SEA-LEVEL CHANGE SCIENCE FOR DECISIONMAKERS

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SUMMARY

Among the many detrimental impacts from climate change, sea-level rise is one of the most damaging, costly, and devastating. Sea-level change poses particular challenges for coastal communities, and is becoming more prevalent in environmental law. Existing scientific literature about how sea-level change works can often be inaccessible to the people that need it. In addition, each coastal community experiences a unique combination of global, regional, and local factors that define sea-level change. This Article provides an overview of how sea-level change works and a repository of data tools available to the public, covering how sea level is defined, measured, and modeled, the processes that change sea level globally and regionally, how these processes have changed over time, and how to interpret the scientific uncertainty present in sea-level science. It then examines how regional and local processes determine sea-level change along the Florida coastline and provides an overview of historical, modern, and future sea-level rise there. The Article can serve as a reference for understanding the science that may come up in legal cases related to sea-level change, and the associated toolkit provides regionally specific information for understanding sea level throughout the United States.

We live in a time defined by the considerable human influence on earth's natural environment. Modern climate change, which is caused by human activity, is a central component of life in this age. There is scientific consensus (i.e., agreement among virtually all climate experts—99% by the most recent measure) that the climate change we are experiencing today is caused by human activity.[1] When we burn fossil fuels to create the energy that makes our cars, homes, and factories run, greenhouse gases (such as carbon dioxide (CO_2)) are released into the atmosphere where they trap heat from the sun. Since the height of the Industrial Revolution in the mid-19th century, our continued use of coal, oil, and gas has increased the atmospheric concentration of these greenhouse gases, resulting in a myriad of climatic and environmental effects.

One significant effect is that as the global average temperature increases, glaciers and ice sheets melt and cause sea level to rise. Warmer ocean waters undergo thermal expansion, which also contributes to sea-level rise. There are several factors that contribute to changing sea level that we will discuss in this Article. These factors, some of which are highly local, can influence how sea-level rise is "felt" at a particular coastline.

Additionally, the rate at which sea level is rising has consistently increased over the past century.[2] Sea-level rise is happening as a result of the changing climate, and will continue as long as we burn fossil fuels.[3] Adaptation is not

Editor's Note: This Article was originally presented at the symposium Science and the Law of Sea Level Rise: Reducing Legal Obstacles to Managing Rising Seas, *hosted by the Environmental Law Institute and Nova Southeastern University's Shepard Broad College of Law on March 21-22, 2024. The symposium was supported by the National Science Foundation Paleoclimate Office, Award Number 2330829.*

1. Krista F. Myers et al., *Consensus Revisited: Quantifying Scientific Agreement on Climate Change and Climate Expertise Among Earth Scientists 10 Years Later*, 16 Env't Rsch. Letters 104030 (2021); Mark Lynas et al., *Greater Than 99% Consensus on Human Caused Climate Change in the Peer-Reviewed Scientific Literature*, 16 Env't Rsch. Letters 114005 (2021).
2. Carling C. Hay et al., *Probabilistic Reanalysis of Twentieth-Century Sea-Level Rise*, 517 Nature 481 (2015).
3. Peter U. Clark et al., *Sea-Level Commitment as a Gauge for Climate Policy*, 8 Nature Climate Change 653 (2018).

sufficient[4]—only by decreasing our society's use of fossil fuels as an energy source can we mitigate the present and future effects of climate change, including rising sea level.

The scientific community is motivated to study sea-level change in large part because of the urgent human effects that result from this phenomenon. In many communities, the effects of sea-level rise are already being felt in dramatic ways. Rising sea level impacts infrastructure, agriculture, businesses, ecosystems, transportation, public health, and more. Roughly 600 million people globally live within 10 meters of sea level, and that number is growing.[5]

Coastal areas are increasingly experiencing dangerous flooding, erosion, surface water and groundwater salinization, and environmental impacts.[6] Beyond threats to infrastructure and the environment, cultural heritage is also at risk.[7] Coastal communities are grappling with the present and emerging need to adapt to sea-level change via infrastructural solutions, and the financial implications of constructing those systems. The financial cost of adapting to (and preventing effects from) sea-level rise is significant, and many adaptive measures can be harmful to the environments in which they are placed.[8]

As the environment continues to change, it is imperative that those who work with law and policy and with the communities directly impacted by rising sea level understand the foundational science. An informed approach to decisionmaking in the face of environmental change will optimize our response and, hopefully, our ability to adapt.[9] In addition to the science, we must acknowledge that historically marginalized communities, including those who have contributed the least to climate change, are disproportionately affected by modern environmental change—i.e., this populace experiences relatively higher negative public health, infrastructural, financial, and cultural impacts.[10]

This Article will cover the broad science of sea-level change as well as a case study of how sea-level rise is currently impacting the state of Florida. Our goal is to assist readers with comprehending the science behind sea-level change, to broaden the context of sea-level change impacts, to identify and dispense with common misconceptions, and to build a toolkit to visualize global and regional sea-level change.

4. Jochen Hinkel et al., *Coastal Flood Damage and Adaptation Costs Under 21st Century Sea-Level Rise*, 111 PNAS 3292 (2014).
5. Gordon McGranahan et al., *The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones*, 19 Env't & Urbanization 17 (2007).
6. *Id.*
7. Paula Ezcurra & Isabel C. Rivera-Collazo, *An Assessment of the Impacts of Climate Change on Puerto Rico's Cultural Heritage With a Case Study on Sea-Level Rise*, 32 J. Cultural Heritage 198 (2018).
8. Hinkel et al., *supra* note 4.
9. Aimée B.A. Slangen et al., *The Evolution of 21st Century Sea-Level Projections From IPCC AR5 to AR6 and Beyond*, 1 Cambridge Prisms: Coastal Futures e7 (2023).
10. Barry S. Levy & Jonathan A. Patz, *Climate Change, Human Rights, and Social Justice*, 81 Annals Glob. Health 310 (2015).

1. Foundations of Sea-Level Change

1.1 What Is Sea Level and What Causes It to Change?

Sea level is the distance between the sea surface and the ocean floor. Changes in sea level at a particular location can occur due to changes in the elevation of either of those boundaries. The sea surface can move due to changes in the amount of water present, or changes in bathymetry. Changes in bathymetry can make bodies of water locally deeper or shallower.

Of course, when the sea surface goes up, sea level goes up and the shoreline encroaches inland. On the other hand, when the solid surface goes up, sea level does the opposite—it goes down relative to adjacent land features, which see the shoreline recede. This is because an increase in the elevation of the seafloor makes the space between the sea surface and earth's surface smaller, thereby causing a relative sea-level fall (and vice versa for a decrease in seafloor elevation). In this case, relative sea level refers to a change in sea level relative to the solid surface, or a point on land.

Climate and sea level change because of both human and nonhuman, or natural, factors. The scale of climate and sea-level change we are experiencing today cannot be explained without human activity.[11] The issue of scale is one that scientists must consider daily in their work and comes up often when studying sea-level change. It is important to understand that the time and spatial scales earth scientists reference are larger than what most fields regularly interface with.

For example, the rate of sea-level rise increasing or global temperatures rising over 150 years may be described as "rapid," especially when taken in the context of geologic timescales that often span thousands, millions, or billions of years. The units of sea-level change will generally increase for longer time periods (e.g., when discussing rates of sea-level rise for the 21st century, the scale is often millimeters or inches, whereas the scale is tens of meters or feet over longer periods). These scales vary due to the diverse, overlapping processes that control sea-level change on different scales.

The processes that cause sea level to rise or fall include ice melting or growing, ocean heat uptake and thermal expansion, rising and falling of earth's surface under the weight of past ice sheets, other vertical land motion (from plate tectonics, oil and groundwater extraction, and sedimentation), and ocean dynamics (see Figures 1 and 2, p. 10765).

Over thousands to tens of thousands of years, the dominant influence on sea-level change is the movement of water between the global ocean reservoir and ice. On a regional scale and over shorter or longer time periods, other factors

11. Judith L. Lean, *Cycles and Trends in Solar Irradiance and Climate*, 1 WIREs Climate Change 111 (2010).

can be more important. Around 2% of the world's water is stored in glaciers and in the Antarctic and Greenland ice sheets. Glacial cycles modulate the extent and size of ice sheets globally. During a glacial period, ice sheets expand, and during an interglacial period, they withdraw.

Figure 3 shows the extent of global ice sheets in North America during the Last Glacial Maximum, roughly 21,000 years ago. These cycles occur roughly every 100,000 years and are controlled by changes in solar radiation exposure driven by cyclic variations in earth's orbit.[12] Think of earth like a toy top that wobbles as it spins. The shape of orbit, as well as the angle and direction of earth's axis, control the planet's exposure to solar radiation. When there is less solar radiation (and therefore less ice) on earth, sea level can be much higher globally (up to hundreds of feet). Conversely, when earth is colder and there is more ice, sea level is much lower.[13]

1.1.1 Ice Melt and Thermal Expansion

Today, two of the most important of factors for sea-level change are the addition of meltwater from receding ice sheets to the global ocean and the thermal expansion of ocean water globally; both factors are in turn driven by increasing temperatures due to increasing greenhouse gases.[14] As temperatures rise, ice sheets melt at the surface and margins because of exposure to warm ocean water, and pieces of the ice break away (called "calving") and eventually melt. Thermal expansion compounds the effects of adding meltwater to global oceans because when water gets warmer, the volume increases, causing more sea-level rise. The impact of thermal expansion on global sea-level rise can be large—one-third of sea-level rise from 1993 to 2010 was due to thermal expansion alone.[15]

Further, there is a lag between greenhouse gas concentration reduction and sea-level change. Sea level continues to rise for a while even after decreasing or eliminating carbon emissions due to the residence time of greenhouse gases (i.e., how long they stay in the atmosphere) and the subsequent ice sheet response time.[16] In the same way that ice stored in a freezer takes some time to thaw after the freezer is unplugged, ice sheets take considerable time to respond to present warming. The Greenland and Antarctic ice sheets are therefore still reacting to warming and would continue to melt even if the increase in global temperature were to pause.

1.1.2 Glacial Isostatic Adjustment

Glacial isostatic adjustment (GIA) refers to a collection of processes that cause earth's surface and the sea surface to change due to long-term effects of changes in ice sheet volume. The weight of large ice sheets and ocean water causes earth's surface to deform. Over thousands of years, as glacial cycles occur, the surface responds to ice and ocean loads by compressing and uplifting, kind of like Silly Putty.

For example, when an ice sheet recedes, the land beneath the ice becomes unburdened and rises back up (i.e., it rebounds like a memory foam mattress when you remove your hand after pressing into it; Figure 4A-B). The area surrounding the former ice sheet (called the "peripheral bulge") is pushed up when the ice grows, and when the ice melts, it goes back down (i.e., it subsides). The changing elevation of these peripheral bulges also moves water around the global ocean reservoir (Figure 4B). This process is called "ocean syphoning." The amount of earth deformation is controlled by the size of ice melt or growth, and how quickly it happens depends on the internal structure of earth underneath the ice. The recent deformational effects from past ice sheets that we experience today occurred over hundreds to thousands of years.

Further away from changing ice sheets, when ice melts and adds more water to the global ocean, the increased load of that added meltwater weighs down the seafloor near coastlines and causes subsidence. Similarly to what happens around an ice sheet, the subsidence at the nearshore causes the land side of the coast to rise up as material inside the earth is displaced (Figure 4C, continental levering).

There is also a gravitational component of GIA (Figure 4A, self-gravitation). When ice melts, sea level within 2,000 kilometers (km) of the ice sheet ("near-field") actually decreases because the gravitational attraction of the ice sheet on the surrounding ocean water decreases. This process happens effectively instantaneously and continues as long as the mass of the ice sheets changes.[17]

1.1.3 Vertical Land Motion and Ocean Dynamics

In addition to GIA, the elevation of earth's surface can also change due to plate tectonics, movement of sediment,[18] and oil or groundwater extraction. When tectonic plates move away from one another, collide together, or get wedged beneath each other, they can impact the shape and size of ocean basins and change land elevation, all of which can alter sea level. Sediment movement can displace ocean water, causing sea level to fall in some places and rise in others. Significant amounts of sediment can also deform

12. Lorraine E. Lisiecki & Maureen E. Raymo, *A Pliocene-Pleistocene Stack of 57 Globally Distributed Benthic δ^{18}O Records*, 20 Paleoceanography & Paleoclimatology PA1003 (2005), https://onlinelibrary.wiley.com/doi/abs/10.1029/2004PA001071.
13. Kurt Lambeck & John Chappell, *Sea Level Change Through the Last Glacial Cycle*, 292 Science 679 (2001).
14. Charles D. Keeling et al., *Exchanges of Atmospheric CO_2 and $^{13}CO_2$ With the Terrestrial Biosphere and Oceans From 1978 to 2000. I. Global Aspects* (2001).
15. Sarah G. Purkey et al., *Relative Contributions of Ocean Mass and Deep Steric Changes to Sea Level Rise Between 1993 and 2013*, 119 J. Geophysical Rsch.: Oceans 7509 (2014).
16. Kirsten Zickfeld et al., *Centuries of Thermal Sea-Level Rise Due to Anthropogenic Emissions of Short-Lived Greenhouse Gases*, 114 PNAS 657 (2017).
17. Marisa Borreggine et al., *Not a Bathtub: A Consideration of Sea-Level Physics for Archaeological Models of Human Migration*, 137 J. Archaeological Sci. 105507 (2022).
18. Ken L. Ferrier et al., *The Importance of Sediment in Sea-Level Change*, 27 PAGES Mag., May 2019, at 24.

earth's surface due to their heavy load.[19] Extraction of resources on land, like oil or water, also causes vertical land motion by removing material from below the surface.[20]

Sea-surface elevation can also be changed from ocean dynamics, such as major current systems and waves.[21] Ocean currents can cause water to pile up in certain places, which impacts local sea level. Similarly, winds can cause water to accumulate and flow around an ocean basin, impacting sea-level change.[22]

1.2 Past Sea Level

There are a variety of ways to determine global or regional sea level in earth's past. Tide gauges and paleoclimate "proxy" data are the primary methods used to estimate past sea level, though archaeological records can also be used to constrain past sea level in certain circumstances.

