

Climate Change Trends and Vulnerabilities, George Washington Birthplace National Monument, Virginia

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Climate Trends for the Area within Park Boundaries

- **Historical temperature** Average annual temperature in the park increased at a statistically significant rate of $1.3 \pm 0.5^{\circ}\text{C}$ ($2.3 \pm 0.9^{\circ}\text{F.}$) per century in the period 1950-2010 (Table 1, Figure 1). Spring temperature increased at the highest rate of the four seasons (Table 1).
- **Historical precipitation** Total annual precipitation increased in the period 1950-2010, but the trend was not statistically significant (Table 2, Figure 2).
- **Projected temperature and precipitation** If the world does not reduce emissions from power plants, cars, and deforestation by 40-70%, models project future heating at up to three times the historical rate (Table 3) and increases in precipitation (Table 4).
- **Possible Aridity** Even if precipitation increases, temperature increases could overcome the cooling effects of increased precipitation, leading to increased evapotranspiration and aridity.
- **Extreme heat** Under the highest emissions scenario, models project an increase of 20-25 more days per year with a maximum temperature $>35^{\circ}\text{C}$ (95°F.) (Kunkel et al. 2013).
- **Extreme storms** Projections under the highest emissions scenario (RCP8.5) project an increase in 20-year storms (a storm with more precipitation than any other storm in 20 years) to once every 5-6 years (Walsh et al. 2014).

Historical Impacts in the Region Attributed to Human Climate Change

- **Sea level rise** Human climate change has caused a statistically significant rise in global sea level from 1901 to 2010 (Church and White 2011, IPCC 2013). The National Oceanic and Atmospheric Administration (NOAA) tidal gauge at Solomons Island, MD, north of the park on the Patuxent River at a similar distance upriver from the ocean as the park, shows that sea level increased 29 ± 2 cm (11 ± 0.8 in.) from 1937 to 2015 (Figure 4).
- **Bird range shifts** Analyses of Audubon Christmas Bird Count data across the United States, including counts at Brooke, Virginia, up the Potomac River northwest of the park, detected a northward shift of winter ranges of a set of 254 bird species at an average rate of

0.5 ± 0.3 km per year from 1975 to 2004, attributable to human climate change (La Sorte and Thompson 2007). Further analyses found poleward shifts in winter distributions of three raptor species listed by the National Park Service Inventory and Monitoring Program as observed in the park: American Kestrel (*Falco sparverius*), Red-tailed Hawk (*Buteo jamaicensis*), and Northern Harrier (*Circus cyaneus*) (Paprocki et al. 2014).

Changes Consistent with, but not Formally Attributed to Human Climate Change

- **Tree growth increase** Monitoring of broadleaf forest plots at the Smithsonian Environmental Research Center, on Chesapeake Bay north of the park, found an increase in tree growth between 1987 and 2009, consistent with, but not formally attributed to, increased atmospheric carbon dioxide and warmer temperatures due to climate change (McMahon et al. 2010). The tree species include sweet gum (*Liquidambar styraciflua*) and tulip tree (*Liriodendron tulipifera*) species found in the park.
- **Tree blooming advance** Smithsonian Institution monitoring showed a statistically significant advance of blooming of 89 tree species in Washington, DC and Baltimore, Maryland by 4.5 days from 1970 to 1999 (Abu-Asab et al. 2001). This is consistent with warmer temperatures caused by climate change. Many of the flowering trees were species found in the park, including box elder (*Acer negundo*), red maple (*Acer rubrum*), sweet gum (*Liquidambar styraciflua*), and tulip tree (*Liriodendron tulipifera*).

Future Vulnerabilities

- **Sea level rise** If the world does not reduce emissions from human activities, climate change may increase sea level by 0.5 m (emissions scenario RCP 2.6) to 0.8 m (emissions scenario RCP 8.5) by 2100 (IPCC 2013; spatial analyses by Maria Caffrey, University of Colorado, technical report in review). Mid-Atlantic sea level rise tends to be greater than global average values (Sweet et al. 2017). Substantial inundation could occur in Dancing Marsh and along Bridges Creek (Figures 5, 6). Analyses of elevation data indicate high exposure of the Visitor Center building and access road to 1 m sea level rise (Peek et al. 2015).
- **Storm surge** Storm surge would occur over and above the projected sea level rise. A category 2 storm can potentially cause flooding of the same magnitude as sea level rise (Figure 7, spatial analyses by Maria Caffrey, University of Colorado, technical report in review).
- **Cultural resources** Observations of flooding of archaeological sites along the Potomac River

east of the park indicate potential future vulnerabilities to inundation by sea level rise (Reeder-Myers 2015).

