National Park Service
U.S. Department of the Interior

South Florida Natural Resources Center
Everglades National Park

Sea Level Rise and Inundation Projections for Everglades, Biscayne and Dry Tortugas National Park Infrastructure

November 21, 2016

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Technical Report

SFNRC 2016:11-21

Cover picture shows the Flamingo visitor center on Florida Bay.

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Homestead, Florida

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EXECUTIVE SUMMARY

It is unequivocal that climate is warming, and since the 1950s many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, snow and ice have diminished, sea level has risen, and concentrations of greenhouse gases have increased.

One of the most robust indicators of a warming climate is rising sea level driven by thermal expansion of ocean water and addition of land-based ice-melt to the ocean, however, sea level rise is not evenly distributed around the globe and the response of a coastline is highly dependent on local natural and human settings. This is particularly evident at the southern end of the Florida peninsula where low elevations and exceedingly flat topography provide an ideal setting for encroachment of the sea.

Here, we illustrate projected impacts of sea level rise to infrastructure in Everglades, Biscayne and Dry Tortugas National Parks at four time horizons: 2025, 2050, 2075 and 2100, and under two sea level rise scenarios, a low projection and a high projection. The projections are derived from a state-of-the-art sea level rise model based on a synthesis of global ocean-atmosphere models, observed tide gauge data, and expert elicitation. Inundation maps are computed by applying these projections to the best available land surface elevation data.

The purpose of this analysis is to inform interested parties on expected spatial and temporal encroachment of the sea in response to a warming climate. The reader can decide which projection best suits their risk–tolerance, the low (median) projection for low–risk infrastructure, or the high (99^{th} percentile) projection for risk–intolerant applications. As scientific understanding of climate change and ocean–atmosphere dynamics improve, such projections will change. The prudent executive will anticipate such changes and continue to adaptively adjust their positions as this information emerges.

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1 Introduction

It is unequivocal that climate is warming, and since the 1950s many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, snow and ice have diminished, sea level has risen, and concentrations of greenhouse gases have increased (*Steffan et al.*, 2015; *IPCC*, 2013).

One of the most robust indicators of a warming climate is rising sea level driven by thermal expansion of ocean water and addition of land-based ice-melt to the ocean. Sea level rise is not evenly distributed around the globe and the response of a regional coastline is highly dependent on local natural and human settings (*Cazenave and Le Cozannet*, 2013). This is particularly evident at the southern end of the Florida peninsula where low elevations and exceedingly flat topography provide an ideal setting for encroachment of the sea.

This report provides projected impacts of sea level rise to infrastructure in Everglades, Biscayne and Dry Tortugas National Parks at four time horizons: 2025, 2050, 2075 and 2100, and under two sea level rise scenarios, a low projection and a high projection. The high projection represents an upper bound of expected sea level rise given current models and observations, while the low projection corresponds to a median sea level rise scenario. Since models, observations and current scientific understanding are incomplete, such projections can not be viewed as absolute or infallible. Indeed, these projections do not account for a rapid collapse of the Antarctic ice-sheets, a development that is currently unfolding with potential to render these projections as lower bounds (*Holland et al.*, 2015; *Wouters et al.*, 2015). Nonetheless, the projections represent the best-available science and technology and are intended to inform planners and decision-makers as to the likely time horizons and spatial impacts of sea level rise at South Florida National Parks.

2 Sea Level Rise

The Intergovernmental Panel on Climate Change (IPCC) is composed of leading scientists from around the globe whose mission is to review and assess the most recent scientific, technical and socio-economic information relevant to the understanding of climate change. Its most recent assessment published in 2014 is the Fifth Assessment Report (AR5) which includes projections of global sea level rise based on different Representative Concentration Pathway (RCP) scenarios reflecting possible future concentrations of greenhouse gases[1]. RCP 8.5, also known as the business-as-usual scenario, is the highest emission and warming scenario under which greenhouse gas concentrations continue to rise throughout the 21st Century, while RCP 6.0 and RCP 4.5 expect substantial emission declines to begin near 2080 and 2040 respectively. Recent assessments of global energy production and population conclude that the RCP 4.5 emission scenario is unobtainable, and there is significant uncertainty as to whether the RCP 6.0 scenario can be realized (*Jones and Warner*, 2016).

[1] The number following RCP quantifies the expected thermodynamic radiative forcing relative to pre-industrial values. For example, RCP 8.5 denotes an additional 8.5 W/m^2 thermal forcing from greenhouse gases.

The IPCC sea level rise scenarios are comprehensive, but do not include contributions from a rapid collapse of Antarctic ice sheets. However, recent evidence suggests that such a collapse may be underway (*Holland et al.*, 2015; *Wouters et al.*, 2015). In addition, the IPCC projections do not account for local processes such as land uplift/subsidence and ocean currents, and do not provide precise estimates of the probabilities associated with specific sea level rise scenarios.

A contemporary study that does estimate local effects and comprehensive probabilities for the RCP scenarios is provided by *Kopp et al.* (2014). This work is based on a synthesis of tide gauge data, global climate models and expert elicitation, and includes consideration of the Greenland ice sheet, West Antarctic ice sheet, East Antarctic ice sheet, glaciers, thermal expansion, regional ocean dynamics, land water storage, and long-term, local, non-climatic factors such as glacial isostatic adjustment, sediment compaction, and tectonics. Even though it includes contributions from the Antarctic ice sheets, these contributions are from dynamic equilibrium models and do not account for an incipient rapid collapse as noted above. Following a review of scientific literature, we have adopted the work of *Kopp et al.* (2014) as the basis for sea level rise scenarios at Everglades, Dry Tortugas and Biscayne National Parks.

2.1 Datums and Mean Sea Level

A tidal datum provides a geodetic link between ocean water level and a land-based elevation reference such as the North American Vertical Datum of 1988 (NAVD88). The National Tidal Datum Epoch (NTDE) in the United States is a 19-year period over which tidal datums specific to each tide gauge are determined. The current NTDE for the United States is 1983–2001 and sea level rise projections are referenced to the midpoint of this period (1992) consistent with procedures for sea level rise design determined by the U.S. Army Corps of Engineers and NOAA's National Climate Assessment (*USACE*, 2014). Common tidal datums include mean sea level (MSL), mean high-higher water (MHHW) and mean low-lower water (MLLW) as defined by the National Oceanic and Atmospheric Administration (*NOAA*, 2016a). As sea level rises, tidal datum elevations also rise and a new tidal datum is established every 20 to 25 years to account for sea level change and vertical adjustment of the local landmass (*NOAA*, 2001).

Kopp et al. (2014) use a local mean sea level reference starting in the year 2000 instead of the NTDE MSL datum centered on 1992. To convert the Kopp projections to NTDE MSL datum we estimate mean sea level rise over the 1992 to 2000 period at Vaca Key with an empirical mode decomposition and add the resulting value of 1.4 cm to the Kopp projections. The NAVD88 datum is 25.3 cm above the NTDE MSL datum at the Vaca Key tide station (*NOAA*, 2016b) so that 25.3 cm has been subtracted from all water levels to convert them from NTDE MSL to NAVD88. Appendix A details the datum and water level conversions.

2.2 Projection

Examination of local sea level rise projections around south Florida finds small differences between Naples, Virginia Key, Vaca Key, and Key West, which are geographically closest to Big Cypress National Preserve, Biscayne National Park, Everglades National Park and Dry Tortugas National Park respectively. We chose the Vaca Key station sea level data as representative of all four natural areas since it best reflects local oceanographic processes that influence coastal sea levels around south Florida.

Regarding selection of greenhouse gas emission scenarios, we employ RCP 8.5. Although significant rhetoric is aimed at global emission reduction, emissions continue to escalate and there is presently no clear socio-economic driver to depart from a carbon-based energy infrastructure. Further as noted above, the RCP4.5 scenario is not obtainable, and the RCP 6.0 is unlikely to be realized (*Jones and Warner*, 2016).

Each emission scenario and geographic location will have a spectrum of projections that span the possible ranges of sea level rise, and this range is expressed as a probability of occurrence. A probability is commonly understood as the chance or likelihood of an event happening out of a large pool of possible events, here the probability refers to occurrence of a specific sea level rise curve out of the many possible sea level rise curves under a given climate scenario such as RCP 8.5. Many different curves are possible for each scenario since there are uncertainties in the observable data (ice sheets, thermal expansion etc.) as well as limitations in the models from which the projections are derived. The median projection (50^{th} percentile) is in the middle of the projections (one-half of the projections are lower, one-half are higher) and can be considered a likely scenario given the current state-of-knowledge. A high percentile projection such as the 99^{th} percentile is one for which it is expected that there is a 1% chance that sea levels would exceed it, and should be considered in a risk-intolerant scenario.

Since this projection is intended to inform authorities of anticipated sea level rise for adaptation and planning purposes, and in light of the significant uncertainties inherent in generation of the projections and future dynamics of the climate, it is prudent to consider the upper percentile range of projections and we select the RCP 8.5 median (50^{th} percentile) as the lower boundary of the projection, and the 99^{th} percentile as the upper boundary. We are therefore conservatively biasing the projections to lie between a lower bound of likely sea level rise and a high projection to be considered in risk assessments for mission critical, costly, or risk-averse applications. Although the high projection is deemed to have a 1% chance of occurrence under current climate conditions and models, in the event of Antarctic ice sheet collapse this high projection is consistent with estimates of the Antarctic ice melt contribution (*Deconto and Pollard*, 2016).

The sea level rise projection for south Florida referenced to the NAVD88 datum for the RCP 8.5 emission scenario and occurrence probabilities of 50% and 99% is shown in figure 1, and is tabulated in Appendix B. These projections have been offset to match currently observed mean sea level in Florida Bay over the period 2008 to 2015 (Appendix C), and do not include tides or storm surges. Water levels will be both higher and lower than mean sea level depending on tidal, weather, and storm conditions.

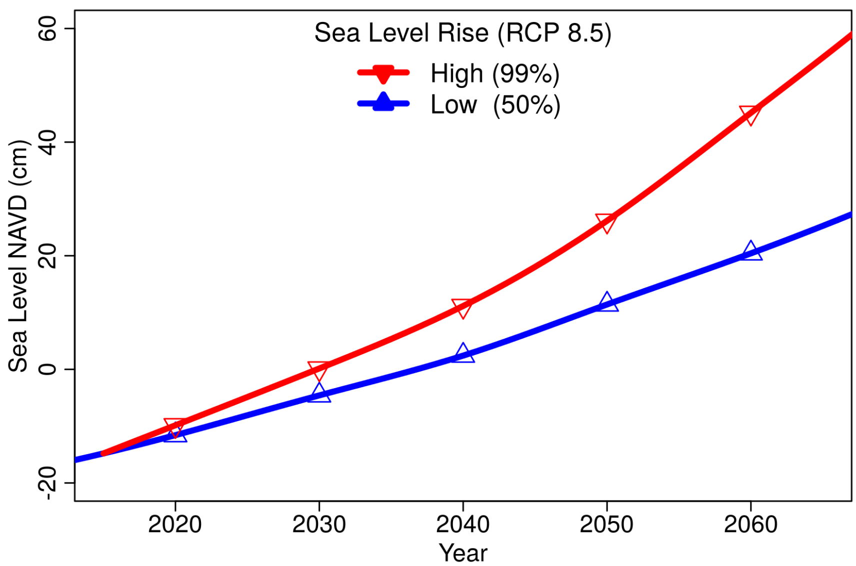


Figure 1.
South Florida sea level rise projection with respect to 2015 mean sea level in Florida Bay for the RCP 8.5 greenhouse gas emission scenario. Units are cm NAVD88.

Low projection in blue is the median (50$^{\text{th}}$ percentile), high projection in red (99$^{\text{th}}$ percentile). Tides and storm surges are not included in this projection. Values are tabulated in Appendix B to year 2120.

3 Inundation Maps for Mean Sea Level

Sea level rise projections at years 2025, 2050, 2075 and 2100 have been mapped to the NAVD88 datum across the boundaries of Everglades, Biscayne, and Dry Tortugas National Parks based on a synthesis of the best available high-resolution digital elevation data (*Fennema et al.*, 2015) as shown in figures 2 and 3. Blue shadings represent the extent of projected mean sea level inundation at the four time horizons of 2025, 2050, 2075 and 2100. Grey areas are elevations higher than the expected mean sea level at 2100.

These projections do not include tides, storm surge or changes in ocean circulation or weather patterns. Areas landward of the mean sea level contours can be expected to experience inundation from high tides prior to the establishment of mean sea level.

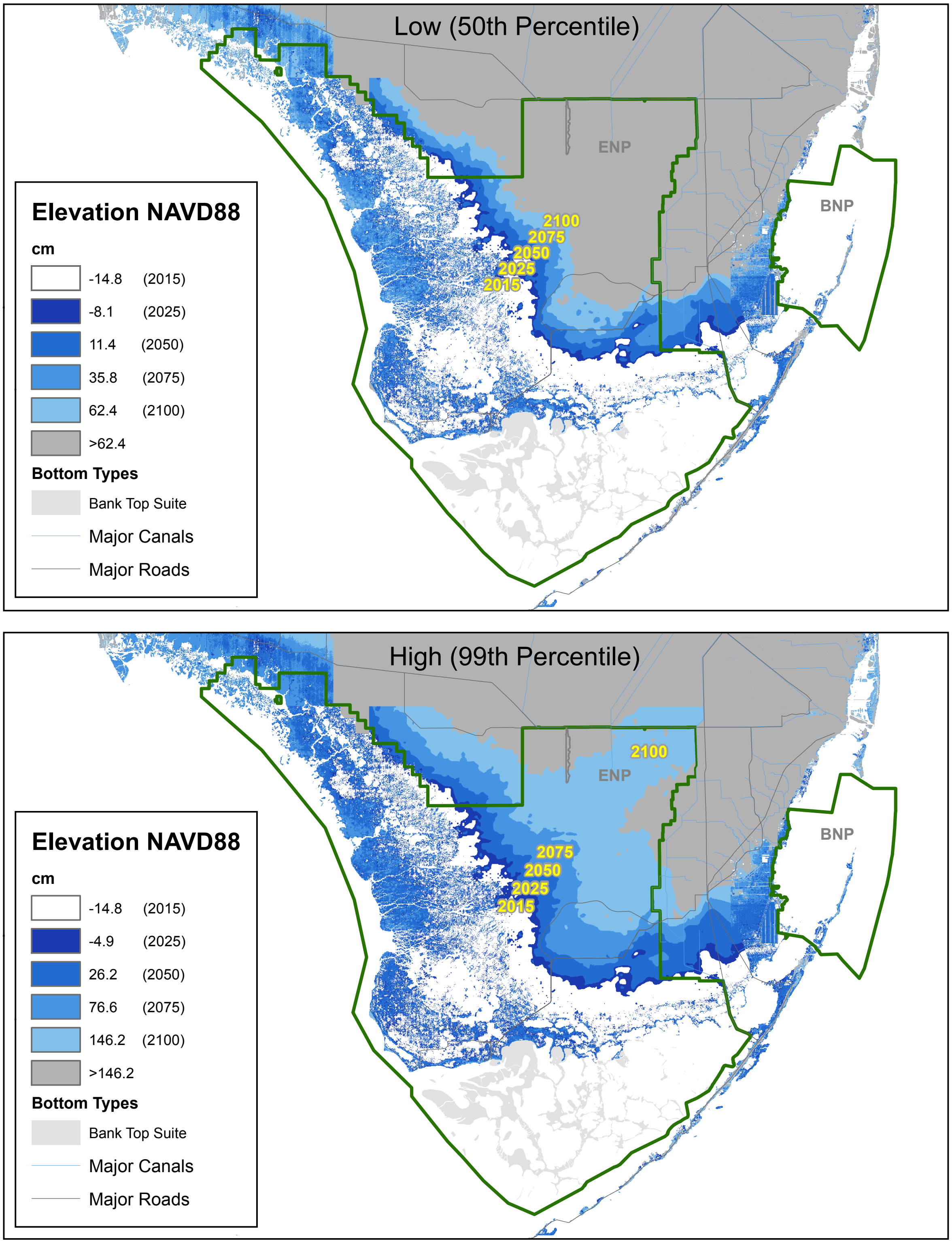


Figure 2. Mean sea level elevation maps for south Florida including Everglades and Biscayne National parks for the median (50^{th}) and high (99^{th} percentile) RCP 8.5 projections using current topography and NAVD. Tides and storm surges are not included in this projection.