Tide gauges are useful for assessing regional sea-level changes over time because the data they provide are specific to one location, and many gauges have been around for more than 100 years. They work by measuring the height of the sea surface relative to local mean sea level.[23] Researchers can combine output from many tide gauges to gain a general understanding of a larger regional, or even global, pattern of sea-level change—for example, tide gauges are an important part of how we know sea level has been rising since just after 1850.[24]

However, since these records use reference points on land, it is often necessary to correct the measurements for vertical motion resulting from GIA or plate tectonics.[25] This correction can be done using observations and mathematical models that use the past shape and size of global ice sheets and the way earth's interior reacts to changing surface loads as input. This approach carries some uncertainties due to incomplete knowledge.[26]

Although past sea level from before the instrumental record cannot be measured directly, paleoclimate proxy data allow scientists to estimate past sea level by using evidence of changes in natural processes that are driven by, and closely reflect, sea-level change. Paleoclimatologists use these proxies to understand what our planet looked like in the past, like an archaeologist uses ceramics to understand past cultures. Similar to tide gauges, many proxies only reflect regional sea level, not a global value.

Commonly used proxies are oxygen isotopes, marine terraces (also called raised beaches), corals, mangroves, glacial moraines, and isolation basins.[27] All of these proxies are combined with dating methods to estimate sea level for particular time periods—with some proxies better suited to certain periods or timescales and available in certain parts of the world—and each can give an idea of what sea level was for a time range of years to thousands of years.[28]

The oxygen isotope method is uniquely useful because it can estimate sea level back millions of years by measuring the ratio of light (oxygen-16) to heavy (oxygen-18) isotopes from ice cores or ocean-floor sediment cores. When ice sheets form, they preferentially take up the lighter oxygen isotope (oxygen-16) and leave behind the heavier isotope (oxygen-18) in the ocean. Scientists can measure the proportions of light and heavy isotopes at different layers in an ice core or seafloor sediment core to estimate global ice volume at the time that each layer was originally deposited. Higher oxygen-18 in a sediment core indicates more global ice, whereas higher oxygen-16 would indicate less ice; vice versa in an ice core. Because water being frozen into and released from ice sheets is the primary driver of global sea level, global ice volume is a proxy for global average sea level[29] and tracks with glacial-interglacial cycles throughout geologic time.

Marine terraces form when waves erode a coastline, creating a flat area, and either the area is subsequently uplifted by different vertical land motion processes or sea level falls; the elevation of present-day terraces combined with evidence of the timing of their formation then can be used to determine past sea level. Corals, which build out over time like the rings of trees and can be dated, are proxies for past sea level because certain species can only grow in specific depths relative to sea level.[30] Similarly, mangroves serve as sea-level proxies because they migrate as sea level changes and the shoreline moves.[31]

Glacial moraines are the materials left behind by melting glaciers, so we can learn about the past extent of ice sheets from them (and therefore, indirectly measure past sea level). Isolation basins can be thought of as small lakes that are exposed during low sea level and submerged during high sea level. Studies of sediment cores taken from these basins reveal past sea-level changes through the changing sediment types.[32]

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19. Ken L. Ferrier et al., *Sea-Level Responses to Erosion and Deposition of Sediment in the Indus River Basin and the Arabian Sea*, 416 Earth & Planetary Sci. Letters 12 (2015).
20. Xuan Yu & Holly A. Michael, *Offshore Pumping Impacts Onshore Groundwater Resources and Land Subsidence*, 46 Geophysical Rsch. Letters 2553 (2019).
21. Sönke Dangendorf et al., *Data-Driven Reconstruction Reveals Large-Scale Ocean Circulation Control on Coastal Sea Level*, 11 Nature Climate Change 514 (2021).
22. Wilton Sturges & Bruce C. Douglas, *Wind Effects on Estimates of Sea Level Rise*, 116 JGR Oceans C06008 (2011), https://onlinelibrary.wiley.com/doi/abs/10.1029/2010JC006492.
23. National Oceanic and Atmospheric Administration (NOAA) National Ocean Service, *What Is a Tide Gauge?*, https://oceanservice.noaa.gov/facts/tide-gauge.html (last updated June 16, 2024).
24. John A. Church & Neil J. White, *Sea-Level Rise From the Late 19th to the Early 21st Century*, 32 Survs. Geophysics 585 (2011).
25. *Id.*
26. Giorgio Spada, *Glacial Isostatic Adjustment and Contemporary Sea Level Rise: An Overview*, *in* Integrative Study of the Mean Sea Level and Its Components 155 (Anny Cazenave et al. eds., Springer 2017).
27. Alessio Rovere et al., *The Analysis of Last Interglacial (MIS 5e) Relative Sea-Level Indicators: Reconstructing Sea-Level in a Warmer World*, 159 Earth-Sci. Revs. 404 (2016).
28. Glenn A. Milne et al., *Identifying the Causes of Sea-Level Change*, 2 Nature Geosci. 471 (2009).
29. Lisiecki & Raymo, *supra* note 12.
30. Rovere et al., *supra* note 27.
31. Juliet Sefton, Evaluating Mangrove Proxies for Quantitative Relative Sea-Level Reconstructions (2020) (Ph.D. thesis, Durham University), https://etheses.dur.ac.uk/13534/1/Sefton000624291_corrected_April20.pdf?DDD14+.
32. Antony J. Long et al., *Isolation Basins, Sea-Level Changes, and the Holocene History of the Greenland Ice Sheet*, 30 Quaternary Sci. Revs. 3748 (2011).

1.3 Current Sea Level

1.3.1 How Do Scientists Assess Current Sea Level?

Contemporary sea level (roughly from the 1990s to today) is mostly measured through tide gauges and satellite altimetry.[33] Satellites measure sea level using a process like radar: sending a signal to the earth's surface and measuring how long it takes for the signal to return—a longer return time means lower sea surface, and a faster return means higher sea surface. This technology has allowed more frequent and precise measurements over a larger area, so we now have a roughly global assessment of sea level on a timescale of days.[34] By comparing this data to historical sea level, scientists can determine a rate of sea-level rise for different time periods (e.g., over the past 5, 10, or 100 years). Comparing rates from the past versus today allows scientists to understand how much the rate of sea-level rise has changed (globally or regionally).[35]

Despite these developments, we still must deal with uncertainty in modern sea-level data. The observations are limited by the extent of spatial sampling (similar to, but not as severe as, spatial sampling issues with historical tide gauges) and necessary corrections for vertical land motion. More dense observations of sea level from satellites means that estimates of nearby sea level in unsampled regions are more accurate, and ground-truthing with buoys, fieldwork, and ocean floats with instruments can provide more information about other ocean conditions. Modern global positioning satellite (GPS) measurements also aid in correcting for vertical land motion over time to produce more accurate sea-level data.[36] Combining estimates of past sea level with observations that reflect modern sea level closely is an important tool for informing model projections of future conditions.[37]

1.3.2 Recent Trends in Sea Level

There has been a shift in reporting sea-level change from global mean (as in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[38]) to regional values (as in the IPCC Fifth Assessment Report[39]),[40] a shift that reflects the importance of acknowledging the inherent regional differences in sea-level projections that can lead to a significant departure from the global mean value. The current global average estimate of the rate of sea-level rise since the start of the satellite era (~1993) is roughly 3 millimeters (mm) per year.[41] The regional rate of sea-level change can vary quite a bit from this value (e.g., from 1993 to today, some regions have seen a rate greater than 10 mm/year, and some have seen negative sea-level trends).[42]

These rates have not always been the same. They have changed throughout geologic time, and have accelerated since the 1960s.[43] From 1901 to 1990, the average global rate was ~1.2 mm/year,[44] rising to ~3.4 mm/year from 1993 to today,[45] and accelerating to ~4.4 mm/year when measured over just the past decade.[46] Compared to sea-level change rates over the past few thousand years, the rates of change we experience today are 10 times higher.[47]

In the United States, regional sea-level change rates vary (an interactive map[48] demonstrates some rates over the past century). Over roughly the past decade (2010-2022), sea level has risen at a rate of more than 10 mm/year in the Southeast and Gulf Coasts.[49] In Southeast Alaska, sea level is actually falling.[50] As discussed in Section 1.1, sea level is geographically variable due to a myriad of geological and oceanographic processes that are specific to each region.

In the case of the southeastern United States, the high rate of rise is due to natural climate variability and anthropogenic climate change. Warming ocean temperatures combined with a change in regional wind patterns have led to a rate that is three times the global mean.[51] In South-

33. Rebecca Lindsey, *Climate Change: Global Sea Level*, Climate.gov (Apr. 19, 2022), http://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level; Milne et al., *supra* note 28.
34. Milne et al., *supra* note 28.
35. Lindsey, *supra* note 33.
36. Milne et al., *supra* note 28; Lindsey, *supra* note 33.
37. R. Steven Nerem et al., *Climate-Change-Driven Accelerated Sea-Level Rise Detected in the Altimeter Era*, 115 PNAS 2022 (2018).
38. Gerald A. Meehl et al., *2007: Global Climate Projections*, *in* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 747 (S. Solomon et al. eds., Cambridge Univ. Press 2007).
39. John A. Church et al., *Sea Level Change*, *in* Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 1137 (T.F. Stocker et al. eds., Cambridge Univ. Press 2013).
40. Slangen et al., *supra* note 9.
41. Nerem et al., *supra* note 37; Hay et al., *supra* note 2.
42. Milne et al., *supra* note 28.
43. Sönke Dangendorf et al., *Persistent Acceleration in Global Sea-Level Rise Since the 1960s*, 9 Nature Climate Change 705 (2019).
44. Hay et al., *supra* note 2.
45. B. Beckley et al., *Global Mean Sea Level Trend From Integrated Multi-Mission Ocean Altimeters TOPEX/Poseidon, Jason-1, OSTM/Jason-2, and Jason-3 Version 5.1* (2021), https://doi.org/10.5067/GMSLM-TJ151.
46. Christine L. May et al., *Coastal Effects*, *in* Fifth National Climate Assessment 9-1 (A.R. Crimmins et al. eds., U.S. Global Change Research Program 2023); Adrien Guérou et al., *Current Observed Global Mean Sea Level Rise and Acceleration Estimated From Satellite Altimetry and the Associated Uncertainty*, 19 Ocean Sci. 431 (2023).
47. Milne et al., *supra* note 28.
48. Julia Engdahl et al., *Interactive Map: How Has Local Sea Level in the United States Changed Over Time?*, Climate.gov (Dec. 20, 2021), https://www.climate.gov/news-features/features/interactive-map-how-has-local-sea-level-united-states-changed-over-time.
49. Jianjun Yin, *Rapid Decadal Acceleration of Sea Level Rise Along the U.S. East and Gulf Coasts During 2010-22 and Its Impact on Hurricane-Induced Storm Surge*, 36 J. Climate 4511 (2023); Sönke Dangendorf et al., *Acceleration of U.S. Southeast and Gulf Coast Sea-Level Rise Amplified by Internal Climate Variability*, 14 Nature Commc'ns 1935 (2023).
50. Yan Hu & Jeffrey T. Freymueller, *Geodetic Observations of Time-Variable Glacial Isostatic Adjustment in Southeast Alaska and Its Implications for Earth Rheology*, 124 J. Geophysical Rsch.: Solid Earth 9870 (2019).
51. Dangendorf et al., *supra* note 21.

east Alaska, land is uplifting faster than sea level is rising, resulting in a relative sea-level fall. This is due in part to GIA—areas of the world that used to have large ice sheets during previous ice ages are rebounding (or, uplifting) since the weight of the ice is no longer weighing down the land (Figure 4B). Different local processes that impact sea level can interact to amplify or diminish one another, such as the effect on sea level and topography from ice melt in Alaska today.[52]

It is important to break down the regional causes of sea-level change so we can plan targeted hazard mitigation efforts and understand future sea-level predictions. For example, in the Southeast and Gulf Coasts, one of the causes of heightened regional sea-level rise is a product of climate variability that will likely die down in the next few decades. While sea level will continue to rise locally due to ongoing climate change, the rate will likely be closer to the global average.[53] Since researchers were able to isolate the causes of sea-level change specific to that area, local decisionmakers have a better idea of what to plan for in the future.

