

**Climate Change Trends, Impacts, and Vulnerabilities in
Blackstone River Valley National Historical Park
New Bedford Whaling National Historical Park
and Roger Williams National Memorial**

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Historical Climate Trends

- **Historical temperature** Average annual temperature in the period 1950-2010 increased in all three national parks (Tables 1, 2, 3, Figures 1, 2, 3, 4), but the rate was only statistically significant in Blackstone River Valley National Historical Park, where it increased at a rate of $1.7 \pm 0.3^{\circ}\text{C}$ ($3.1 \pm 0.5^{\circ}\text{F.}$) per century. Temperatures increased across almost the entire region (Figure 1).
- **Historical precipitation** Total annual precipitation in the period 1950-2010 increased in all three national parks (Tables 1, 4, 5, Figures 5, 6, 7), with increases statistically significant in New Bedford Whaling National Historical Park ($44 \pm 12\%$ per century) and Roger Williams National Memorial ($23 \pm 11\%$ per century).
- **Extreme events** For the Northeast U.S. as a whole, five-year storms (a storm with more precipitation than any other storm in five years) showed a statistically significant increase of 50% from 1901 to 2012 (Walsh et al. 2014).
- **Hurricanes** The U.S. National Climate Assessment has stated that “The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain” (Walsh et al. 2014). Reasons for the inability to attribute hurricane changes to human climate change include changing historical methods of tracking hurricanes, incomplete understanding of physical mechanisms, and tropical cyclone variability change (IPCC 2013).

Historical Impacts Attributed to Human-Caused Climate Change

- **Sea level rise** Human-caused 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 Providence, RI, shows that sea level increased 18 ± 2 cm (7 ± 0.8 in.) from 1938 to 2016 (Figure 8).

- **Bird range shifts** Analyses of Audubon Christmas Bird Count data across the United States, including counts at New Bedford, MA, 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).

Projected Climate Trends

- **Projected temperature** Under a scenario of highest carbon emissions from power plants, cars, and deforestation, models project future heating at up to four times the historical rates (Tables 1, 6, 7). Under a scenario of carbon emissions reductions, temperature increases could be held to the current rate.
- **Projected precipitation** If the world does not reduce emissions from power plants, cars, and deforestation by 40-70%, models project future increases in precipitation up to $15\% \pm 8\%$ (Tables 1, 8, 9). The range of four scenarios and variation in projections among the climate models generates a cloud of possible futures (Figures 9, 10).
- **Extreme heat** Under the highest emissions scenario, models project an increase of six to nine 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 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) and 15 to 18 more days with precipitation > 2.5 cm (1 inch) (Kunkel et al. 2013).
- **Hurricanes** Models project an increase in hurricane-associated storm intensity and rainfall rates under continued climate change (Walsh et al. 2014), although projections of the total number of North Atlantic hurricanes under climate change do not agree (IPCC 2013).

Future Projected Vulnerabilities

- **Sea level rise** If the world does not reduce emissions from human activities, climate change under the highest emissions scenario may increase sea level 70 cm (2 ft. 4 in.) by 2100 at New Bedford Whaling National Historical Park and Roger Williams National Memorial (IPCC 2013, Caffrey et al. in press). Under a scenario of carbon emissions reductions, climate change may raise sea level 45 cm (1 ft. 6 in.). Sea level rise of 90 cm (3 ft.) could inundate

parts of New Bedford Whaling National Historical Park near the Acushet River (Figure 11) (Sweet et al. 2017). Sea level rise of 1 m (3 ft. 3 in.) could inundate parts of the Bourne Counting House, Waterfront Park, State Pier, State Route 18, and the Wharfinger Building (Peek et al. 2015).

