CHAPTER 2
CLIMATE CHANGE AND THE COAST

This purpose of this chapter is to set the context for adaptation planning by providing an overview of the value of our nation's coastal resources and how they may be affected by climate change. As a coastal manager, you already appreciate the importance and value (market as well as nonmarket) of your coasts. Understanding these values and how they may be affected by climate change will play a significant role in adaptation planning, providing a basis for informed decision making and helping to tell the story and gain stakeholder support. While this chapter looks at our coasts and climate change from a national perspective, it can be adapted to tell your state-specific story.

The Value of Our Coasts

Our coasts are critically important to our nation, supporting a large percentage of its population as well as its economy. In 2007, According to the National Ocean Economics Program (NOEP), the coastal zone was home to an estimated 127 million people, supported 57 million jobs, and contributed $6.7 trillion to the U.S. economy, accounting for 42 percent of the U.S. population and 49 percent of its national economic output (NOEP 2009a).

In its 2009 *State of the U.S. Ocean and Coastal Economies report*, the NOEP provided a snapshot of the "ocean economy." The ocean economy consists of economic activities that are tied to the ocean or Great Lakes, or that are partially related to the ocean or Great Lakes, and are located in a shore-adjacent zip code. In 2004 (the most recent year for which the information is available), the ocean economy contributed $138 billion to the U.S. economy:

- Tourism and recreation: $70 billion
- Marine transportation: $28 billion
- Offshore minerals: $20 billion
- Ship and boat building: $11 billion
- Living resources: $7 billion
- Marine construction: $3 billion

Measuring the ocean economy is complicated, and data are limited. In order to make data compatible and comparable across all six sectors, some sector data were excluded in the NOEP study. Sector-specific reports from other sources, which use different definitions, methodologies, and parameters, can provide greater detail. For example, NOAA's National Marine Fisheries Service reported that the commercial fishing industry generated over $103 billion in sales and $44 billion in income in 2006. That same year, recreational fishing contributed $82 million in sales (largely in durable equipment) to the U.S. economy and generated $38 billion in value-added impacts (NOAA n.d. Fisheries).

The coasts also provide a number of services that do not have traditional market values but in total may be even more valuable than those that do. The value of coastal wetlands, for example, has been estimated to be between $3 and 13 million per km^2 (Knogge et al. 2004). And, additional research suggests that the storm protection services they provide are worth $23.2 billion annually (Costanza et al. 2008). The total nonmarket value for U.S. coastal and ocean resources is "at minimum tens of billions of dollars per year and likely much more" (NOEP 2009b).

According to the Millennium Ecosystem Assessment, "coastal ecosystems—coastal lands, areas where fresh water and salt water mix, and nearshore marine areas—are among the most productive yet highly threatened systems in the world. These ecosystems produce disproportionately more services relating to human well-being than most other systems" (Hassan et al. 2005). Some of the nonmarket services provided by coastal ecosystems (e.g., estuaries, marshes, coral reefs, mangroves, lagoons, salt ponds, seagrass) include flood and storm protection, erosion control, water quality maintenance, biological productivity, fish and wildlife habitat, recreational opportunities, and aesthetic values.

Impacts and Consequences of Climate Change on the Coast

Our nation's coasts are particularly susceptible to climate change. They are already subject to an array of social and environmental stressors that have resulted in habitat loss and conversion, habitat degradation, and overexploitation. Key stressors include coastal development, storms and other natural processes (e.g., erosion and subsidence), deforestation, pollution, invasive species, unsustainable and destructive fishing practices, recreational activities, energy development, etc. Climate change, defined by the Intergovernmental Panel on Climate Change (IPCC) as "any change in climate over time, whether due to natural variability or as result of human activity," will exacerbate these stressors (IPCC 2007a). Implications are expected to be far reaching for coastal communities, economies, and ecosystems (Karl et al. 2009).

Since 1900, the global average surface temperature of the Earth has risen by about 1.5ºF (Karl et al. 2009). And, the 2000s decade (2000-09) was the warmest on record, with 9 of its 10 years (2001-09) ranking among the top 10 warmest years on record (NOAA 2010a). Significantly, it was the global warming that occurred over the last 50 years that accounts for the majority of the increase, which is largely attributable to human activities (i.e., greenhouse gas emissions). In the United States, the average temperature has risen more than 2°F over the last 50 years (Karl et al. 2009).

