

Features

Planning for the impact of sea-level rise on U.S. national parks

By Maria Caffrey and Rebecca Beavers

GLOBAL MEAN SEA LEVELS have been rising since the last ice age approximately 20,000 years ago (Archer and Rahmstorf 2010; IPCC 2007). Relative to the past two to three thousand years, the rate of rise has increased significantly and is projected to increase at an accelerating pace throughout the 21st century because of climate change (IPCC 2007). In 2007 the Intergovernmental Panel on Climate Change's (IPCC) fourth assessment report projected that global mean sea levels will rise 18–59 cm (7–23 in) by 2100; however, these projections have been criticized as being conservative, lacking data, and failing to take into account dynamic changes in large, land-based ice sheets (Rahmstorf et al. 2007; Horton et al. 2008; Overpeck and Weiss 2009; Rahmstorf 2010). The aim of this article is to introduce three major sources of sea-level change, describe related complexities and uncertainties in projecting sea-level rise, and discuss how the National Park Service can best manage for climate change in the coastal zone.

Sources of sea-level rise

Changes in sea level can occur as a result of numerous drivers. Steric sea-level change is driven by a change in water density, thermosteric changes are the result of changes in temperature, and halosteric change is caused by changes in salinity. The term “eustasy” is commonly used in the literature to describe sea-level change that is the result of a change in water volume (Sverdrup et al. 2003; Milne et al. 2009). Global mean sea level responds to a number of environmental sources that result in a change in eustasy that the

IPCC (2007) has broadly categorized as continental ice cap and sheet melt, ocean thermal expansion, and shifts in terrestrial storage capacity (table 1).

Increasing temperatures (driven by increased atmospheric loading of carbon dioxide [CO_2]) are melting glaciers and ice sheets (IPCC 2007). Melting of the Greenland ice sheet alone raised the global mean sea level by an average 0.21 ± 0.07 mm/yr (0.01 ± 0.002 in/yr) from 1993 to 2003 (IPCC 2007). Archer and Rahmstorf (2010) calculated that if both the entire Greenland and Antarctic ice sheets were to melt, global sea levels would rise by around 65 m (210 ft), although global climate models suggest that the complete loss of continental ice sheets is extremely unlikely. Overpeck et al. (2006) predicted that a rise in relative sea level is more likely to be on the order of several meters. The disparity in these projections highlights the difficulty of modeling the contributions of melting ice to sea-level rise (SLR). In addition to the melting occurring near the poles, melting ice caps and glaciers in other regions such as the Himalayas and the Andes are contributing to increasing sea levels. Additionally the IPCC (2007) expects that the eastern section of the Antarctic ice sheet could increase in size over this century because of projected changes in precipitation and runoff, although it is highly unlikely that this will result in lower global rates of sea-level rise.

Ocean thermal expansion is an increase in volume (and decrease in density) of ocean waters (Wigley and Raper 1987). While the rate of thermal expansion is expected to vary with temperature, there

Abstract

Rising sea levels present a challenge for National Park System managers over the next century as they incorporate the latest sea-level rise information, including regional parameters when available, into individual park management plans. Rates of sea-level change vary throughout the National Park System, so the National Park Service (NPS) cannot define a single rate applicable to all parks. This complicates park planning and requires interpretation of research and modeling results. In this article we discuss many of the latest developments in sea-level rise research, including the drivers of sea-level change, global sea-level projections for this century, and what these mean for park managers. We also explain why tide gauge data in some regions have recorded decreasing mean sea levels and why potential storm surge should be included in planning.