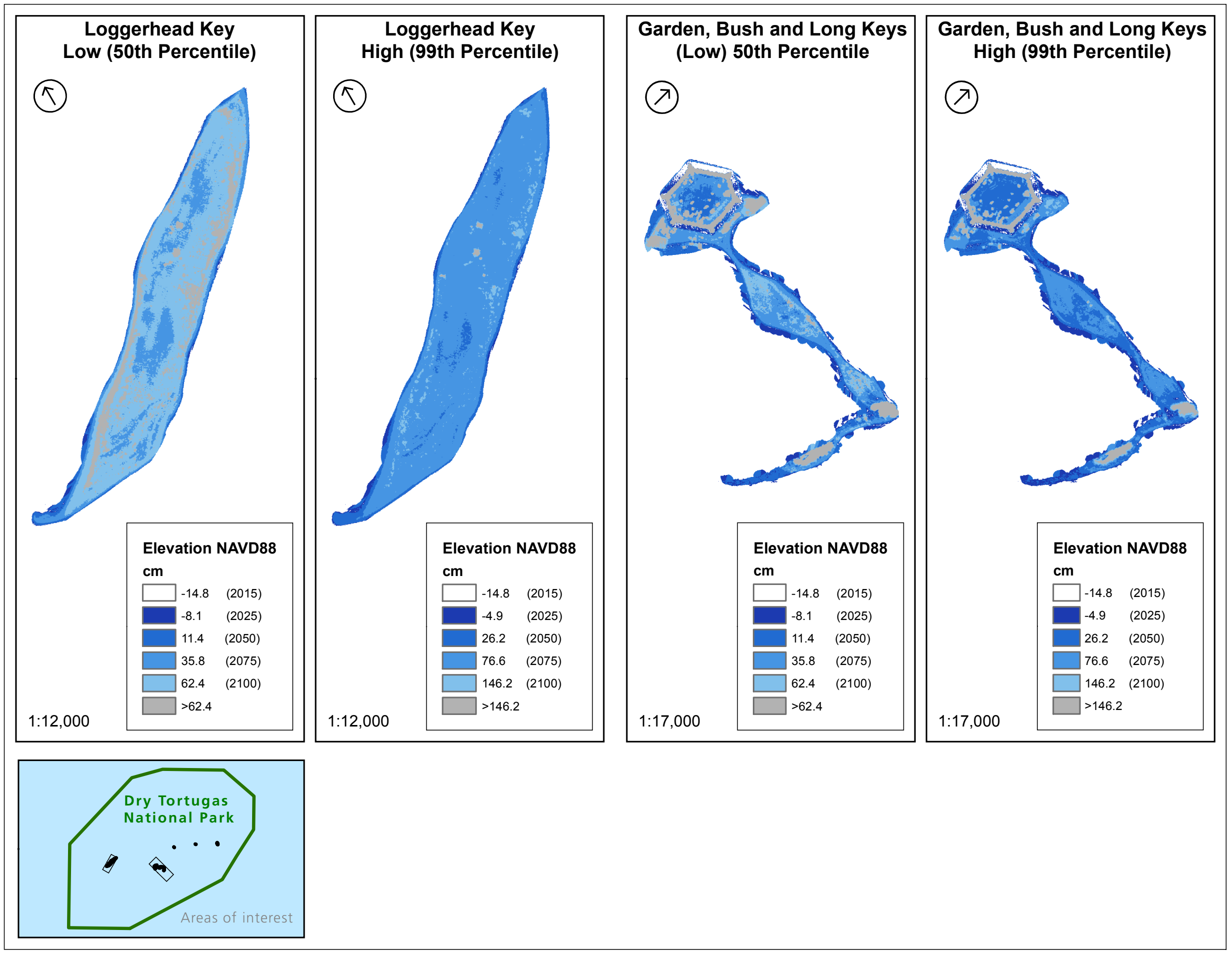


Figure 3. Mean sea level elevation maps for Dry Tortugas National Park at Loggerhead, Garden, Bush, and Long Keys for the median (50th) and high (99th percentile) RCP 8.5 projections. Tides and storm surges are not included in this projection.

4 General Influence of Sea Level Rise

As noted above, these projections are adjusted to match mean sea level in Florida Bay over the period from 2008 to 2015 (-14.8 cm NAVD88) which is represented in the maps with the white color level. This could be misleading since it indicates that southern Everglades National Park is currently at mean sea level and possibly inundated with seawater. However, these regions are freshwater marsh and freshwater to salt-tolerant transition zones. It is important to realize there is a dynamic equilibrium between freshwater flowing from the Everglades and the sea, and with sufficient freshwater elevation the seawater is effectively kept at bay. Increasing freshwater flow into the Everglades under current restoration plans will serve to mitigate the impacts of sea level rise protecting both ecological and water supply resources (National Research Council, 2014). Another important factor is the buttonwood and mangrove ridge defining the boundary between Florida Bay and freshwater marsh serving as a hydraulic barrier and allowing the freshwater to maintain elevations above mean sea level thereby limiting salt and freshwater mixing. This ridge will eventually be permanently inundated allowing seawater to flow freely inland, but even then as Florida Bay expands, freshwater flowing downstream will serve to mitigate the extent of saltwater intrusion.

Over the next ten years, represented by the 2025 estimates, dramatic change in sea level is not anticipated. The expected sea level rise is 7 cm (3 in) for the low scenario and 10 cm (4 in) for the high projection. These changes will result in more frequent tidal inundation along coastal regions, however, the buttonwood ridge located along the north shore of Florida Bay will remain above sea level. This modest increase is not likely to impact the terrestrial portions of Dry Tortugas or Biscayne National Park.

By 2050 sea level is expected to increase between 26 and 41 cm (10 and 16 in). The effect on Shark Slough is similar for both projections with an increase in perennially inundated areas. It is difficult to project ecological impacts here since the amount of freshwater exerts important influence over the ecological response. Taylor Slough appears to experience significant impact under both scenarios with increasing pressure from sea level advancing up the slough perhaps as far as the Old Ingraham Highway. The eastern panhandle of the Park is more heavily impacted by the high estimate than the low estimate simply because the high estimate exceeds the land surface elevation in this area and begins to over top the buttonwood ridge.

By 2075 sea level elevations are anticipated to increase by 51 and 91 cm (1.7 and 3.0 ft) for the low and high projections respectively. Assuming that the buttonwood ridge does not increase in elevation from accretion or deposition, it appears that sometime between 2050 and 2075 much of the buttonwood ridge will be permanently inundated. This could signal an important tipping-point in the ecological response of freshwater marshes since freshwater basins delineated by the ridge will no longer be viable. It appears likely that these impacts will extend to the Ingraham Highway.

By 2100 the projected sea level rise is 77 cm (2.5 ft) for the low projection and 161 cm (5.3 ft) for the high scenario. It is likely that widespread ecological changes will be evident around the coastal Everglades as Florida Bay expands. In the case of the low-lying islands of Biscayne and Dry Tortugas national parks, many of these can be expected to become submerged.

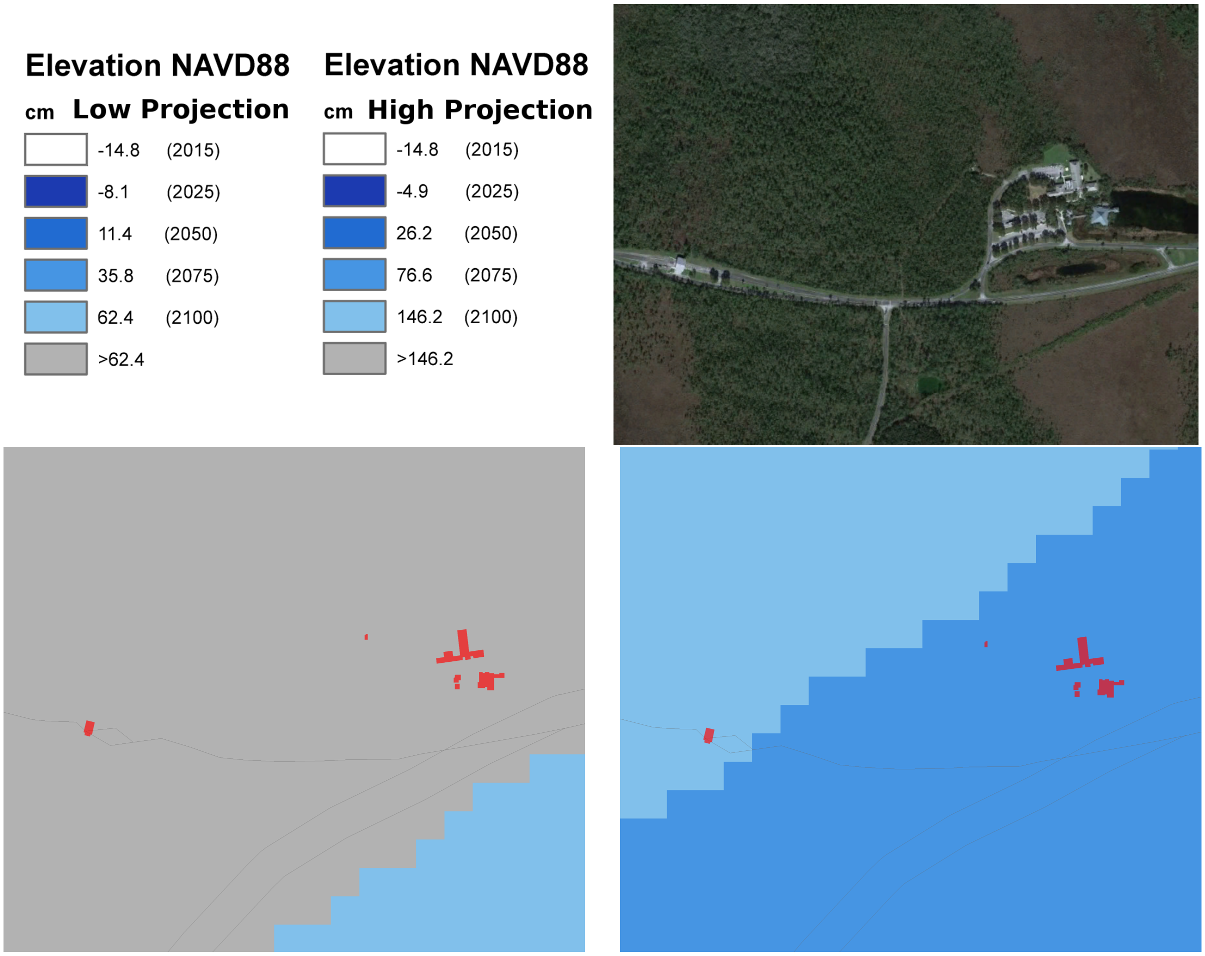
5 Infrastructure Elevations and Mean Sea Level Inundation

Figures 4 through 13 present application of the two sea level rise scenarios to areas surrounding building infrastructure in Everglades National Park, figures 14 through 15 apply to Dry Tortugas National Park. Figure 16 is specific to Big Cypress National Preserve, and figures 17 through 20 apply to Biscayne National Park.

These figures present comparisons of projected mean sea level with the best available land elevation surrounding the infrastructure and do not represent the actual finished floor elevations of structures which are likely higher than the surrounding land elevation. Generally, areas that are above mean sea level are shaded gray, and areas where mean sea level is forecast to reach are shaded various colors of blue corresponding to one of the time horizons (2025, 2050, 2075 and 2100). Note that the low and high projections do not share a common legend, that is, the shade of blue which corresponds to a specific land elevation is not the same between the low and high projections, however, the time horizon at which mean sea level reaches an elevation does correspond to the same shade of blue in both projections.

It is also important to note that mean sea level in Florida Bay fluctuates by approximately 30 to 40 cm (12 to 16 in) in a yearly oceanographic cycle, as well as up to 70 cm (2.3 ft) in daily and monthly tidal cycles so that effects of tidal inundation will be observed during high tides several years before the projected dates when mean sea level reaches a specific land elevation.