The cumulative and secondary impacts from development in the coastal zone can threaten coastal resources and exacerbate impacts of climate change.

The IPCC has projected a likely rise in the average global surface temperature of an additional 2 to 11.5°F by 2100 (relative to the 1980-99 time period) based on an assumption of no changes in climate policy. In the United States, the average temperature is projected to increase by approximately 7 to 11°F under a higher emissions scenario and by approximately 4 to 6.5°F under a lower emissions scenario (Karl et al. 2009).

In addition to increases in air temperature, there is evidence that other associated changes are taking place. Some of these climate change "phenomena," which are discussed throughout this guide, include rising sea levels, declining Great Lake levels, increasing storm intensity/frequency (tropical and cold-season storms), changing precipitation patterns, increasing water temperature, and ocean acidification. The effects of these changes are being observed across all sectors in the United States and around the world (Karl et al. 2009).

Our understanding of the effects of climate change on the United States is still evolving. According to the U.S. Global Change Research Program, future changes in some phenomena are more difficult to project than others (e.g., changes in precipitation are more difficult to project than changes in temperature) (Karl et al. 2009). A lot remains uncertain and depends on the success of our efforts to mitigate climate change. Nevertheless, despite the uncertainties, current climate change projections are considered reliable enough to warrant and support adaptation planning (Karl et al. 2009).

The Summary of Climate Change Phenomena: Observed and Projected Changes table summarizes how climate change may affect—and in some cases is already affecting—coastal communities. It presents a general overview of the issues with national-level observations and projections and offers a starting point for discussions. Specifically, the table calls out the key climate change phenomena and their associated impacts and consequences that may fall, albeit possibly in a very limited way, within the purview of state coastal management programs and that are addressed further in this guide. (The public health discussion is largely limited to consequences of extreme weather events/conditions. Agriculture, forestry, and emergency preparedness and response are not included.) The table also includes observed and projected changes, which are for the United States and taken from the *Global Climate Change Impacts in the United States* (Karl et al. 2009) report unless specified otherwise. Brief descriptions of the potential impacts and consequences of the phenomena follow the table. It should be noted that while these descriptions are written in the future tense, some of the impacts and consequences are already being felt.

It is vitally important to recognize that these phenomena and their resultant impacts and consequences will not occur in isolation. They will interact with the stressors discussed above as well as other social and economic stressors. The possibility of cumulative and secondary impacts should be considered, as this combination of phenomena and stressors will likely result in more severe impacts than those caused by individual factors. And, for some systems, these impacts may be irreversible.

The general nature of the guide does not allow for a more thorough examination of how these phenomena may vary by region, although strong regional variations in most of these phenomena are expected. For more information about some of these regional variations, see Appendix C.

Summary of Climate Change Phenomena: Observed and Projected Changes

Climate Change Phenomenon	Associated Potential Impacts	Associated Potential Consequences	Observed Changes	Projected Changes* (to mid to late 21st century)
Increasing Air Temperature *Note: With the exception of ocean acidification, all phenomena listed here are driven by increasing air temperature.*	• Heat waves • Drought • Wildfire • Invasive species • Shift in species range • Changes in timing of ecological events • Loss of sea ice • Reduction in snowpack	• Illnesses, injuries, and loss of life • Loss/degradation/alteration/ migration of coastal ecosystems and the goods and services they provide • Decline in quantity and quality of freshwater • Destruction and damage to coastal property and infrastructure • Economic losses	• The average temperature has risen more than 2°F over the past 50 years, generally resulting in longer warm seasons and shorter, less intense cold seasons • The number of days with high temperatures above 90°F is projected to increase throughout the country	• By 2100, the average temperature is projected to increase by approximately 7 to 11°F under a higher emissions scenario and by approximately 4 to 6.5°F under a lower emissions scenario
Rising Sea Levels	• Coastal inundation • Erosion • Storm surge flooding • Rising water tables • Saltwater intrusion • Nonpoint source pollution • Introduction of toxics	• Illnesses, injuries, and loss of life • Destruction and damage to coastal property and infrastructure • Loss/degradation/alteration/ migration of coastal ecosystems and the goods and services they provide • Loss of beach access • Decline in quantity and quality of freshwater • Loss of cultural resources • Population displacement/ migration • Economic losses	• During the last 50 years, sea level has risen up to 8 inches or more along some areas of the U.S. coast and has fallen in others • Global average sea level rose 1.7 mm (~.067 in)/year during the 20th century, 1.8 mm (~.071 in)/year between 1961 and 2003, and 3.1 mm (~.122 in)/year between 1993 and 2003 (it is unknown if the increase in the latter reflects natural variability or a long-term trend) (IPCC 2007b)	• Recent estimates substantially exceed IPCC estimates, suggesting global sea level rise between 3 and 4 feet by 2100 • Global average sea level is projected to rise from 8 to 24 inches by the end of the century (this excludes contributions to sea level rise due to changes in ice sheet dynamics)