- **Invasive species** The park is in an area of high vulnerability to invasive plant and animal species due to accidental introductions from people and to climate change (Early et al. 2016).
- **Poison Ivy** Experimental increases of atmospheric carbon dioxide in a North Carolina forest indicate that climate change could increase the growth and toxicity of poison ivy (*Toxicodendron radicans*) (Mohan et al. 2006).
- **Biome shifts** The park is in an area of high vulnerability to the combined effects of biome shifts and habitat loss (Eigenbrod et al. 2015), with mixed conifer-broadleaf forest potentially shifting to temperate broadleaf forest due to climate change. The decline in recruitment of loblolly pine (*Pinus taeda*) in the 1900s (Abrams and Black 2000) is consistent with this future vulnerability.

Table 1. Historical average temperatures and temperature trends of the area within the boundaries of the park. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$. (Data: Daly et al. 2008; Analyses: Wang et al. in preparation)

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	°C		°C century ⁻¹			°C century ⁻¹		
Annual	14.6	0.5	1	0.2	***	1.3	0.5	*
December-February	3.9	1.5	1.4	0.5	**	1.1	1.4	
March-May	13.8	0.9	1.1	0.3	***	1.7	0.6	**
June-August	25.1	0.7	0.9	0.3	***	1.5	0.5	**
September-November	15.7	0.8	0.7	0.2	**	1	0.5	
January	2.4	2.4	0.3	0.8		0.5	2.4	
February	4	2.3	2	0.8	*	0.8	2.3	
March	8.5	1.5	1.1	0.5	*	2.8	1	**
April	14	1.3	1.7	0.4	***	1.5	0.9	
May	19	1.2	0.5	0.3		0.6	0.7	
June	23.7	1.1	1.1	0.3	***	1.7	0.6	**
July	26.2	1.1	0.8	0.3	*	1.1	0.8	
August	25.3	1	0.9	0.3	**	1.8	0.6	**
September	21.8	1.1	0.3	0.4		0.9	0.8	
October	15.4	1.5	0.3	0.4		0	1	
November	10	1.5	1.6	0.4	***	2.3	0.9	*
December	5	2.4	1.5	0.6	**	1.8	1.4	

Table 2. Historical average precipitation totals and precipitation trends of the area within the boundaries of the park. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$. (Data: Daly et al. 2008; Analyses: Wang et al. in preparation)

	1971-2000		1895-2010			1950-2010	
	mean	SD	trend	SE		trend	SE
	mm y ⁻¹		% century ⁻¹			% century ⁻¹	
Annual	1126	171	7	4		18	12
December-February	252	76	3	7		10	21
March-May	302	82	8	7		25	20
June-August	311	83	-7	6		5	18
September-November	261	89	31	9	***	38	21
January	86	39	-4	15		15	40
February	78	42	-9	13		-18	35
March	108	51	10	12		13	34
April	81	33	-6	11		16	28
May	113	42	19	12		43	34
June	94	46	-6	10		38	26
July	116	45	-4	11		20	27
August	102	42	-12	11		-40	31
September	98	66	33	16	*	58	38
October	86	47	19	14		45	43
November	76	39	42	16	*	5	40
December	88	44	13	11		15	32

