Adapting to Rising Sea Levels

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Legal Challenges and Opportunities

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To Mom and Dad

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A Note about the Figures

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Adapting to Rising Sea Levels

Chapter 1

Introduction to Sea Level Rise

In the coming years, one of the most visible impacts of climate change will be rising seas. Since the industrial revolution, average global sea level has already risen 8 inches.[1] Sea level is projected to continue rising well into the future as a result of both increased warming of the oceans and melting of ice sheets and glaciers. The 2013 report of Intergovernmental Panel on Climate Change's ("IPCC") Working Group I—a component of the IPCC's Fifth Assessment Report—concludes that depending on future greenhouse gas ("GHG") emissions scenarios, sea levels will rise an additional 0.85 to 3.2 feet globally by 2100.[2] The Third National Climate Assessment projects that the United States will experience between 2 and 6 feet of sea level rise by the end of the century.[3]

Rising seas will have a number of important impacts on coastal zones. Chief among these impacts will be the gradual inundation of low-lying coastal areas and key infrastructure—such as major seaports—that lie within those coastal areas. In the United States, EPA has estimated that 1 meter (approximately 3 feet) of sea level rise will result in the loss of 10,000 acres of land.[4] Rising sea levels will also increase the impacts of coastal storm surges, which in combi-

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1. United States Global Change Research Program, Climate Change Impacts in the United States: The Third National Climate Assessment 44 (2014) [hereinafter NCA2014].

2. IPCC, *Summary for Policymakers, 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 25 (2013) (noting likely ranges of sea level rise ranging from 0.26 to 0.82 m, depending on the emissions scenario considered).

3. NCA2014, *supra* note 1, at 45.

4. James G. Titus, *Chapter 7: Sea Level Rise*, *in* Report to Congress: The Potential Effects of Global Climate Change on the United States 123, 123 (Environmental Protection Agency 1989).

nation with sea level rise will threaten important coastal infrastructure. In addition, sea level rise can render coastal aquifers useless when they suffer from saltwater intrusion.

Collectively, these hazards pose a significant challenge not only for the United States' coastal zone but for the country as a whole. This book explores the significant legal challenges and opportunities that will arise in the face of rising sea levels. Focusing primarily on state experiences in California, North Carolina, and Texas, the book will examine how coastal management structures impact the ability of state and local governments to carry out effective measures to adapt to sea level rise. Building upon the lessons learned from these states, the book will also evaluate the legal challenges and opportunities for the private sector as it seeks to respond to rising seas.

Before proceeding to legal issues, this chapter will explain what we know about sea level rise and the impacts of climate change on storm activities—two key factors in defining the scope of the adaptation challenge.

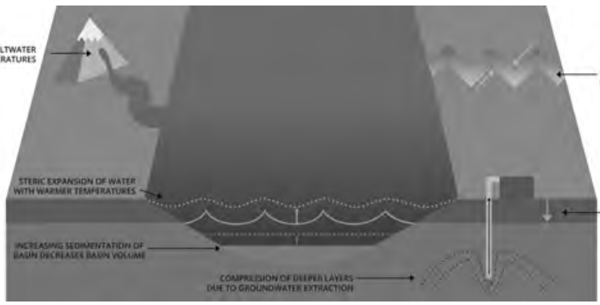
How Do We Know That Sea Level Is Rising?

A discussion of sea level rise should begin with a basic question: how do we know that sea level is rising? The simple answer is that we know sea level is rising because of the availability of historical measurements. Historically, measurements of sea level have depended on a global network of tide gauges, which measure the height of the sea relative to the land on which they are placed.[5] While tide gauges provide an important measure of relative sea level rise, they are subject to the movement of the land on which they are placed and influenced by other factors that may limit or accelerate the rate of regional sea level rise. In addition, tide gauge distribution has historically been more dense in the northern hemisphere. As a result, tide gauges may be limited in their ability to provide global estimates of sea level rise.

5. *How We Observe the Ocean: Tide Gauges*, NOAA Ocean Climate Observation Program, http://oco.noaa.gov/tideGauges.html (last visited Feb. 9, 2016).

What Is Relative Sea Level Rise?

The sea level rise experienced by a coastal region is a product of the amount by which sea level increases, the movement of natural land forms, and other factors that can increase or decrease the amount of sea level rise an area actually experiences. For example, in a coastal area experiencing natural land subsidence, relative sea level rise will be greater than the rate of sea level rise because the coastal land is sinking at the same time the sea is rising.



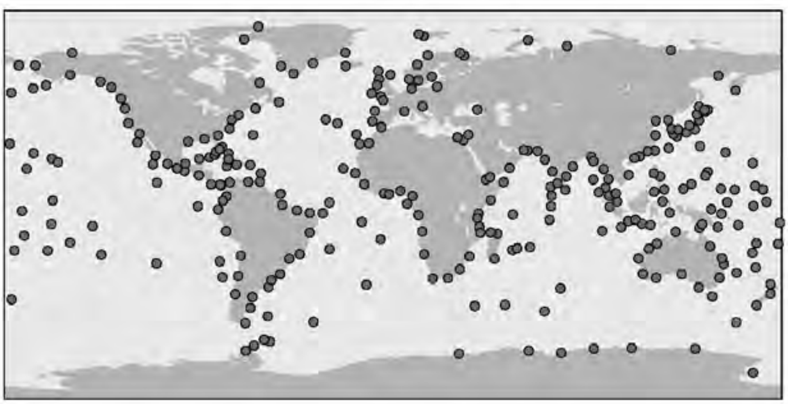


Figure 1: Global Distribution of Tide Gauges
Source: Global Sea Level Observing System (GLOSS)

Since 1992, scientists have had an additional tool available to measure sea levels: satellite altimetry. Satellite altimetry is a precise tool that measures the height of the ocean's surface using microwave radiation.[6] The satellites used to measure sea surface height cover the whole globe every 10 days. Because of their global coverage, satellite measurements of sea level rise make it possible to understand both average global and regional rates of sea level rise.[7] Satellite measurements have revealed that there is considerable regional variation in sea level rise:[8] satellite data shows that while global average sea level rise from 1993 to 2008 has averaged 0.11 inches (3 mm) per year, some regions experienced sea level rise as high as 0.4 inches (10 mm) per year and in others, sea level has actually fallen.[9]