Key words

eustasy, glacial melting, isostasy, storm surge, thermal expansion

is a degree of thermal inertia, or lag time, between the time when CO_2 -driven warming is observed and subsequent thermal expansion occurs. Domingues et al. (2008) found that ocean thermal expansion in the upper 700 m (2,297 ft) of the water column has overtaken the melting of the Antarctic and Greenland ice sheets as the second largest contributor (ahead of the melting of glaciers and ice caps) to rising sea levels over the past 10 years. Rates of thermal expansion are the subject of active research with many questions remaining about rates of thermal inertia. Vermeer

Table 1. Rates of sea-level rise by source

Source of Sea-Level Rise	Rate of Rise in mm (in) per Year	
	1961–2003 ¹	1993–2003
Thermal expansion	0.42 ± 0.12 (0.02 ± 0.004)	1.6 ± 0.5 (0.06 ± 0.02)
Glaciers and ice caps	0.50 ± 0.18 (0.02 ± 0.01)	0.77 ± 0.22 (0.03 ± 0.01)
Greenland ice sheet	0.05 ± 0.12 (0.002 ± 0.004)	0.21 ± 0.07 (0.01 ± 0.03)
Antarctic ice sheet	0.14 ± 0.41 (0.006 ± 0.02)	0.21 ± 0.35 (0.01 ± 0.01)
Sum of individual climate contributions listed above	1.1 ± 0.5 (0.04 ± 0.02)	2.8 ± 0.7 (0.11 ± 0.03)
Observed total SLR	1.8 ± 0.5 (0.07 ± 0.02)	3.1 ± 0.7 (0.12 ± 0.03)
Difference (observed minus sum of estimated climate contributions) ²	0.7 ± 0.7 (0.03 ± 0.03)	0.3 ± 1.0 (0.01 ± 0.04)

Note: Sea-level rise data are from the fourth IPCC climate assessment report (IPCC 2007).
¹Numbers prior to 1993 are from tide gauges; those after 1993 are from satellite altimetry.
²Differences between observed and estimated climate contributions represent other contributors to sea-level rise, such as increased runoff from land (discussed above). Differences can also occur because of sampling error.

and Rahmstorf (2009) calculate that thermal expansion will contribute 55–70% of eustatic rise by 2100. Rates of ocean thermal expansion have already caused an increase in sea-level rise from 0.42 ± 0.12 mm/yr (0.02 ± 0.005 in/yr) over the last 40 years (1961–2003), compared with 1.6 ± 0.05 mm/yr (0.06 ± 0.002) at the end of the 20th century (1993–2003; IPCC 2007).

Changes in precipitation are predicted to alter the balance between water storage on land and that in the oceans (Church et al. 2008; Llovel et al. 2011). In addition to greater precipitation over some oceans, some terrestrial regions can expect greater precipitation, resulting in increased runoff. In other regions, drought conditions will lead to a greater human reliance on freshwater aquifers, creating an opportunity for greater saltwater intrusion and local reductions in sea levels, as we explain below. In comparison with the ice sheets, changes in the amount of precipitation over the oceans have not been studied intensively (Koster et al. 2000). However, overall change in terrestrial water storage is not expected to generate anywhere near the same level of eustatic rise in sea levels as

that created by the melting of continental ice caps and sheets and thermal expansion (Milly et al. 2003).

A number of scientists have modeled how sea levels could rise in the future (table 2, next page). The fourth IPCC climate assessment report projected sea levels based on climate scenarios ranging up to a maximum warming of 5.2°C (9.4°F) by 2100 (IPCC 2007). This estimate *does not* consider the full range of IPCC temperature scenarios that predict a maximum 6.4°C (11.5°F) temperature increase under their most fossil-fuel-intensive A1FI scenario (Archer and Rahmstorf 2010). Updated SLR predictions in the fifth IPCC assessment report, expected in late 2013, will use the new Representative Concentration Pathways (RCPs; van Vuuren et al. 2011) of four greenhouse gas concentration trajectories. These are also based on radiative forcing values and will eventually replace the Special Report on Emissions Scenarios (SRES) trajectories that were used in the third and fourth IPCC reports (IPCC 2000, 2001, 2007). For example, Jevrejeva et al. (2012) predicted rates of sea-level rise using RCPs that estimated

that these rates will be almost double those predicted by the IPCC in their fourth report.