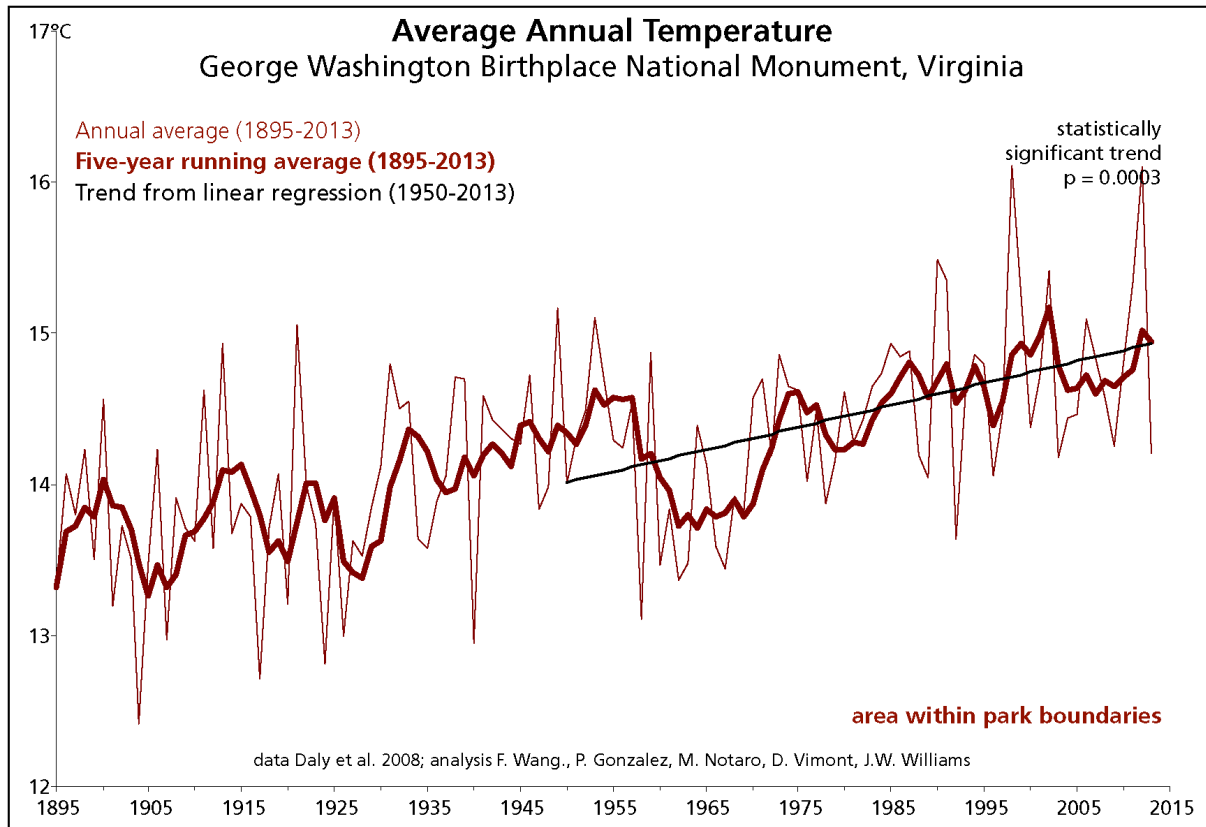
Table 3. Projected temperature increases (°C), 2000 to 2100, for the area within the boundaries of the park, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation. (Data: IPCC 2013; Analyses: Wang et al. in preparation)

	Emissions Scenarios							
	Reductions		Low		High		Highest	
	RCP2.6		RCP4.5		RCP6.0		RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.6	0.6	2.7	0.7	3.1	0.7	4.8	0.9
December-February	1.6	0.8	2.7	1	2.9	0.9	4.4	1.2
March-May	1.5	0.6	2.3	1.1	2.8	0.7	4.1	1.2
June-August	1.7	0.7	2.8	0.9	3.3	0.9	5.1	1.1
September-November	1.7	0.8	3.1	1.5	3.3	0.9	5.3	1.8
January	1.6	1	2.7	1.2	2.9	0.8	4.4	1.5
February	1.5	0.9	2.5	1	2.9	1.1	4.2	0.9
March	1.4	0.7	2.1	1.3	2.5	0.8	3.7	1.3
April	1.5	0.7	2.5	1.2	2.9	0.8	4.2	1.3
May	1.5	0.6	2.4	1.1	3	0.6	4.5	1.3
June	1.6	0.6	2.6	1.1	3.1	0.8	4.8	1.2
July	1.7	0.7	2.8	0.9	3.4	0.9	5.1	1.2
August	1.8	0.8	3.1	1	3.5	1.1	5.5	1.4
September	1.8	0.8	3.2	1.3	3.5	1	5.6	1.7
October	1.7	0.9	3.1	1.6	3.3	1	5.5	2
November	1.7	0.8	2.9	1.7	3.1	0.8	4.9	1.9
December	1.7	0.9	2.9	1.8	3	1	4.7	1.9

Table 4. Projected precipitation changes (%), 2000 to 2100, for the area within the boundaries of the park, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation. (Data: IPCC 2013; Analyses: Wang et al. in preparation)