Thermal expansion of warming ocean water and melting glaciers were the biggest contributors to global sea-level rise in the 20th century,[54] and are similarly important contributors today (ice melt contributes 2 mm/year[55] and thermal expansion contributes 1 mm/year[56] to the present global average sea-level rise of ~3 mm/year). Today, the role of melting from the Greenland and Antarctic ice sheets has been increasing.[57] Land-water storage used to contribute more to sea-level change in the 20th century but is less influential today.[58] Contributions to sea-level change from vertical land motion due to the effects of plate tectonics and GIA are highly variable across the globe.

There are some important specific, regional processes that must also be considered when discussing sea-level rise today. For example, the Gulf Stream has been slowing down since the early 1980s.[59] Since this strong current usually moves ocean water away from the U.S. East Coast, when it slows down, sea level rises around the southeastern United States.[60]

52. Milne et al., *supra* note 28.
53. Dangendorf et al., *supra* note 49.
54. Church et al., *supra* note 39.
55. Jianli Chen et al., *Contribution of Ice Sheet and Mountain Glacier Melt to Recent Sea Level Rise*, 6 Nature Geosci. 549 (2013).
56. Church et al., *supra* note 39.
57. *Id.*
58. Robert E. Kopp et al., *Probabilistic 21st and 22nd Century Sea-Level Projections at a Global Network of Tide-Gauge Sites*, 2 Earth's Future 383 (2014); Baylor Fox-Kemper et al., *Ocean, Cryosphere, and Sea Level Change*, *in* Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 1211 (V. Masson-Delmotte et al. eds., Cambridge Univ. Press 2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter09.pdf.
59. Christopher G. Piecuch & Lisa M. Beal, *Robust Weakening of the Gulf Stream During the Past Four Decades Observed in the Florida Straits*, 50 Geophysical Rsch. Letters e2023GL105170 (2023).
60. Joseph Park & William Sweet, *Accelerated Sea Level Rise and Florida Current Transport*, 11 Ocean Sci. 607 (2015).

1.4 Future Sea Level

1.4.1 How Do Scientists Predict Future Sea Level?

Similar to past sea level, scientists cannot directly measure what future sea level will be. Instead, data and observations, past and present sea level, as well as the factors that control how sea level changes, are used to model future scenarios. Models take in observations and data about a phenomenon, apply mathematical equations, and output different information about that phenomenon.

Sea-level models can use information about global ice shapes and sizes, ice dynamics, topography, the structure below earth's surface, and temperature as inputs to output a range of potential future sea-level scenarios. Future sea-level predictions often deal with ranges (from lowest to highest possible sea-level change relative to today) to account for uncertainties about the factors listed above and how they may change going forward. Ranges can be produced as a global average, or for a specific region, and are reported relative to a mean sea level for a representative period (e.g., the past 30 years).

The ranges of potential sea-level rise that come from predictive modeling vary due to decisions that modelers must make about what inputs to use (e.g., the amount of CO_2 emissions and resulting temperature increase, the amount of ice melting and from what location, or if a model takes long-term changes like GIA or local influences into account). Variations in any of these factors produce different future sea-level curves. The uncertainty associated with these scenarios is often grouped either into "process uncertainty" or "emissions uncertainty," where process refers to the mechanisms that affect sea-level change (e.g., thermal expansion, vertical land motion, or ice dynamics) and emissions refers to the amount of greenhouse gases that may be emitted and their effects on climate.[61]

Changing what physical processes are considered in a model (and how well the math in a model reflects how those processes work) will change the predicted sea-level output. Similarly, if we vary the amount of greenhouse gases in a model, the estimated temperature and resulting ice melt and sea-level change will vary too. Higher temperatures lead to higher future sea-level rise projections.[62] For example, in the Sixth Assessment Report from the IPCC[63] (the global authority for understanding climate change and sea-level rise), various temperature and sea-level outcomes of different climate "pathways," determined by different emissions scenarios, are presented. These pathways combine earth science and economics to determine likely envi-

61. William V. Sweet et al., NOAA, Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines 10 (2022), https://cdn.oceanservice.noaa.gov/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf.
62. *Id.*
63. Fox-Kemper et al., *supra* note 58.

ronmental outcomes for certain policy decisions regarding climate change.

In an ideal situation, scientists and policymakers would have complete knowledge of how every process that affects sea level works, in addition to the amount of emissions each country would produce in the future. However, that is not the case. A few main scientific factors contribute to the uncertainty that results in the ranges for potential future sea-level rise. One of the most important factors is process uncertainty from the ice sheet projection applied to a model, or the prediction of how global ice shape and size will change based upon changing temperature and melt. Part of this projection is also how a model portrays basic ice dynamics (i.e., how ice flows, grows, and melts), and what may trigger ice to melt rapidly over the next few decades.[64]

Uncertainty can be compounded in sea-level rise predictions, too. For higher emissions scenarios, questions about how ice responds to increasingly elevated temperatures create further uncertainty. This is reflected in the fact that predictions for sea-level rise for different underlying scenarios tend to be relatively similar until 2050, where the ranges for potential outcomes become bigger (and thus, more uncertain).[65] Some processes (see Section 1.4.3) are so uncertain that experts cannot agree how they work: phenomena labeled "deep uncertainty."[66] These questions underscore the importance of glaciological fieldwork aimed at observing and understanding basic ice dynamics, as those observations advance the scientific community's knowledge of poorly understood processes and enable improved model predictions.[67]

The other important factors that scientists study to help create more accurate sea-level rise predictions are vertical land motion and climate dynamics (i.e., what causes the climate to vary, such as how the ocean, atmosphere, and land interact with one another). As discussed in Section 1.1, vertical land motion from GIA, plate tectonics, and/or oil and groundwater extraction can increase or decrease sea-level rise. Geophysicists can predict how GIA will impact future sea level, but those predictions are limited by our understanding of where past global ice was located, how much of it there was, and how earth's interior responds to certain ice changes. Generally, these vertical land motion factors can be hard to predict far into the future.[68]

Finally, the climate models that are used to predict environment and sea-level changes are limited by the technology available to run them and the underlying mathematical methods available for their design. Often, their resolution is coarse, so predicting local (e.g., city- and state-level) sea-level changes is hard. Regional climate models have better resolution but are computationally expensive. Similar to modeling ice dynamics, climate dynamics are also not perfectly understood. Additionally, relevant short-term processes, like changes in daily weather conditions, and decadal-scale processes, like El Niño, can be difficult to predict.[69] Once more, the importance of fieldwork and climate research aimed at these basic concepts is crucial for improving our models of how sea level will change in the future.

1.4.2 Global and Regional Trends

Sea-level rise in this century will impact our country's built environment, natural ecosystems, and economy. Future extreme events related to sea-level change are very likely (90-100% chance) to increase in some regions by the end of the century.[70] We can expect that coastal communities will be hit by more intense, more frequent floods and storms, with coastal flooding very likely to occur five to 10 times more frequently in 2050 than in 2020 and major coastal flooding expected nearly daily by 2100.[71] For the highest future emissions scenarios by the end of the century, the resulting sea-level rise could lead to the displacement of more than 100 million people in coastal zones globally.[72] For low- and middle-range emissions scenarios, several million people in these areas may be displaced.[73]

Since the 1960s, the rate of sea-level rise has been steadily accelerating due to ice melt, thermal expansion, and ocean circulation changes (Sections 1.1.1, 1.1.3).[74] Sea level is certain to continue rising beyond 2100, and the acceleration is very likely to continue throughout the 21st century as temperatures continue to rise and ice continues to melt.[75] Reducing greenhouse gas emissions would aid in stabilizing global temperatures, which would reduce the rate of sea-level rise.[76] However, even with reduced greenhouse gas emissions, earth's climate will take thousands of years to equilibrate due to the amount of CO_2 and how long it tends to stay in the atmosphere.[77] With these certainties in mind, it is crucial to understand the differences between the expected future global average sea-level rise

64. Jonathan L. Bamber et al., *Ice Sheet Contributions to Future Sea-Level Rise From Structured Expert Judgment*, 116 PNAS 11195 (2019); Fox-Kemper et al., *supra* note 58.
65. Fox-Kemper et al., *supra* note 58; William V. Sweet et al., *Sea Level Rise, in* 1 Climate Science Special Report: Fourth National Climate Assessment 333 (D.J. Wuebbles et al. eds., U.S. Global Change Research Program 2017), https://science2017.globalchange.gov/downloads/CSSR_Ch12_Sea_Level_Rise.pdf; Slangen et al., *supra* note 9; Robert E. Kopp et al., *Communicating Future Sea-Level Rise Uncertainty and Ambiguity to Assessment Users*, 13 Nature Climate Change 648 (2023).
66. Slangen et al., *supra* note 9; Kopp et al., *supra* note 65.
67. Bamber et al., *supra* note 64; Slangen et al., *supra* note 9.
68. Slangen et al., *supra* note 9.
69. *Id.*; Kevin Schwarzwald & Nathan Lenssen, *The Importance of Internal Climate Variability in Climate Impact Projections*, 119 PNAS e2208095119 (2022).
70. Church et al., *supra* note 39.
71. May et al., *supra* note 46; Sweet et al., *supra* note 61.
72. Robert J. Nicholls et al., *Sea-Level Rise and Its Possible Impacts Given a "Beyond 4 C World" in the Twenty-First Century*, 369 Phil. Transactions Royal Soc'y A: Mathematical Physical & Eng'g Scis. 161 (2011).
73. Michael Oppenheimer et al., *Sea Level Rise and Implications for Low Lying Islands, Coasts, and Communities, in* IPCC Special Report on the Ocean and Cryosphere in a Changing Climate 321 (H.-O. Pörtner et al. eds., Cambridge Univ. Press 2019).
74. Dangendorf et al., *supra* note 43.
75. Church et al., *supra* note 39.
76. Nicholls et al., *supra* note 72.
77. Peter U. Clark et al., *Consequences of Twenty-First-Century Policy for Multi-Millennial Climate and Sea-Level Change*, 6 Nature Climate Change 360 (2016).

and regional sea-level changes so communities can plan and adapt accordingly.

Just like in the past and present, sea-level change will vary across locations in the future (Sections 1.2, 1.3.2). Regional variations are a function of GIA from ice changes long ago, modern ice melt or growth, local vertical land motion, and changes in ocean dynamics.[78] Similar to global models of sea-level change, future regional sea-level change is often reported as a range due to uncertainties about future temperature changes and ice sheet dynamics (see Section 1.4.3).

For the highest future emissions scenarios, global temperatures by 2081-2100 are very likely to reach an average 4.4 degrees Celsius (°C) higher than the global average before industrialization, and the resulting global average sea-level rise would likely be between ~0.6 and ~1 m (~2 to ~3.3 feet) compared to 1995-2014. For the intermediate scenario, global temperatures by the end of the century are very likely to reach 2.7°C higher than the pre-industrial average, likely resulting in ~0.4 to ~0.8 m of global sea-level rise (~1.4 to ~2.5 feet). For the lowest emissions, global temperatures would very likely increase by 1.4°C and sea level would likely rise by ~0.3 to ~0.6 m (~1 to ~1.8 feet).[79]

In the past, most U.S. coastlines have seen relative sea-level rise higher than that of the global average, with rates of rise accelerating over time. The highest rate of recent regional sea-level rise in the United States is in the western part of the Gulf Coast, 0.23 m (~9 inches) over the past 30 years, followed closely by the Atlantic and eastern Gulf Coasts at a rate of 0.15 m (~6 inches) over the same time period (Figure 5).[80] As mentioned in Section 1.3.2, some parts of the United States (e.g., the Northwest) are seeing lower rates of rise due to specific regional processes.

These trends are expected to continue, with future sea-level rise predicted to be higher on the U.S. Atlantic Coast compared to the Pacific Coast. For an intermediate emissions scenario, sea-level rise from 2020 to 2050 is likely to be ~0.4 m (15 inches) in the western Gulf Coast, ~0.25-0.3 m (10-12 inches) along the Atlantic Coast, and ~0.2 m (9 inches) in the eastern Gulf Coast by 2050 compared to a 2000 baseline.[81] Accelerated rates of sea-level rise are also predicted to continue, with an average 0.28 m (~11 inches) rise relative to 2020 levels along the contiguous U.S. coastline likely by 2050.

This change over 30 years is the same amount of change that the United States experienced over the past 100 years.[82] The regional rates here illustrate the fact that global average sea-level rise predictions are generally not useful when making plans for coastal cities—to quote Robert Kopp et al., "local decisions require local projections"[83] and should take into account the community's values and timescale of decisionmaking.