More recently Parris et al. (2012) released their sea-level rise scenarios as part of the U.S. National Climate Assessment. Their projections are global sea-level scenarios that provide greater detail regarding the state of the scientific literature along with scales of confidence. While research like Parris et al. (2012) is very useful in planning, it usually provides specific numbers only for end-of-the-century sea-level rise. The full data set has not been published, making it difficult to graph how sea level could change throughout the century. Park managers often need to cite specific numbers in their planning documents that are based on a 5-year, 20-year, or somewhat longer time horizon. Furthermore, these values do not include projected storm surge values on top of SLR data, which could further complicate the management of coastal lands (UKCP09; Burkett 2012). The potential impacts of increased storm surges on coastal parks like Cape Hatteras and Cape Lookout National Seashores could potentially engulf the entire park units (fig. 1, page 10; Sallenger et al. 2012).

Historical sea-level change data

Predicting how sea level will affect coastal park units is complex. In addition to considering eustatic sea-level rise, researchers must take into account changes in *isostasy* (the raising or lowering of land levels when a mass, such as a glacier or ice sheet, is lost or added). In Alaska where land-based ice is melting rapidly, tide gauge data suggest that mean relative sea levels in six southeastern coastal parks (Sitka and Klondike Gold Rush National Historical Parks; Glacier Bay, Lake Clark, and Katmai National Parks and Preserves; and Kenai Fjords National Park) have decreased. In

Table 2. Projected magnitudes of global mean sea-level rise by 2100

Published Source	Range		Methods
	m	ft	
Intergovernmental Panel on Climate Change (IPCC 2007)	0.18–0.59	0.59–1.94	Data published as part of the fourth IPCC climate assessment report “Climate change 2007: The physical science basis.” The IPCC is the most commonly cited source of SLR projections, which are based on six scenario families defined in IPCC 2000. Projections are modeled based on a maximum global mean temperature increase of 5.2°C (9.4°F) by 2100.
Rahmstorf (2007)	0.50–1.40	1.64–4.59	One of the first sources to apply semiempirical modeling to project future sea-level rise. This model connects rates of warming to sea-level rise in which rates of rise are expected to be proportional to global mean surface temperature.
Horton et al. (2008)	0.54–0.89	1.77–2.92	Calculated using a semiempirical global model based using IPCC scenarios (scenarios A1B, A2, and B1).
Pfeffer et al. (2008)	0.80–2.00	2.62–6.56	Projections based on kinematic scenarios of increased ice dynamics (based on projected differences in the breakup and melt rate of ice).
Grinsted et al. (2010)	0.90–1.30	2.95–4.27	Analyzed the last 2,000 years of global temperatures and sea levels in order to model future sea levels based on IPCC scenario A1B.
Vermeer and Rahmstorf (2009)	0.75–1.90	2.46–6.23	Based on observed data from 1880 to 2000. Modeled global sea-level rise using all IPCC scenarios.
United Kingdom Climate Projections 2009 (UKCP09)	0.23–1.90	0.75–6.23	United Kingdom report using calculations based on IPCC scenarios A1B, A1FI, and B1. Also includes their own H++ scenario modeled after a 2.4 m (7.9 ft) rate of sea-level rise per century during the last interglacial period. The H++ is considered unlikely in most regions. Model projections predict rates of sea-level rise around the UK only. Model outcomes are not weighted based on observations.
Jevrejeva et al. (2012)	0.57–1.10	1.87–3.61	Modeled global sea-level rise using four new representative concentration pathways of radiative forcing scenarios. <i>Note:</i> Range values reported here represent median confidence limits. Upper and lower confidence limits project a maximum rise of 1.65 m (5.41 ft) and lowest rise of 0.36 m (1.18 ft) based on 95% and 5% confidence limits, respectively.
Meehl et al. (2012)	0.25–1.45	0.81–4.76	Numbers were calculated based on RCP2.6, RCP4.5, and RCP8.5 (van Vuuren et al. 2011). Lower-range numbers are based on RCP2.6 SLR anomalies (taking into account contributions from continental ice coupled with thermal expansion). The higher-range number was calculated using a semiempirical method for RCP8.5.