	Emissions Scenarios							
	Reductions		Low		High		Highest	
	RCP2.6		RCP4.5		RCP6.0		RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	7	5	9	6	10	7	13	8
December-February	6	9	13	10	13	11	22	14
March-May	7	8	9	8	11	6	13	9
June-August	9	11	9	14	11	18	11	20
September-November	6	9	7	11	6	10	8	11
January	7	14	14	15	11	15	25	18
February	7	12	15	18	15	19	23	20
March	5	10	9	12	11	12	16	13
April	9	12	11	10	14	11	15	14
May	9	12	8	17	8	10	8	16
June	6	11	4	12	8	16	5	16
July	8	14	10	17	9	20	13	22
August	12	16	14	20	16	28	15	29
September	9	14	11	14	8	14	10	21
October	5	18	2	19	4	18	3	18
November	4	13	8	18	7	13	10	14
December	7	14	12	15	17	16	20	15

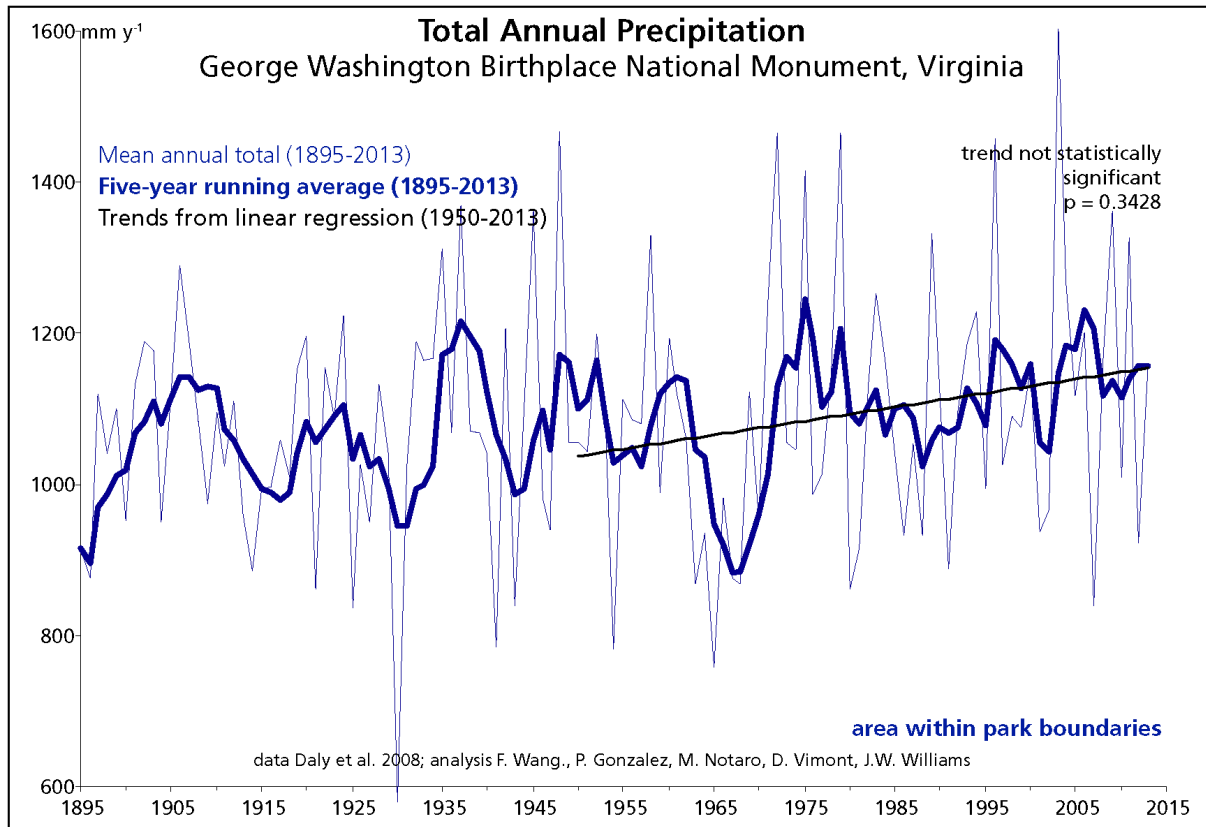
Figure 1.



Main conclusion: Temperature increased, but the rate was not statistically significant.

Note that the U.S. weather station network was more stable for the period starting 1950 than for the period starting 1895. (Data: Daly et al. 2008. Analysis: Wang et al. in preparation, University of Wisconsin and U.S. National Park Service).