1.4.3 Important Potential Contributors to Future Sea Level

Before we discuss how to apply this knowledge, we will review some processes that have the potential to increase future sea-level rise. While future global mean sea level is expected to be primarily controlled by thermal expansion and ice mass loss (i.e., melting of glaciers, ice caps, and ice sheets; Sections 1.1.1, 1.3.2),[84] two phenomena known as marine ice sheet instability (MISI) and marine ice cliff instability (MICI) are possible drivers of rapid sea-level change over hundreds to thousands of years[85] (Figure 6). These processes are relevant for the Greenland and Antarctic ice sheets, and represent low-likelihood, high-risk scenarios for our future climate.[86]

Uncertainty in sea-level predictions out to 2100 mainly comes from the dynamics of MISI in West Antarctica and modeling surface ice melt in Greenland.[87] Research is ongoing to understand how these ice dynamics work and whether they will be contributors to future sea-level rise, but they are important to understand when considering the highest ranges of predicted global and regional sea-level change (see the discussion of process uncertainty, Section 1.4.1). We do know that MISI and MICI have the potential to substantially increase the contribution of global ice sheets to future sea-level rise.

MISI refers to a process wherein marine ice sheets (ice sheets with a core resting on bedrock below sea level and margins—called ice shelves—floating above a lens of seawater) experience melting at their edges and become unstable. Both heat from air above and liquid water beneath the floating ice shelves drive melting and calving. As ocean water warms, the "grounding line," where the ice sheet transitions from grounded to floating and becomes the ice shelf, migrates inward.[88] Where the bedrock has a "retrograde" slope (i.e., slopes downwards away from the edge of the sheet), the grounding line is unstable, which causes further "runaway" ice loss at the margins and consequently further inwards retreat of the grounding line. As the glacier

78. Slangen et al., *supra* note 9; May et al., *supra* note 46.
79. IPCC, Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 184 (H. Lee et al. eds., 2023), https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf.
80. May et al., *supra* note 46.
81. Sweet et al., *supra* note 61; May et al., *supra* note 46.
82. May et al., *supra* note 46.
83. Kopp et al., *supra* note 58, at 383.
84. Church et al., *supra* note 39.
85. David G. Vaughan & John R. Spouge, *Risk Estimation of Collapse of the West Antarctic Ice Sheet*, 52 Climate Change 65 (2002).
86. Kopp et al., *supra* note 65; Jonathan L. Bamber et al., *Reassessment of the Potential Sea-Level Rise From a Collapse of the West Antarctic Ice Sheet*, 324 Science 901 (2009) [hereinafter Bamber et al., 2009]; Jonathan L. Bamber et al., *Ice Sheet and Climate Processes Driving the Uncertainty in Projections of Future Sea Level Rise: Findings From a Structured Expert Judgement Approach*, 10 Earth's Future e2022EF002772 (2022) [hereinafter Bamber et al., 2022].
87. Ching-Yao Lai et al., *Vulnerability of Antarctica's Ice Shelves to Meltwater-Driven Fracture*, 584 Nature 574 (2020); Bamber et al., 2022, *supra* note 86.
88. Bethan Davies, *Grounding Lines*, AntarcticGlaciers.org (Feb. 7, 2022), https://www.antarcticglaciers.org/glacier-processes/grounding-lines/; Bamber et al., 2009, *supra* note 86.

becomes grounded in deeper and deeper water, more and more ice is lost, and sea level rises rapidly (Figure 6A).[89]

The West Antarctic ice sheet (WAIS) is of particular concern because the retrograde slope conditions for MISI are present under much of the ice sheet. Estimates of global mean sea-level rise that could result from a full collapse of WAIS alone are currently up to 5.3 m (that is, not considering other sources, such as thermal expansion, the Greenland ice sheet, etc.).[90] For partial and full WAIS collapse scenarios, the Pacific and Atlantic Coasts of the United States are predicted to see the highest regional sea-level change.[91] Ocean circulation and heat content, as well as feedback processes from GIA, impact MISI and their interactions are uncertain.[92] Research is ongoing to determine whether modern levels of warming could lead to rapid melting of WAIS through MISI.

MICI is a related process to MISI that could lead to increased sea-level rise, but with more unknowns.[93] MICI also deals with ice sheet instability—the main idea is that ice cliffs at the margins of ice sheets can only get so tall before they collapse. The maximum height is hypothesized to be 100 m above sea level before a cliff fails.[94]

Normally, ice sheets taper off into floating ice shelves with much less topographic relief above sea level. However, as ice shelf calving accelerates, new, taller, and less stable edges closer to the ice shelf core are exposed, which are less stable and melt more quickly. Ice shelf calving rates are driven by a process called "hydrofracture," where melting on the surface of the ice sheet flows into a crevasse, makes the crevasse deeper, and cuts off the shelf.[95]

Ice shelves serve as a buttress to the ice sheet, so when floating ice is removed in this way, this can lead to further instability and cliff failure, all of which contribute to more sea-level rise (Figure 6B).[96] Think of the ice shelves like a belt holding back the ice sheet—without them, there is less stability. Future global sea-level rise predictions are considerably higher when the underlying ice sheet models account for MICI.[97] Similar to MISI, research is ongoing to understand if and how MICI could impact ice sheets in this century.

1.4.4 What We Know and What We Do Not Yet Know

Right now, the greatest source of uncertainty in predicting future sea-level change is our ability to model future ice sheet behavior and to predict how much ice will melt due to anthropogenic climate change. We cannot be 100% certain of what will happen in the future environment, specifically as it relates to sea-level change, without perfect knowledge of ice sheet dynamics, future greenhouse gas emissions (and therefore resulting atmospheric and oceanic temperature rise), and all other contributors to sea-level change. Newer scientific models have better simulations of ice sheet behavior, leading to more accurate sea-level predictions (e.g., the 2022 Sea Level Rise Technical Report has a relatively narrow range of uncertainty for sea-level rise predictions up to 2050[98]).[99]

However, the models have room for improvement on several fronts, including ice dynamics, topography below glaciers, modeling environmental feedbacks, and the deep uncertainty issues discussed above.[100] Recent research has also demonstrated the importance of modeling ice melt in a way that reflects ice shape and size variations, instead of holding ice sheet geometry constant as it melts.[101] Meltwater from continental and mountain glaciers will also need to be considered.[102] Regional sea-level projections need to take into account local ocean dynamics, vertical land motion, and GIA.[103] Finding ways to reduce uncertainty in future sea-level predictions is critical for planning and reducing risk from ongoing climate change. Scientists are working on reducing uncertainty by doing field work to monitor and understand glaciers better, incorporating findings into climate models, and increasing international collaboration.[104]

The consequence of this uncertainty is that scientists cannot give an exact value for what regional sea-level change will be for a certain year in the future—policymakers, urban planners, and coastal communities will have to make decisions based on a range of potential sea-level change outcomes. This does not mean that the numbers from sea-level reports are not meaningful or useful. The ranges reported are useful to determine several potential scenarios based on social, economic, political, and environmental inputs. Since some amount of sea-level rise

89. Bethan Davies, *Marine Ice Sheet Instability*, AntarcticGlaciers.org (Oct. 21, 2020), https://www.antarcticglaciers.org/antarctica-2/west-antarctic-ice-sheet-2/marine-ice-sheets/; Bamber et al., 2009, *supra* note 86; Frank Pattyn, *The Paradigm Shift in Antarctic Ice Sheet Modelling*, 9 Nature Commc'ns 2728 (2018).
90. Kaitlin A. Naughten et al., *Unavoidable Future Increase in West Antarctic Ice-Shelf Melting Over the Twenty-First Century*, 13 Nature Climate Change 1222 (2023).
91. Bamber et al., 2009, *supra* note 86.
92. Bamber et al., 2022, *supra* note 86; Natalya Gomez et al., *Sea-Level Feedback Lowers Projections of Future Antarctic Ice-Sheet Mass Loss*, 6 Nature Commc'ns 8798 (2015), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5426515/; Samuel B. Kachuck et al., *Rapid Viscoelastic Deformation Slows Marine Ice Sheet Instability at Pine Island Glacier*, 47 Geophysical Rsch. Letters e2019GL086446 (2020).
93. Robert E. Kopp et al., *Usable Science for Managing the Risks of Sea-Level Rise*, 7 Earth's Future 1235 (2019).
94. David Pollard et al., *Potential Antarctic Ice Sheet Retreat Driven by Hydrofracturing and Ice Cliff Failure*, 412 Earth & Planetary Sci. Letters 112 (2015).
95. *Id.*; Lai et al., *supra* note 87.
96. Pollard et al., *supra* note 94; Pattyn, *supra* note 89.
97. Tamsin L. Edwards et al., *Revisiting Antarctic Ice Loss Due to Marine Ice-Cliff Instability*, 566 Nature 58 (2019).
98. Sweet et al., *supra* note 61.
99. Slangen et al., *supra* note 9.
100. Martin Siegert et al., *Twenty-First Century Sea-Level Rise Could Exceed IPCC Projections for Strong-Warming Futures*, 3 One Earth 691 (2020).
101. Jeremy Roffman et al., *Spatial and Temporal Variability of 21st Century Sea Level Changes*, 235 Geophysical J. Int'l 342 (2023).
102. *Id.*
103. Nerem et al., *supra* note 37.
104. Nicholls et al., *supra* note 72; Martin Siegert & Pam Pearson, *Reducing Uncertainty in 21st Century Sea-Level Predictions and Beyond*, 9 Frontiers Env't Sci. 751978 (2021), https://www.frontiersin.org/articles/10.3389/fenvs.2021.751978.

even with climate change mitigation is certain,[105] adaptation measures are necessary. Expressing future scenarios in terms of probabilities is helpful for communities to think about what their specific risk tolerance and resources for adaptation are.

In scientific consensus reports, statements are accompanied by confidence levels that reflect the scientific agreement and amount of evidence backing up a particular data point, so people using the data can be transparent about uncertainty and deliberate about their approach to risk tolerance.[106] The IPCC uses formal uncertainty terms called "calibrated uncertainty language"—these terms tell you how much evidence is available for a claim and the level of agreement about it in the scientific community. Since the IPCC's Sixth Assessment Report, the confidence in an assessment ranges from "very low" to "very high." Confidence specifically reflects the type of evidence, how much there is, and its consistency.[107] The mathematical likelihood ranges from exceptionally unlikely (0-1%) to virtually certain (99-100%).[108]

The IPCC also uses Shared Socioeconomic Pathways (SSPs) to combine social, economic, and environmental factors in their predictions of future climate outcomes. The "very high emissions" scenario you may often see is SSP5-8.5. Older reports used the familiar "RCP8.5," or Representative Concentration Pathway (the numbers represent the magnitude of global warming in watts/m^2 for each emission scenario).[109] When using the data from IPCC reports, it is important to accompany the numbers with this calibrated language to help people understand the context surrounding the values.

The uncertainty we have discussed here has often given rise to dramatic media articles that are not always useful in decisionmaking contexts. For example, Thwaites Glacier in West Antarctica has been nicknamed "Doomsday Glacier" because of its potential to collapse due to MISI (Section 1.4.3) and cause rapid sea-level rise.[110] While recent studies have shown that moderate amounts of melt could lead to concerning instability for this glacier,[111] planners and policymakers have to make decisions based on scenarios that are likely to occur, which are not necessarily the worst-case scenarios. Choosing which scenario to plan for depends on the priorities and risk tolerance of the community.

Whatever the scenario presented or utilized, it is important to explain the environmental inputs (e.g., what ice dynamics are considered or not considered, whether the model is a global average or regionally specific) and any caveats. Climate change adaptation policies will tend to oversimplify sea-level projections, and while this is necessary to a certain degree, planners and community members need reliable data and context to make decisions.[112]

To help navigate the many resources available for future sea-level predictions, this external table (accessible at https://www.tinyurl.com/SeaLevelTools) introduces some of the tools and what scenarios may be most applicable for each tool. Many of these tools are available on the National Oceanic and Atmospheric Administration's (NOAA's) Digital Coast website.[113]

2. Case Study: Sea-Level Rise in Florida

With an understanding of foundational sea-level change on a global and regional scale, we can examine how these processes create sea-level change on a specific regional coastline. Our area of interest is Florida, a U.S. state that is on the frontlines of both the scientific and societal efforts contending with sea-level rise. Understanding the regional and local factors that determine how communities experience the effects of sea-level rise helps decisionmakers prepare for current and future impacts of sea-level rise. In addition to geographic variation in the financial, technological, economic, and social barriers communities face when living with sea-level change,[114] climatological, geological, and ecological processes affect sea-level change on a regional scale.

Here, we aim to provide an overview of the large-scale processes that drive regional trends in sea-level rise, summarize the state of historical, current, and future estimates of sea-level rise, and survey the local environmental, climatic, and anthropogenic factors that can determine how a community feels the effects of sea-level rise. Florida is already home to a number of existing efforts studying regional sea-level rise,[115] as well as adaptation and resilience programs.[116] With this case study, we hope to provide an informed foundation on sea-level rise in Florida, so decisionmakers are better empowered in future conversations about sea-level rise as well as able to make informed decisions.