Climate Change Phenomenon	Associated Potential Impacts	Associated Potential Consequences	Observed Changes	Projected Changes* (to mid to late 21st century)
Declining Great Lake Levels	• Water loss • Bluff erosion • Hypoxia • Harmful algal blooms • Invasive species	• Decline in quantity and quality of freshwater • Water dependent coastal infrastructure impairment • Navigational challenges • Loss/degradation/alteration of coastal ecosystems and the goods and services they provide • Destruction and damage to coastal property and infrastructure • Reduced access to waterfront facilities • Public trust conflicts • Economic losses	• Since 1961, with the exception of Lake Superior, Great Lakes water levels have dropped almost .25 feet, on average • Since the early 1970s, there has been a decrease in extent of Great Lakes ice coverage, which leads to more evaporation	• Under lower emissions scenarios, Great Lakes water levels will fall no more than 1 foot by 2100, but under high emissions scenarios, they will fall between 1 and 2 feet
Increasing Storm Intensity/Frequency*	• Flooding • High wind • High waves • Erosion • Salinity shifts • Nonpoint source pollution • Introduction of toxics	• Injuries and loss of life • Destruction and damage to coastal property and infrastructure • Loss/degradation/alteration of coastal and marine ecosystems and the goods and services they provide • Decline in quality of freshwater • Economic losses	• The power and frequency of Atlantic hurricanes has increased in recent decades, but there has been little increase in the number of hurricanes that make landfall • Since the 1980s, the number of tropical storms in the eastern Pacific has decreased, but the strongest storms have become stronger • Cold-season storm tracks have shifted northward and the strongest storms have become stronger	• The intensity of Atlantic hurricanes is likely to increase, but more slowly than observed in recent decades • The strongest hurricanes are likely to get stronger in both the eastern Pacific and the Atlantic oceans • Cold-season storms will continue to track northward; *strong* cold season storms are likely to become stronger and more frequent

* This includes both tropical and cold-season storms (extratropical).

Climate Change Phenomenon	Associated Potential Impacts	Associated Potential Consequences	Observed Changes	Projected Changes* (to mid to late 21st century)
Changing Precipitation Patterns	Increasing Precipitation			
	• Flooding • Erosion • Nonpoint source pollution • Introduction of toxics • Salinity shifts	• Illnesses, injuries, and loss of life • Destruction and damage to coastal property and infrastructure • Loss/degradation/alteration of coastal ecosystems and the goods and services they provide • Decline in quality of freshwater • Economic losses	• Total average precipitation increased by about 7% during the 20th century (5% in the last 50 years) • The amount of rain in the heaviest 1% of downpours increased about 20% in the last century • Regional patterns indicate that precipitation increased the most in the wettest areas	• The widespread trend toward more heavy downpours is expected to continue; precipitation will be less frequent but more intense • Regional patterns will continue
	Decreasing Precipitation			
	• Drought • Wildfire • Nonpoint source pollution • Salinity shifts	• Illnesses, injuries, and loss of life • Loss/degradation/alteration/ migration of coastal ecosystems and the goods and services they provide • Decline in quantity and quality of freshwater • Destruction and damage to coastal property and infrastructure • Economic losses	• Droughts have become more frequent and intense during the past 40 to 50 years	• Droughts are likely to become more frequent and severe in some regions