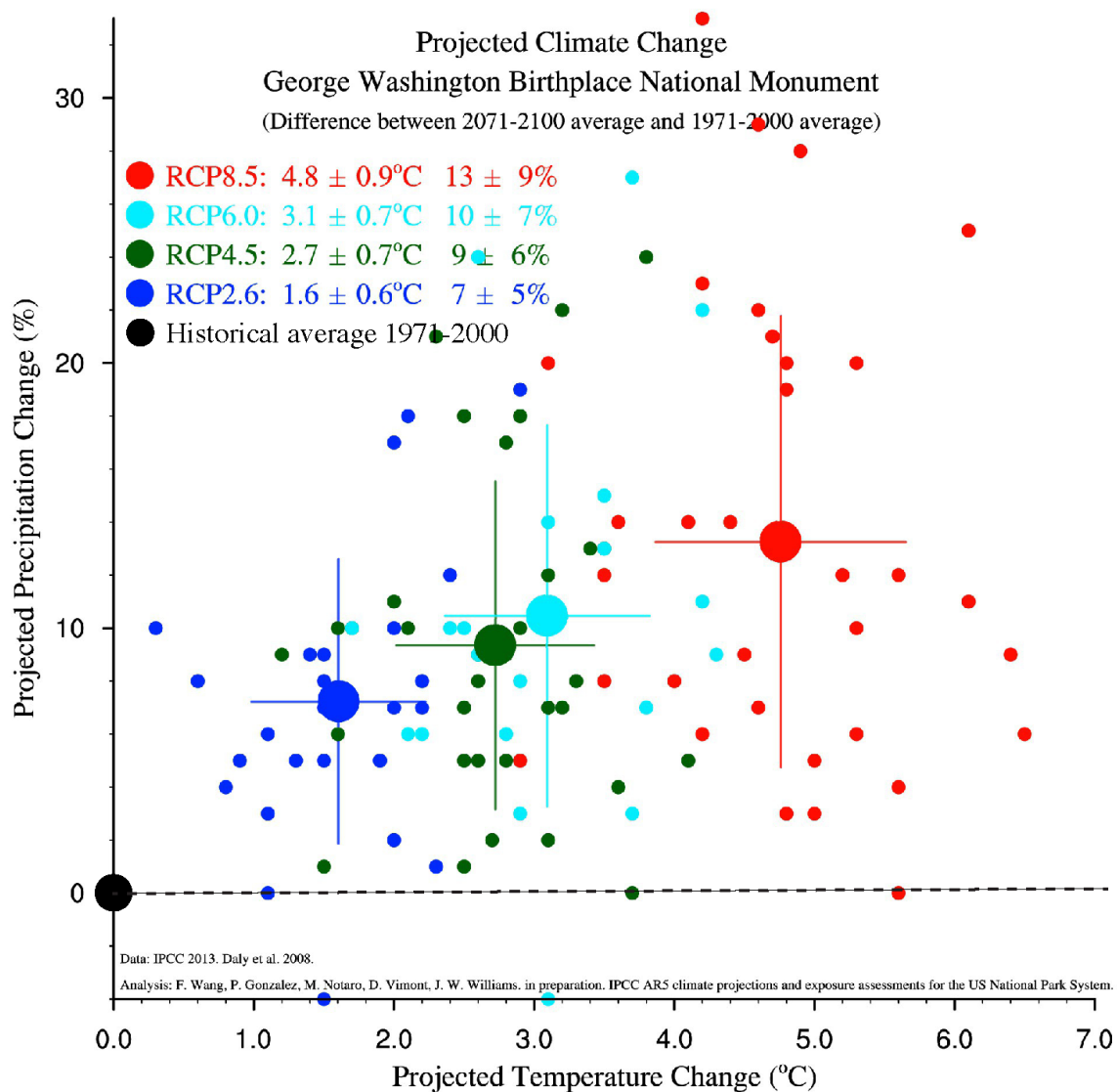
Figure 2.



Main conclusion: Precipitation did not show a statistically significant trend.

Note that the U.S. weather station network was more stable for the period starting 1950 than for the period starting 1895. (Data: Daly et al. 2008. Analysis: Wang et al. in preparation, University of Wisconsin and U.S. National Park Service).

Figure 3.