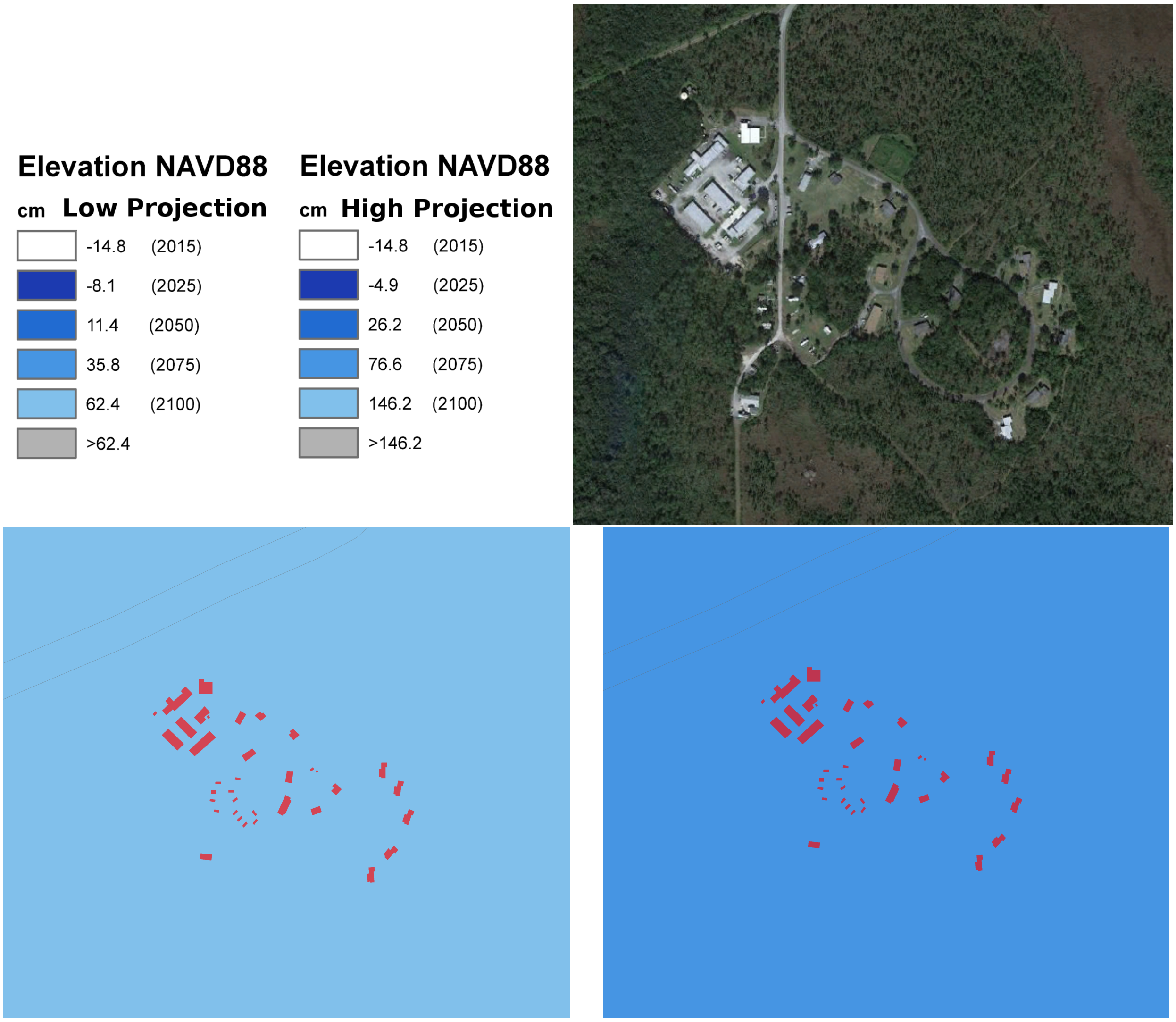
5.1 ENP: Ernest F. Coe Visitor Center and Park Entrance



(a) **Low Projection** (b) **High Projection**

Figure 4. Everglades National Park: Mean sea level elevations at the main Park entrance, the Ernest F. Coe visitor center, and the Park headquarter offices. Red indicates a building footprint. Under the low sea level rise scenario these buildings will not be perennially inundated out to 2100. In the high scenario, land surrounding the Ernest F. Coe visitor center can be expected to be tidally inundated by 2075, while the main Park entrance is expected to become inundated by 2100.

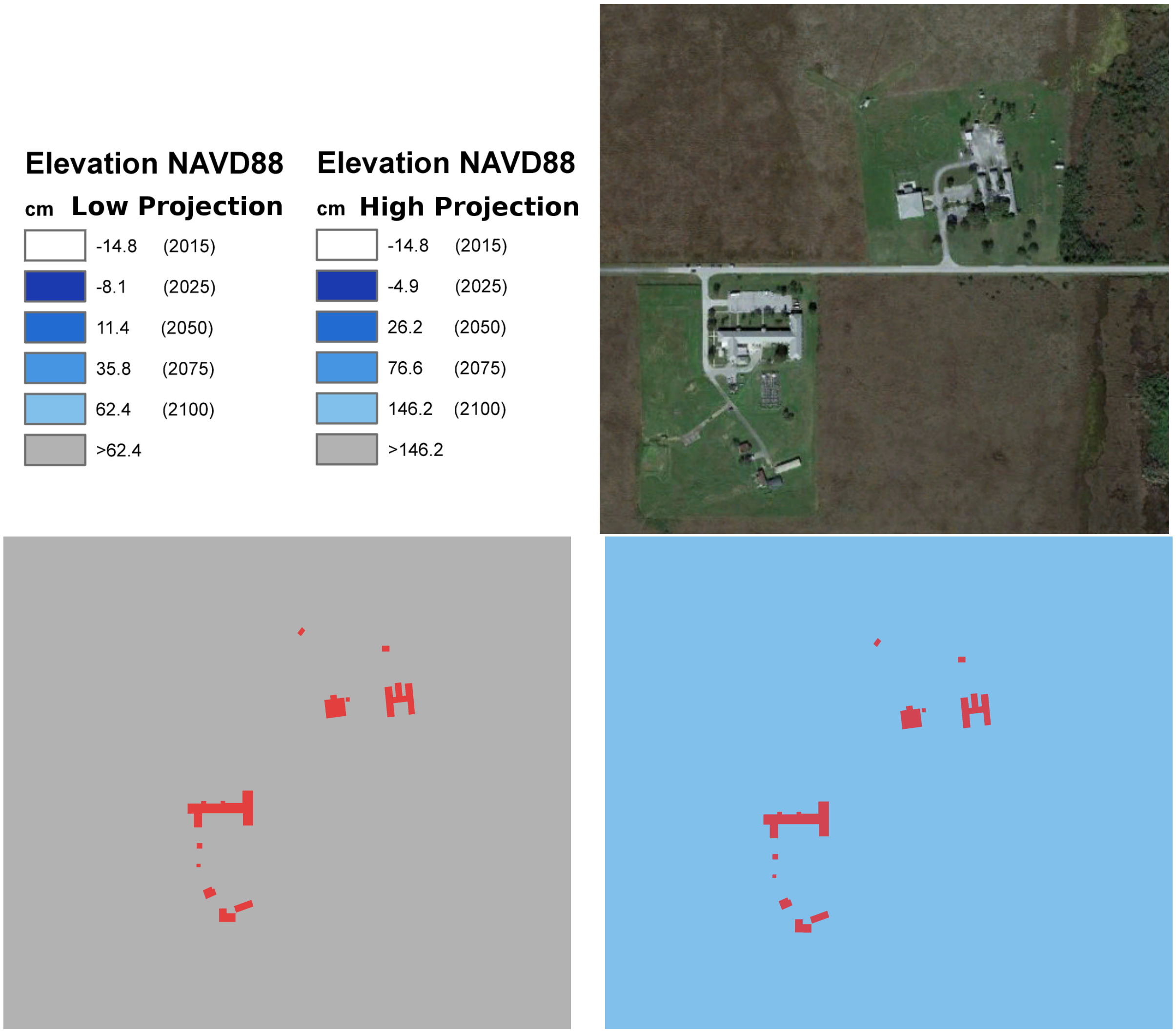
5.2 ENP: Pine Island



(a) **Low Projection** (b) **High Projection**

Figure 5. Everglades National Park: Mean sea level elevations at the Pine Island supply, maintenance and housing complex. Red indicates a building footprint. Under the low sea level rise scenario land surrounding these buildings will be perennially inundated by 2100. In the high scenario tidal inundation will occur by 2075.

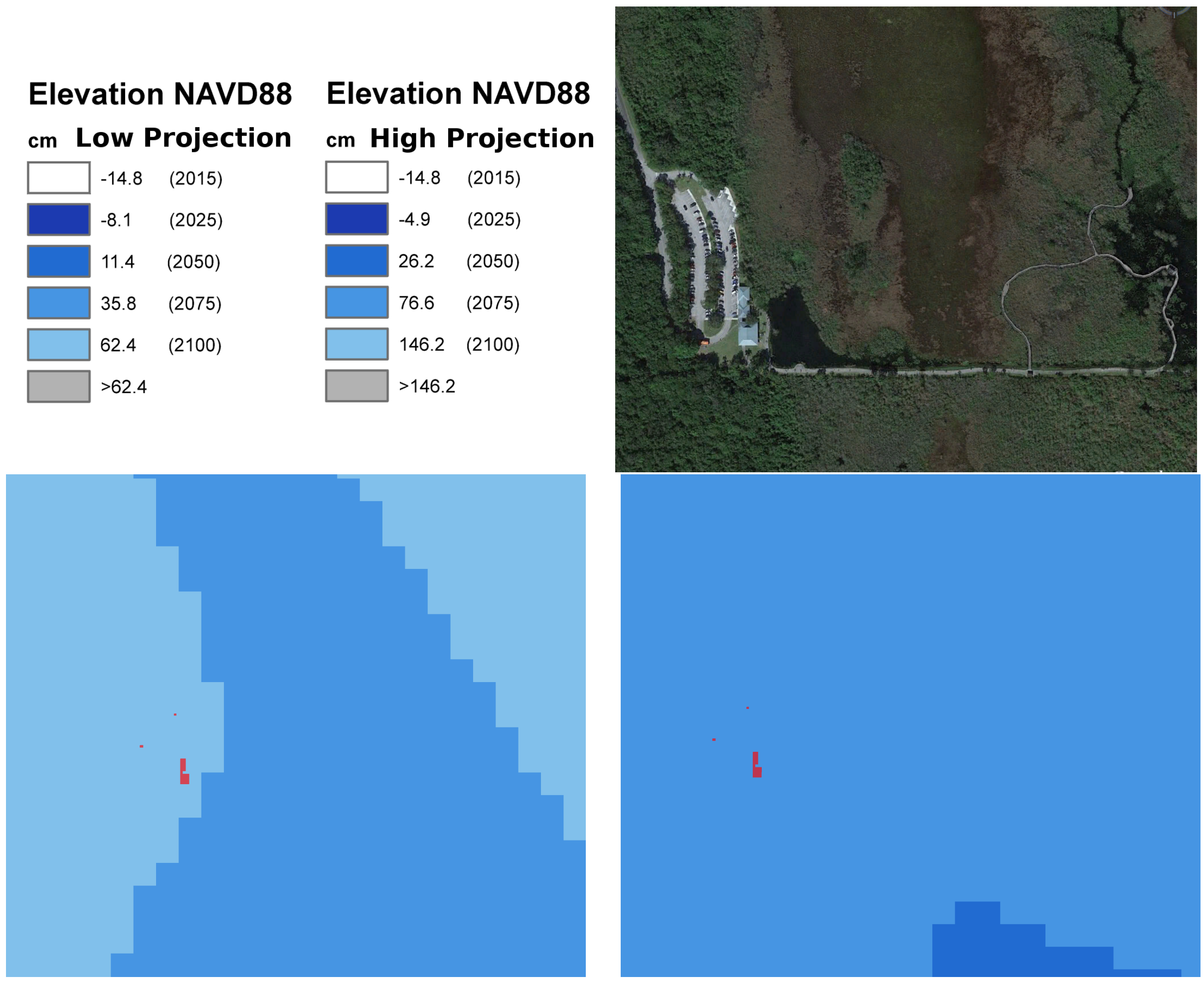
5.3 ENP: Daniel Beard and Robertson Centers



(a) **Low Projection** (b) **High Projection**

Figure 6. Everglades National Park: Mean sea level elevations at the Daniel Beard and Robertson centers. Red indicates a building footprint. Under the low sea level rise scenario these buildings will not be perennially inundated out to 2100. In the high scenario, land surrounding the these centers can be expected to be tidally inundated by 2100.

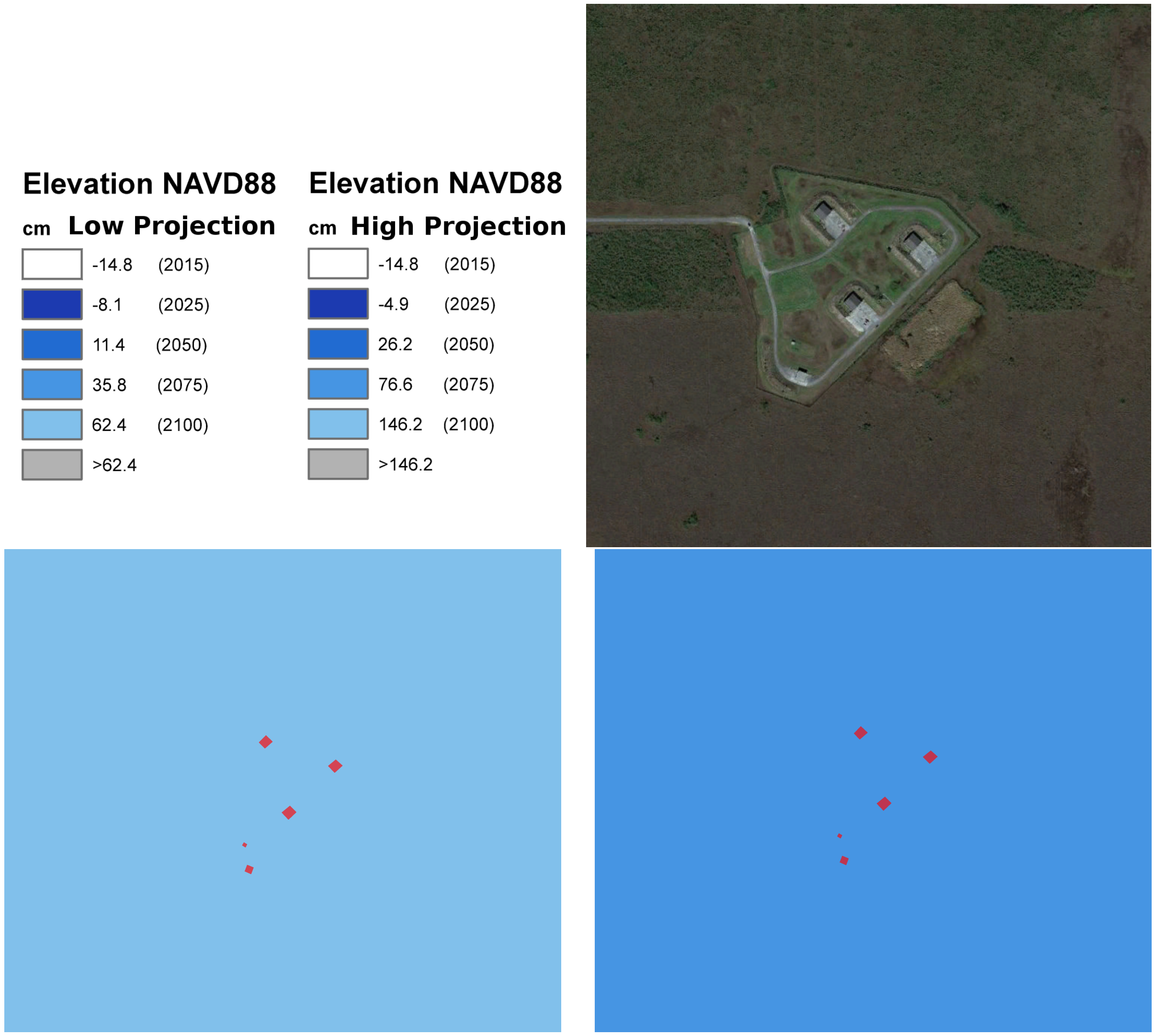
5.4 ENP: Royal Palm Visitor Center



(a) **Low Projection**   (b) **High Projection**

Figure 7. Everglades National Park: Mean sea level elevations at the Royal Palm visitor center. Red indicates a building footprint. Under the low sea level rise scenario land surrounding these buildings will be perennially inundated by 2100. In the high scenario tidal inundation will occur by 2075.