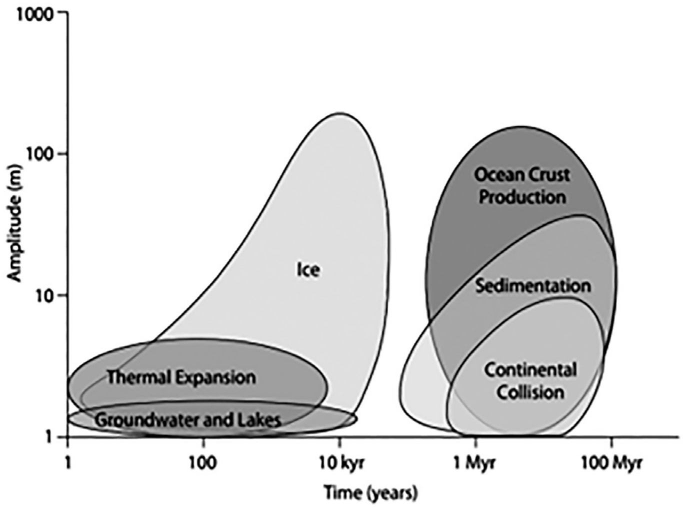
2.1 Regional Setting

Regional processes create patterns in sea-level change that vary on top of global sea-level changes (see Section 1.1). These can be oceanographic, climatological, or geological, and play a large role in determining the specific impacts of sea-level rise on a local scale. Understanding how these regional trends manifest in Florida helps us not only

105. Church et al., *supra* note 39.
106. Nicholls et al., *supra* note 72.
107. Kopp et al., *supra* note 65.
108. Fox-Kemper et al., *supra* note 58.
109. *Id.*; Slangen et al., *supra* note 9.
110. Jeff Goodell, *The Doomsday Glacier*, Rolling Stone (May 9, 2017), https://www.rollingstone.com/politics/politics-features/the-doomsday-glacier-113792/.
111. Peter E.D. Davis et al., *Suppressed Basal Melting in the Eastern Thwaites Glacier Grounding Zone*, 614 Nature 479 (2023).
112. Kopp et al., *supra* note 65.
113. NOAA Office for Coastal Management, *Tools*, https://coast.noaa.gov/digitalcoast/tools/ (last modified Aug. 5, 2024).
114. Jochen Hinkel et al., *The Ability of Societies to Adapt to Twenty-First-Century Sea-Level Rise*, 8 Nature Climate Change 570 (2018).
115. Southeast Florida Regional Climate Change Compact, *Regionally Unified Sea Level Rise Projection*, https://southeastfloridaclimatecompact.org/initiative/regionally-unified-sea-level-rise-projection/ (last visited July 25, 2024); Florida Climate Center, *Sea Level Rise*, https://climatecenter.fsu.edu/topics/sea-level-rise (last visited July 25, 2024).
116. Florida Department of Environmental Protection, *Resilient Florida Program*, https://floridadep.gov/ResilientFlorida (last visited July 25, 2024); Miami-Dade County, *Sea Level Rise Strategy*, https://www.miamidade.gov/global/economy/resilience/sea-level-rise-strategy.page (last visited July 25, 2024).

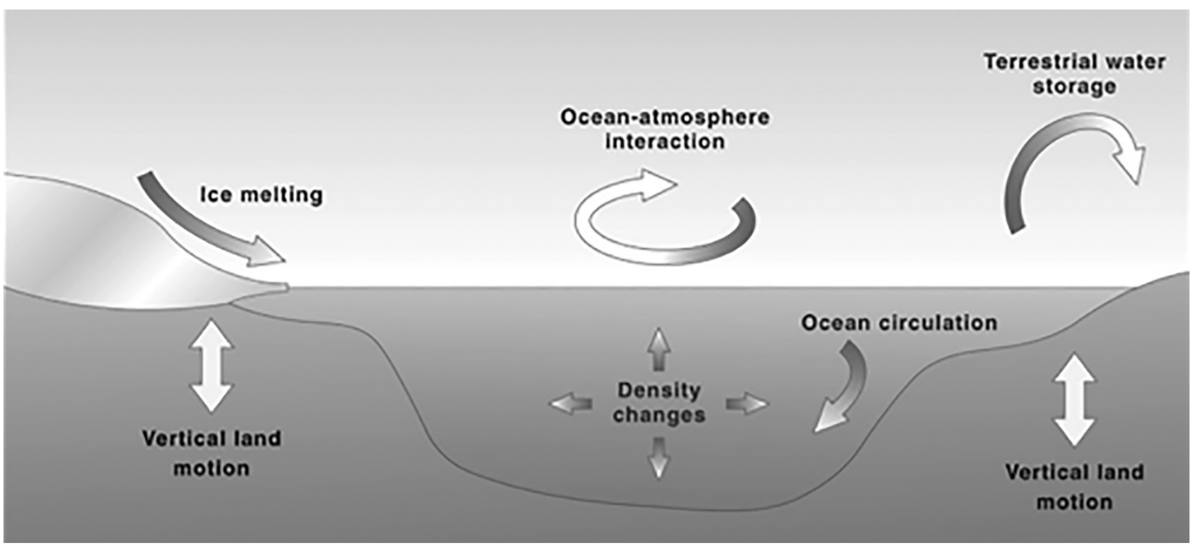
Section 1 Figures

Figure 1. Mechanisms for Sea-Level Change



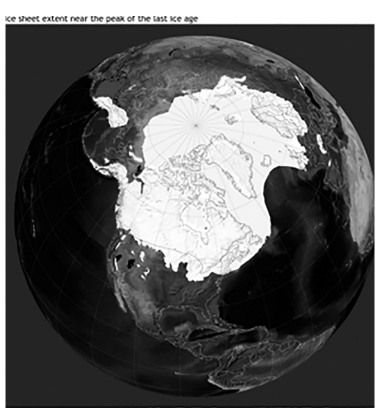
Source: Kenneth G. Miller et al., *A 180-Million-Year Record of Sea Level and Ice Volume Variations From Continental Margin and Deep-Sea Isotopic Records*, 24 Oceanography 40 (2011). The x-axis shows the timescale of physical processes driving sea-level change, and the y-axis shows the amplitude in log scale, or the amount of sea-level rise associated with each phenomenon. Kyr is thousands of years. Myr is millions of years. Reproduced under Creative Commons Attribution 4.0 International License.

Figure 2. Processes Affecting Sea Level



Source: Glenn A. Milne et al., *Identifying the Causes of Sea-Level Change,* 2 Nature Geosci. 471 (2009). Reproduced with permission from Springer Nature Customer Service Centre.

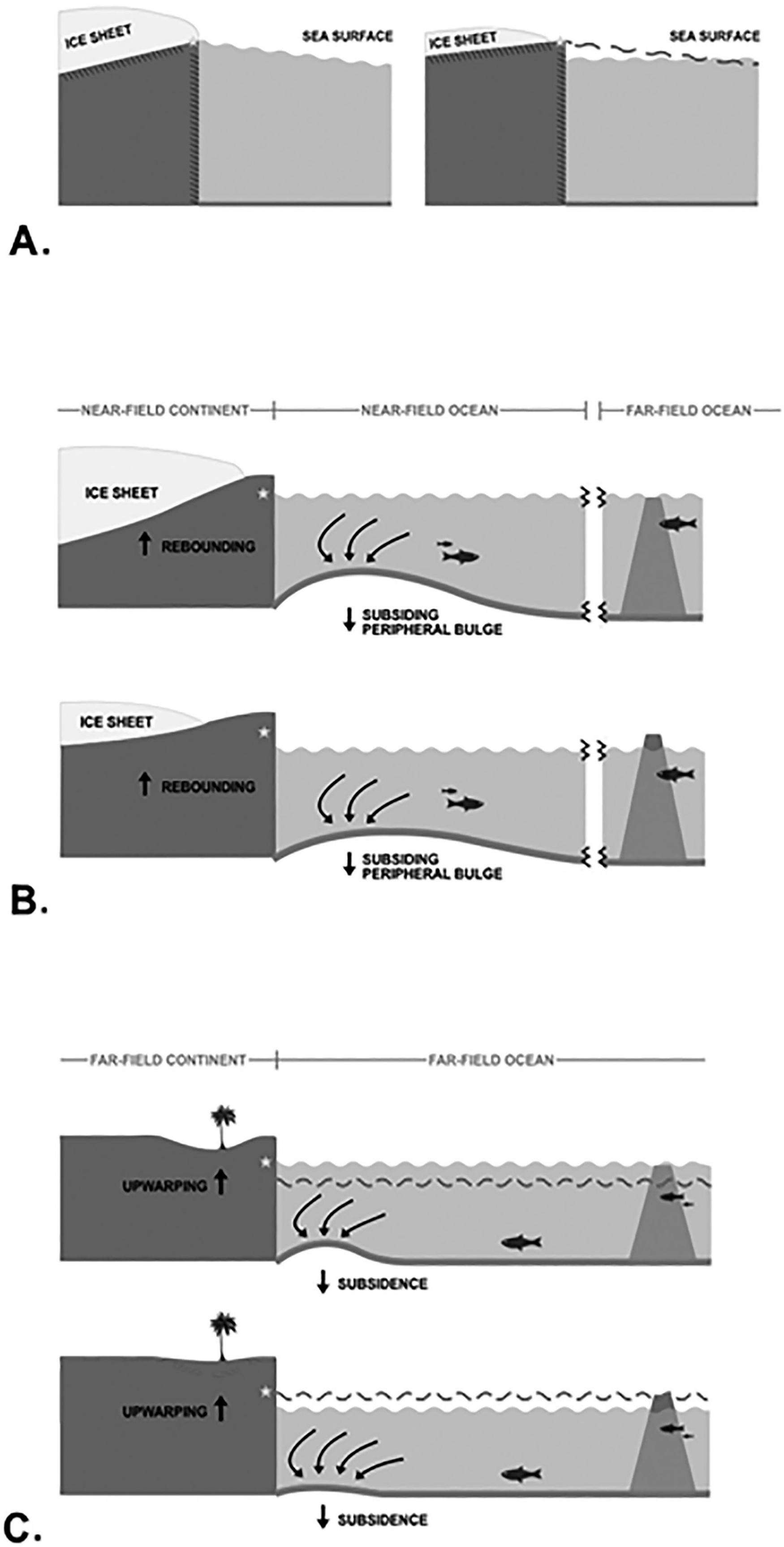
Figure 3. Ice Extent at the Last Glacial Maximum



Source: Image from climate.gov created using data from University of Zurich Applied Sciences and Science on a Sphere. Climate.gov, *Ice Sheet Extent Near the Peak of the Last Ice Age*, https://www.climate.gov/media/11951 (last visited Aug. 6, 2024); Science on a Sphere, *Blue Marble: Sea Level, Ice and Vegetation Changes - 19,000BC - 10,000AD*, https://sos.noaa.gov/catalog/datasets/blue-marble-sea-level-ice-and-vegetation-changes-19000bc-10000ad/ (last visited Aug. 6, 2024). Topography and ice are shown for 21,000 years ago.

Figure 4. The Physics of Ice Age Sea-Level Change

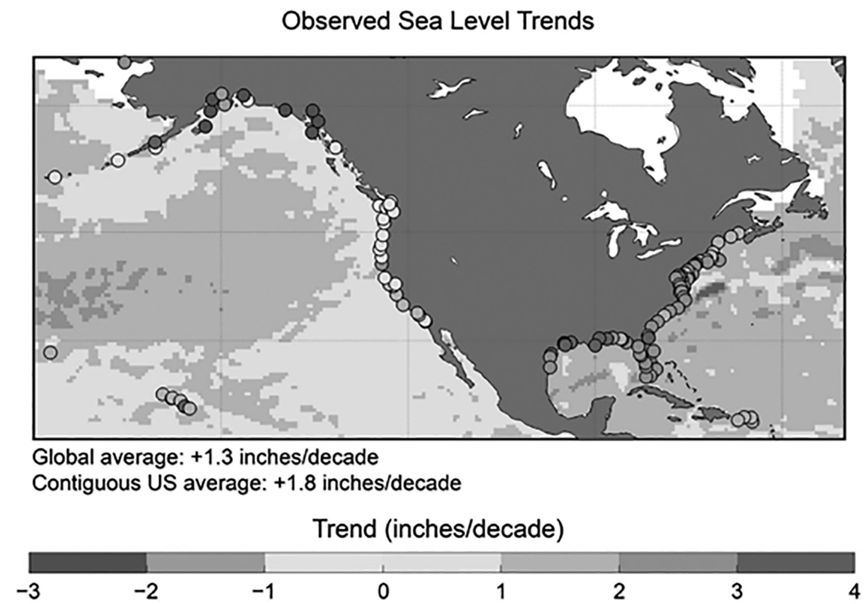
GIA processes active during geological periods of warming and ice melt.



A. Self-gravitation during periods of active ice melt. Black curve at right represents previous sea surface from the left panel. **B**. Crustal deformation processes in the near-field of ice cover (at left) and the contribution of peripheral bulge dynamics to ocean syphoning (at right). Ocean arrows show water moving in from the far-field to near-field. Land arrows show earth rebounding from ice melt. **C**. Crustal deformation (continental levering) along far-field continental shorelines (at left) and the contribution of this process to ocean syphoning (at right). Black curve at the top is sea surface prior to ice melt. Black curve at the bottom is land position and sea surface from the top panel. Ocean arrows show increased water load near the continental margin. Arrows under ocean floor show the ocean bottom going down due to increased water load. Arrows on continent show upwarping (ground elevation increasing) as earth's crust material is displaced back toward the continent.