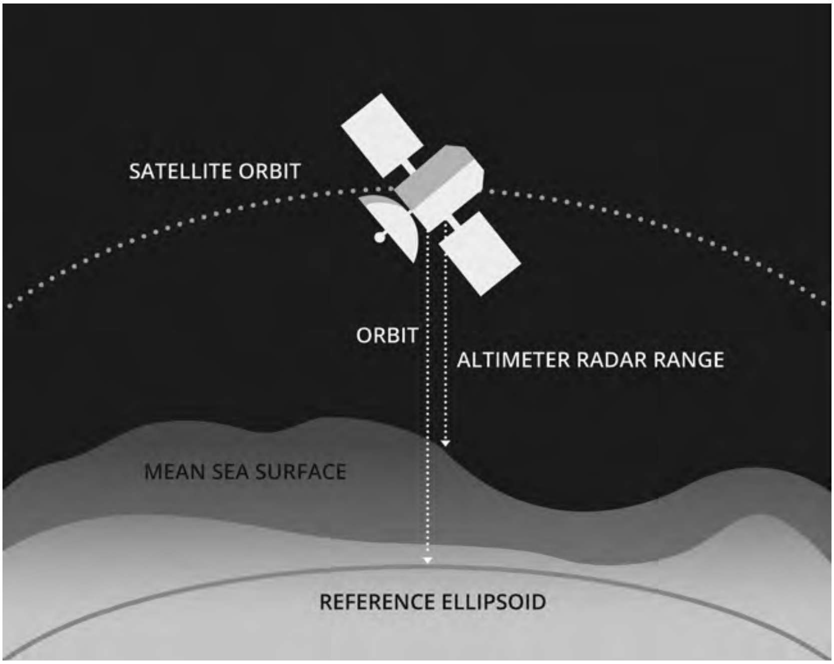


Figure 2: Satellite Altimetry

6. Anny Cazenave & William Llovel, *Contemporary Sea Level Rise*, 2010 Ann. Rev. Marine Science 145, 148.

7. *Id.* at 149.

8. *Id.*

9. *Id.* at 149, 151; Glenn A. Milne, W. Roland Gehrels, Chris W. Hughes & Mark E. Tamisiea, *Identifying the Causes of Sea Level Change*, 2 Nature Geoscience 471, 471 (2009).

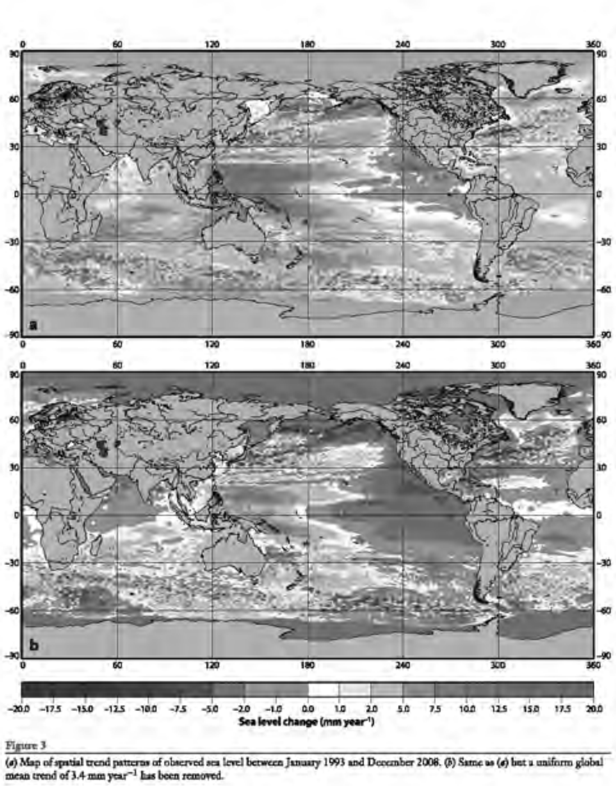


Figure 3: Satellite Altimetry Map of Sea Level Rise Differences

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What Causes Sea Level Rise?

There are two principal causes of sea level rise: changes in density of sea water and addition of new waters to the ocean. Addition of new waters to the ocean—principally the result of melting ice sheets and glaciers—increases the amount of water that is in the ocean. In contrast, increases in ocean temperature and decreases in ocean salinity can make ocean waters less dense, meaning that the same amount of water will take up a larger volume.

Sea Level Rise Due to Changes in the Density of Seawater

Changes in the density of seawater that lead to sea level rise are caused by both the warming of the oceans and changes in ocean salinity.[10] As global temperatures rise due to climate change, the oceans have been an important heat sink. It is estimated that the ocean has taken up over 90% of total planetary warming between 1971 and 2010,[11] and this heat uptake is thought to be resulting in slower rates of atmospheric warming than would otherwise be experienced.[12] This warming of the oceans causes sea water to expand, meaning that the same amount of water now occupies a larger volume.[13] In the ten years prior to 2003, scientists estimate that ocean thermal expansion caused 50% of sea level rise.[14] Domingues et al. find that from 1961 to 2003, heating of the surface layer of the ocean contributed 1.3 mm/yr to global sea level rise.[15] Since that time, ocean thermal expansion seems to have paused.[16] However, because the ocean continues to get warmer, scientists attribute the pause to natural variability caused by other environmental factors, as historical records of sea level rise caused by ocean warming demonstrate considerable variability over time.[17]

Scientists are only beginning to understand the role of changes in ocean salinity in causing sea level rise. The freshening of seawater—caused by the introduction of fresh water into the oceans—also causes the density of ocean water to decrease. As a result, in areas where large amounts of fresh water enter

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10. Detlef Stammer, Anny Cazenave, Rui M. Ponte & Mark E. Tamisiea, *Causes for Contemporary Regional Sea Level Changes*, 5 Ann. Rev. Marine Science 21, 23 (2013).

11. Monika Rhein et al., *Chapter 3 Observations: Ocean* 265, *in* Intergovernmental Panel on Climate Change, Climate Change 2013: The Physical Science Basis (2013).

12. S.S. Drijfhout, A.T. Baker, S.A. Josey, A.J.G. Nurser, B. Sinha & M.A. Balmaseda, *Surface Warming Hiatus Caused by Increased Heat Uptake Across Multiple Ocean Basins*, 41 Geophysical Research Letters 7868, 7873 (2014).