Climate Change Phenomenon	Associated Potential Impacts	Associated Potential Consequences	Observed Changes	Projected Changes* (to mid to late 21st century)
Increasing Water Temperature	• Coral bleaching • Hypoxia • Pathogens and disease • Harmful algal blooms • Invasive species • Shift in species range • Changes in timing of ecological events	• Loss/degradation/ alteration/migration of coastal and marine ecosystems and the goods and services they provide • Decreased water quality • Economic losses	• Since the 1970s, coastal water temperatures have risen by about 2°F in several regions	• Increases in water temperature will accompany increases in air temperature
Ocean Acidification	• Dissolution of calcium carbonate in marine shell-forming organisms	• Loss/degradation/ alteration/migration of coastal and marine ecosystems and the goods and services they provide • Economic losses	• Globally, the pH of seawater has decreased significantly (0.1 units) since 1750, making it more acidic (IPCC 2007c)	• Globally, the pH of seawater will drop much more dramatically (0.14-0.35 units) by 2100 if carbon dioxide concentrations continue to increase (IPCC 2007c)

Increasing Air Temperature

With the exception of ocean acidification, all of the phenomena discussed in this chapter can be attributed to increasing air temperature. Increasing temperatures will also mean more droughts, wildfires, and heat waves, which are expected to threaten human and other populations and strain infrastructure and its capacity to provide the services we have grown accustomed to. Within ecosystems, native species may leave or die-off if they cannot handle the higher temperatures. Invasive species may replace them or take advantage of their weakness and force them out. And, changes in the timing of ecological events (i.e., lifecycle stages) as a result of warmer air may cause disruptions in the food web, further stressing ecosystems and local economies that depend on them.

Increasing temperatures will also cause more precipitation to fall as rain than snow and shift the timing of the melting of snowpack to earlier in the year. In areas where snowpack runoff is a critical source of water, reduced snowpack and earlier snow melt (which means reduced stream flows later in the year) will pose significant challenges.

In the Arctic, warming will reduce sea ice and cause permafrost to thaw. As sea ice melts, the coast will be more prone to damage and destruction. Thawing permafrost will damage buildings, roads, airstrips, pipelines, and other infrastructure. It will also have impacts on drainage, ground water, river runoffs, and ecosystems and will release carbon sequestered in the frozen soil (NOAA n.d. Arctic).

Rising Sea Levels

Global sea level rise is largely attributable to the thermal expansion of the oceans and the melting of glaciers and polar ice sheets resulting from a warming atmosphere (Karl et al. 2009). Relative sea level, which is the sea level measured against land elevation at a given particular location, is influenced by these as well as localized processes such as plate tectonics (e.g., earthquakes), postglacial rebound, and land subsidence. Atmospheric and oceanic

Storm surge on a Louisiana highway shows the potential effects of rising sea levels.

circulation, which will be altered by climate change, will also influence relative sea levels. As a result of the variability of these processes, relative sea level rise, and its impacts and consequences, will vary by location.

In general, rising sea levels will inundate coastal wetlands, barrier islands, and other low-lying lands and intensify erosion and flooding as new areas are exposed to storm surges, waves, currents, and tides. Inundation, erosion, and flooding will threaten human health, coastal property, and infrastructure as well as coastal ecosystems, especially those that cannot migrate inland or are sediment-starved. Any changes to these ecosystems will, in turn, affect the biological, ecological, and physical services they provide. Human and ecosystem populations will also suffer from a loss in quantity and quality of freshwater as saltwater inundates estuaries, marshes, rivers, and aquifers; water tables rise; and inundated lands and infrastructure introduce more nonpoint source pollutants and toxic substances into the rising seas.

Ultimately, rising sea levels mean land and ecosystem loss. Some degree of economic loss is inevitable. In 1991, the Federal Emergency Management Agency (FEMA) estimated that a one-foot rise in sea level by 2100 would increase annual flood damage to insured property by 36-58 percent and a three-foot rise would increase annual damage by 102-200 percent. Recent estimates indicate that a sea level rise of nearly 20 inches by 2100 would cause $23-170 billion in damage to U.S. coastal property (Ruth et al. 2007). In addition, as land and ecosystems are inundated, associated cultural resources may also be lost, especially where populations, both human and otherwise, are forced to relocate.