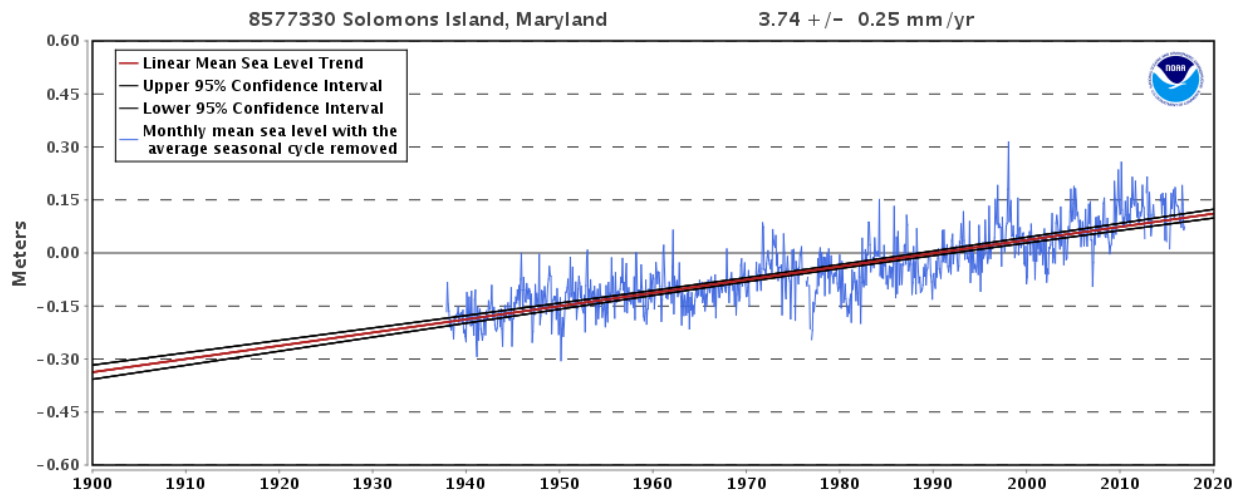


Main conclusion: Models agree on projection of temperature increases and total precipitation increases in the park.

Each small dot is the output of a single climate model. The large color dots are the average values for the four IPCC emissions scenarios and the historical baseline. The lines are the standard deviations of each average value.

Figure 4.