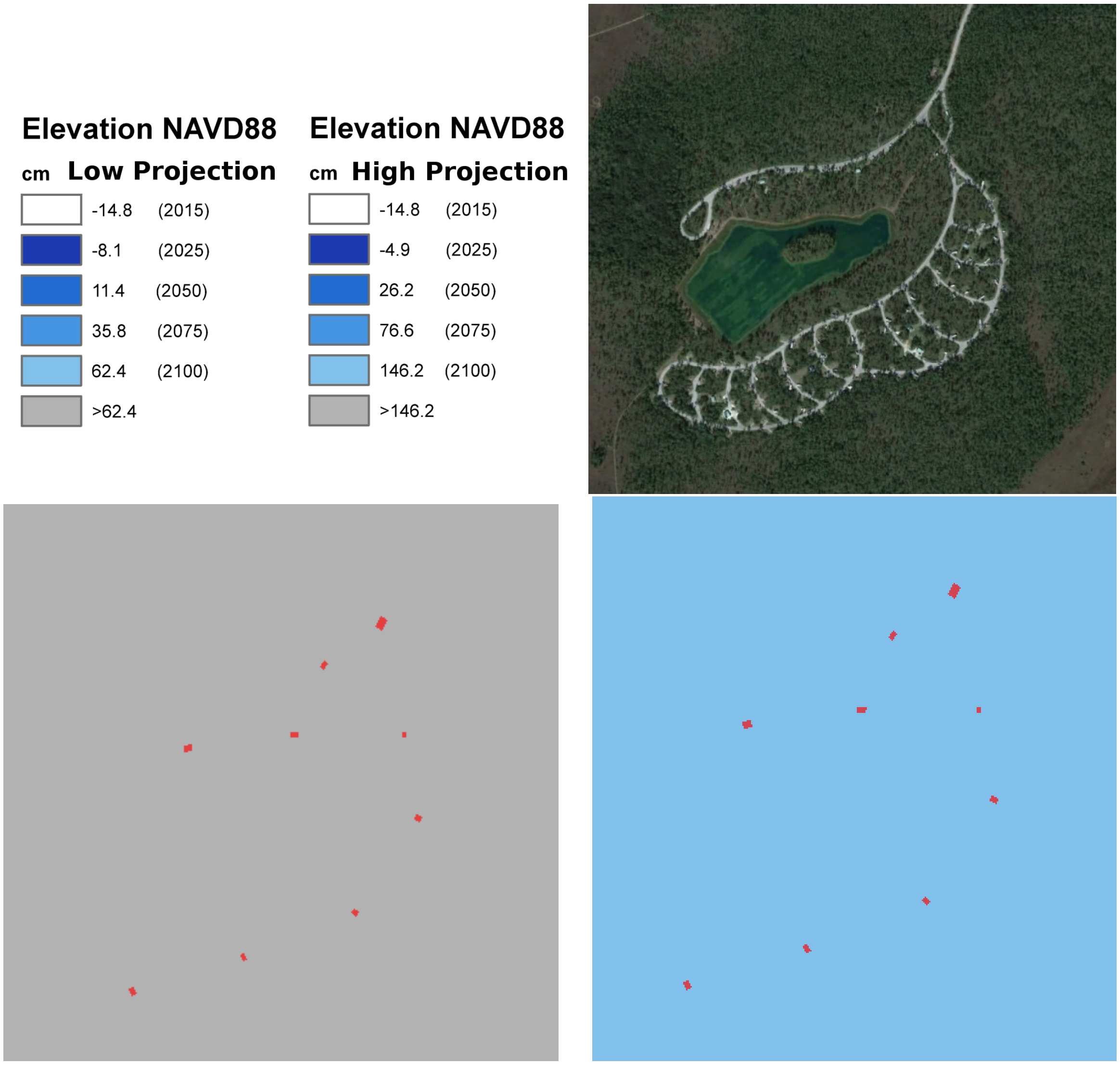
5.5 ENP: Nike Missle Base



(a) **Low Projection** (b) **High Projection**

Figure 8. Everglades National Park: Mean sea level elevations at the Nike missile base. Red indicates a building footprint. Under the low sea level rise scenario land surrounding these buildings will be perennially inundated by 2100. In the high scenario tidal inundation will occur by 2075.

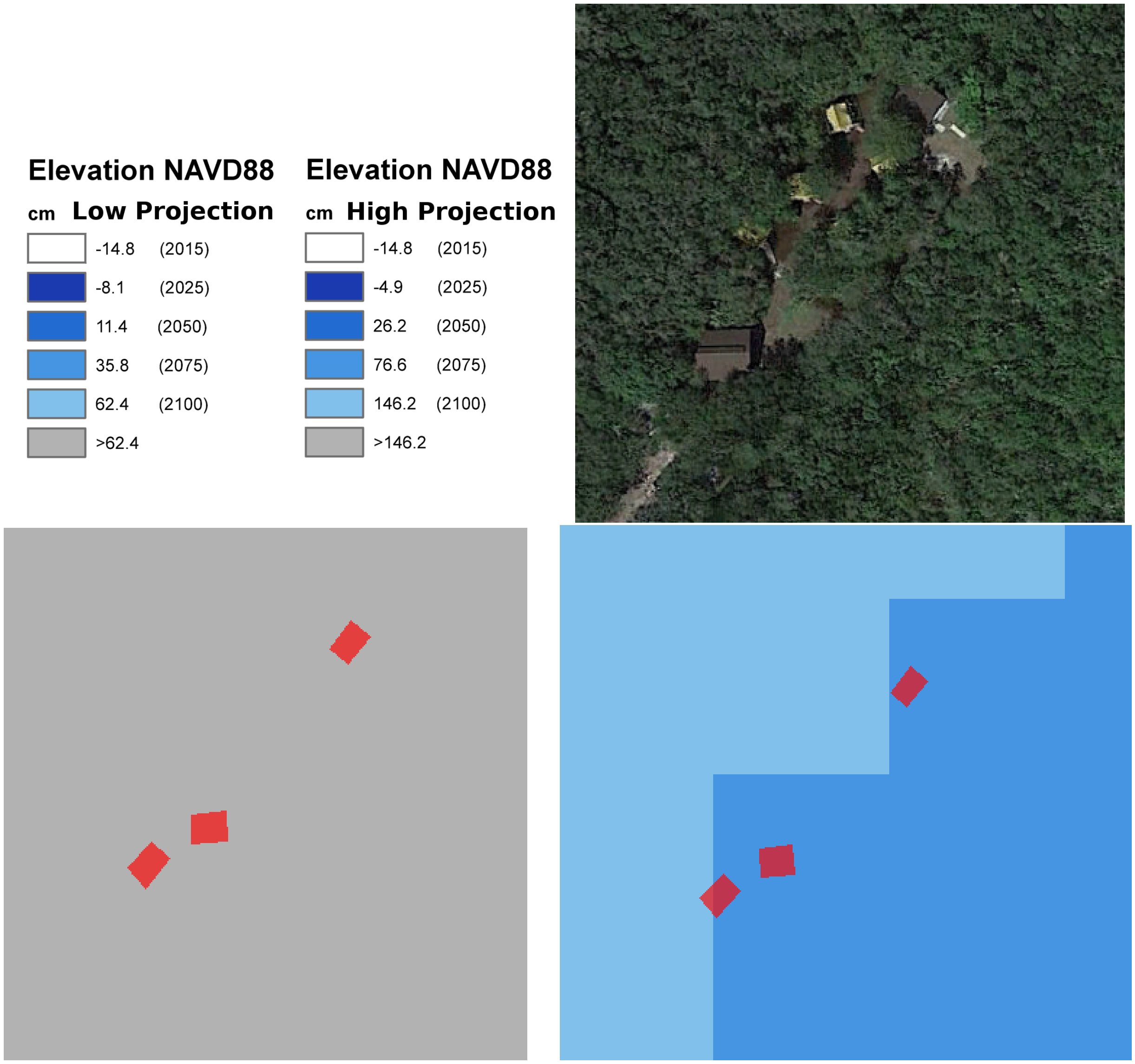
5.6 ENP: Long Pine Key



(a) **Low Projection** (b) **High Projection**

Figure 9. Everglades National Park: Mean sea level elevations at Long Pine Key. Red indicates a building footprint. Under the low sea level rise scenario this area will not be tidally submerged out to 2100. In the high scenario tidal inundation is expected to occur by 2100.

5.7 ENP: Hidden Lake Education Center

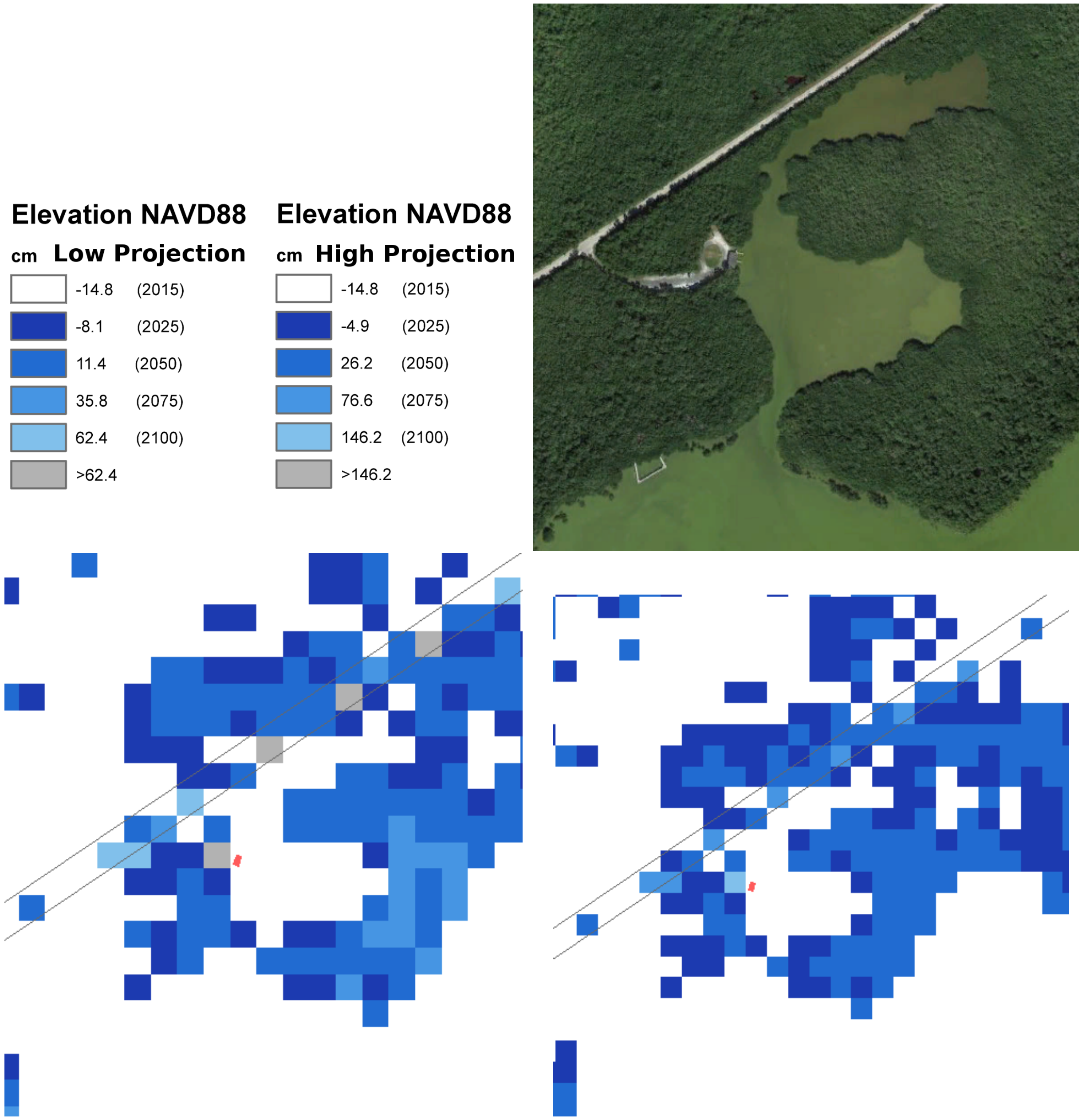


(a) **Low Projection**

(b) **High Projection**

Figure 10. Everglades National Park: Mean sea level elevations at Hidden Lake education center. Red indicates a building footprint. Under the low sea level rise scenario the area will not be tidally submerged out to 2100. In the high scenario tidal inundation is expected to occur by 2075.

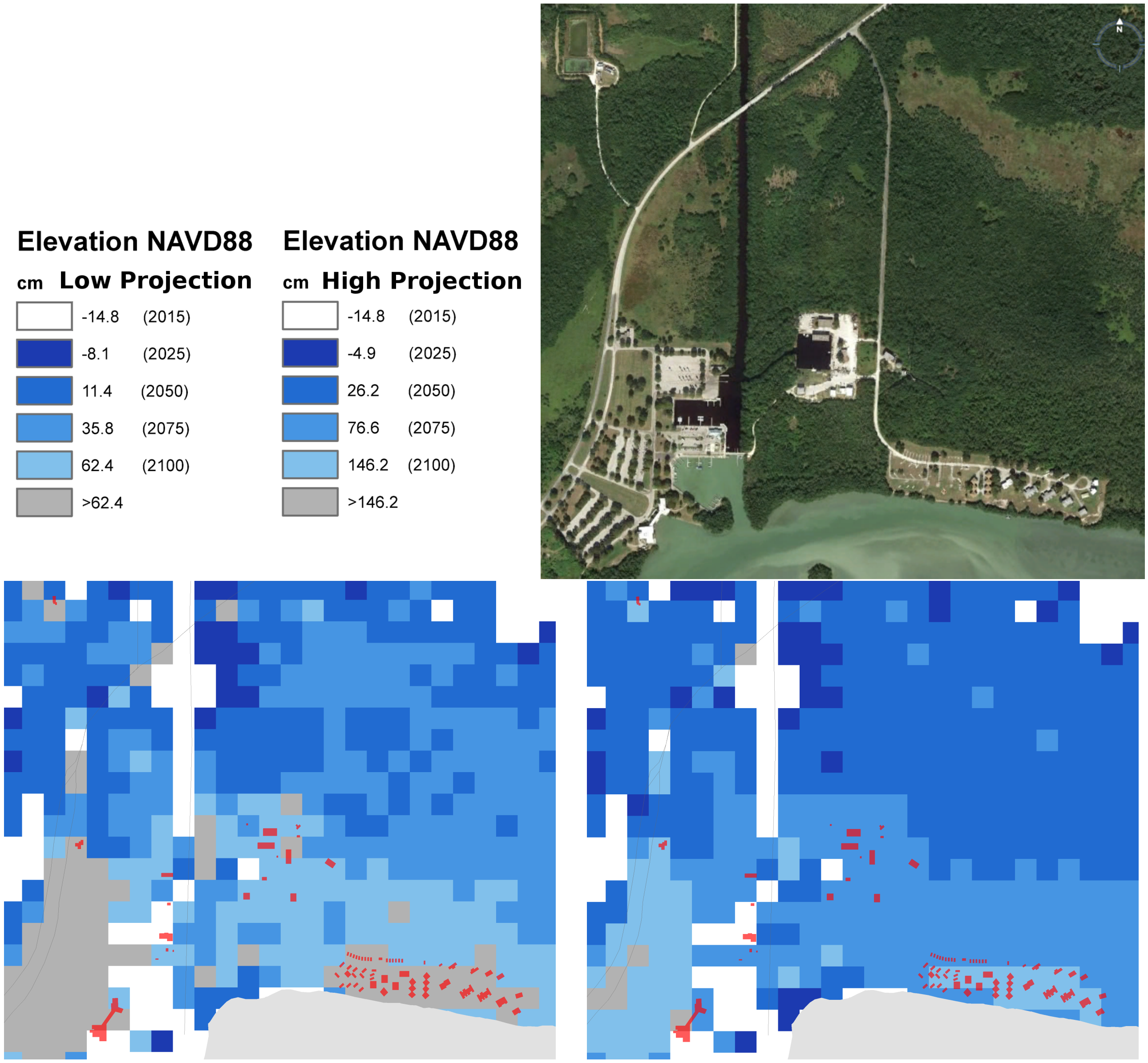
5.8 ENP: West Lake



(a) **Low Projection** (b) **High Projection**

Figure 11. Everglades National Park: Mean sea level elevations at West Lake. Red indicates a building footprint. Under the low sea level rise projection the parking lot is not expected to be tidally inundated by 2100. Under the high projection the parking lot is at mean sea level by 2100.