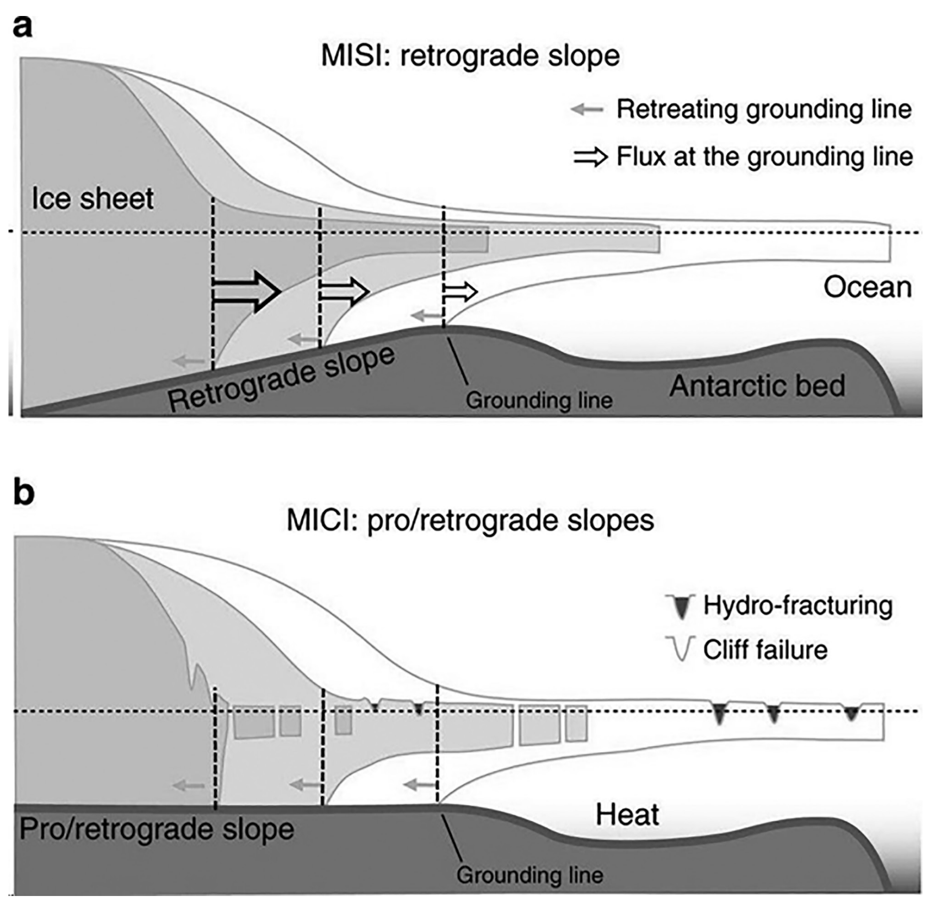
Source: Marisa Borreggine et al., *Not a Bathtub: A Consideration of Sea-Level Physics for Archaeological Models of Human Migration*, 137 J. Archaeological Sci. 105507 (2022). Reproduced under the Creative Commons Attribution-NonCommercial-No Derivatives License (CC BY NC ND).

Figure 5. Sea-Level Trends (Inch/Decade) for the Contiguous United States From Satellite and Tide Gauge Data, 1993-2020



Source: Figure from Kate Marvel et al., *Climate Trends*, *in* Fifth National Climate Assessment 2-1 (A.R. Crimmins et al. eds., U.S. Global Change Research Program 2023) (adapted from William V. Sweet et al., NOAA, Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines (2022), https://cdn.oceanservice.noaa.gov/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf). Refer to Fifth National Climate Assessment, *All Figures*, https://nca2023.globalchange.gov/all-figures/ (last visited July 25, 2024), to see the full-color version of this figure.

Figure 6. Instability Scenarios



A. MISI. **B.** MICI. Black dotted line represents sea level.

Source: Frank Pattyn, *The Paradigm Shift in Antarctic Ice Sheet Modelling*, 9 Nature Commc'ns 2728 (2018). Reproduced under the Creative Commons Attribution 4.0 International License.

understand sea-level rise on a community/local scale, but also contextualize how Florida fits into larger discussions on global sea-level changes. Here, we review the regional processes relevant to Florida and discuss what role they play in regional trends in sea-level rise.

Florida's regional geologic setting provides the foundation upon which a coastline/communities experience sea-level rise. The elevation and shape of the ground surface, known as topography, can either amplify or dampen the harmful impact sea-level rise has on a coastline. Florida has an extensive coastline, around 8,436 miles in length.[117] Much of this coastline is shallow and low-lying, which can extend considerably far inland.

Some notable regions, such as the Florida Keys, are extremely low-lying, with a large proportion of its landmass within five feet of sea level.[118] This leaves much of the coastline in a vulnerable position, as it takes a relatively small vertical rise in sea level to produce harmful consequences. This also leaves urban coastal communities very susceptible to small amounts of sea-level rise, as the topography provides little to no natural barrier against rising seas.

Sea-level rise driven by the melt of polar ice sheets is a large contributor to modern-day increases and is predicted to become even greater in the future, which creates distinct regional patterns in sea-level rise that impact the Florida coastline. As discussed in Section 1.1.2, melt from polar ice sheets creates different patterns of sea-level change depending on how far a specific location is from the ice sheet. When a large ice sheet melts, changes in the earth's gravity cause the meltwater to migrate far away from its source, which leads to sea-level fall directly next to the ice sheet, reduced sea-level rise in the near-field to the ice sheet, and amplified sea-level rise in the far-field of the ice sheet.[119] Consequently, the further a location is from the ice sheet, the greater the resulting sea-level rise.

Due to Florida's location relative to our current major polar ice sheets, melt from the Antarctic ice sheet leads to disproportionately high sea-level rise compared to the global mean. Melting ice also leads to changes in the earth's rotation, which create a relative sea-level rise in the Florida region.[120] While ice melt from Greenland still contributes to sea-level rise around Florida, the same gravitational and rotational effects reduce the amount of sea-level rise compared to melt coming from the Antarctic. As melt from the Greenland and Antarctic ice sheets continues to accelerate, it will contribute to an increasingly greater proportion of local sea-level rise. The increased impact the Antarctic ice sheet melt has on sea-level rise in Florida makes it an important process to keep in mind when planning for future sea-level rise.

Ocean dynamics, driven by climatic (wind and atmospheric pressure) and oceanographic (water temperature, salinity, and ocean currents) processes, can also create regional variations in sea-level change. Large-scale ocean currents, which transport water along consistent routes through the world's oceans, can create sea-level change as they push water away from or pull water toward a coastline. Along the southeast U.S. coastline, the Florida current, a component of the larger Gulf Stream that transports heat through the North Atlantic Ocean, creates sea-level change as it shifts the sea-surface height.[121]

In recent decades, a reduction in strength of the Florida current is leading to higher regional sea level, though this effect will likely reduce over the next decade.[122] Conditions such as wind stress and ocean temperature changes can also create regional variations in local sea level.[123] The variations created by these processes supplement other longer/larger trends in sea-level change, such as those driven by ice melt, and thus are important contributors to the patterns in sea-level change experienced day-to-day in coastal communities.[124] These processes operate on different timescales, including shorter-term seasonal variations driven by winds, to decadal variations such as the Florida current, to multi-decadal variations driven by ocean circulation.[125]

2.2 Current Sea-Level Rise in Florida

For many communities, historical records and modern measurements of sea-level change are available for large portions of the coastline, and Florida is no exception. These are commonly calculated using tide gauges and satellite measurements (see Section 1.3.1), many of which are publicly available (e.g., see NOAA Tides and Currents[126]). Estimates of current rates of sea-level rise are an important resource for discussing sea level in the near future, while historical records help us see how we arrived at modern rates of sea-level rise and where they may go in the future.

An important note is that estimates may differ depending on a few factors. The elevation sea level is measured relative to is known as the reference datum (e.g., sea-level rise calculated relative to the North American Vertical Datum

117. NOAA Office for Coastal Management, *Florida*, https://coast.noaa.gov/states/florida.html (last modified July 24, 2024).
118. *The $27 Billion Question: Can the Florida Keys Adapt to Sea-Level Rise?*, Nature Conservancy (Jan. 9, 2023), https://www.nature.org/en-us/about-us/where-we-work/united-states/florida/stories-in-florida/the-11-billion-question-can-the-florida-keys-adapt-to-sea-level-rise/.
119. Carling Hay et al., *The Sea-Level Fingerprints of Ice-Sheet Collapse During Interglacial Periods*, 87 Quaternary Sci. Revs. 60 (2014).
120. Roffman et al., *supra* note 101.
121. Park & Sweet, *supra* note 60.
122. Dangendorf et al., *supra* note 49; Piecuch & Beal, *supra* note 59; Park & Sweet, *supra* note 60.
123. Park & Sweet, *supra* note 60; Denis L. Volkov et al., *Interannual Sea Level Variability Along the Southeastern Seaboard of the United States in Relation to the Gyre-Scale Heat Divergence in the North Atlantic*, 46 Geophysical Rsch. Letters 7481 (2019); Arnoldo Valle-Levinson et al., *Spatial and Temporal Variability of Sea Level Rise Hot Spots Over the Eastern United States*, 44 Geophysical Rsch. Letters 7876 (2017).
124. Volkov et al., *supra* note 123.
125. Francisco M. Calafat & Don P. Chambers, *Quantifying Recent Acceleration in Sea Level Unrelated to Internal Climate Variability*, 40 Geophysical Rsch. Letters 3661 (2013); Christopher M. Little et al., *On the Relationship Between the Meridional Overturning Circulation, Alongshore Wind Stress, and United States East Coast Sea Level in the Community Earth System Model Large Ensemble*, 122 J. Geophysical Rsch.: Oceans 4554 (2017).
126. NOAA National Centers for Environmental Information, *Tides and Currents Map: An Interactive Map of All CO-OPS Stations*, https://www.tidesandcurrents.noaa.gov/map/ (last visited July 25, 2024).

of 1988 versus mean sea level at a specific tide gauge).[127] Changing the reference datum can change the measured sea-level value. Sea-level rise can be calculated over different time intervals, depending how far back a given record stretches. Additionally, we have different methods to observe sea-level change, such as tide gauge measurements[128] versus satellite altimetry.[129]

Also important to note is that rates of sea-level rise (change in sea level over time) will change depending on the time period over which one is calculating the rate of change. As the rate of sea-level rise increases, so will the amount of sea-level rise over a given amount of time (typically one year). For example, looking at a record that records an increase in the rate of sea-level rise, calculating a rate of sea-level rise over a recent 10-year period would show a greater change per year than calculating sea-level rise over a 50- or 100-year period.

There are a number of current records for sea-level change up to present day for the Florida coastline. Broadly, historical records and modern-day observations show that Florida coastlines are already experiencing sea-level rise, which continues to grow at increasing rates,[130] both on larger regional and more specific local scales. Using historical records such as tide gauges, many of which have continuous records going back decades, we evaluate how much sea-level rise we have experienced up to the present. Looking back to the 1950s, current estimates find as much as eight inches of sea-level rise since the 1950s, both generally along the Florida coastline and at specific tide gauge sites such as Virginia Keys, Florida.[131]

In more recent years, sea-level tide gauge sites such as Key West, Florida, have risen ~3.9 inches (measured between 2000-2017, calculated using a five-year moving average).[132] In terms of rates, sea-level rise rates in the southeastern United States measured since the 1990s are estimated at ~0.12 inch per year, increasing to ~0.3 inch per year around the past decade (measured at the Virginia Keys, Florida, tide gauge).[133] Broadly, both satellite altimetry measurements and tide gauges have observed an especially rapid acceleration in sea-level rise along the Southeast and Gulf Coasts in the most recent decade (2010-2022).[134]

Many tide gauge records used in existing literature use the NOAA Tides and Currents[135] database, which has easily accessible tide gauge records for many sites around Florida, some dating back to the early 1900s. Understanding the state of sea-level rise, especially at a local level, is a foundational step to preparing for future sea-level change.

2.3 Future Sea-Level Rise in Florida

Regional projections of future sea-level rise are a key part of decisionmaking surrounding sea-level rise adaptations, as they provide a way to quantify how much sea-level rise a community will face under a specific scenario. Here, we discuss the different kinds of regional projections available for Florida, including examples of notable existing projections, discuss important factors to keep in mind when considering a prediction of future sea-level change, and touch on the uses of different scenarios for different objectives. Our goal is not to endorse specific projections as the best, future result—different estimates are useful for different purposes and estimates are frequently revised based on the scientific community advancing our understanding of sea-level rise. We want to provide a foundation on what future projections of regional sea-level rise look like, how they are created, and what assumptions underlie each one, to enhance understanding and to support Florida communities living with local sea-level rise.