Sea level rise

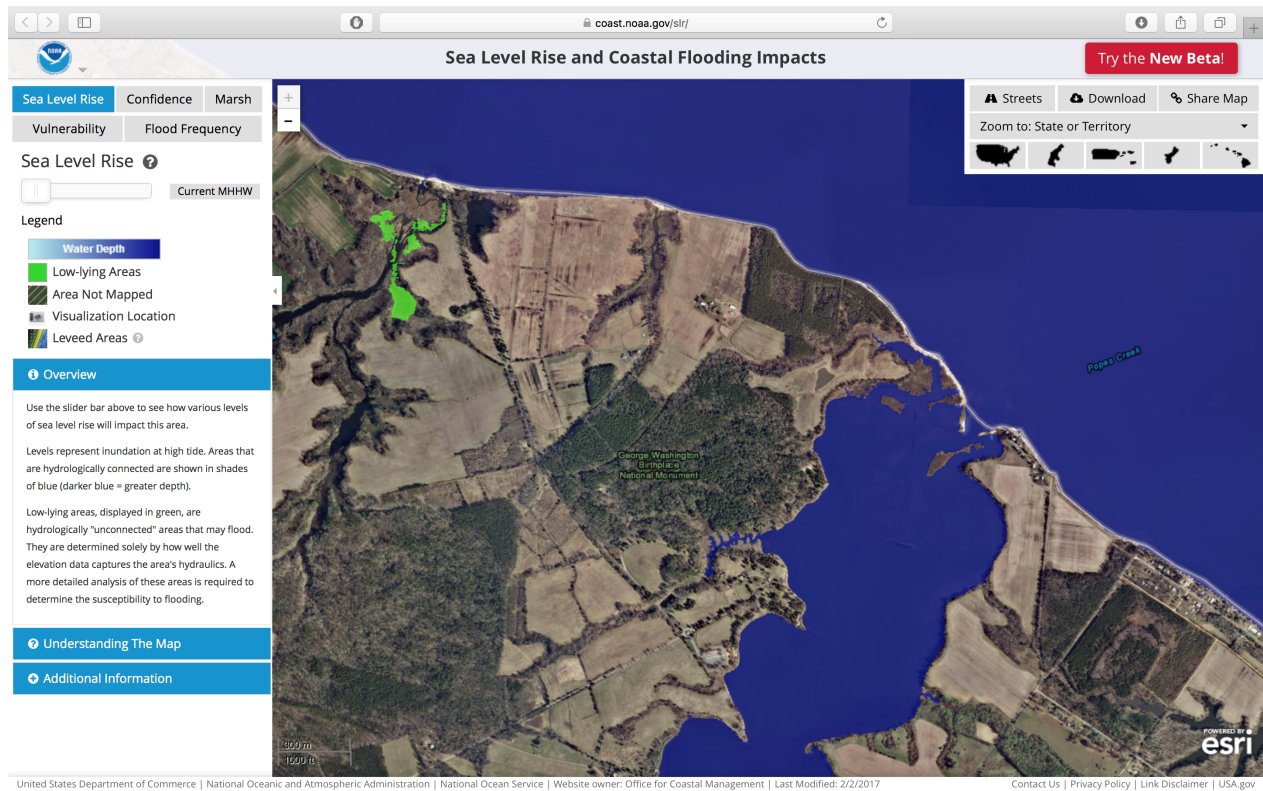


Main conclusion: Human climate change has raised sea level at a statistically significant rate near the park.

Sea level shown in relation to the 1983-2001 vertical datum. Data and graph: National Oceanic and Atmospheric Administration.

Figure 5.

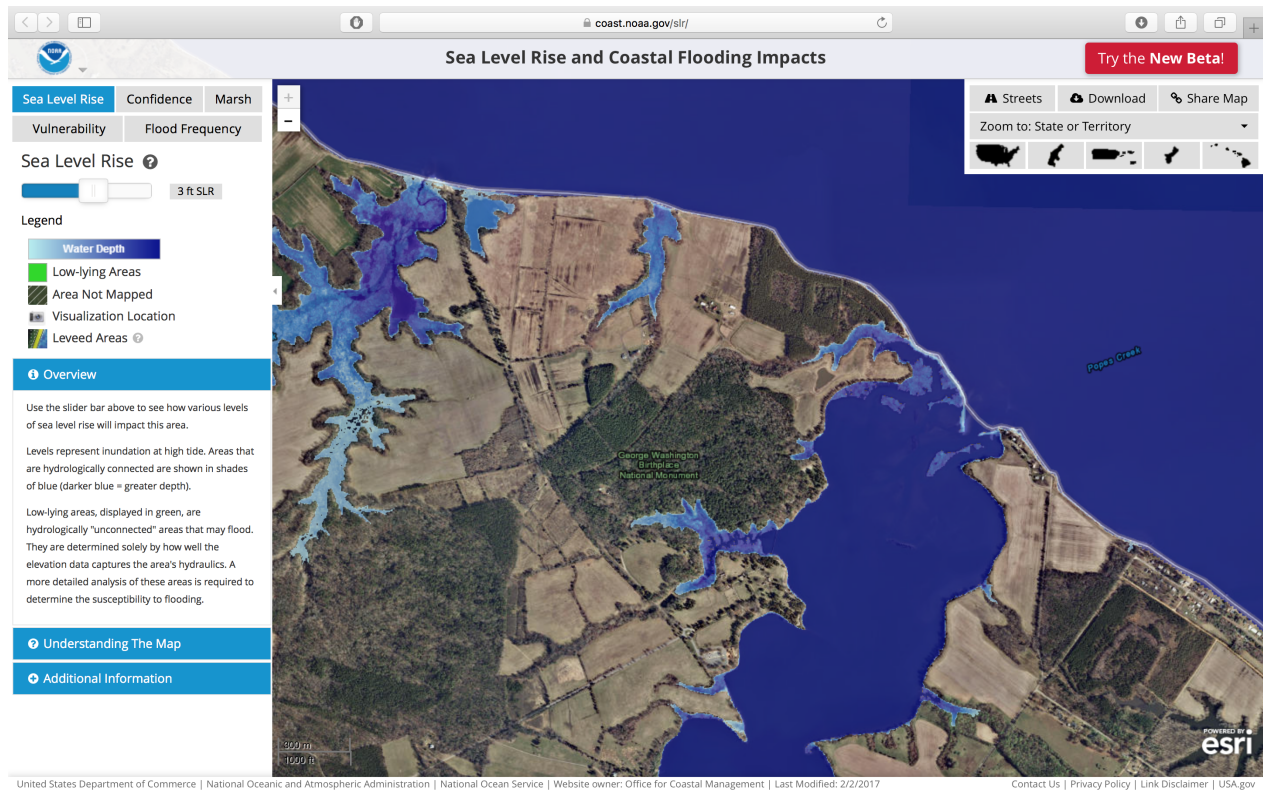
Current sea level at George Washington Birthplace NM



Data and map: National Oceanic and Atmospheric Administration

Figure 6.