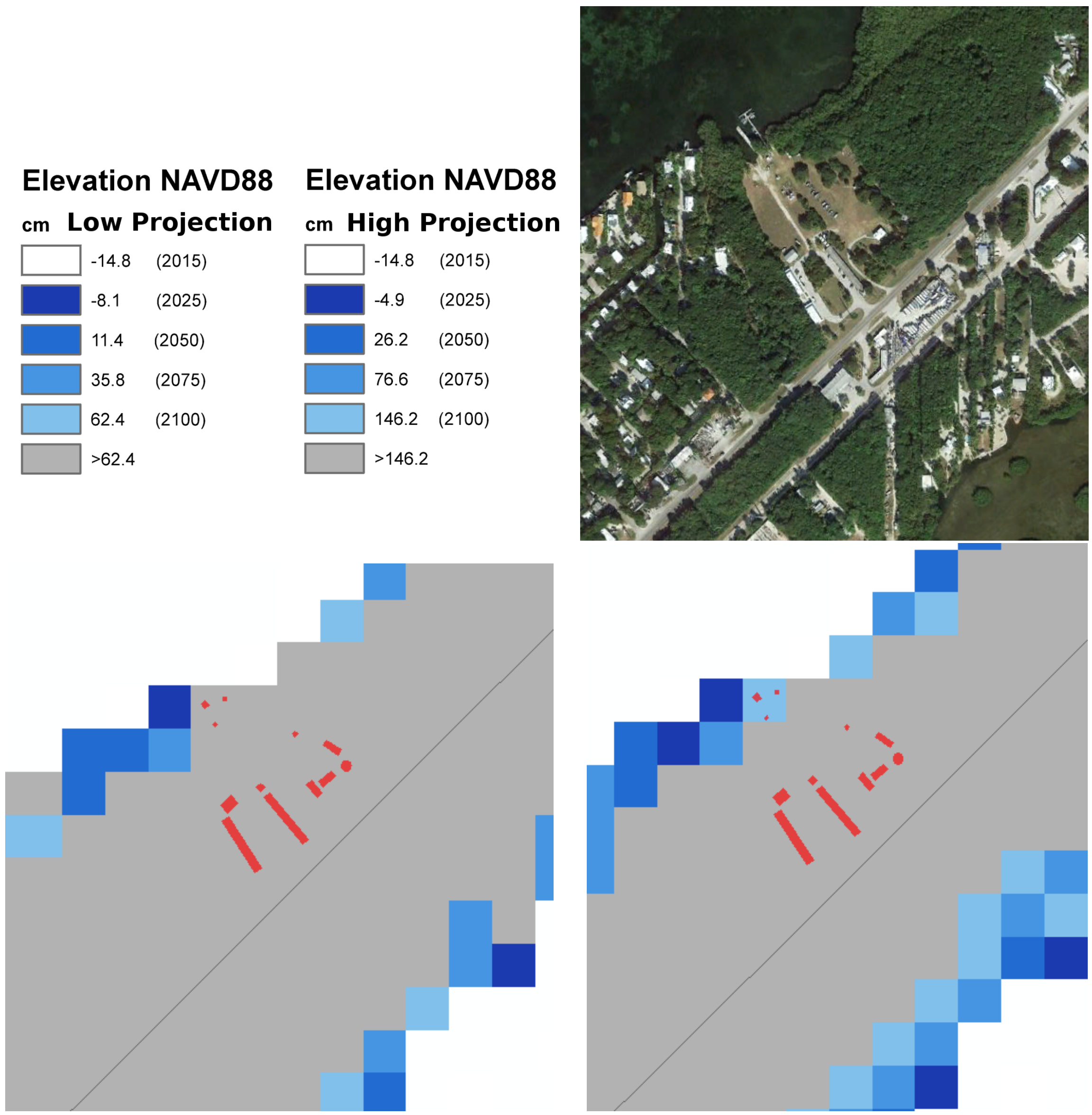
5.9 ENP: Flamingo



(a) **Low Projection** (b) **High Projection**

Figure 12. Everglades National Park: Mean sea level elevations at Flamingo. Red indicates a building footprint. Under the low sea level rise projection the visitor center and housing are not expected to be continuously inundated by 2100. The boat basin, maintenance yard and water plant can expect perennial inundation by 2100. The wastewater treatment plant is not expected to be tidally inundated by 2100, but the surrounding area is likely to be at mean sea level by 2050. Under the high projection the housing area is at mean sea level by 2100, the visitor center will be partially inundated by 2050, and the maintenance yard and water plant by 2075.

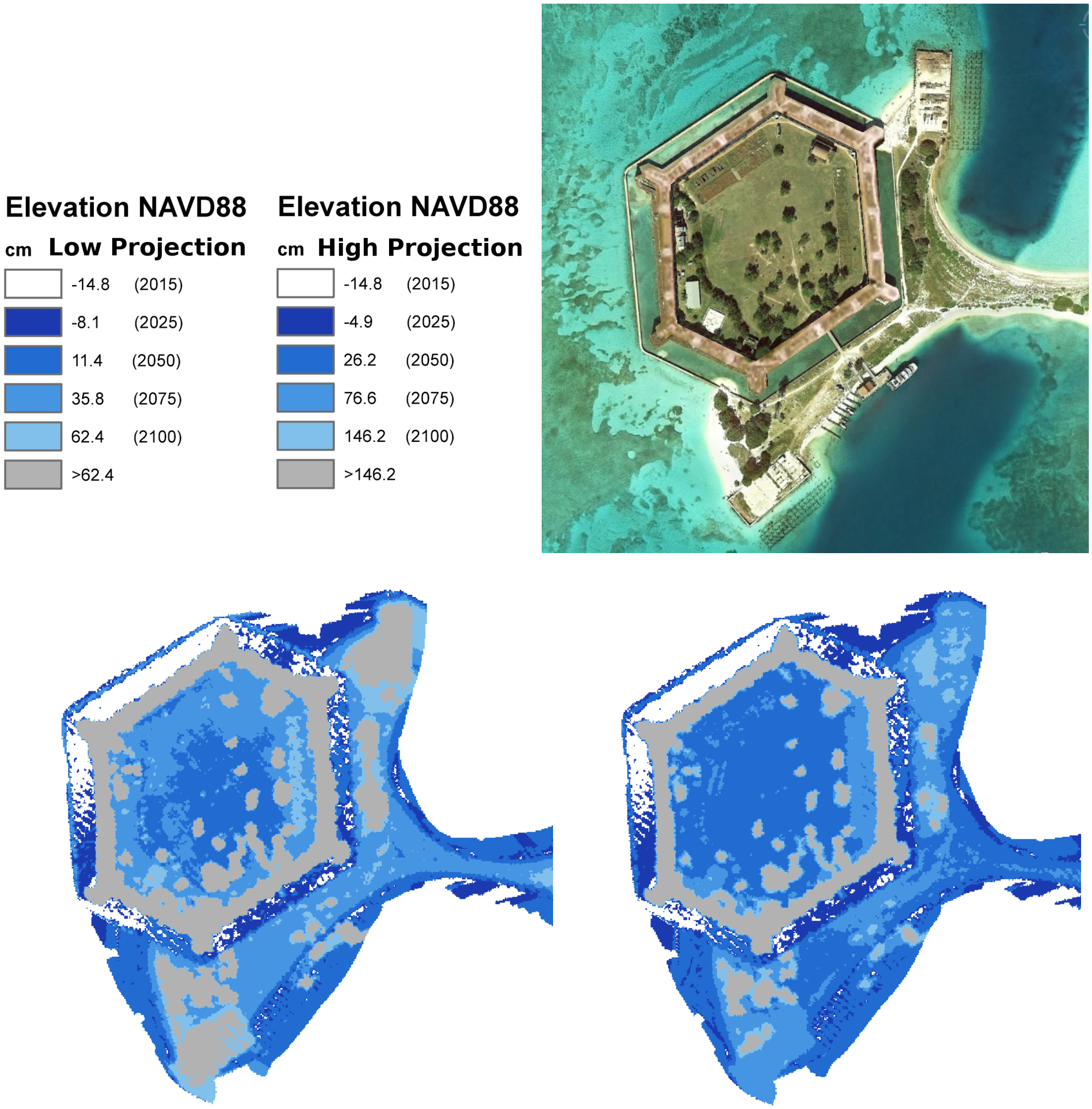
5.10 ENP: Florida Bay Ranger Station and Science Center



(a) **Low Projection** (b) **High Projection**

Figure 13. Everglades National Park: Mean sea level elevations at the Florida Bay Ranger Station and Science Center. Red indicates a building footprint. The Ranger Station, Science Center and housing are not expected to be tidally inundated out to 2100 under both the low and high sea level rise projections. Under the high projection, the fueling station is expected to be at mean sea level by 2100.

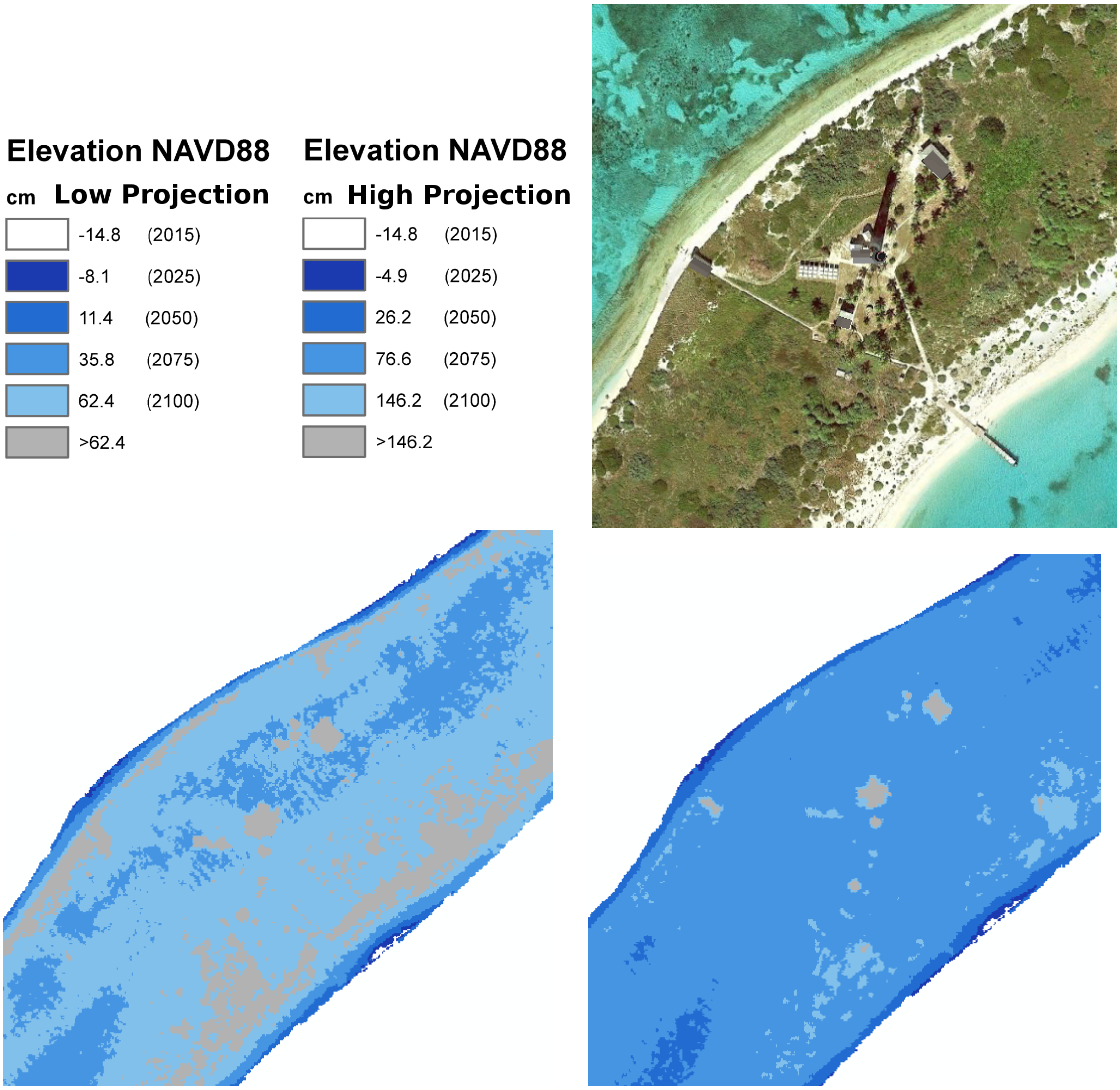
5.11 DRTO: Fort Jefferson



(a) **Low Projection** (b) **High Projection**

Figure 14. Dry Tortugas National Park: Mean sea level elevations at Fort Jefferson. Under the low sea level rise projection the north coal docks and campground remain above mean sea level to 2100. Land around the ferry dock is expected to be at mean sea level by 2075, as is the isthmus to Bush and Long Keys. Under the high projection much of the north coal dock and campground will be at mean sea level by 2075, as will much of the land between the ferry dock and moat although a portion of this will be at sea level by 2050. The isthmus to Bush Key is expected to be at mean sea level by 2050.