A quantitative projection of future sea-level rise can be created using a variety of data sources, can consider one or multiple underlying climate scenarios, and can consider different geographic scopes. A common source for future projections is technical reports generated by working groups, such as the 2017[136] and 2022[137] sea-level rise technical reports, which summarize the current (as of this writing) scientific understanding of sea-level science, as well as provide technical information, including regional sea-level rise projections. These inform larger climate assessments and provide the necessary data used in sea-level rise projection tools (see Sea Level Rise Toolkit[138]).

Different projections are also driven by different climate scenarios (see Section 1.4.1 for discussion on uncertainty and Section 1.4.4 to introduce named scenarios), which represent different greenhouse gas emissions scenarios and the resulting climatic effects. Different amounts of greenhouse gas emissions will yield different climatic responses (i.e., temperature changes), which lead to different rates of, for example, ice melt, and diverging amounts of sea-level rise. Depending on the underlying climate scenario, we see different quantitative estimates of future sea-level rise. Estimates based on different projections are not inherently bet-

127. Southeast Florida Regional Climate Change Compact, *supra* note 115.
128. Jayantha Obeysekera et al., *Climate Change and Its Implications for Water Resources Management in South Florida*, 25 Stochastic Env't Rsch. & Risk Assessment 495 (2011); NOAA National Centers for Environmental Information, *supra* note 126.
129. Beckley et al., *supra* note 45.
130. Florida Climate Center, *supra* note 115; Southeast Florida Regional Climate Change Compact, *supra* note 115.
131. Florida Climate Center, *supra* note 115; NOAA National Centers for Environmental Information, *Relative Sea Level Trend 8723214 Virginia Key, Florida*, https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8723214 (last visited July 25, 2024).
132. Southeast Florida Regional Climate Change Compact, *supra* note 115; NOAA National Centers for Environmental Information, *Relative Sea Level Trend 8724580 Key West, Florida*, https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8724580 (last visited July 25, 2024).
133. Florida Climate Center, *supra* note 115; NOAA National Centers for Environmental Information, *supra* note 132.
134. Yin, *supra* note 49.
135. NOAA National Centers for Environmental Information, *supra* note 126; Florida Climate Center, *supra* note 115; Southeast Florida Regional Climate Change Compact, *supra* note 115.
136. William V. Sweet et al., NOAA, Global and Regional Sea Level Rise Scenarios for the United States (2017), https://doi.org/10.7289/v5/tr-nos-coops-083.
137. Sweet et al., *supra* note 61.
138. Marisa Borreggine, *Sea Level Rise Toolkit*, https://www.tinyurl.com/SeaLevelTools (last updated Mar. 7, 2024).

ter or worse than each other; they are useful for different purposes. Different local projections use multiple scenarios to create upper and lower bounds (with or without intermediate values); the scenarios underlying the upper and lower bounds can also differ between projections.

For example, the Unified Sea Level Rise Projection for Southeast Florida[139] uses the IPCC RCP8.5 Median projection[140] as a lower bound as well as the NOAA Intermediate-High, High, and Extreme projections[141] as progressively higher upper bounds. Whether a single value or range of estimates, different underlying projections may lead to some predictions to not be directly comparable; thus, they are an important factor to keep in mind when looking at future projections. As discussed above in Section 1.4.4, it becomes harder to make future predictions due to known uncertainties in how climatic processes will respond to continued warming.

Projections informed by historical data also need to account for future climate uncertainties, as historical sea-level rise occurred under different climatic conditions than present and future sea-level rise.[142] As a consequence, the range in predicted sea-level rise amongst different scenarios tends to increase looking further into the future. More current estimates show that the range amongst all projected sea-level rise scenarios is narrower up to 2050 (i.e., there is less of a difference between the different possible outcomes), which diverges more significantly past 2050 (i.e., there is a greater difference between the different possible outcomes).[143] Processes such as MICI and MISI (see Section 1.4.3) contribute additional uncertainty beyond the year 2070.

One important factor to consider is the geographic scope of a projection—is it global, regional, or specific to a single geographic location? For making city to statewide decisions, regional and local projections are most useful, as they likely account for the different regional processes that create sea-level change that varies from the global mean. In a given report or study, pay attention to the geographic scope under which a projection is made (e.g., Key West, Florida, is used as the baseline site in the Southeast Florida Regional Climate Sea Level Rise Ad Hoc Working Group report,[144] while other reports may provide estimates for regions such as the Southeast and Eastern Gulf regions[145]).

Estimates that take a global look at sea-level change, while not a direct reflection of sea-level change at a specific site, are a useful tool for discussing larger trends in global sea-level change. Global estimates can also provide a foundation for regional estimates, which can be derived using regionalization methods. Additionally, as with measurements of historical and current sea-level rise, the reference datum (the point where sea-level rise is measured from) will also influence projected sea-level rise (e.g., Figure 1 versus Figure 2 from the Southeast Florida Unified Sea Level Rise Projection report[146]).

Current projections of future sea-level rise directed at Florida come from a range of sources. The Florida Climate Center, based out of Florida State University's Center for Ocean-Atmospheric Prediction Studies, estimates sea-level rise of ~10-12 inches (0.25-0.30 m) over the contiguous U.S. coastline from 2020 to 2050, comparable to sea-level rise over the past 100 years (1920-2020).[147] Further into the future, they project sea-level rise of 0.6-2.2 m up to 2100 and 0.8-3.9 m up to 2150, compared to the 2000 baseline.

The Unified Sea Level Rise Projection for Southeast Florida report, prepared by the Southeast Florida Regional Climate Change Compact's Sea Level Rise Ad Hoc Work Group, provides a unified regional projection for future sea-level rise, aimed toward informing decisionmakers.[148] They employ four projection scenarios: a lower bound from the IPCC RCP8.5 Median projection,[149] the NOAA Intermediate-High and High projections as intermediate and higher bounds, and NOAA extreme projection included as an additional point of reference.[150] All scenarios are calculated for the Key West, Florida, tide gauge.[151] Each projection comes with associated guidance on which curve is most appropriate for use in decisionmaking depending on the risk levels and/or lifetimes of projects/decisions.

2.4 Local Risk Factors

In addition to global and regional drivers that lead to sea-level rise, such as thermal expansion and ice melt, local factors also play a role in amplifying (or dampening) the impact of sea-level rise on a coastline. Coastlines host a wide range of different environmental and anthropogenic settings and face different climatic and oceanographic conditions, which all interact with larger, regional-scale processes to generate the trends in sea-level change experienced by coastal communities.

To understand how a local experiences sea-level rise, one must account for any relevant risk factors. This section addresses some of the specific risk factors found on the Florida coastline that affect sea-level rise and must be accounted for when addressing sea-level rise at a local level, specifically flooding and storm surges, shoreline and ecosystem dynamics, infrastructure, and subsidence.

2.4.1 Flooding and Storm Surges

Flooding, a high-water event driven by storm surges, tides, or other factors, is one of the environmental forces

139. Southeast Florida Regional Climate Change Compact, *supra* note 115.
140. IPCC, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (C.B. Field et al. eds., 2014).
141. Sweet et al., *supra* note 136.
142. Obeysekera et al., *supra* note 128.
143. Sweet et al., *supra* note 61.
144. Southeast Florida Regional Climate Change Compact, *supra* note 115.
145. Sweet et al., *supra* note 61.
146. Southeast Florida Regional Climate Change Compact, *supra* note 115.
147. Florida Climate Center, *supra* note 115; Sweet et al., *supra* note 61.
148. Southeast Florida Regional Climate Change Compact, *supra* note 115.
149. IPCC, *supra* note 140.
150. Sweet et al., *supra* note 136.
151. NOAA National Centers for Environmental Information, *supra* note 132.

most directly felt by coastal communities and often one of the earliest consequences of sea-level rise.[152] Coastal flood risks are highly dependent on a number of local factors, including shoreline geomorphology (such as shallow, low-lying coastlines), local storm conditions, and any human-built shoreline features.[153] Many low-lying coastlines also host large populations, which increases the risk from flood damage.

Flood risks/conditions are directly impacted by local sea-level rise; as the local sea-level baseline from which coastal flooding starts changes, it provides a starting point that is higher and further inland, impacting both the magnitude and the frequency of coastal flooding.[154] Throughout the text, we introduce several factors that contribute to flooding (see Figure 7 for a visual breakdown of flood risk components). As regional sea level rises, it builds upon the local drivers of flood risk, thus changing what flooding looks like for a local community. To understand the impacts of sea-level rise, it is critical to address the additional issue of flood risks.

One way to understand the impact of sea-level rise on flooding is to look at the changes in flood regimes (i.e., changes in the frequency of floods of different magnitudes). The recurrence intervals of minor, moderate, and major flood events are currently based on records of historical events.[155] Due to sea-level rise, both historical sea-level rise since the time periods used to calculate flood statistics and accelerating sea-level rise moving into the future, floods will occur under progressively higher and higher sea-level baselines, a consistent regional change that will add itself onto higher-frequency flood events.[156] As a result, future floods will not follow the same frequency patterns predicted by historical recurrence intervals. Flood statistics quantify the change in frequency that floods of specific magnitudes occur as a result of local sea-level rise; for example, what are considered today to be "century" events and what is the 100-year floodplain may occur more frequently than once every 100 years.[157]

Floods of all magnitudes will occur with greater frequency.[158] As sea level continues to rise, projected recurrence intervals for different flood magnitudes (multiple times a year, once a year, once a decade, once a century) will shorten (e.g., a flood previously projected to occur once a year may occur multiple times in a year). Of specific importance is the occurrence of floods defined as extreme, or high-risk but low-frequency, which cause the greatest damage to coastlines and communities but do not occur as frequently as other flood events.

As sea level rises, these extreme floods will occur more and more frequently, surpassing the recurrence interval observed in historical data, which puts coastal communities vulnerable to extreme flood events at greater risk for damage. Sea level does not have to rise dramatically to drive more frequent flood events—only as little as 10s of centimeters—which makes sea-level rise one of the most immediately felt consequences of anthropogenic climate change experienced by coastal communities.[159]

Storm surges (weather-driven events that push coastal waters inland) are a specific source of major flood events. The general mechanics of how floods are impacted by sea-level rise also applies to storm surges, as rising sea level gives a higher starting baseline from which the water levels move inland, increasing the water levels storm surges reach, which increases the amount of coastline inundated and worsens any damage.[160] This compounds the independent trend of the increasing magnitude of storm events.

Anthropogenic climate change is changing storm behavior, which itself brings an increasing risk of extreme water levels.[161] Greater extreme weather events create more extreme storm surges, amplifying the existing trend of flood magnification coming from sea-level rise, creating even worse storm surge events and further increasing the risk of coastal flooding.[162] While a more thorough dive into change in extreme weather events is outside of the purview of this Article, it remains an important driving influence that builds upon the existing risks of extreme water levels due to sea-level rise.

Tidal inundation and groundwater flooding will also worsen through the same mechanics as other general flood events. Tidal floods are an additional source of damaging high-water levels, especially as they can occur without associated storm events, making these sometimes known as "sunny day" or "nuisance" floods.[163] A higher baseline gives tides a starting point further inland, allowing them to reach further inland with a larger footprint, and creating a greater local flood risk.[164]

2.4.2 Shoreline and Ecosystem Dynamics

The characteristics of a coastline will influence how coastal communities experience sea-level rise.[165] A coast's shape, slope, and sediment supply will determine whether or not

152. Nathaniel L. Bindoff et al., *Observations: Oceanic Climate Change and Sea Level*, *in* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 385 (S. Solomon et al. eds., Cambridge Univ. Press 2007).
153. Jonathan D. Woodruff et al., *Coastal Flooding by Tropical Cyclones and Sea-Level Rise*, 504 Nature 44 (2013).
154. *Id*.
155. Mohsen Taherkhani et al., *Sea-Level Rise Exponentially Increases Coastal Flood Frequency*, 10 Sci. Reps. 6466 (2020).
156. Christopher M. Little et al., *Joint Projections of US East Coast Sea Level and Storm Surge*, 5 Nature Climate Change 1114 (2015).
157. Claudia Tebaldi et al., *Modelling Sea Level Rise Impacts on Storm Surges Along US Coasts*, 7 Env't Rsch. Letters 014032 (2012).
158. Taherkhani et al., *supra* note 155.
159. Kopp et al., *supra* note 93; Taherkhani et al., *supra* note 155.
160. Tebaldi et al., *supra* note 157.
161. Woodruff et al., *supra* note 153.
162. *Id.*; Little et al., *supra* note 156; Kopp et al., *supra* note 93; Yin, *supra* note 49.
163. Michael C. Sukop et al., *High Temporal Resolution Modeling of the Impact of Rain, Tides, and Sea Level Rise on Water Table Flooding in the Arch Creek Basin, Miami-Dade County Florida USA*, 616/617 Sci. Total Env't 1668 (2018).
164. Taherkhani et al., *supra* note 155.
165. Kopp et al., *supra* note 93.

sea-level rise causes a coastline to retreat landward. Ecosystems that make their home on coastlines, such as marshes or mangroves, may shelter a coastline from extreme water levels or leave a coastline vulnerable if they disappear. Damaged coastlines also increase vulnerability to extreme phenomena storm events, even without taking into account a change in storm frequency.[166] Understanding how a coastal community experiences sea-level rise requires consideration of the different coastline characteristics and how they will change as a result of sea-level rise.