13. Stammer et al., *supra* note 10, at 27.

14. A. Cazenave, K. Dominh, S. Guinehut, E. Berthier, W. Llovel, G. Ramillien, M. Ablain & G. Larnicol, *Sea Level Budget over 2003–2008: A Reevaluation from GRACE Space Gravimetry, Satellite Altimetry, and ARGO*, 63 Global Planetary Change 83, 83 (2009).

15. Catia M. Domingues, John A. Church, Neil J. White, Peter J. Gleckler, Susan E. Wijffels, Paul M. Barker & Jeff R. Dunn, *Improved Estimates of Upper-Ocean Warming and Multi-Decadal Sea Level Rise,* 453 Nature 1090 (2008).

16. Cazenave et al., *supra* note 14, at 83.

17. *Id.*; IPCC, Climate Change 2007: Working Group I: The Physical Science Basis 5.5.3 Ocean Density Change, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch5s5-5-3.html (last visited Feb. 9, 2016).

the oceans, for example where glaciers are melting, the decrease in ocean salinity is a potentially important contributor to sea level rise. In fact, some studies have suggested that changes in ocean density caused by salinity changes will be the dominant component of sea level rise in the Arctic.[18] Conversely, seawater that is very salty has a higher density and may be able to counteract some of the sea level rise that would otherwise result from ocean warming.[19]

Sea Level Rise Caused by Melting Ice

The other major contributor to sea level rise is melting ice sheets and glaciers. Since 2003, satellite measurements of ice sheets and glaciers show that they have contributed 75–85% of sea level rise.[20] A significant influence on this rise in sea levels is the melting of terrestrial glaciers, which adds to the volume of the ocean.[21] Since 1992, one of Greenland's largest glaciers has doubled its flow speed—the rate at which the glacier moves across land—and is thinning rapidly.[22] Greenland's glaciers are losing mass because existing glacial ice is melting faster than new ice is formed by snow accumulation.[23] As of 2004, Rignot et al. projected that this melting of Greenland's glaciers results in additional sea level rise of .04 mm per year.[24] More recent studies find that the combined melting of the Greenland and Antarctic Ice Sheets contributes as much as 1.5 mm per year to rising sea levels,[25] and the melting of land ice in the Canadian Arctic Archipelago contributes a further .17 mm per year to sea level rise.[26] While many scientists consider it unlikely, the complete melting of the Greenland Ice Sheet would raise global sea levels by almost 23 feet

18. *See* Stammer et al., *supra* note 10, at 24.

19. *Id.*

20. Cazenave et al., *supra* note 14, at 86.

21. Cazenave & Llovel, *supra* note 6, at 154.

22. Richard B. Alley, Peter U. Clark, Philippe Huybrechts & Ian Joughin, *Ice-Sheet and Sea-Level Changes*, 310 Science 456, 458 (2005).

23. E. Rignot, D. Braaten, S.P. Gogineni, W.B. Krabill & J.R. McConnell, *Rapid Ice Discharge from Southeast Greenland Glaciers*, 31 Geophysical Research Letters L10401 (2004).

24. *Id.*

25. R. Thomas, E. Frederick, J. Li., W. Krabill, S. Manizade, J. Paden, J. Sonntag, R. Swift & J. Yungel, *Accelerating Ice Loss from the Fastest Greenland and Antarctic Glaciers*, 38 Geophysical Research Letters L10502 (2011).

26. Alex S. Gardner, Geir Moholdt, Bert Wouters, Gabriel J. Wolken, David O. Burgess, Martin J. Sharp, J. Graham Cogley, Carsten Braun & Claude Labine, *Sharply Increased Mass Loss from Glaciers and Ice Caps in the Canadian Arctic Archipelago*, 473 Nature 357, 357 (2011).

Why Don't Icebergs Contribute to Sea Level Rise?

The sea already has lots of ice floating in it in the form of icebergs and sheets of sea ice. This ice is like ice in a glass of water, as it melts it doesn't cause the glass to get any fuller. As a result, the melting of sea ice and icebergs does not contribute to sea level rise. In contrast, when glaciers on land melt, it is like adding new water to the glass, causing the water level to rise.

(7 m) and the melting of the West Antarctic Ice Sheet would raise global sea levels by between 9.8 and 16.4 feet (3 to 5 m).[27]

At this time, scientists do not expect the complete melting of the ice sheets, but uncertainty over the response of ice sheets to sea levels remains a major challenge in projecting future sea level rise.[28] Ice sheets and glaciers have been melting at a rate that is faster than projected by the IPCC models.[29] This melting may be driven in part by warmer air temperatures, ice sheets being in contact with warmer ocean waters, and changing glacial dynamics.[30] Recent studies of the West Antarctic Ice Sheet conclude that the ice sheets have experienced rapid thinning over the last two decades, and that early stage collapse of the West Antarctic Ice Sheet may already be underway.[31]

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27. Cazenave & Llovel, *supra* note 6, at 152.

28. *See* J.A. Church, P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer & A.S. Unnikrishnan, *Chapter 13 Sea Level Change* 1137, 1145, 1172–73, *in* Intergovernmental Panel on Climate Change, Climate Change 2013: The Physical Science Basis; J.L. Bamber & W.P. Aspinall, *An Expert Judgement Assessment of Future Sea Level Rise from the Ice Sheets*, 3 Nature Climate Change 424, 425 (2013).

29. E. Rignot, I. Velicogna, M.R. van den Broeke, A. Monaghan & J. Lenaerts, *Acceleration of the Contribution of the Greenland and Antarctic Ice Sheets to Sea Level Rise*, 38 Geophysical Research Letters L05503 (2013).

30. Bamber & Aspinall, *supra* note 28, at 424.

31. Fernando S. Paolo, Helen A. Fricker & Laurie Padman, *Volume Loss from Antarctic Ice Shelves is Accelerating*, 348 Science 327, 330 (2015); Ian Joughin, Benjamin E. Smith & Brooke Medley, *Marine Ice Sheet Collapse Potentially Underway for the Thwaites Glacier Basin, West Antarctica*, 344 Science 735 (2014); *see also* Robert M. DeConto & David Pollard, *Contribution of Antarctica to Past and Future Sea Level Rise*, 531 Nature 591 (2016) (finding that Antarctica has the potential to contribute more than a meter of sea level rise by 2100 and more than 15m by 2500).