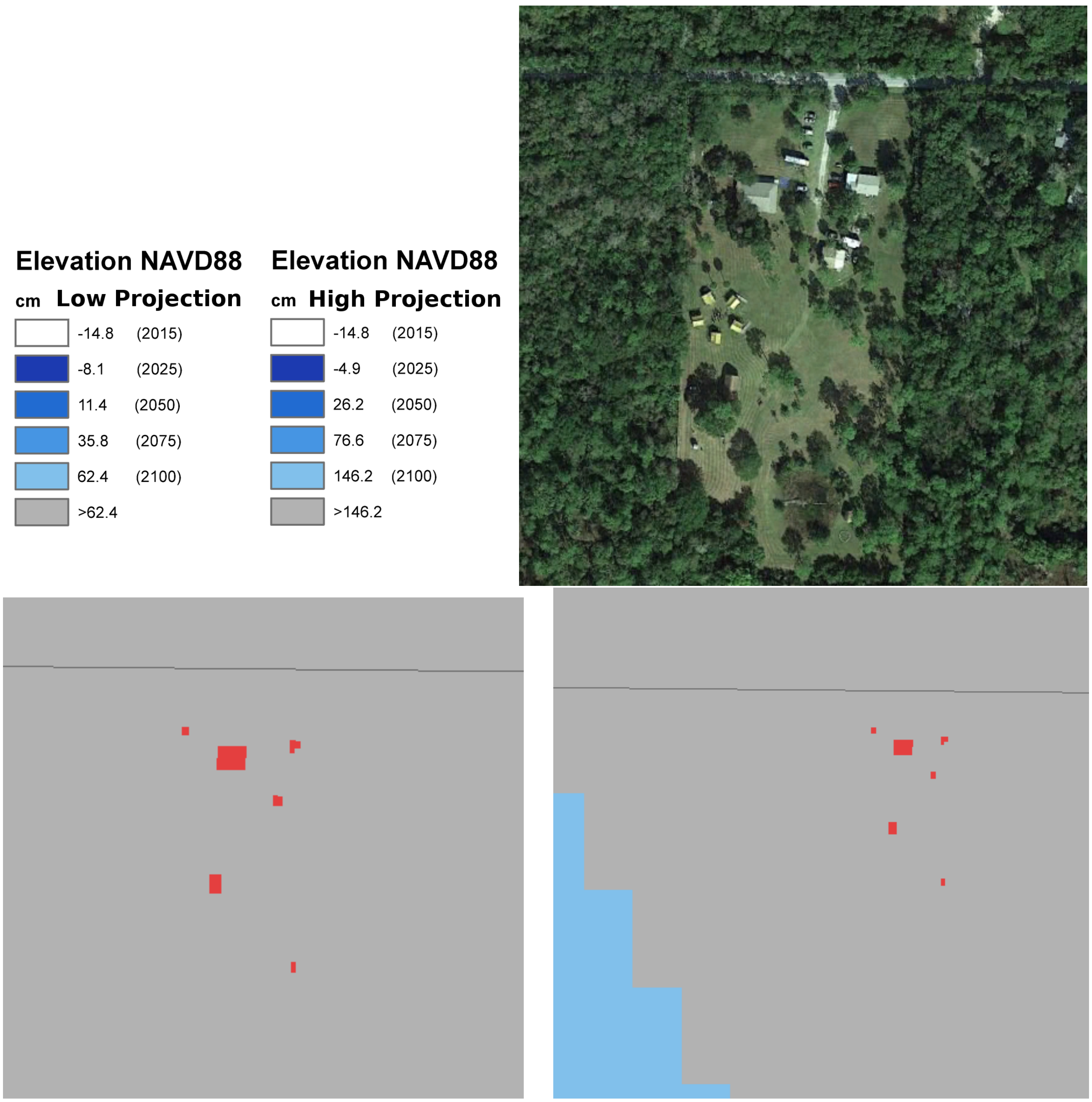
5.12 DRTO: Loggerhead Key



(a) **Low Projection** (b) **High Projection**

Figure 15. Dry Tortugas National Park: Mean sea level elevations at Loggerhead Key. Under the low sea level rise projection the majority of the key will be tidally inundated by 2100 with thin exposed ridges around the periphery. Under the high projection the key will be perennially inundated by 2075.

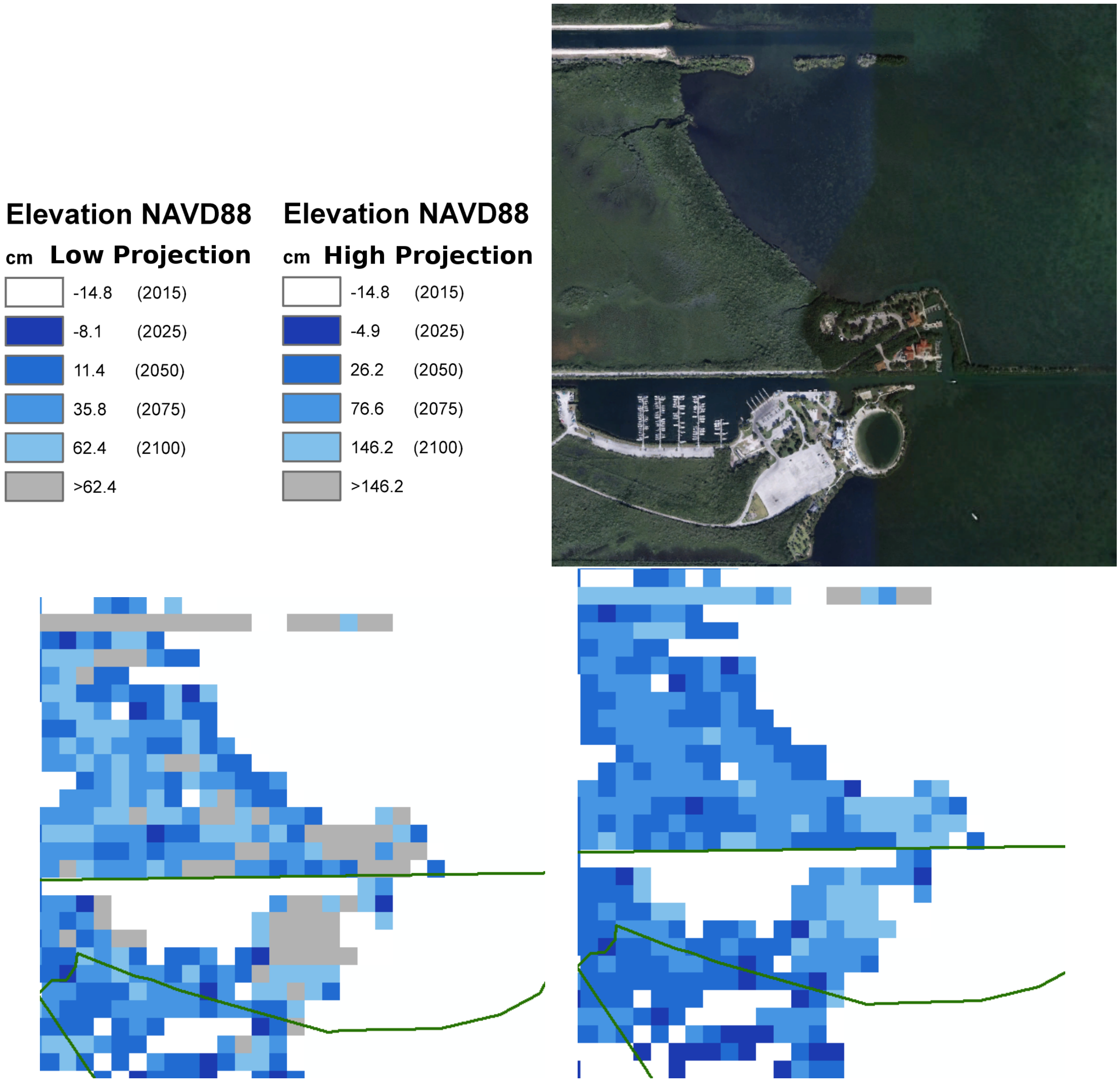
5.13 BCNP: Loop Road Education Center



(a) **Low Projection** (b) **High Projection**

Figure 16. Big Cypress National Preserve: Mean sea level elevations at the Loop Road education center in Big Cypress National Preserve. Red indicates a building footprint. Under the low sea level rise projection this area is not expected to be tidally inundated out to 2100. Under the high projection the center remains above mean sea level out to 2100 with the establishment of tidal inundation to the west.

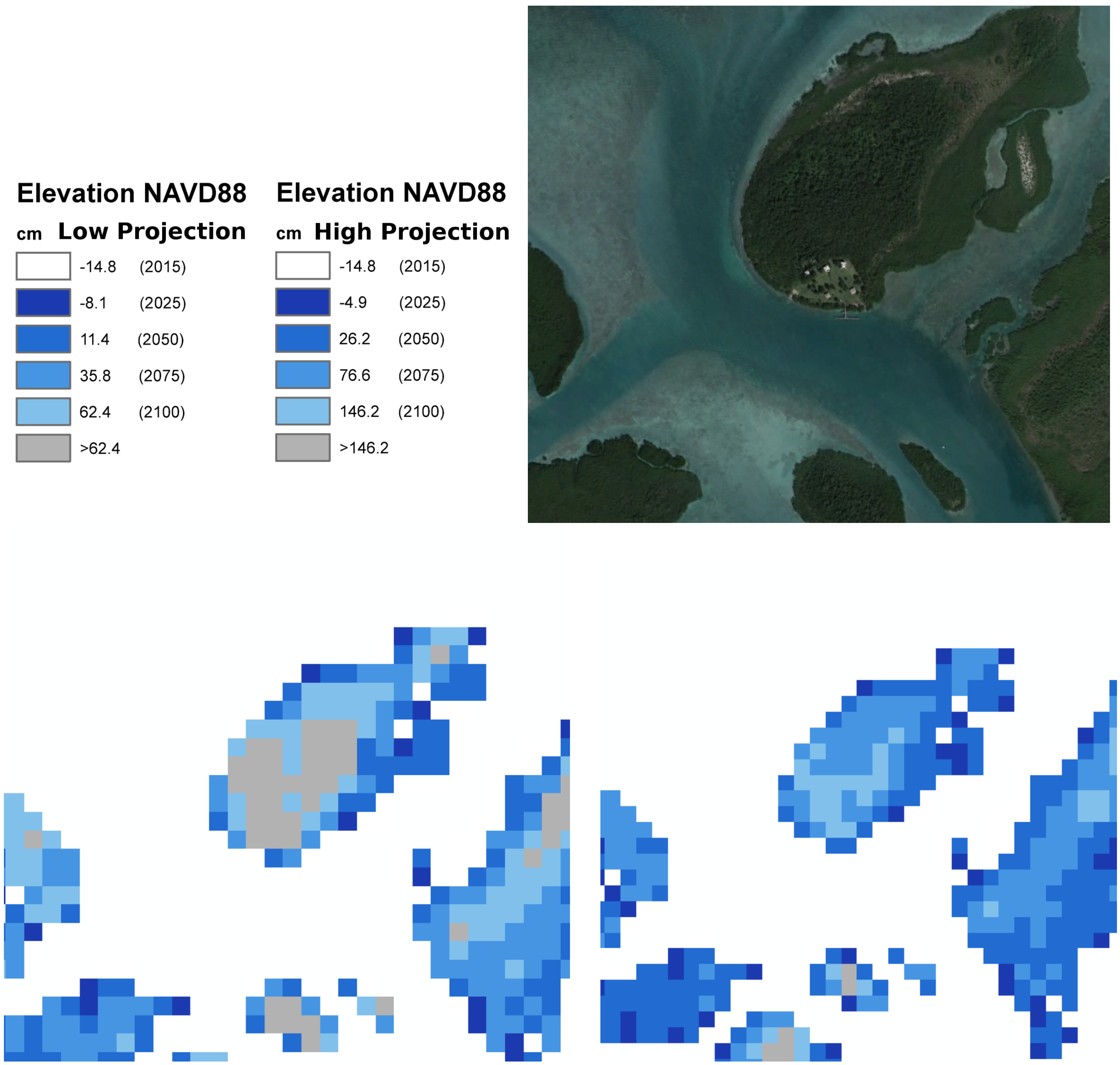
5.14 BISC: Dante Fascell Visitor Center



(a) **Low Projection** (b) **High Projection**

Figure 17. Biscayne National Park: Mean sea level elevations at the Dante Fascell Visitor Center in Biscayne National Park. Under the low sea level rise projection the center is not expected to be tidally inundated out to 2100. Under the high projection mean sea level will reach the center area between 2075 and 2100. Under both scenarios it is likely that SW 328th street will be partially tidally inundated by 2050.

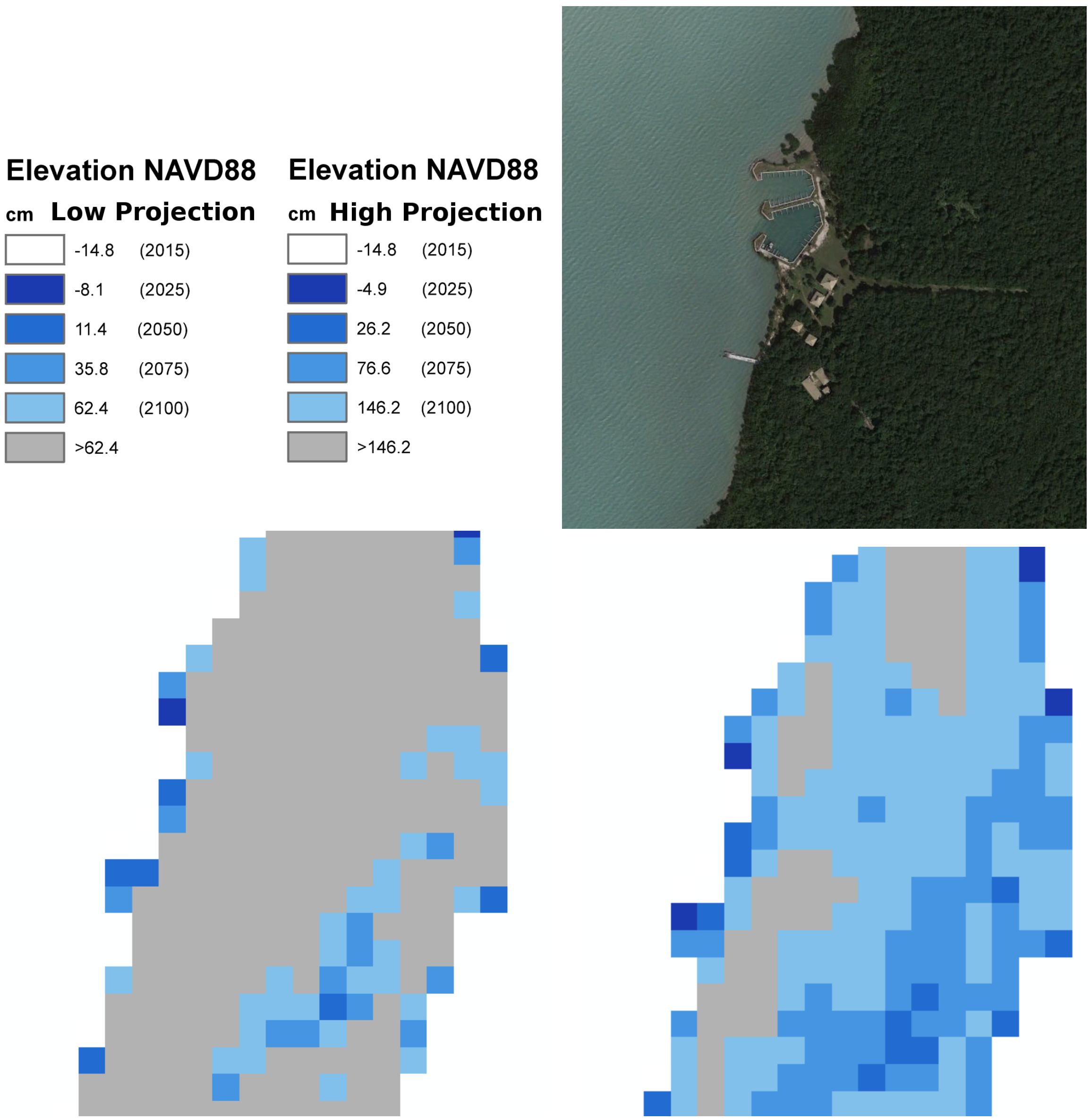
5.15 BISC: Adams Key



(a) **Low Projection** (b) **High Projection**

Figure 18. Biscayne National Park: Mean sea level elevations at Adams Key in Biscayne National Park. Under the low sea level rise projection this area is not expected to be tidally inundated out to 2100. Under the high projection the area is expected to be at mean sea level between 2075 and 2100.