The morphology of a coastline—elements such as the slope of a beach, whether it is made up of sand or gravel, and whether the beach is connected to land or exists as an island—plays an important role in what sea-level rise actually looks like on a given coastline. Sea-level rise can lead to increased coastal erosion, where processes such as wave onlap remove material from a coastline faster than it can be replenished, resulting in a reduced amount of dry land as the waterline moves landward or pushing the back edge of a coastline further into the shore, a process known as shoreline retreat. When a shoreline retreats, coastal land can shrink temporarily until the sediment supply is replenished, or be lost permanently.[167] Even if a coastline is only experiencing erosion during extreme events, damage can build up cumulatively over time, leading to large loss of coastland.

Low-lying coastlines, which make up a large portion of the Florida shoreline, are at especially high risk for increased erosion and shoreline retreat.[168] The shallow slope means a relatively small vertical increase in sea level creates a large amount of sea level moving inland, causing significant shoreline retreat rates. Higher sea level can also change how waves and tides interact with a coastline, which can lead to further shoreline retreat.[169]

Coastal features such as barrier islands, features with low-lying topography that rely on the redistribution of unconsolidated sediment to continue existing, are at especially high risk from sea-level rise as longer periods of overwash or inundation by seawater lead to coastal erosion.[170] Deltas, which form when river sediments are deposited along a coastline, are also dependent on sediment supply to survive continuous coastal erosion due to sea-level rise. In the geologic record, we can see that past times of rapid sea-level rise lead to significant shoreline retreat, which supports the modern observations and future predictions of shoreline retreat.[171]

Coastal ecology is also an important factor in determining the impact sea-level rise will have on a coastline. Coastal ecosystems such as wetlands, mangroves, and other green spaces can act as a buffer for local sea-level rise and extreme water levels, as well as support sediment-driven aggradation, help control coastal water quality, reduce coastal erosion, and provide important natural and cultural resources.[172] Unfortunately, these ecosystems are vulnerable to sea-level rise. As sea level rises, coastal environments become more marine, and they can migrate landwards, or collapse entirely.[173]

As a result, coastlines can experience changes such as higher water levels and increased coastal flooding.[174] If a shoreline is already experiencing landward migration, coastal ecosystem collapse can hasten the process.[175] Changing coastal environments can also have add-on effects on other vulnerable coastal features such as barrier islands.[176] One specific important coastal ecosystem found in Florida is the mangrove ecosystem.[177]

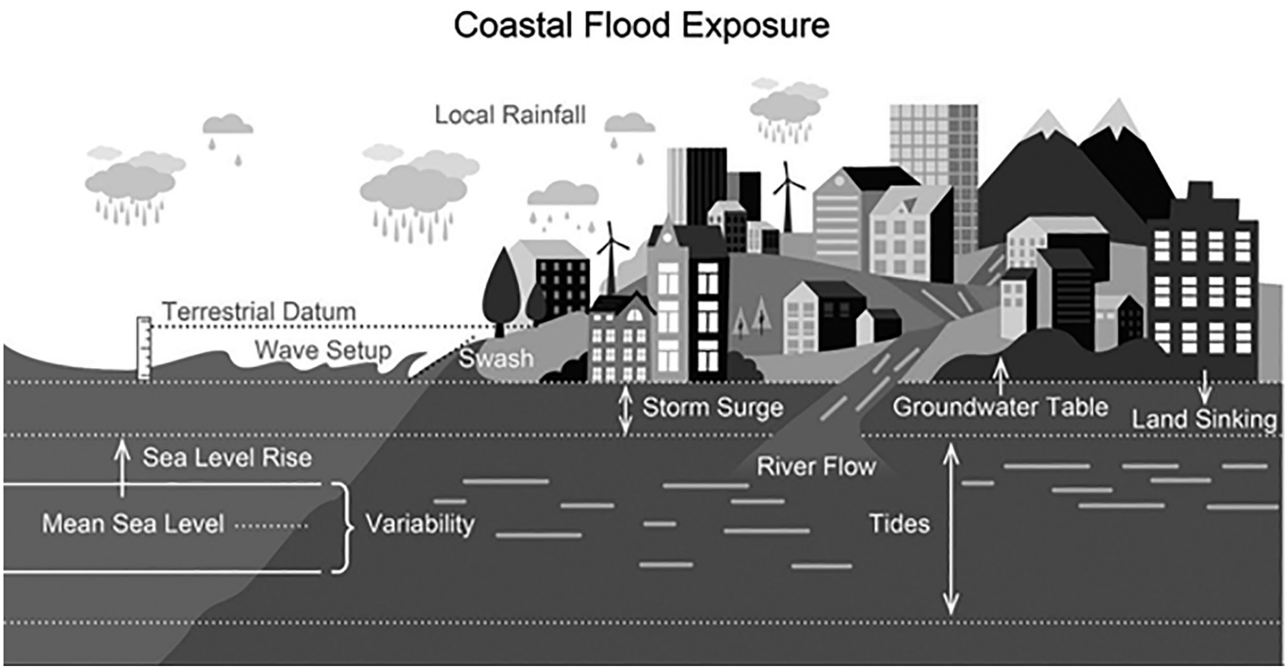
Mangrove ecosystems such as those found in the Everglades are at risk from sea-level rise, as changes in water heights and salinity will likely have negative consequences for the ecosystem.[178] Reconstructions of mangrove ecosystems during intervals of past rapid sea-level rise show that there are very few established mangrove ecosystems in these intervals, suggesting that it is unlikely that modern mangrove ecosystems will be able to keep up with future sea-level rise driven by anthropogenic climate change, though the different slope of modern coastlines (more shallow compared to historical steep coastlines) may change this relationship.[179] This risk is further complicated by ecological and sediment dynamics (such as primary litter production and sediment input) that change when terrestrial land is inundated by sea-level rise, as environments such as marshes and mangroves require a steady source of sediment to keep up with sea-level rise.[180] Thresholds exist, beyond which coastal environments such as marshes will undergo extreme changes, potentially disappearing entirely.[181]

2.4.3 Infrastructure

The kinds and conditions of infrastructure built near current sea level can either heighten a community's risk to sea-level rise or mitigate any negative effects.[182] Transportation infrastructure, such as bridges, can be vulnerable to storm

166. Andrew D. Ashton et al., *A Discussion of the Potential Impacts of Climate Change on the Shorelines of the Northeastern USA*, 13 Mitigation & Adaptation Strategies for Glob. Change 719 (2008).
167. *Id.*; Woodruff et al., *supra* note 153.
168. Woodruff et al., *supra* note 153.
169. Ashton et al., *supra* note 166.
170. Davina L. Passeri et al., *Dynamic Modeling of Barrier Island Response to Hurricane Storm Surge Under Future Sea Level Rise*, 149 Climactic Change 413 (2018); Kopp et al., *supra* note 93.
171. Woodruff et al., *supra* note 153.
172. Joanna C. Ellison & David R. Stoddart, *Mangrove Ecosystem Collapse During Predicted Sea-Level Rise: Holocene Analogues and Implications*, 7 J. Coastal Rsch. 151 (1991); Emma M. Glass et al., *Potential of Marshes to Attenuate Storm Surge Water Level in the Chesapeake Bay*, 63 Limnology & Oceanography 951 (2018); Kopp et al., *supra* note 93.
173. Ellison & Stoddart, *supra* note 172; Ashton et al., *supra* note 166.
174. Robert J. Nicholls & Anny Cazenave, *Sea-Level Rise and Its Impact on Coastal Zones*, 328 Science 1517 (2010); Ty V. Wamsley et al., *The Potential of Wetlands in Reducing Storm Surge*, 37 Ocean Eng'g 59 (2010); Glass et al., *supra* note 172.
175. Kopp et al., *supra* note 93.
176. Ashton et al., *supra* note 166.
177. Ellison & Stoddart, *supra* note 172.
178. Obeysekera et al., *supra* note 128.
179. Ellison & Stoddart, *supra* note 172.
180. *Id.*; Nicholls & Cazenave, *supra* note 174.
181. Ashton et al., *supra* note 166.
182. Kopp et al., *supra* note 93.

Figure 7. Oceanographic and Coastal Features That Impact Local Flood Exposure



Source: Figure from L. Ruby Leung, *Earth Systems Processes, in* FIFTH NATIONAL CLIMATE ASSESSMENT 3-1 (A.R. Crimmins et al. eds., U.S. Global Change Research Program 2023) (adapted from WILLIAM V. SWEET ET AL., NOAA, GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES: UPDATED MEAN PROJECTIONS AND EXTREME WATER LEVEL PROBABILITIES ALONG U.S. COASTLINES 10 (2022), https://cdn.oceanservice.noaa.gov/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf).

surges, high-water levels, and the subsequent water loading, all of which are set to worsen due to sea-level rise.[183] Important infrastructural features, such as water control systems that direct/manage coastal waters, stormwaters, and may be combined with wastewater systems, are also at high risk. Sea-level change on the order of 10s of centimeters can drastically reduce the capacity of structures to deal with floodwaters.[184] Additionally, sea-level rise can increase the footprint of extreme water levels and expose water control systems previously unaffected by high-water levels to urban flooding.

Sewers are also at risk from increased surface flooding and raised tidal waters, which could migrate into the previously isolated sewers. Combined sewer systems that manage both sewage/wastewater and flooding and connect with sewage treatment plants can be infiltrated by high-water levels through inflow (when stormwater enters a system externally through storm drains or in existing pipe connections), or infiltration (when water enters a waste system through cracks or leaks in the pipes) can expose other urban water systems to sewage.[185] Many of these systems are not designed to deal with extreme water levels and flooding, which makes them vulnerable to sea-level change.

Groundwater systems near sea level are also at risk of seawater inundation, which poses a large risk to public infrastructure that distributes freshwater.[186] Infrastructure constructed to mitigate rising water levels can significantly influence how a coastline responds to sea-level rise, such as changing the way high-water levels move along a coastline and potentially worsen overland flooding.[187]

2.4.4 Subsidence

The geology underlying Florida can also contribute to sea-level rise. The geologic phenomena where land sinks vertically downwards—known as subsidence—leads to sea-level change as the distance between the sea surface and the ground surface changes, providing a similar effect as rising water levels. This can occur naturally through sediment compaction and sinkhole activity or due to human activities such as groundwater or natural resource/fossil fuels extraction.[188]

183. Katherine A. Anarde et al., *Impacts of Hurricane Storm Surge on Infrastructure Vulnerability for an Evolving Coastal Landscape*, 19 NAT. HAZARDS REV. 04017020 (2018).
184. Jefferson F. Flood & Lawrence B. Cahoon, *Risks to Coastal Wastewater Collection Systems From Sea-Level Rise and Climate Change*, 27 J. COASTAL RSCH. 652 (2011); Obeysekera et al., *supra* note 128.
185. Flood & Cahoon, *supra* note 184.
186. Miami-Dade County, *supra* note 116.
187. Anarde et al., *supra* note 183; Kopp et al., *supra* note 93.
188. Nicholls & Cazenave, *supra* note 174; Shimon Wdowinski et al., *Land Subsidence Contribution to Coastal Flooding Hazard in Southeast Florida*, 382 PROC. IAHS 207 (2020), https://piahs.copernicus.org/articles/382/207/2020/.

Land subsidence can amplify existing rates of sea-level rise and increase the risk for processes associated with sea-level rise, such as coastal flooding from storm surges.[189] In urban areas developed on reclaimed marshland, subsidence due to sediment compaction is an important factor in determining coastal hazard levels. In areas where higher subsidence rates are observed, there is a notable increase in coastal flooding, but this is a highly localized phenomena that does not occur at high rates uniformly along large spans of coastline.[190]

3. Conclusions

This Article covered sea-level science from two perspectives—the foundations of the science and a case study of sea-level rise for the state of Florida. The foundations section covered the processes that create sea-level change, how to measure and observe sea level in the past and present and predict it into the future, how sea-level change differs on global and regional scales, and the role uncertainty plays in understanding future sea-level rise. The case study illustrated how regional processes and local considerations impact sea-level rise for coastal communities in Florida, and gave an overview of the current understandings of modern and future sea-level rise.

Sea-level science, like all scientific fields, is always changing and improving. The information provided here is a snapshot of our current scientific understanding that can serve as a reference for decisionmakers. This review contains a series of takeaways. Readers can ground their interpretations of science in the news, professional interactions, and in working with scientists within a foundational understanding of sea-level change on global, regional, and local scales. We hope the reader will be empowered to make informed decisions when helping communities prepare for and adapt to the reality of sea-level change.

More generally, we hope this information will help alleviate confusion or any sense of overwhelm when encountering sea-level science in all parts of life. Finally, we hope this information will spread beyond this Article, and readers will share this information with their communities so they may feel equipped to confidently participate in conversations about modern environmental change.

189. Woodruff et al., *supra* note 153.
190. Wdowinski et al., *supra* note 188; Southeast Florida Regional Climate Change Compact, *supra* note 115.