Declining Great Lake Levels

In the Great Lakes, water levels may drop as a result of a warming climate. Average lake levels depend on a balance between precipitation and runoff and evaporation and outflow. While precipitation is expected to increase in the winter and spring, with more precipitation falling as rain and less as snow, evaporation is due to increase because of higher temperatures and reduced lake ice and is expected to outpace precipitation (Karl et al. 2009).

Declining lake levels will impact water supplies and utilities, hydroelectric and nuclear power plants, commercial navigation, property owners, marine recreation and tourism, marinas, beaches, and more. Navigation will be impeded, water quantity and quality will be diminished, and lakefront property and water dependent infrastructure will be farther away from the water's edge, reducing accessibility and raising issues of public trust. In general, erosion will be less of a problem, but bluff failure may result from decreased hydrostatic pressure.

Water level decreases will also have broad impacts on lake ecosystems. Coastal wetlands fronted by

As Great Lakes water levels decline, ports and marinas will be increasingly ill-equipped to meet the needs of shipping and fishing vessels.

barrier beaches will be cut off from the lakes, and as water levels drop, wetlands may dry up. In addition, lower water levels may result in an increase in the concentration of nutrients and pollutants and a decrease in dissolved oxygen concentrations, which in conjunction with associated warmer air and water temperatures may exacerbate harmful algal blooms and hypoxia. Changing ecological conditions may facilitate invasion by new species or encourage expansion of previously established invaders.

Storm Intensity and Frequency

As coastal storms become more intense, and these stronger storms become more frequent in the case of cold-season storms (e.g., nor'easters), damage to the built and natural environments from flooding, erosion, and high winds will become more commonplace. Consequences of these storms may include injuries and loss of life as well as damage to and destruction of coastal property and infrastructure.

In recent decades, coastal storms have accounted for the majority of U.S. annual disaster losses (Heinz Center 1999; NOAA 2010a). Thus, in coastal areas, where real estate values may be very high, the potential economic impacts of natural disasters, which will be exacerbated by climate change, could be significant. The 2004 Atlantic hurricane season caused damage and incurred associated costs estimated at more than $50 billion. One year later, Hurricane Katrina alone cost approximately $134 billion, becoming the costliest U.S. storm on record (NOAA 2010a).

In addition to the physical damage caused by flooding, erosion, and high winds, shifts in salinity (excess freshwater as well as saltwater) and the introduction of pollutants and toxic substances from stormwater runoff will likely stress habitats. Some will bounce back, but others, under the weight of cumulative impacts (e.g., multiple storms, rising sea levels, preexisting stressors, etc.), will be degraded or lost, which will lead to diminished or loss of productivity, temporarily or permanently. And, damage to and loss of natural protective features such as coral reefs, barrier islands, beaches, dunes, and wetlands will leave coastal communities more vulnerable to future storms.

Changing Precipitation Patterns

The overall effect of changing precipitation patterns, which will have strong regional variations, is that there will be too much or too little water, either seasonally or throughout the year (Karl et al. 2009). Some regions may experience the impacts and consequences of both extremes.

In either case, water quality will be negatively impacted. Increased runoff associated with heavy rains will further pollute coastal waters with nitrogen and phosphorous, sediments, and other, sometimes toxic, contaminants and negatively impact dissolved oxygen levels. Conversely, diminished water supplies will be threatened by increased concentrations of pollutants. Shifts in the salinity gradient as a result of too much freshwater, or not enough, will also stress coastal ecosystems.

Heavy downpours will likely cause flooding and erosion that could damage or destroy property and infrastructure and harm ecosystems along the coasts and throughout watersheds. Existing water/flood management systems and structures (e.g., drainage systems, combined sewer overflow systems, dams) were likely not planned and designed with climate change in mind and will likely be taxed by, and possibly unable to handle, increased quantities of water.