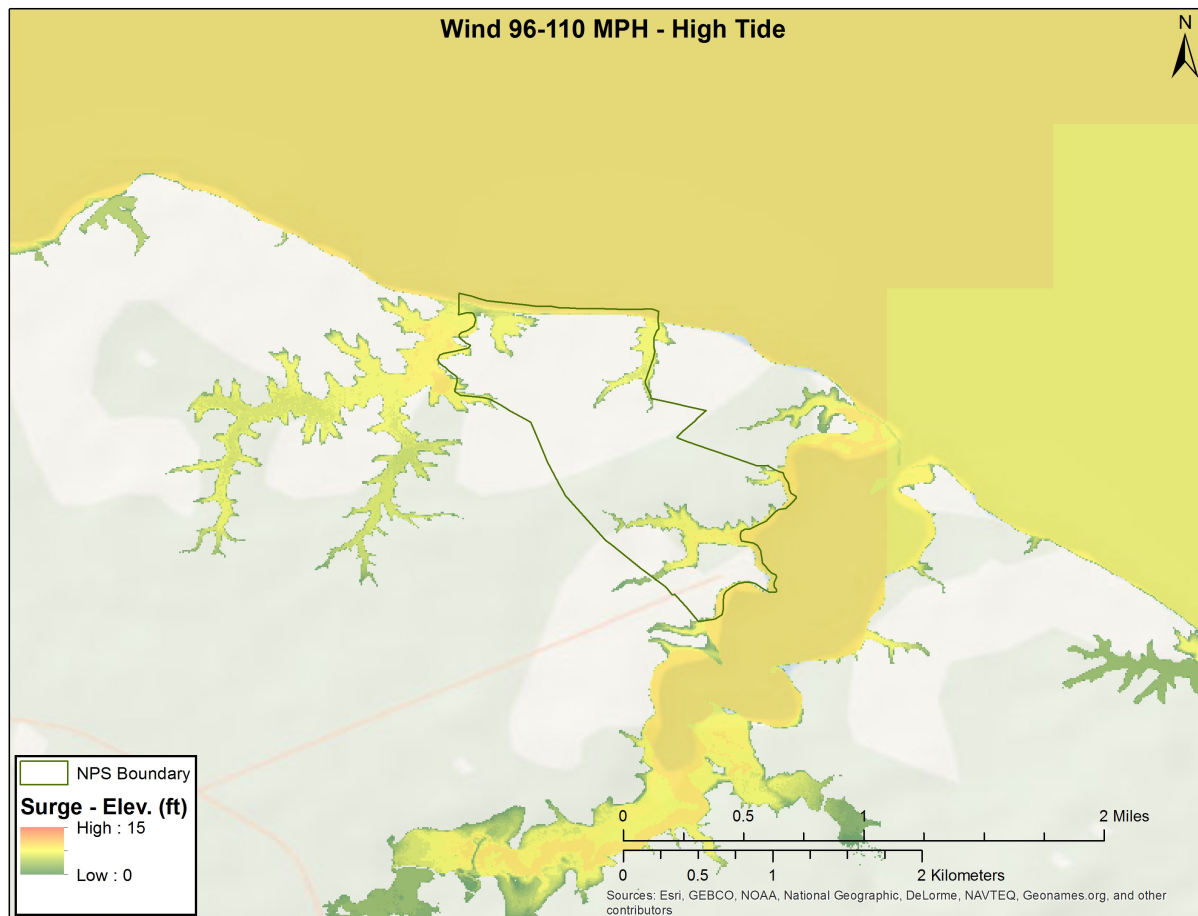
Projected sea level rise of 1 meter at George Washington Birthplace NM



Data and map: National Oceanic and Atmospheric Administration (Sweet et al. 2017)

Figure 7.

Modeled storm surge of a Category 2 storm at high tide at George Washington Birthplace NM



Data and map: Maria Caffrey, University of Colorado, technical report in review

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