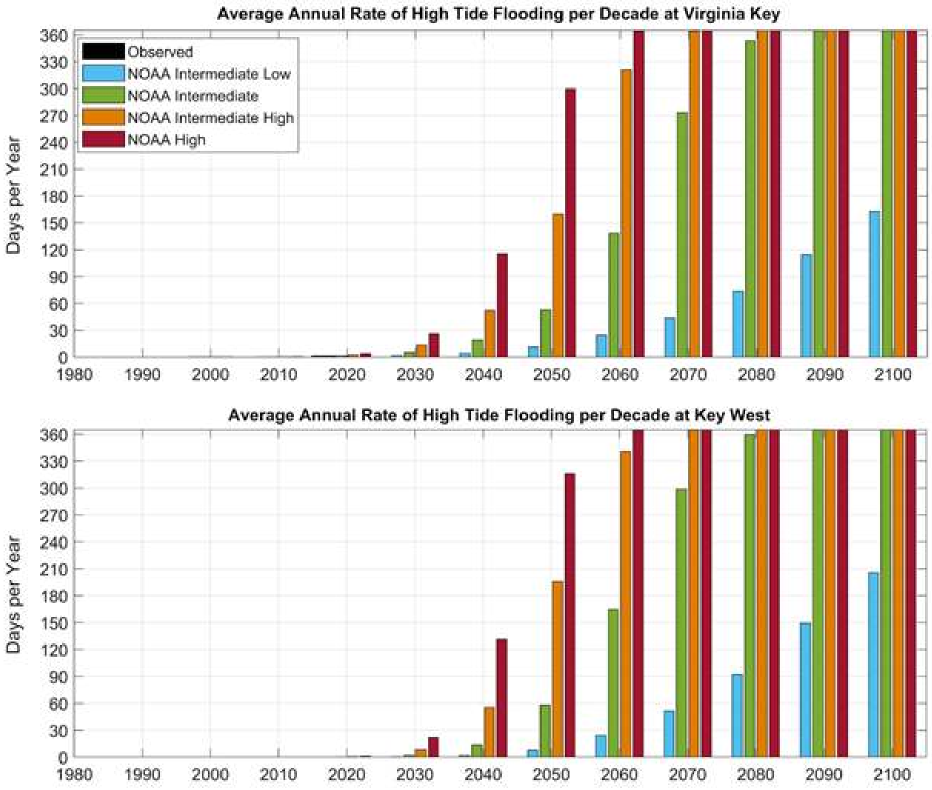

FIGURE A-7: Projected annual frequencies of high tide flooding associated with the NOAA sea level rise (Sweet et al., 2017) estimated at NOAA tide gauges in Virginia Key and Key West. High tide flooding threshold values levels above MHHW are 0.52 meters for Virginia Key, and 0.53 meter for Key West (Courtesy of William Sweet - NOAA National Ocean Service).

Groundwater Rise and Reduced Drainage Capacity

Sea level rise may also affect flooding by raising the water table and reducing the ability of rainfall to infiltrate and be stored in the soil. In coastal areas of Southeast Florida, groundwater levels were observed to rise at the same rate as sea level rise over the long term (Decker et al., 2019; Sukop et al., 2018). Flooding as a consequence of groundwater rise and reduced soil storage is anticipated to double or triple in flood frequency over the next 40 years (Sukop et al., 2018; Obeysekera et al., 2019). By 2070, certain coastal areas of South Florida are projected to lose all wet season storage capacity (Obeysekera et al., 2019).

In one example, Sukop et al. (2018) examined the long-term record of water levels in a well (G-852, in the North Miami/Arch Creek area) approximately one mile from tide water at Biscayne Bay. The water levels in the well have been increasing at approximately 2.8 millimeters/year since at least 1974. This rate is consistent with the rate of sea level rise at Key West of 2.42 millimeters/year over the same time period. (https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8724580).

As part of an assessment for the Florida Building Commission, Obeysekera et al. (2019) used projections of sea level rise from previous versions of this report in groundwater models to estimate the change in water table elevation in Miami-Dade County by 2069. Between 2010 and 2069, drainage capacity is estimated to decrease by four to ten inches of water in most of the county (Figure A-8) under the high sea level rise scenario.