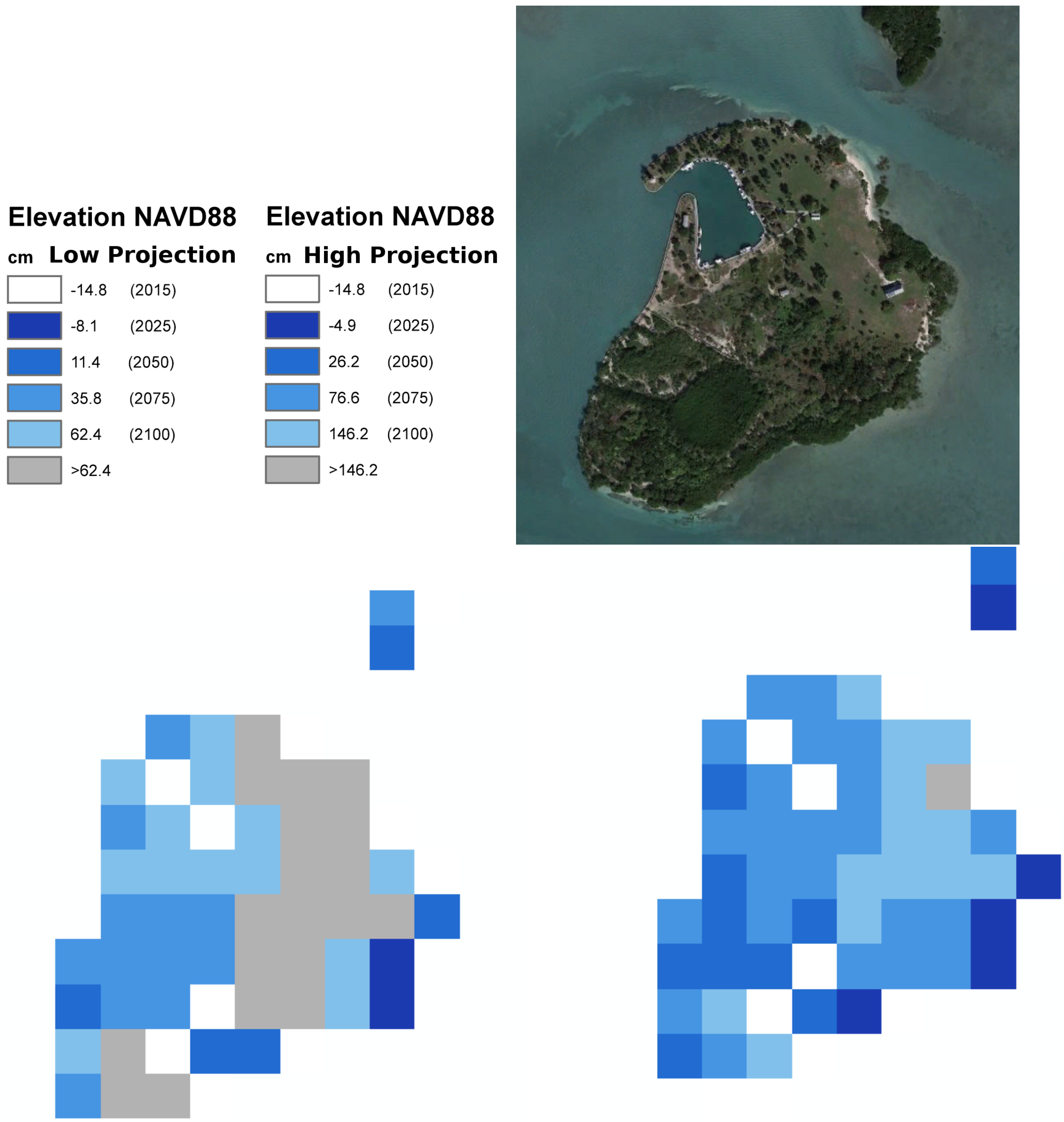
5.16 BISC: Elliot Key Ranger Station



(a) **Low Projection** (b) **High Projection**

Figure 19. Biscayne National Park: Mean sea level elevations at the Elliot Key Ranger Station in Biscayne National Park. Under the low sea level rise projection this area is not expected to be tidally inundated out to 2100. Under the high projection the area is expected to be at mean sea level between 2075 and 2100.

5.17 BISC: Boca Chita Key



(a) **Low Projection**

(b) **High Projection**

Figure 20. Biscayne National Park: Mean sea level elevations at Boca Chita Key in Biscayne National Park. Under the low sea level rise projection the buildings are not expected to be at mean sea level by 2100, but the key will be about one-half its current area. Under the high projection the key will be entirely tidally inundated by 2100.

6 Processes not included in the projections

These mean sea level projections represent the contemporary state-of-the-art in local sea level rise projection. However, knowledge of all processes and feedbacks driving sea levels is limited, and the models on which these projections are based are necessarily incomplete. The models do not have the spatial resolution and physical process representation required to resolve fine-scale oceanographic processes such as tides and changes in the Florida Current. This means that inundation will be observed during high tides and peaks of seasonal sea level cyles several years before the projected dates when mean sea level reaches a specific land elevation.

6.1 Tides and Seasonal Cycles

Tides represent the most regular and familiar sea level changes at a coast, but are highly variable in height and timing depending on regional and local bathymetric features. Along the Cape Sable region tides produce a water level change of up to 70 cm (2.3 ft) in daily and monthly cycles. There is also a regional yearly cycle of water level from oceanographic forcings with water level changes of 30 to 40 cm (12 to 16 in, Appendix C).

6.2 Florida Current

The Florida Current is one of the strongest and most climatically important ocean currents forming the headwater of the Gulfstream (*Gyory et al.*, 1992). As the Florida Current fluctuates in intensity, sea levels along the Atlantic coast of Florida respond to a geostrophic balance by falling when the current increases, and rising when current decreases (*Montgomery*, 1938).

The Gulfstream and Florida Current are components of the Atlantic meridional overturning circulation (AMOC), a component of the global ocean conveyor belt. Climate models agree that as the ocean warms and fresh meltwater is added there will be a decline in the strength of the AMOC (*Rahmstorf et al.*, 2015). A weakening AMOC is expected to result in a weakening of the Florida Current and a subsequent increase in sea levels. The extent of this change is difficult to forecast, but recent evidence suggests that a 10% decline in transport has contributed 60% of the roughly 7 cm increase in sea level at Vaca Key over the last decade (*Park and Sweet*, 2015). Continued reduction of the AMOC and Florida Current could be expected to contribute an additional 10 to 15 cm of sea level rise to south Florida over this century. This potential is not reflected in the sea level rise projections, but should be considered by authorities and planners that use them.

6.3 Storm Surge

Although sea level rise and increases in coastal flooding are important physical stresses on south Florida natural areas, it is the infrequent, high-impact storm surge events that drastically change the landscape over the course of a few hours. For example, Hurricane Wilma in 2005 had a profound impact on the ecology of the Cape Sable region of Everglades National Park (Smith et al. 2009 (*Whelan et al.*, 2009) producing extensive damage at the Flamingo Visitor Center of Everglades National Park permanently closing the Flamingo Lodge and Buttonwood Cafe.

Storm surge is highly dependent on the severity and path of the storm, as well as the local bathymetric and topographic features of the coast, and since they occur infrequently it is difficult to develop robust predictions of these rare events. A popular approach is to fit an extreme-value probability distribution to the highest water levels observed at a water level monitoring gauge. However, gauges have short periods of record, typically a few decades at most, and they fail or are destroyed during extreme storms such that peak water levels are not recorded. A predictive storm surge database, SurgeDat was developed in part to address this shortcoming by providing a statistical combination of data from multiple events within an area of interest (*Needham et al.*, 2013). SurgeDat records storm surge water levels from all available sources, often from post-event high-water marks where gauge data are not available. SurgeDat then applies a statistical regression to estimate storm surge recurrence intervals. A recurrence interval is the length of time over which one can expect a storm surge to meet or exceed a specific inundation level. A familiar example is the 100-year flood level, which is really a 100-year recurrence interval at the specified flood level. In other words, in any one year there is a 1/100, or 1% chance that the flood level will be matched or exceeded. An excellent discussion of this can be found at the United States Geological Survey webpage water.usgs.gov/edu/100yearflood.html.

Relevant to south Florida, a subset of SurgeDat storm surge events were selected within a 25 mile radius of 25.2º N, 80.7º W to represent Florida Bay impacts and is tabulated in Appendix D. Based on these events, the SurgeDat projection for storm surge recurrence intervals shown in figure 21 suggest that a 180 cm (6 ft) surge event can be expected every 20 years. This same level of sea level rise is not anticipated to occur until at least 2100.

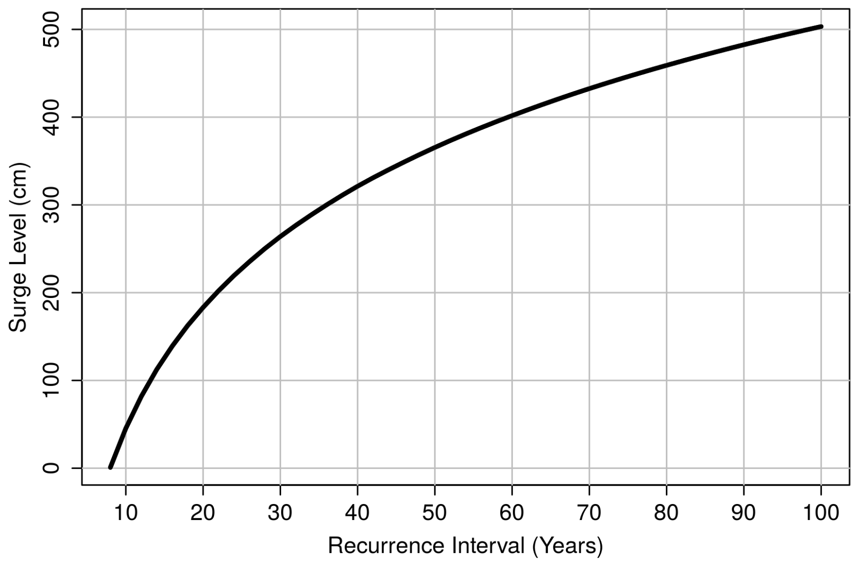


Figure 21.
Storm surge recurrence intervals from the SurgeDat database and Return Periods Predictor for a 25 mile radius centered on 25.2° N, 80.7° W.

The recurrence interval projection is by necessity based on a sparse data set, and caution should be used in its interpretation. As projection intervals become longer, it is more likely that the observed data are inadequate to robustly represent all possibilities. Also, these projections do not incorporate changes from sea level rise, or from a changing climate which can alter the strength and frequency of storms. An important aspect of sea level rise is that it significantly shortens the expected recurrence intervals of storm surge. For example, under a median sea level rise projection at Key West, *Park et al.* (2011) find that a 1-in-50 year storm surge based on historic data in 2010 can be expected to occur once every 5 years by 2060.

7 Conclusion

Sea level rise is one of the most robust indicators of climate change and a warming planet. The national parks of south Florida are intimately tied to the ocean, and are already experiencing physical and ecological changes in response to sea level rise. Based on a review of the available science, we developed a sea level rise projection to inform park interests on anticipated sea level rise, inundation, and recurrence intervals of storm surge. The sea level rise projections are based on the RCP 8.5 emissions scenario published by the IPCC AR5, as this scenario is deemed the most likely given the continued increase of atmospheric carbon dioxide and lack of widespread technological breakthroughs needed to replace carbon-based economies.

Two estimates are provided which bracket the anticipated range of sea level rise. The low projection is the 50^{th} percentile (median) forecast, while the high projection corresponds to the 99^{th} percentile with a 1% chance that mean sea level will reach or exceed this level. However, these projections do not incorporate contributions from a collapse of Antarctic ice-sheets, changes in the Florida Current. Although the high projection is deemed to have a 1% chance of occurrence under current conditions, a collapse of the Antarctic ice-sheets would render it more likely.

It is important to realize that these projections are for mean sea level and do not consider inundation due to tides or storms. Impacts from tidal inundation will first be noticed at spring tides, and then from daily high tides several years or even a decade prior to mean sea level effects.

While some Everglades infrastructure such as the Ernest F. Coe visitor center, main park entrance, Long Pine Key, Hidden Lake education center, Daniel Beard science center and Robertson fire centers are projected to be unaffected by the low sea level rise scenario out to 2100, all of these locations would be tidally inundated under the high sea level rise projection at horizons from 2075 to 2100. Pine Island, the Royal Palm visitor center and Nike missile base are expected to be at mean sea level by 2100 under the low projection and by 2075 under the high scenario. Conditions at Flamingo are mixed, with the low projection expecting the housing and visitors center to remain above mean sea level out to 2100, but with the boat basin, maintenance yard and water plant reaching mean sea level by 2100. Under the high projection the housing area is at mean sea level by 2100, the visitor center will be partially inundated by 2050, and the maintenance yard and water plant by 2075. The Key Largo Ranger Station and Science Center is not expected to be tidally inundated out to 2100, although under the high projection the fueling station will be at mean sea level by 2100.

At Dry Tortugas the projections indicate that as early as 2075 or as late as 2100 Loggerhead Key will be tidally submerged. At Fort Jefferson the north coal dock and campground remain above mean sea level to 2100 while areas around the ferry dock and the isthmus to Bush and Long Keys are expected to be at mean sea level by 2075 under the low sea level rise projection. Under the high projection much of the north coal dock and campground will be at mean sea level by 2075, as will much of the land between the ferry dock and moat although a portion of this will be at sea level by 2050. The isthmus to Bush Key is expected to be at mean sea level by 2050.

At Biscayne National Park areas surrounding the Dante Fascell Visitor Center, Adams Key and the Elliot Key Ranger Station are not expected to be at mean sea level by 2100 under the low sea level rise projection, although access to the Visitor Center on SW 328th St. is expected to be tidally inundated by 2050. Under the high projection these areas are anticipated to be at mean sea level between 2075 and 2100. Boca Chita key is expected to be about one-half below mean sea level by 2100 under the low projection, although the buildings may remain above mean sea level. Under the high projection Boca Chita will be entirely tidally submerged by 2100.

The foregoing projections and their anticipated impacts are based on the best available models and information, however, as models, observations, and our understanding of dynamic sea level and its interaction with the Everglades improves, more accurate projections will likely become available. Regardless of the specific sea level rise projection, Everglades restoration and increased freshwater flow and elevation will serve to mitigate the impacts of sea level rise over the next century.

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Appendix A Datum and Water Level Conversions

Application of sea level rise projections from *Kopp et al.* (2014) to South Florida is a two-step process. First, the projections are referenced to the geodetic datum NAVD88. Second, the projection is applied to current mean sea level in Florida Bay.