Notes: The summary is of projections published since the IPCC fourth climate assessment report (IPCC 2007).
The range of sea-level rise estimates shown here is calculated relative to the mean tide levels for the period 1990–2000.

Sitka, tide gauge data reveal that sea level has decreased by 2.11 ± 0.29 mm/yr (0.08 ± 0.01 in/yr) from 1924 to 2011 (Zervas 2009) because rates of eustatic rise did not exceed the rate of isostatic rebound of the land. This is a sharp contrast to parks in the continental United States, such as those in southern Louisiana, where compaction of Mississippi River delta sediments leads to a high rate of relative sea-level rise, for example at Jean Lafitte National Historical Park and Preserve. The tide gauge nearest the park indicates sea level has risen by 9.07 ± 0.49 mm/yr (0.36 ± 0.02 in/yr) from 1947 to 2012 (Zervas 2009).

Local tide gauge trend data can be used in conjunction with sea-level rise models to determine how sea level has changed in the past, although rates of rise over the last

century have varied spatially and temporally. The U.S. Army Corps of Engineers has released a “Sea Level Change Calculator” (USACE 2013) that uses tide gauge data as part of their sea-level change calculations, which predict the amount of sea-level change going forward. Unfortunately, many national parks do not contain a tide gauge, which can be a hindrance in using the USACE calculations. Including Alaska where sea-level change data are limited as well as complicated by long-term uplift, 92% of coastal U.S. national parks have experienced an increase in sea level over the past century based on National Oceanic and Atmospheric Administration (NOAA) tide gauge data recorded either in or near coastal national parks. However, mean water levels are not rising uniformly; for example, variations in tide gauge distribution, water temperatures, salinity, and

ice masses have been discussed as potential drivers of recently identified increases in sea level over a 60-year period at an area known as the “Northeast hotspot” (along the Atlantic coast from North Carolina to Massachusetts). Sallenger et al. (2012) found that rates of sea-level rise in this area are three to four times greater than global SLR rates from 1950 to 2009. However, others have hypothesized that this apparent difference could be an artifact associated with a lack of tide gauges both spatially and temporally (Chambers et al. 2012). The Northeast hotspot is a good example of how dynamic the science concerning sea-level rise can be.

Choosing among these sources of data can be a dilemma for park managers as they plan for climate change. Tide gauges are needed to determine historical rates of

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sea-level rise, but most are located outside the parks and may not contain a very long record (a minimum 30-year record is necessary to determine historical relative sea level). The NOAA National Water Level Observation Network (NWLON) manages a network of 175 long-term gauges. The data from these stations are used to analyze rates of relative sea-level rise. However, extensive spatial “gaps” in the tide gauge network make it difficult to calculate regional SLR trends for all coastal parks. Historical data (either paleoenvironmental proxy data or tide gauge data exclusively) should not be used exclusively to predict local to regional changes in sea level; however, the lack of these data sets makes it difficult to create and test any models that are necessary for predicting future sea-level changes. Filling in these gaps in the tide gauge network is the first step toward a more comprehensive monitoring network that could be essential to identifying whether regions such as the proposed Northeast hotspot are experiencing greater-than-average rates of sea-level rise (Chambers et al. 2012).

The NPS Oceans and Coastal Resources Branch and the NPS Climate Change Response Program are working with NOAA to help close these information gaps. An optimal solution would be to expand the network by installing permanent tide stations in all of the gap areas, but this is currently cost-prohibitive. As an alternative, a pilot project was implemented at Assateague Island National Seashore (Maryland) where a temporary tide station

was installed in a gap area. This station will collect water-level data for one year from which a local tidal datum will be established. The equipment can then be removed and installed in another park with a gap. The newly established local tidal datum will be correlated with the closest NWLON stations, enabling the park to take advantage of NWLON’s long-term water level and trend data.