Why Is Local Sea Level Rise Different from the Global Average?

When considering the impacts of sea level rise along a particular portion of the coast, there are two important factors that may cause regional sea level rise to be different from the global average. First, rates of sea level rise are not uniform across the globe. Second, when considering impacts of sea level rise on a particular piece of land, the relevant measure is relative sea level rise, which is how much the sea is rising with respect to the land.

Scientists have concluded that spatial variation in ocean warming is the most significant contributor to the uneven amounts of sea level rise observed across the globe (as shown in Figure 3).[32] In addition, local variations in salinity can lead to local variations in sea level rise.[33] Thus variations in the changes of ocean water density in different regions are an important driver of the differences in the amount of sea level rise experienced in different parts of the world.

In addition to changes in ocean water density, larger regional phenomena can act to suppress or enhance sea level rise. For example, since the mid-1970s the West Coast of the United States has experienced slower than average coastal sea level rise with sea levels that have been nearly unchanged since the 1980s. A study by Bromirski et al. concludes that this suppression in coastal sea level rise has been caused by large-scale wind stress patterns associated with a broader climate phenomenon known as the Pacific Decadal Oscillation ("PDO").[34] Bromirski et al. also find that wind stress patterns along the West Coast appear to be changing to be more like those observed prior to 1970, and they conclude that this shift could lead to a resumption of coastal sea level rise and rates of sea level rise that are higher than the global average.[35]

Recent research has concluded that the slowing of the Gulf Stream as a result of climate change may increase the rate of sea level rise along the Atlantic Coast. The Gulf Stream is a fast-moving current that carries water along the southern U.S. Coast to Cape Hatteras and then heads out towards Bermuda. The Gulf Stream is one of the major currents that is part of Atlantic Merid-

32. Cazenave & Llovel, *supra* note 6, at 154.

33. *Id.* at 162.

34. Peter D. Bromirski, Arthur J. Miller, Reinhard E. Flick & Guillermo Auad, *Dynamical Suppression of Sea Level Rise Along the Pacific Coast of North America: Indications for Imminent Acceleration*, 116 J. Geophysical Research C07005 at 6 (2011).

35. *Id.* at 9.

Did You Know the Sea Is Not Flat?

While it may seem strange, the surface of the ocean is not actually flat. Instead, some areas of the sea surface will be higher than others. There are several sources of changes in sea surface height. They include:

1. variations in the topography of the ocean floor;
2. geostrophic forces (the combination of physical forces acting upon the earth that results in the uneven distribution of water);
3. large-scale ocean currents and gyres; and
4. decadal variability in large-scale climate patterns.

These differences in sea surface height are important for sea level rise for two reasons. First, some areas will experience relatively more or less sea level rise than the global average. Second, changes in broad-scale climate patterns can alter both sea surface height and the rate of sea level rise.

ional Overturning Circulation ("AMOC"), which is illustrated in Figure 4. Because the Gulf Stream is a fast-moving current, it tends to push water away from the shore north of Cape Hatteras, meaning that the ocean along places like New Jersey is lower than it otherwise would be and sailing out into the Atlantic is like sailing up a hill. As the Gulf Stream slows, this effect is slowed, in essence causing the ocean water to flow downhill and back towards the coastline. As a result, scientists have found that the slowing of the Gulf Stream will cause significant increases in sea level rise from Cape Hatteras, North Carolina, all the way to Newfoundland, Canada.[36] While the IPCC currently has low confidence that there has been sustained slowing of Atlantic Meridional Overturning Circulation,[37] Yin et al. project that a complete collapse of AMOC

36. Jianjun Yin, Michael E. Schlesinger & Ronald J. Stouffer, *Model Projections of Rapid Sea-Level Rise on the Northeast Coast of the United States*, 2 Nature Geoscience 262, 263 (2009).

37. Rhein et al., *supra* note 11, at 282–84.

could itself cause over 3 feet (1 m) of sea level rise along the East Coast of the U.S. north of Cape Hatteras.[38]

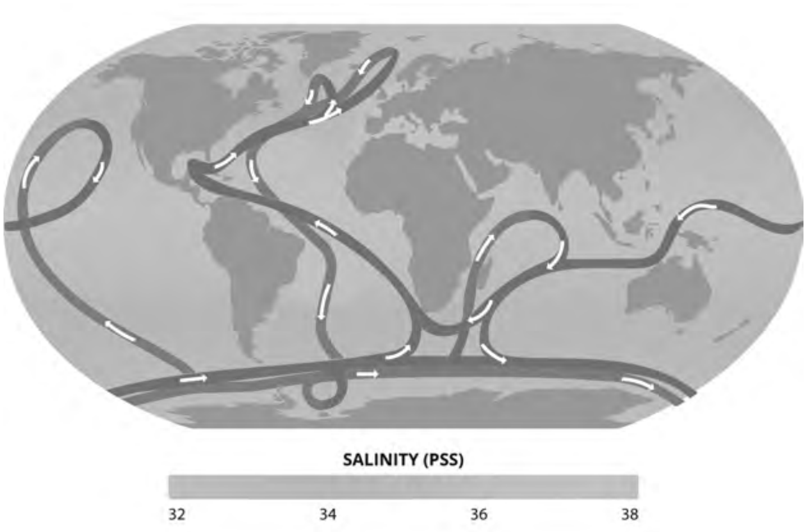

Figure 4: Explanation of Atlantic Meridional Overturning Circulation and Sea Surface Height

Thermohaline circulation is the circulation of ocean waters that is driven by differences in temperature and salinity. In the North Atlantic Ocean, the formation of sea ice causes the surrounding water to become colder and saltier, increasing its density. This denser water sinks becoming part of the deep ocean currents that are sometimes referred to as the "ocean conveyor belt."