Kopp et al. (2014) assumed a water level reference of mean sea level starting at year 2000, however, the mean sea level datum at the Vaca Key tide gauge, which can be referenced to NAVD88, is with respect to the National Tidal Datum Epoch (NTDE) centered on 1992. To reference the Kopp projection to NAVD88 we must first account for sea level rise at the tide gauge from 1992 through 2000. We quantified this sea level rise at Vaca Key with an empirical mode decomposition resulting in value of 1.4 cm. This sea level rise offset is added to the Kopp projections to account for the fact that their projections start in year 2000, but that the NTDE mean sea level at Vaca Key is referenced to 1992.

Next, we convert the projections with respect to the NTDE mean sea level datum to the NAVD88 geodetic datum of the topographic elevations. Table 1 lists the NTDE and NAVD88 elevations at the Vaca Key tide gauge, where we find that the NAVD88 datum is 25.1 cm above the NTDE mean sea level (MSL) datum. In other words: MSL referenced to NAVD88 is equal to the NAVD88 datum elevation minus 25.1 cm. We therefore subtract 25.1 cm from all projected water levels with respect to mean sea level in order to reference them to the NAVD88 datum.

Datum	Value	Description
NAVD88	1.182	North American Vertical Datum of 1988
MHHW	1.072	Mean Higher-High Water
MHW	1.040	Mean High Water
MSL	0.931	Mean Sea Level
MLW	0.822	Mean Low Water
MLLW	0.775	Mean Lower-Low Water
STND	0.000	Station Datum

Table 1. Elevations on Station Datum in meters at Vaca Key, FL (NOAA station: 8723970). Tidal datum epoch: 1983-2001.

Finally, we apply the sea level rise projections with respect to NAVD88 to current mean sea level which is not at zero elevation NAVD88. As above, we note that the NTDE (1992) mean sea level at Vaca Key is -25.1 cm NAVD88, while the current sea level in Florida Bay averaged over 2008-2015 is -14.8 cm NAVD88 (Appendix C). The difference of 10.3 cm reflects sea level rise from 1992 to 2015 and any local influences of dynamic height between Vaca Key and the three stations where mean sea level was estimated.

Putting this all together, the elevation of -14.8 cm NAVD88 is the starting elevation of the sea level projections as shown in figure 1 and Appendix B. The projections from *Kopp et al.* (2014) which have been converted to NAVD88 are then added to this base sea level elevation to predict future mean sea level in Florida Bay.

The cautious reader might consider that there has been a double accounting of sea level rise, 1.4 cm representing the change from 1992 to 2000, and 10.3 cm for sea level rise from 1992 to 2015. However, these are two independent adjustments. The 1.4 cm adjustment was solely for the purpose of referencing the Kopp projections to the mean sea level datum (NTDE), which was then referenced to NAVD88, a datum conversion independent of the projection starting time. The 10.3 cm accounts for the fact that we choose 2015 as the starting point of the projections. Had we selected year 2000 as the starting point then the 1.4 cm datum conversion would still apply, while the adjustment to a starting sea level of 2000 would be less than the 10.3 cm determined for a 2015 start time.

Appendix B Tabulated Sea Level Rise Projection

Sea Level Rise in cm NAVD88 from *Kopp et al.* (2014) at Vaca Key. Values between decades (2010, 2020, etc.) have been interpolated with a cubic spline. Low is the 50th percentile of the RCP 8.5 projection, High the 99th percentile. An offset of 1.4 cm has been added to account for sea level rise from 1992 to 2000 to convert the Kopp projections starting in 2000 to the NTDE MSL datum of 1992. The NAVD88 datum is 25.3 cm above the NTDE MSL so that 25.3 cm has been subtracted to convert NTDE MSL to NAVD88. The projections have been offset to match observed mean sea level over the period 2008 2015 in Florida Bay of -14.8 cm NAVD88 (Appendix C).

Year	Low	High	Year	Low	High	Year	Low	High	Year	Low	High
2015	-14.8	-14.8	2045	6.8	18	2075	35.8	76.6	2105	68.3	159.9
2016	-14.2	-13.8	2046	7.7	19.6	2076	36.9	79	2106	69.5	162.7
2017	-13.6	-12.8	2047	8.6	21.1	2077	38	81.5	2107	70.8	165.4
2018	-12.9	-11.8	2048	9.6	22.8	2078	39.2	84	2108	72	168.3
2019	-12.3	-10.8	2049	10.5	24.4	2079	40.3	86.5	2109	73.2	171.2
2020	-11.6	-9.8	2050	11.4	26.2	2080	41.4	89.2	2110	74.4	174.2
2021	-10.9	-8.9	2051	12.3	27.9	2081	42.6	91.8	2111	75.6	177.2
2022	-10.2	-7.9	2052	13.2	29.7	2082	43.7	94.5	2112	76.7	180.3
2023	-9.5	-6.9	2053	14.1	31.6	2083	44.8	97.2	2113	77.9	183.5
2024	-8.8	-5.9	2054	15	33.5	2084	45.9	100	2114	79	186.8
2025	-8.1	-4.9	2055	15.9	35.4	2085	47.1	102.8	2115	80.1	190.1
2026	-7.4	-3.9	2056	16.8	37.3	2086	48.2	105.6	2116	81.2	193.4
2027	-6.7	-2.9	2057	17.7	39.3	2087	49.3	108.5	2117	82.2	196.8
2028	-6	-1.9	2058	18.6	41.2	2088	50.3	111.3	2118	83.3	200.2
2029	-5.3	-0.9	2059	19.5	43.2	2089	51.4	114.2	2119	84.4	203.7
2030	-4.6	0.2	2060	20.4	45.2	2090	52.4	117.2	2120	85.4	207.2
2031	-3.9	1.2	2061	21.4	47.1	2091	53.4	120.1			
2032	-3.2	2.2	2062	22.3	49	2092	54.4	123			
2033	-2.6	3.2	2063	23.3	51	2093	55.4	125.9			
2034	-1.9	4.3	2064	24.3	52.9	2094	56.3	128.9			
2035	-1.2	5.3	2065	25.3	54.9	2095	57.3	131.8			
2036	-0.5	6.4	2066	26.3	56.9	2096	58.3	134.7			
2037	0.2	7.6	2067	27.3	58.9	2097	59.3	137.6			
2038	0.9	8.7	2068	28.3	60.9	2098	60.3	140.5			
2039	1.6	9.9	2069	29.4	63	2099	61.3	143.3			
2040	2.4	11.2	2070	30.4	65.2	2100	62.4	146.2			
2041	3.2	12.4	2071	31.5	67.3	2101	63.5	148.9			
2042	4.1	13.8	2072	32.6	69.6	2102	64.7	151.7			
2043	5	15.1	2073	33.6	71.8	2103	65.9	154.4			
2044	5.9	16.6	2074	34.7	74.2	2104	67.1	157.1			

Table 2. Sea Level Rise in cm NAVD88 from *Kopp et al.* (2014).

Sea Level Rise in feet NAVD88 from *Kopp et al.* (2014) at Vaca Key. Values between decades (2010, 2020, etc.) have been interpolated with a cubic spline. Low is the 50th percentile of the RCP 8.5 projection, High the 99th percentile. An offset of 0.55 inches has been added to account for sea level rise from 1992 to 2000 to convert the Kopp projections starting in 2000 to the NTDE MSL datum of 1992. The NAVD88 datum is 0.83 feet above the NTDE MSL so that 0.83 feet has been subtracted to convert NTDE MSL to NAVD88. The projections have been offset to match observed mean sea level over the period 2008 2015 in Florida Bay of -0.49 feet NAVD88 (Appendix C).

Year	Low	High	Year	Low	High	Year	Low	High	Year	Low	High
2015	-0.49	-0.49	2045	0.22	0.59	2075	1.17	2.51	2105	2.24	5.25
2016	-0.47	-0.45	2046	0.25	0.64	2076	1.21	2.59	2106	2.28	5.34
2017	-0.45	-0.42	2047	0.28	0.69	2077	1.25	2.67	2107	2.32	5.43
2018	-0.42	-0.39	2048	0.31	0.75	2078	1.29	2.76	2108	2.36	5.52
2019	-0.40	-0.35	2049	0.34	0.80	2079	1.32	2.84	2109	2.40	5.62
2020	-0.38	-0.32	2050	0.37	0.86	2080	1.36	2.93	2110	2.44	5.72
2021	-0.36	-0.29	2051	0.40	0.92	2081	1.40	3.01	2111	2.48	5.81
2022	-0.33	-0.26	2052	0.43	0.97	2082	1.43	3.10	2112	2.52	5.92
2023	-0.31	-0.23	2053	0.46	1.04	2083	1.47	3.19	2113	2.56	6.02
2024	-0.29	-0.19	2054	0.49	1.10	2084	1.51	3.28	2114	2.59	6.13
2025	-0.27	-0.16	2055	0.52	1.16	2085	1.55	3.37	2115	2.63	6.24
2026	-0.24	-0.13	2056	0.55	1.22	2086	1.58	3.46	2116	2.66	6.35
2027	-0.22	-0.10	2057	0.58	1.29	2087	1.62	3.56	2117	2.70	6.46
2028	-0.20	-0.06	2058	0.61	1.35	2088	1.65	3.65	2118	2.73	6.57
2029	-0.17	-0.03	2059	0.64	1.42	2089	1.69	3.75	2119	2.77	6.68
2030	-0.15	0.01	2060	0.67	1.48	2090	1.72	3.85	2120	2.80	6.80
2031	-0.13	0.04	2061	0.70	1.55	2091	1.75	3.94			
2032	-0.10	0.07	2062	0.73	1.61	2092	1.78	4.04			
2033	-0.09	0.10	2063	0.76	1.67	2093	1.82	4.13			
2034	-0.06	0.14	2064	0.80	1.74	2094	1.85	4.23			
2035	-0.04	0.17	2065	0.83	1.80	2095	1.88	4.32			
2036	-0.02	0.21	2066	0.86	1.87	2096	1.91	4.42			
2037	0.01	0.25	2067	0.90	1.93	2097	1.95	4.51			
2038	0.03	0.29	2068	0.93	2.00	2098	1.98	4.61			
2039	0.05	0.32	2069	0.96	2.07	2099	2.01	4.70			
2040	0.08	0.37	2070	1.00	2.14	2100	2.05	4.80			
2041	0.10	0.41	2071	1.03	2.21	2101	2.08	4.89			
2042	0.13	0.45	2072	1.07	2.28	2102	2.12	4.98			
2043	0.16	0.50	2073	1.10	2.36	2103	2.16	5.07			
2044	0.19	0.54	2074	1.14	2.43	2104	2.20	5.15			

Table 3. Sea Level Rise in feet NAVD88 from *Kopp et al.* (2014).

Appendix C Mean Sea Level in Florida Bay

Mean sea level (MSL) was determined by averaging data over the last 7 years at three sea level stations across Florida Bay. Sea levels were first aggregated into daily averages, followed by a 30-day moving average at each station. The MSL estimate consists of an average of these three stations from July 1st 2008 through July 1st 2015 as shown in figure 22, and this MSL value of 0.97 ft NGVD29 or -14.8 cm NAVD88 (-0.49 feet NAVD88) is used as the starting point of the projections in 2015.

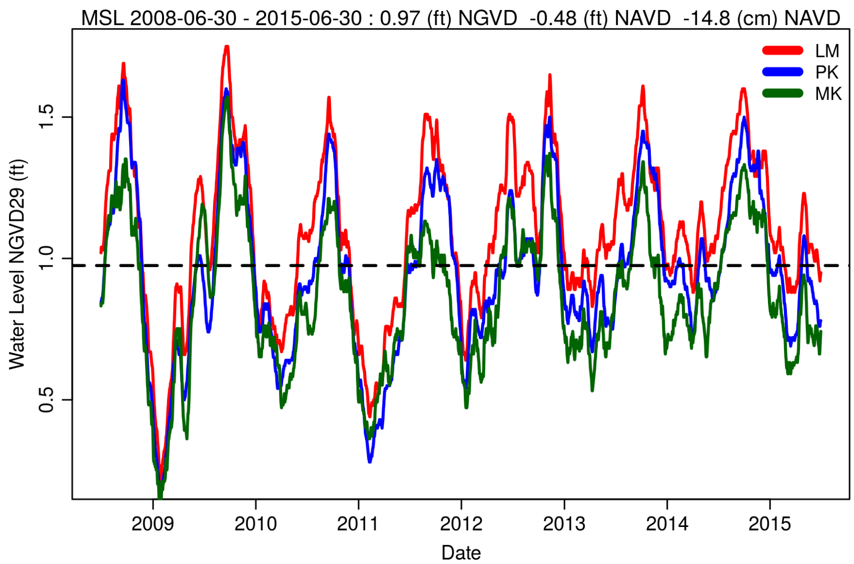

Figure 22.
30 day moving averages of daily mean sea level at Murray Key (MK), Peterson Key (PK) and Little Madeira Bay (LM) in Florida Bay. The dashed line is the mean of all three data sets.

Appendix D SurgeDat Database for Florida Bay

Storm Name	Year	Longitude	Latitude	Surge (m)	Datum	Location
Katrina	2005	-81.0369	25.1294	1.22	Extreme	SW Florida
Rita	2005	-80.7200	24.8605	1.22	NGVD 29	Middle and Upper Keys
Wilma	2005	-81.0352	25.3523	2.50		Shark River 3
Gordon	1994	-80.5139	25.0108	1.22	Above Sea Level	Upper Florida Keys
Andrew	1992	-80.9120	25.1431	1.50		Flamingo
David	1979	-80.6263	24.9231	0.61	Above Normal	Islamorada
Gladys	1968	-80.5135	25.0110	0.15	Above Normal	Tavernier
Inez	1966	-80.5297	24.9976	1.10	Above Normal	Plantation Key
Alma	1966	-80.5135	25.0110	0.30	Above Normal	Tavernier
Betsy	1965	-80.5148	25.0096	2.35	Mean Low Water	Tavernier
Donna	1960	-80.6353	24.9133	4.11		Upper Matecumbe Key
Labor Day	1935	-80.7375	24.8516	5.49		Lower Matecumbe
Unnamed	1929	-80.3885	25.1848	2.68	Mean Sea Level	Key Largo

Table 4. SurgeDat database entries for a 25 mile radius centered on 25.2° N, 80.7° W in Florida Bay.

Interval (Yr)	Surge (m)	Interval (Yr)	Surge (m)
10	0.45	56	3.88
12	0.82	58	3.95
14	1.12	60	4.02
16	1.39	62	4.08
18	1.62	64	4.15
20	1.83	66	4.21
22	2.02	68	4.27
24	2.19	70	4.33
26	2.35	72	4.38
28	2.50	74	4.44
30	2.64	76	4.49
32	2.77	78	4.54
34	2.89	80	4.59
36	3.00	82	4.64
38	3.11	84	4.69
40	3.21	86	4.73
42	3.31	88	4.78
44	3.40	90	4.82
46	3.49	92	4.87
48	3.57	94	4.91
50	3.65	96	4.95
52	3.73	98	4.99
54	3.81	100	5.03

Table 5. Recurrence Interval projection in Years from the Florida Bay SurgeDat data. Note that this projection does not take into account future sea level rise.