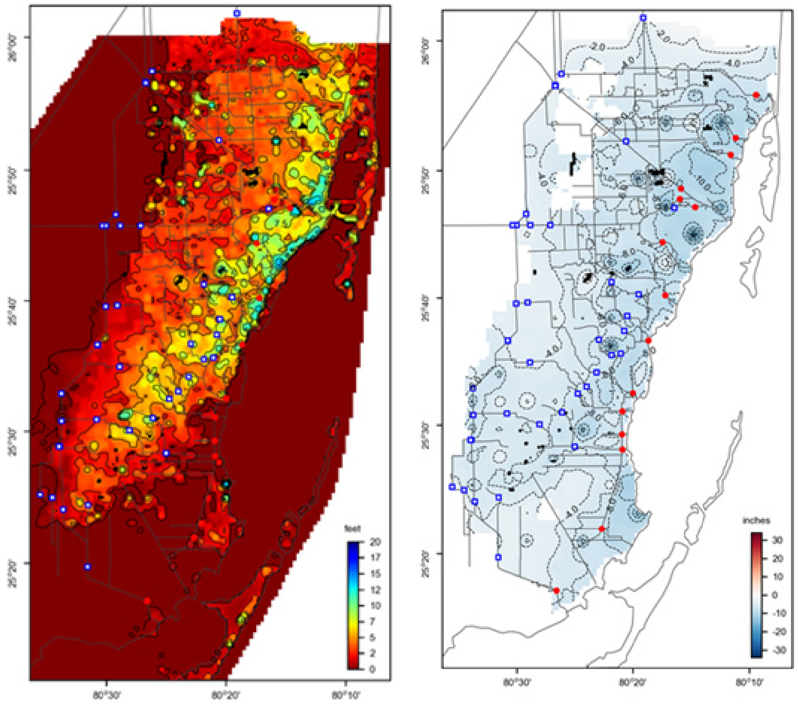

FIGURE A-8: Miami-Dade County depth to water in 2069 (left) and loss of wet season soil storage capacity from 2015 through 2069 (right) (Obeysekera et al., 2019).

Increasing sea levels also have the potential to compromise the capacity of coastal water control structures (also known as salinity barriers). As the ocean-side water levels increase, the water control gates of these gravity structures cannot be opened due to the threat of saltwater entering into the canals they serve and potentially contributing to saltwater intrusion (Obeysekera et al. 2011).

Storm Surge, Waves, and Sea Level Rise

Storm surge and sea level rise are independent coastal processes that, when occurring simultaneously, lead to compounded impacts. Sea level rise has the potential to increase the inland areal extent inundated by surges, the depth of flooding, power of the surge, and the extent and intensity of damage associated with storm surge and waves. As a result, severe storms of the future may cause significantly more damage than storms of equal intensity occurring at today's sea level. The frequency of extreme sea levels that cause severe flooding will also increase as a consequence of sea level rise (Rasmussen, 2018). To avoid impacts from surge, coastal infrastructure design elevations and reinforcement will need to consider the relationship between future sea level rise and surge.

The effects of sea level rise on storm tides or surge is nonlinear and location specific. Analyses that superimpose sea level rise projections on top of surge depths are likely not capturing the nonlinearity of the processes, and may possibly underestimate depths and forces. Reduction of sea bottom stress and tidal wave energy dissipation in waters deepened by sea level rise can result in higher surge heights in shallow nearshore waters (Arns et al., 2015). Similarly, changes in deep water wave heights and wave periods can increase wave setup and swash zone activity (Melet et al., 2018). Location- specific projections of future waves and the interactions between sea level, tides and surges are not yet available (Oppenheimer et al., 2019), but site-specific modeling of the impacts of future severe storms on infrastructure has occurred for projects across the Compact four-county region by increasing water levels to represent future conditions.

Rare, extreme water levels that typically occured once every 100 years in the past are projected to occur annually or more frequently by 2065 in response to sea level rise (Oppenheimer et al., 2019). The Intergovernmental Panel on Climate Change has concluded high confidence in this projected frequency and suggested adaptation planning occur before extreme events become regular in the latter half of the 21st century. Moreover, the duration, precipitation, landfalls, and intensity of future hurricanes is predicted to increase with global warming (IPCC, 2014; Knutson et al., 2015; Scoccimarro et al., 2017; Yamada et al., 2017).

Natural Resource Degradation

As sea level rise increasingly inundates coastal areas, natural resources in the ecologically diverse and important transition zone—including mangrove forests, tidal flats, and beaches—will be degraded unless focused effort is devoted to: 1) accommodating the inland migration of coastal habitats, and 2) implementing coastal management practices that maintain coastal elevation at pace with sea level rise rates (Glick 2006, Florida Oceans and Coastal Council 2010). In Southeast Florida, existing urban development in the form of seawalls, roads, and other infrastructure currently blocks much of the ability of coastal habitats to migrate as sea level rises. Reduced freshwater delivery and conversion of coastal areas to non-vegetated lands limit or eliminate plant growth, diminish the capacity for coastal areas to maintain natural system functions, and result in natural system decline. Intrusion of saltwater inland, into inland water bodies, and within the aquifer is already negatively impacting freshwater resources. With further sea level rise, these impacts will worsen or accelerate without adaptation that includes coastal management. Inundation of shorelines will also increase the extent and severity of beach erosion in previously stable coastal areas. In combination, these impacts will cascade throughout the region's ecosystems even if they are not immediately adjacent to open water areas.

These ecosystems (natural infrastructure) and the natural resources they support, are critical to the resilience of people and the urban environment. Natural systems provide many important benefits. These include providing nesting, spawning, and feeding habitat for numerous species including sea turtles, shorebirds, fish, and invertebrates; contributing to climate change mitigation via sequestration of carbon dioxide from the atmosphere; enhancing storm protection, water and air purification; moderating urban heat effects; and supporting livelihoods and economic activity throughout South Florida that depend on tourism and recreational and commercial fisheries. The region can manage for natural resource benefits by providing space for habitat transitions, implementing practices that help adapt coastlines to sea level rise, and reducing anthropogenic pressures (e.g., nutrient and solid waste pollution, recreational activities that can damage natural resources, development practices) that would compound the degrading effects of sea level rise.

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