Once all the regional components contributing to the ocean's rise are factored in, there is an additional component to consider to determine impacts on land: the movement of the land itself, which can increase or lessen the impacts of sea level rise. For example, along the Mississippi River Delta, subsidence due to extraction of oil and groundwater, changes in land management practices upriver that have decreased sediment supply, and compaction of the area's peat soils are causing the delta to sink.[39] Because the land itself is falling,

38. Yin et al., *supra* note 36, at 265.

39. *See generally* Alexander S. Kolker, Mead A. Allison & Sultan Hameed, *An Evaluation of Subsidence Rates and Sea-Level Variability in the Northern Gulf of Mexico*, 38 Geophysical Research Letters L21404 (2011) (discussing the role of fluid withdrawal in

the amount of relative sea level rise will be larger. In contrast, certain regions of the country that were covered by glaciers during the last ice age are still rising up in response to the removal of the weight of the glaciers—a process called glacial isostatic adjustment.[40] These regions will experience less relative sea level rise because the rise of the sea may be partially offset by the rise of coastal lands. In fact, regions that are currently covered in ice that is projected to melt in a warming climate, such as Greenland, West Antarctica, and Alaska, are expected to experience a net drop in sea levels due to the rise of land.[41]

How Much Will Sea Level Rise and When?

The 2013 report of Working Group I of the Intergovernmental Panel on Climate Change projects that by the end of the century, sea levels will rise an additional 0.85 to 3.2 feet globally, depending on future greenhouse gas emissions.[42] The 2014 National Climate Assessment concludes that, depending on future greenhouse gas emissions, the United States can expect to experience an additional 2 to 6 feet of sea level rise, with 4 feet of sea level rise being a likely upper-end estimate.[43] All models suggest that the amount of sea level rise we experience in the future is directly related to the future pathway of greenhouse gas emissions and resultant climate change: if global greenhouse gas concentrations continue to increase, the models project that we will experience additional warming of both the oceans and the atmosphere, which will lead to greater amounts of sea level rise in the future. For example, in an analysis of recent papers, Nicholls et al. concluded that if global temperatures are allowed to increase 4°C—a value that is twice the goal under the United Nations Framework Convention for Climate Change,

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coastal subsidence); Michael D. Blum & Harry H. Roberts, *Drowning of the Mississippi Delta Due to Insufficient Sediment Supply and Global Sea Level Rise*, 2 Nature Geoscience 488 (2009) (calculating accelerations in relative sea level rise due to sediment trapping upriver); Torbjörn E. Törnqvist, Davin J. Wallace, Joep E.A. Storms, Jakob Wallinga, Remke L. van Dam, Martijn Blaauw, Mayke S. Derksen, Cornelis J.W. Klerks, Camiel Meijneken & Els M.S. Snijders, *Mississippi Delta Subsidence Primarily Caused by Compaction of Holocene Strata*, 1 Nature Geoscience 173 (2008) (providing estimates of subsidence rates due to compaction).

40. Mark E. Tamisiea & Jerry X. Mitrovica, *The Moving Boundaries of Sea Level Change: Understanding the Origins of Geographic Variability*, 24 Oceanography 24, 27–28 (2011).

41. Stammer et al., *supra* note 10, at 37.

42. IPCC, *supra* note 2, at 25.

43. NCA2014, *supra* note 1, at 45.

but seems possible given current global GHG concentrations and emissions—a "pragmatic" estimate of sea level rise by 2100 is in the range of 1.6 to 6.7 feet.[44]

Rising global temperatures are projected to result in sea level rise due to both the isostatic expansion of sea water and the melting of land ice, including the Greenland and West Antarctic Ice Sheets. As far back as 1978, Mercer argued that a 5 m rise in sea level driven by rapid deglaciation was underway.[45] Over the last century, documented sea level rise occurred at a rate of 1–2 mm per year.[46] Furthermore, the geologic record reveals that historic increases in carbon dioxide concentrations are associated with vast changes in the extent of ice cover.[47] Around 1920, the rate of sea level rise began to increase rapidly, reaching the rate observed today.[48] Gehrels et al. found that this increase in the rate of sea level rise corresponded to global temperature increases, and concluded that continuing sea level rise in the Western Atlantic may be largely attributed to global warming.[49]

How Will Climate Change Alter Hurricane Activity?

Projecting the impacts of climate change on hurricane strength and frequency is far more complicated than understanding the potential for future sea level rise. Unlike global sea levels, which are primarily controlled by atmospheric and oceanic warming, the formation and landfall of hurricanes are controlled by a greater number of factors. These factors include large-scale climatic features, such as the El Niño Southern Oscillation and the location of

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44. Robert J. Nicholls, Natasha Marinova, Jason A. Lowe, Sally Brown, Pier Vellinga, Diogo de Gusmão, Jochen Hinkel & Richard S.J. Tol, *Sea-Level Rise and Its Possible Impacts Given a "Beyond 4°C World" in the Twenty-First Century*, 369 Phil. Trans. Royal Soc. A 161, 168 (2011).

45. *See generally* J.H. Mercer, *West Antarctic Ice Sheet and CO2 Greenhouse Effect: A Threat of Disaster*, 271 Nature 321 (1978).

46. Alley et al., *supra* note 22, at 456; John A. Church, Neil J. White, Richard Coleman, Kurt Lambeck & Jerry X. Mitrovica, *Estimates of the Regional Distribution of Sea Level Rise Over the 1950–2000 Period*, 17 J. Climate 2609, 2609 (2004).

47. Alley et al., *supra* note 22, at 456.

48. W. Roland Gehrels, Jason R. Kirby, Andreas Prokoph, Rewi N. Newnham, Eric P. Achterberg, Hywel Evans, Stuart Black & David B. Scott, *Onset of Recent Rapid Sea-Level Rise in the Western Atlantic Ocean*, 24 Quaternary Science Rev. 2083, 2083 (2005).

49. *Id.*

the North Atlantic Oscillation,[50] as well as changes in wind shear and sea surface temperatures. Because hurricane strength and activity are controlled by several environmental variables that are not related to climate change, it is difficult to discern the contribution of climate change and rising sea surface temperatures to changes in hurricane strength and frequency.[51] In fact, the National Climate Assessment concludes that the frequency and duration of Atlantic hurricanes, as well as the frequency of category 4 and 5 hurricanes has increased since the 1980s, but that the relative contributions of human and natural causes of this change remain uncertain.[52] As discussed below, there is an emerging scientific consensus that warmer sea surface temperatures are associated with *stronger* hurricanes; the effect of increasing temperatures on the *frequency* of hurricanes depends upon the ocean basin under consideration.