In most cases we do not recommend that park managers use tide gauges outside national parks to extrapolate potential rates of sea-level rise. In addition to not taking into account future changes in the rate of sea-level rise, the accuracy of these results will vary depending on how close the gauges are to the park, basin shape and size, and length of the record. We need to add more tide gauges in coastal national parks to measure these trends and help protect our coastal natural and cultural resources over the long term.

Storm surge

In addition to evaluating various drivers of relative sea-level change, park planners and managers need to consider projected storm surge values added to sea-level rise magnitudes, which could further complicate the management of coastal lands (UKCP09). Storm surges occurring at coastal parks like Cape Hatteras and Cape Lookout National Seashores (North Carolina) will continue to change the land- and seascapes of these areas, with the potential

to completely submerge them (fig. 1, next page). The likelihood of increased storm intensity added to increasing rates of sea-level rise makes predicting the reach of future storm surges especially difficult.

More than 100 national parks are vulnerable to the combined effects of sea-level rise and storm surge, and Strauss et al. (2012) calculate that in the United States approximately 3.7 million people live within the zone of a projected 1 m (3.3 ft) sea-level rise. However, based on the projected amounts of sea-level rise by 2100 (table 2), this may be a conservative estimate. Such estimates do not take into account how storm surge on top of increased relative sea levels will spread into areas previously untouched by storms. Tebaldi et al. (2012) estimate that by 2050, some locations in the United States will experience century-scale storm surges annually. In many locations today we have accepted that century-scale stormwater levels can now be expected decadal (Tebaldi et al. 2012).

Thus, the state of the science for storm surge prediction is even more uncertain than it is for sea-level rise. Accordingly, in summer 2013 we began a new study that aims to provide sea-level rise and storm surge data for 105 coastal parks. We are using local tide gauge data in conjunction with NOAA sea, lake, and overland surge from hurricanes (SLOSH) data to predict how the parks could be affected by climate change-related factors over this century. The results of this research will be discussed in context with other project

data (e.g., the coastal vulnerability index described in Pendleton et al. 2010) to inform NPS planning in foundation documents and general management plans. The results of this research are expected to be published in the academic literature along with a full park-by-park report by 2016.

Disaster response and adaptation planning

In 2012, Hurricane Sandy catapulted the subject of sea-level rise and storm surge into national debate when it struck the Atlantic coast in October. The National Park Service expected flooding at about 40 coastal parks. Sandy was at hurricane strength when it made landfall near Atlantic City, New Jersey, south of Fire Island National Seashore (New York) and Gateway National Recreation Area (New York and New Jersey). Flooding was greatest in the New York City area. Docks at Statue of Liberty National Monument were destroyed and historical structures suffered severe water damage from the powerful storm surge (fig. 2).

In response, the National Park Service established a rapid review team to identify sustainability and natural and cultural resource priorities for recovery and reconstruction projects. This team is still active and meets regularly to ensure that the proposed projects are carried out effectively. For example, work at the Sandy Hook Unit of Gateway National Recreation Area in New Jersey and at the Statue of Liberty will elevate critical building systems such as boilers and electrical panels above expected future stormwater levels. Other infrastructure will be designed to be submersible or to withstand storm surges. Related work is under way to record the