While these heavy downpours are likely to be more frequent, longer periods of time between rainfalls are also expected (i.e., precipitation will become less frequent but more intense) (Karl et al. 2009). This lack of regular precipitation, combined with higher air temperatures, may lead to drought. Similarly, increased runoff could reduce infiltration, limiting the amount of water available for groundwater recharge and also resulting in drought. Drought conditions would limit water availability for all sectors and stress human and ecosystem health and could also result in increased incidence of wildfire and losses to both the built and natural environments.

Increasing Water Temperature

Increasing air temperatures are leading to warmer conditions in both marine and fresh water systems

Harmful algal blooms, which can have toxic or harmful effects on people, fish, shellfish, marine mammals, and birds, will be exacerbated as water temperatures rise.

(Karl et al. 2009). In addition to their role in sea level rise, increases in water temperature, and associated changes to coastal currents that moderate ocean temperatures and increased stratification, will impact the quality of coastal and marine waters and their living resources, affecting species distribution and biological productivity and connectivity.

Warming seas will likely be accompanied by more incidences of coral bleaching, hypoxia, pathogens and disease, harmful algal blooms, and invasive species. Ecosystems, habitats, and species will be weakened or lost (although some may just relocate). Consequences may be severe where fisheries, ecosystems, and coastal communities depend on a vulnerable resource for sustenance, livelihoods, tourism, etc.

Ocean Acidification

In addition to global warming, the buildup of carbon dioxide in the atmosphere has also been linked to changes in the chemistry of the oceans, changes that are "essentially irreversible over a time scale of centuries" (Karl et al. 2009). Ocean acidification is the result of an increase in carbon dioxide absorption by ocean water and the corresponding decrease in pH. As seawater becomes less alkaline (more acidic), less calcium carbonate is available for corals, shellfish, and other sea life to build their shells and skeletons. Threats to these ecosystems and species will be wide-ranging across the marine food web and associated coastal communities.

Key Resources

- Climate Change—Science, EPA. http://epa.gov/climatechange/science/
- Climate Change 2007: The Physical Science Basis, IPCC. www.ipcc.ch/
- Climate Change 2007: Synthesis Report, IPCC. www.ipcc.ch/
- Climate Change: Fitting the Pieces Together (online training), University Corporation for Atmospheric Research, Cooperative Program for Operational Meteorology, Education and Training. www.meted.ucar.edu/broadcastmet/climate/
- Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change, National Assessment Synthesis Team, U.S. Global Change Research Program (2000, includes regional and sectoral assessments). www.globalchange.gov/publications/reports/scientific-assessments/first-national-assessment
- Climate Change Indicators in the United States, EPA Climate Change Division. www.epa.gov/climatechange/indicators.html
- Climate Literacy—The Essential Principles of Climate Science: A Guide for Communities and Individuals, U.S. Climate Change Science Program. www.globalchange.gov/resources/educators/climate-literacy
- Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region, U.S. Climate Change Science Program. www.globalchange.gov/publications/reports/scientific-assessments/saps
- Fisheries Economics and Sociocultural Status and Trends Series, NOAA National Marine Fisheries Service. www.st.nmfs.noaa.gov/st5/publication/
- Global Climate Change Impacts in the United States, U.S. Global Change Research Program. www.globalchange.gov/publications/reports/scientific-assessments/us-impacts
- National Ocean Economics Program Web Site (includes state summaries). www.oceaneconomics.org/
- NOAA Climate Service. www.climate.gov/
- NOAA Great Lakes Environmental Research Laboratory. www.glerl.noaa.gov/
- PMEL Ocean Acidification Home Page, NOAA Pacific Marine Environmental Laboratory. www.pmel.noaa.gov/co2/OA/
- Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources, U.S. Climate Change Science Program. www.globalchange.gov/publications/reports/scientific-assessments/saps
- State of the U.S. Ocean and Coastal Economies—2009, National Ocean Economics Program. www.oceaneconomics.org/nationalreport/
- Thresholds of Climate Change in Ecosystems, U.S. Climate Change Science Program. www.globalchange.gov/publications/reports/scientific-assessments/saps
- Weather and Climate Extremes in a Changing Climate: Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands, U.S. Climate Change Science Program. www.globalchange.gov/publications/reports/scientific-assessments/saps
- U.S. Global Change Research Program Web Site. www.globalchange.gov/