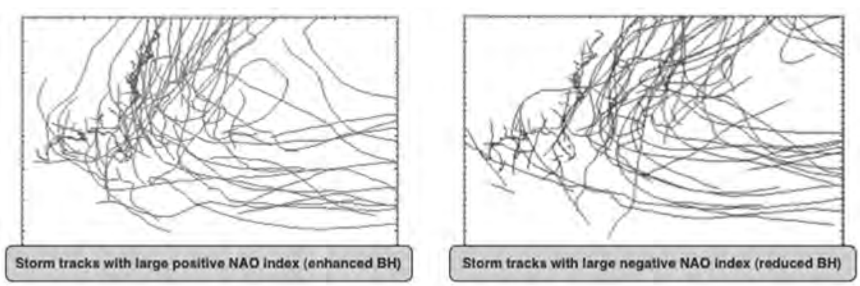

Figure 5: Explanation of Impact of North Atlantic Oscillation on Landfalling Hurricanes

The North Atlantic Oscillation ("NAO") is a large-scale atmospheric circulation feature that is characterized by positive and negative phases based on the location of two pressure centers over the North Atlantic. The NAO, which can vary considerably both seasonally or multi-year time scales impacts storm tracks including those of hurricanes. Positive phases of the NAO will cause hurricanes to track closer to the U.S. East coast, while negative phases will tend to steer hurricanes out to sea.

Source: ©2017 Climatological Consulting Corporation, http://www.ccc-weather.com

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50. The El Niño Southern Oscillation and North Atlantic Oscillation are larger pressure fronts whose movements influence both the ability of hurricanes to form and their tracks across the ocean. *See* Mark Denny, How the Ocean Works: An Introduction to Oceanography (2008).

51. *See* P.J. Webster, G.J. Holland, J.A. Curry & H.-R. Chang, *Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment*, 309 Science 1844, 1844 (2005).

52. NCA2014, *supra* note 1, at 41.

Warmer sea surface temperatures have been associated with increases in the intensity of tropical storms. Emanuel finds that the Power Dissipation Index, a measure of storm intensity, is positively correlated with increased sea surface temperatures and the peak potential wind speed of hurricanes increases 5% for every 1°C of warming.[53] Other studies have also found an increase in hurricane intensity that is associated with higher sea surface temperatures, and this effect is particularly significant in the North Atlantic.[54] For example, Knutson et al. project that there will be a significant increase in the frequency of category 4 and 5 storms in the North Atlantic,[55] Bender finds that the number of category 4 and 5 storms will nearly double, and the IPCC SREX report finds some models project an 80% increase in category 4 and 5 Atlantic Hurricanes.[56]

While many studies project increases in hurricane intensity due to ocean warming, there does not appear to be an increase in the number of storms that are forming. To the contrary, Gleixner et al. find that a range of models project that warmer ocean temperatures will decrease the number of storms that form, and their results suggest that in this century there will be a 22% decrease in the number of storms in the Southern Hemisphere and a 6% decrease in the number of storms in the Northern Hemisphere.[57] Overall, it appears that while the number of storms may not increase, stronger storms will make up a

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53. Kerry Emanuel, *Increasing Destructiveness of Tropical Cyclones Over the Past 30 Years*, 436 Nature 686 (2005).

54. *See* James B. Elsner, James P. Kossin & Thomas H. Jagger, *The Increasing Intensity of the Strongest Tropical Cyclones*, 455 Nature 92, 93 (2008) (finding an increase in maximum lifetime wind speeds of hurricanes, and noting a particularly strong trend in the North Atlantic where sea surface temperatures have greatly increased); Webster et al., *supra* note 51, at 1846 (finding that increases in hurricane intensity are related to increased SSTs); Kerry Emanuel, Ragoth Sundararajan & John Williams, *Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations*, 89 Bull. Am. Meteorological Soc. 347, 365 (2008).

55. Thomas R. Knutson, Joseph J. Sirutis, Gabriel A. Vecchi, Stephen Garner, Ming Zhao, Hyeong-Seog Kim, Morris Bender, Robert E. Tuleya, Isaac M. Held & Gabriele Villarini, *Dynamical Downscaling Projections of Twenty-First Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-Based Scenarios*, 26 J. Climate 6591, 6601 (2013).

56. M.A. Bender, T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner & I.M. Held, *Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes*, 327 Science 454 (2010); IPCC, Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) 162 (2012).

57. Stephanie Gleixner, Noel Kennlyside, Kevin I. Hodges, Wan-Ling Tseng & Lennart Bengtsson, *An Inter-Hemispheric Comparison of Tropical Storm Response to Global Warming*, 42 Climate Dynamics 2147, 2152 (2014).

greater proportion of the total number of storms.[58] Holland and Bruyère examine current storm activity and conclude that there is no climate-driven effect on storm frequency, but that there are significant increases in the number of both stronger (category 4 and 5) and weaker (category 1 and 2) storms, with fewer storms of intermediate strength (category 3).[59] Overall, they suggest that the proportion of category 4 and 5 hurricanes will increase from 25% of all storms to 35%.[60] Kossin et al. examine the historical record and find a similar increase in the proportion of stronger storms, but conclude that these impacts are basin-specific noting that there have been "dramatic changes in the frequency distribution of lifetime maximum intensity (LMI) [for hurricanes] in the North Atlantic, while smaller changes are evident in the South Pacific and South Indian Oceans."[61]

Another factor that will influence the impact of future hurricanes on coastal communities is whether they make landfall or remain at sea. The future landfall of hurricanes is likely to vary regionally and will be dependent upon both long-term natural variability (e.g., the North Atlantic Oscillation) and climate-driven changes in oceanic and atmospheric circulation patterns. Hall & Yonekura model future ocean warming and its impacts on landfall, and find that warmer sea surface temperatures are projected to lead to statistically significant increases in major hurricane landfall in Texas and along the north Gulf Coast.[62] However, the East Coast is not similarly impacted in their models because changes in sea surface temperature appear to alter storm tracks and steer them away from land.[63] Barnes et al. modeled the possibility of another Hurricane Sandy making landfall under projected future conditions, and concluded that the changes projected by climate models will decrease the frequency of the steering patterns that caused Hurricane Sandy to make landfall.[64] As a re-

58. IPCC SREX, *supra* note 56, at 162.

59. Greg Holland & Cindy L. Bruyère, *Recent Intense Hurricane Response to Global Climate Change*, 42 Climate Dynamics 617, 624 (2014).