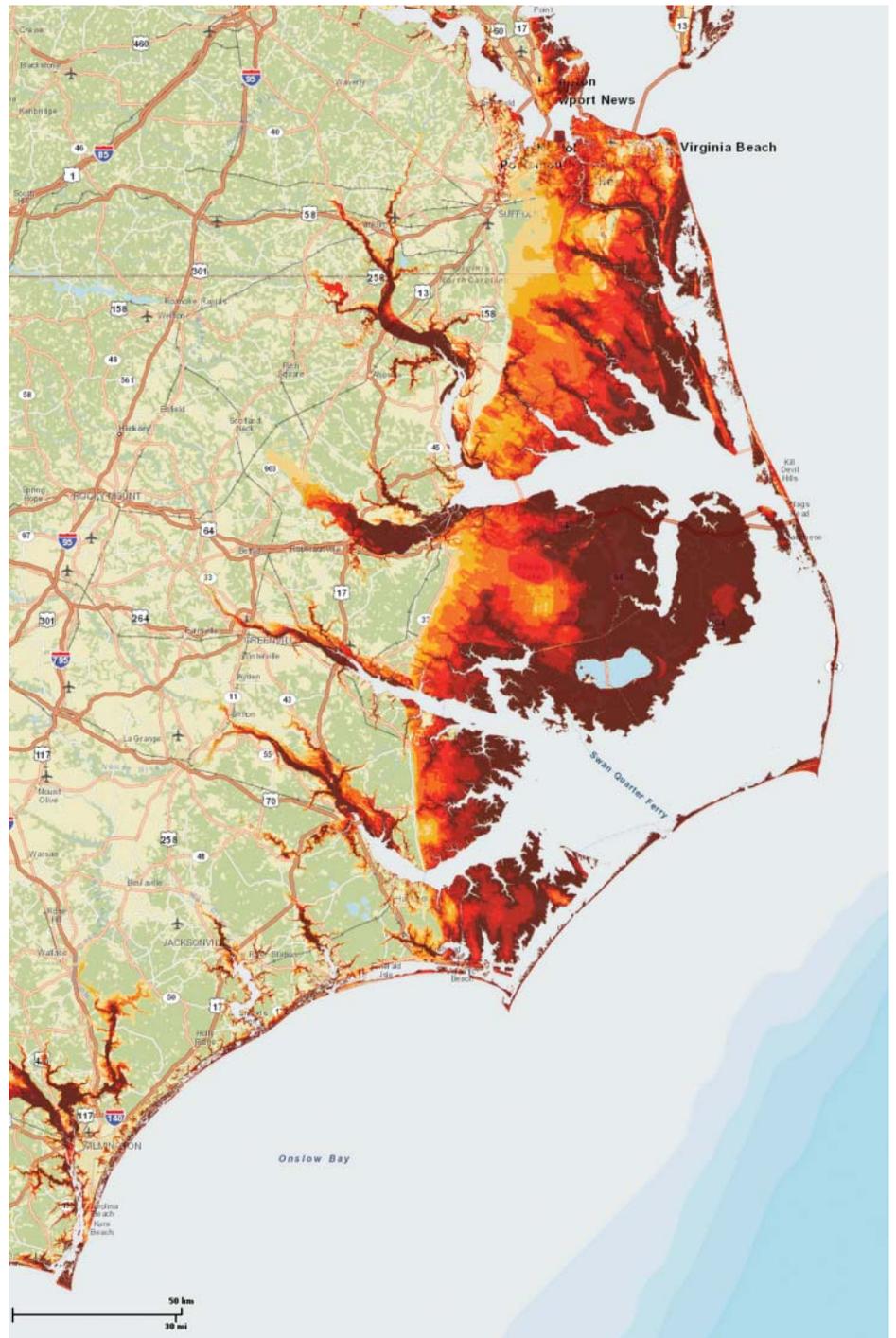


Figure 1. The map depicts areas potentially inundated by sea-level rise and increases in storm surge severity in the vicinity of Cape Hatteras and Cape Lookout National Seashores, North Carolina. The dark brown areas will be submerged by a 1 m (3 ft) rise in sea level. Red-to-yellow areas would be affected by additional flooding caused by storm surges from 1 to 4 m (3 to 13 ft).

SOURCES: PROJECTIONS ARE BASED ON WEISS ET AL. (2011); BASE MAPS PROVIDED BY ESRI



Figure 2. Damaged by Hurricane Sandy in November 2012, this dock at Liberty Island in New York Harbor is a stark reminder of the combined effects of sea-level rise and storm surge. As sea levels increase, severity of potential storm surge also increases. Storm surge is often overlooked by managers planning for the impacts of sea-level rise.

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elevation of all assets affected by Sandy. Federal regulations require that post-storm reconstruction meet a 1–2 ft (0.3–0.6 m) safety factor above projected sea-level rise and storm surge levels (Hurricane Sandy Rebuilding Task Force 2013). The elevation inventory is necessary to ensure proper planning and compliance. This experience is helping the National Park Service to develop adaptation strategies and decision frameworks that will assist other coastal national parks that must respond to and recover from a future storm.

Caffrey and Beavers (2008) described the coastal adaptation strategies of *retreat* (e.g., Cape Hatteras lighthouse, Cape Hatteras National Seashore) and *fortify*

in place (e.g., Fort Massachusetts, Gulf Islands National Seashore, Mississippi) for major coastal historical infrastructure such as lighthouses and forts. One challenge related to climate change that has yet to be fully articulated and addressed is the imminent loss of some of our cultural heritage to sea-level rise or storm surge and the resulting coastal erosion. For example, vulnerable archeological sites on Jamestown Island in Colonial National Historical Park (Virginia) are at risk from a rising water table because of sea-level rise. Sea-level rise causes the water table to rise when overlying freshwater is forced upward by more dense salt water that intrudes into coastal aquifers. Once these sites are saturated, traditional archeo-

logical excavation and documentation techniques cannot be used for a variety of reasons (e.g., excavation pits become flooded and artifacts can become damaged or destroyed by the water). Likewise, archeological sites along the Chukchi Sea in northwestern Alaska at Cape Krusenstern National Monument and Bering Land

Bridge National Preserve are experiencing sea-level rise and increased coastal erosion because of diminished sea ice that once protected these sites during coastal storms (Manley and Lestak 2012). Park managers are prioritizing archeological studies at the most highly vulnerable locations so they can maximize documentation of these sites before they are claimed by the sea.

The National Park Service plays a leading role in developing innovative strategies for coastal parks to adapt to sea-level rise and storm surge, and coastal storms are opportunities to apply highly focused responses. Major storms, floods, tsunamis, and even fires in the coastal zone are often followed by special recovery funding to refurbish infrastructure and mitigate future vulnerabilities. Yet the National Park Service needs to ensure that future recovery and rehabilitation projects also address needs to protect habitat (Stabeneau et al. 2011; Nielsen and Dudley 2013) and cultural resource sites. For example, we need to plan for opportunities to simultaneously relocate structures away from eroding shorelines, facilitating the natural development of future habitat. We should act as soon as possible, because even with this level and scope of adaptation planning we may have only a limited amount of time to protect, move, or adapt vulnerable infrastructure and document irreplaceable cultural resources.

Scenario planning

The rates of sea-level change are dramatically different across the diverse geography of the National Park System. A single rate of sea-level rise cannot be defined for all parks. Local to regional information on sea-level change, in addition to global estimates, is needed in order to develop sea-level rise projections that are relevant for coastal planning and management. To manage parks despite these uncertainties, the National Park Service is using scenario

planning to develop and test adaptive strategies under a variety of plausible climate futures (Weeks et al. 2011). Scenario planning is a “living process.” Information such as site-specific storm surges and SLR vulnerability assessments are needed and must be updated, for example after major coastal storms, to feed into the process in order for coastal park planning to be effective (Pendleton et al. 2010).

The National Park Service will continue to support use of the best available science for coastal management decisions. We are closely monitoring states’ recommendations. In places such as California, Florida, and New York, we are incorporating the local or regional, geographically specific findings into NPS scenario and other planning. By collaborating with various partners, we are optimistic that the National Park Service will be able to adapt to and mitigate many of the impacts of sea-level rise and storm surge over the 21st century.

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About the authors

Maria Caffrey is a research associate at the University of Colorado–Boulder. She is a research partner with the National Park Service Geologic Resources Division, where she serves as a visiting scientist through the Geological Society of America GeoCorps America program. **Rebecca Beavers** is coordinator of the coastal geology program in the National Park Service Geologic Resources Division. Questions or requests for further information can be directed to maria.caffrey@colorado.edu or rebecca_beavers@nps.gov.