60. *Id.*

61. James P. Kossin, Timothy L. Olander & Kenneth R. Knapp, *Trend Analysis with a New Global Record of Tropical Cyclone Intensity*, 26 J. Climate 9960, 9973 (2013).

62. Timothy Hall & Emmi Yonekura, *North American Tropical Cyclone Landfall and SST: A Statistical Model Study*, 26 J. Climate 8422, 8437 (2013).

63. *Id.*

64. Elizabeth A. Barnes, Lorenzo M. Polvani & Adam H. Sobel, *Model Projections of Atmospheric Steering of Sandy-Like Superstorms*, 110 Proceedings Nat'l Acad. Science 15211, 15213–14 (2013).

sult, future climate conditions could make it more likely that a Sandy-like storm would travel out into the Atlantic Ocean.[65]

Because of the many factors—both climate driven and otherwise—that influence hurricane formation, the projected increase in the number of strong hurricanes is a significant concern for coastal communities. Rising sea levels will combine with those storms and intensify the impacts of coastal flooding due to storm surge.[66] And, even if storm levels were to remain constant, current patterns of coastal development will still increase societal exposure to storms as more people move into the coastal zone.[67] Further, modeling of future exposure to hurricanes in the United States indicates that a 10% increase in storm intensity will increase storm damage experienced by coastal communities by more than 50%.[68] This damage estimate does not include the often substantial damage that inland communities experience as a result of powerful hurricanes that make landfall.[69]

What Are the Impacts on the Coastal Zone?

Globally, more than 770,000 square miles of land are less than 1 meter (approximately 3 feet) above sea level.[70] While local amounts of sea level rise will vary based on the factors discussed above, all of these assets are potentially vulnerable to the range of global average sea level rise projected by the end of the century. In the United States, nearly 5 million people live within 4 feet of the local high-tide level—an amount of sea level rise the National Climate Assessment concludes is possible by the end of the century.[71] Further, the National Climate Assessment concludes that more than 5,790 square miles and $1 trillion of property and structures in the United States are at risk of inun-

65. *Id.*

66. For estimates of the impact of sea level rise on storm-surge flood events, *see* Robert J. Nicholls, *Analysis of Global Impacts of Sea Level Rise: A Case Study of Flooding*, 27 Physics & Chem. of the Earth 1455 (2002).

67. Roger A. Pielke, Jr., *Are There Trends in Hurricane Destruction?*, 438 Nature E11 (2005); *see also* Chapter 2.

68. Stefanie Hallegatte, *The Use of Synthetic Hurricane Tracks in Risk Analysis and Climate Change Damage Assessment*, 46 J. Applied Meteorology & Climatology 1956, 1956 (2007).

69. *Id.*

70. Milne et al., *supra* note 9, at 471.

71. NCA2014, *supra* note 1, at 45.

dation with only 2 feet of sea level rise—an amount that is possible by 2050 under high emissions scenarios.[72]

Due to the combined effects of sea level rise and storms, the National Climate Assessment estimates that the incremental annual damage to capital assets in the coastal zone along the Gulf Coast caused by climate change could reach $2.7 to $4.6 billion per year by 2030 and $8.3 to $13.2 billion per year by 2050.[73] Twenty percent of the assets included in these figures are related to the oil and gas industry,[74] raising the possibility that future sea level rise and storminess could have significant impacts on the energy industry in the United States. In addition, U.S. ports handled over $1.9 trillion in goods and over 90% of consumer goods in 2010.[75] Ports are inherently vulnerable to sea level rise due to their location directly on the coast and the fact that much of their support infrastructure is in low-lying coastal zones.[76] Given that substantial sea level rise would continue in the future even if all greenhouse gas emissions were halted today,[77] it is clear that significant investments in adaptation will be necessary to avoid disruptions to key sectors of the United States' economy.

To illustrate the extent of the potential impacts of sea level rise in the next century, Figures 6–8 highlight the areas that may be vulnerable to sea level rise along the Texas and North Carolina coasts and in the San Francisco Bay.

This inundation will also have significant environmental impacts. On sandy shorelines, Hinkel et al. find that without nourishment to counteract erosion, sea level rise will lead to the loss of 43 to 66 square miles of sandy beach by 2100.[78] The loss of beaches will impact both sandy beach ecosystems and the recreational tourism industry, which accounts for 85% of annual tourism revenues, or over $595 billion in the United States.[79]

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72. *Id.* at 589.

73. *Id.*

74. *Id.*

75. *Id.*

76. Austin H. Becker, Michele Acciaro, Regina Asariotis, Edgard Cabrera, Laurent Cretegny, Philippe Crist, Miguel Esteban, Andrew Mather, Steve Messner, Susumu Naruse, Adolf K.Y. Ng, Stefan Rahmstorf, Michael Savonis, Dong-Wook Song, Vladimir Stenek & Adonis F. Velegrakis, *A Note on Climate Change Adaptation for Seaports: A Challenge for Global Ports, A Challenge for Global Society*, 120 Climatic Change 683, 685–86 (2013).

77. Benjamin H. Strauss, *Rapid Accumulation of Committed Sea-Level Rise from Global Warming*, 110 Proc. Nat'l Acad. of Sci. 13699, 13699 (2013).

78. Jochen Hinkel, Robert J. Nicholls, Richard S.J. Tol, Zheng B. Wang, Jacqueline M. Hamilton, Gerben Boot, Athanasios T. Vafeidis, Loraine McFadden, Andrey Ganopolski & Richard J.T. Klein, *A Global Analysis of Erosion of Sandy Beaches and Sea-Level Rise: An Application of DIVA*, 111 Global and Planetary Change 150, 154 (2013).

79. NCA2014, *supra* note 1, at 589.

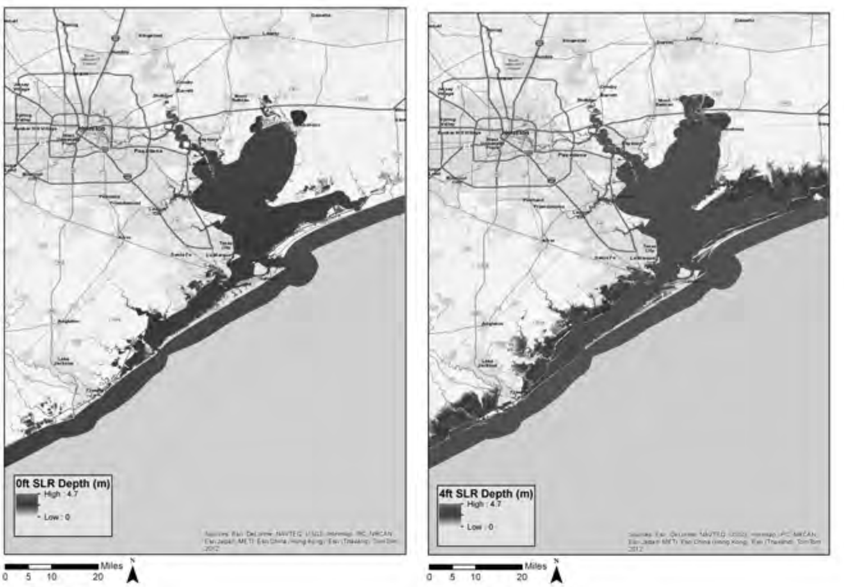

Figure 6: Map of Projected Sea Level Rise on the Texas Coast

In addition, while marshes with adequate sediment supply may be able to keep pace with slower rates of sea level rise, models project that if sea levels rise more than 1 meter by 2100, most marshes will permanently submerge.[80] Marshes play a number of important functions including purifying water, serving as breeding and hatchery grounds for fish and birds, and reducing storm surges.[81] If marshes are permanently submerged and converted to open ocean, these functions will be lost.

This chapter has explained the evidence for and causes of sea level rise. By 2100, it is likely that the United States will experience between 2 and 4 feet of sea level rise, though local levels of relative sea level rise may be more or less than this amount. Rising seas put key infrastructure and ecosystems in the United States' coastal zone at risk. These risks are potentially amplified by projected increases in the proportion of more intense hurricanes and the associated storm surges that result. Because continued sea level rise is inevitable,

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80. Matthew L. Kirwan, Glenn R. Guntenspergen, Andrea D'Alpaos, James T. Morris, Simon M. Mudd & Stijn Temmerman, *Limits on the Adaptability of Coastal Marshes to Rising Sea Level*, 37 Geophysical Research Letters L23401 at 4 (2010).

81. United States Environmental Protection Agency, Economic Benefits of Wetlands (2015), http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000D2PF.txt.

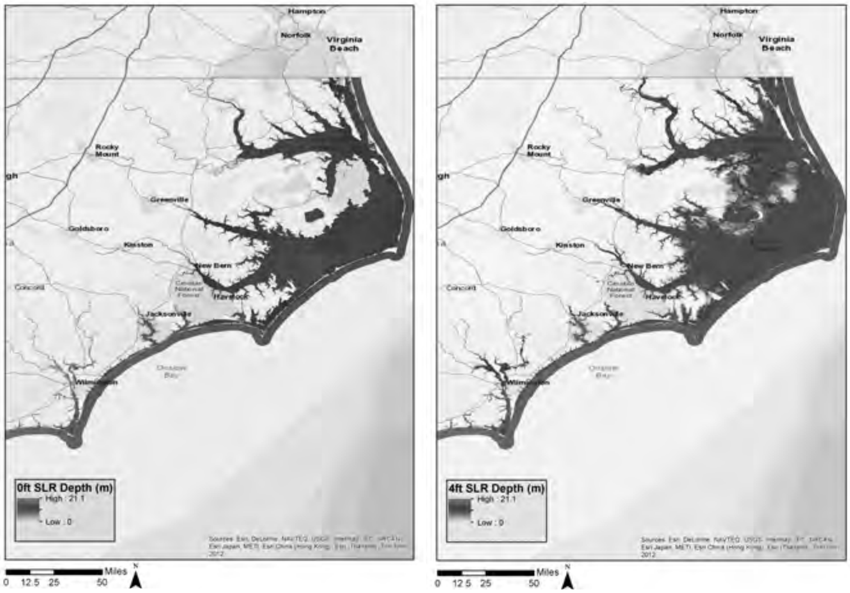

Figure 7: Map of Projected Sea Level Rise on the North Carolina Coast

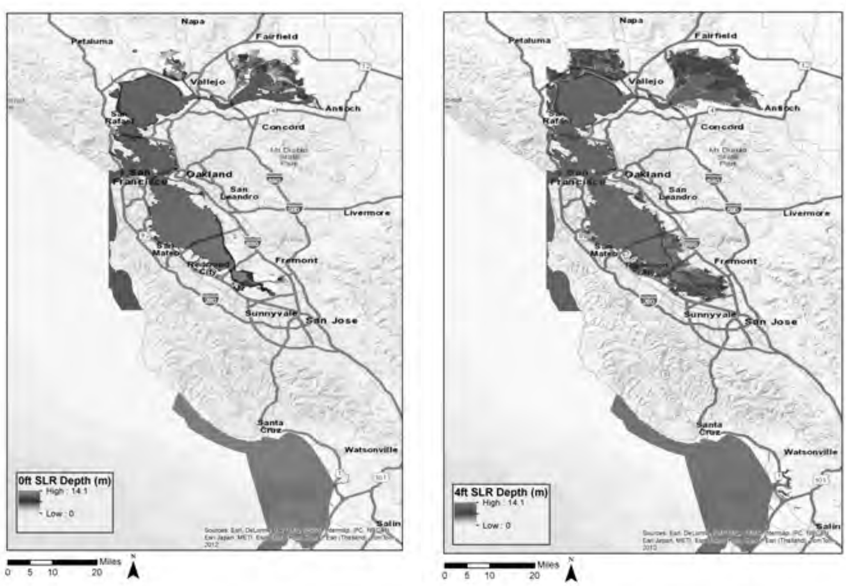

Figure 8: Map of Projected Sea Level Rise in San Francisco Bay

citizens and businesses in coastal communities will be forced to adapt. The choice becomes whether they will engage in proactive measures to reduce projected future hazard exposure due to sea level rise and storms or wait for sea levels to rise and respond to coastal inundation as it happens. Either way, the path towards adaptation will be filled with legal challenges and opportunities that are the focus of the remainder of this book.