- **Storm surge** Storm surge would occur over and above the projected sea level rise. A category 2 hurricane can currently cause flooding of much of New Bedford Whaling National Historical Park (Figure 12, Caffrey et al. in press) and Roger Williams National Memorial (Figure 13, Caffrey et al. in press). A combination of storm surge from a category 3 hurricane over and above 60 cm (2 ft.) of sea level rise could flood much of New Bedford Whaling National Historical Park (Figure 14, Longley and Lipsky 2014).
- **River flows** In much of New England, flood magnitudes have increased since 1920, although climate is just one contributing factor (Peterson et al. 2013), with land cover change exerting a strong influence (Yang et al. 2015). In the Connecticut River, west of the parks, climate change could advance peak spring flows earlier into the year (Parr et al. 2014) but at a lower total annual flow (Demaria et al. 2016). In New England, river runoff could increase in the winter (Hayhoe et al. 2007) and decrease in other seasons (Naz et al. 2016), due to earlier snow melt under climate change (Demaria et al. 2016, Dudley et al. 2017).
- **River erosion** Higher rainfall could leave river banks generally more vulnerable to increased water erosion when a hurricane passes (Yellen et al. 2015).
- **Tree shifts** In the region of Blackstone River State Park, part of Blackstone River Valley National Historical Park, climate change could reduce maples and beeches as oaks and hickories shift from the south (Iverson et al. 2008).

Table 1. Blackstone River Valley National Historical Park. Historical rates of change and projected future changes per century in annual average temperature and annual total precipitation for the park as a whole (data Daly et al. 2008, IPCC 2013; analysis Wang et al. in preparation). The table gives the historical rate of change per century calculated from data for the period 1950-2013. The U.S. weather station network was more stable for the period starting 1950 than for the period starting 1895. The table gives central values with standard errors (historical) and standard deviations (projected).

	1950-2013	2000-2100
Historical		
temperature	+1.7 ± 0.3°C per century (3.1 ± 0.5°F.)	
precipitation	+47 ± 21% per century	
Projected (compared to 1971-2000)		
Reduced emissions (IPCC RCP2.6)		
temperature	+1.7 ± 0.8°C per century (+3.1 ± 1.4°F.)	
precipitation	+6 ± 6% per century	
Low emissions (IPCC RCP4.5)		
temperature	+2.9 ± 0.8°C per century (+5.2 ± 1.4°F.)	
precipitation	+10 ± 6% per century	
High emissions (IPCC RCP6.0)		
temperature	+3.3 ± 0.9°C per century (+5.9 ± 1.6°F.)	
precipitation	+11 ± 6% per century	
Highest emissions (IPCC RCP8.5)		
temperature	+5.0 ± 1°C per century (+9 ± 1.8°F.)	
precipitation	+15 ± 8% per century	

Table 2. New Bedford Whaling National Historical Park. 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	10.7	0.7	1.1	0.3	***	-0.4	0.5	
December-February	0	1.4	1.3	0.5	*	-1	1.2	
March-May	8.7	0.9	0.9	0.3	**	-0.4	0.6	
June-August	21.5	0.9	1.5	0.3	**	0.5	0.7	
September-November	12.6	0.9	0.9	0.3	**	-0.9	0.5	
January	-1.1	2.4	0.2	0.7		-1.9	2	
February	-0.5	2	1.9	0.7	**	-1.2	1.9	
March	3.5	1.5	1	0.4	*	-0.2	0.8	
April	8.5	1.1	1.2	0.3	***	-0.8	0.7	
May	14.2	1.2	0.6	0.3		-0.2	0.8	
June	19.4	1.1	1.3	0.4	**	0.3	0.8	
July	22.9	1	1.3	0.3	***	0.3	0.7	
August	22.3	1.1	1.8	0.4	***	1	0.9	
September	18.3	1	1	0.4	**	0.4	0.8	
October	12.4	1.4	0.4	0.4		-2	0.9	*
November	7.2	1.5	1.2	0.4	**	-1.2	0.8	
December	1.7	2.4	1.5	0.5	**	0.3	1.3	

Table 3. Roger Williams National Memorial. 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	10.5	0.6	0.3	0.2		1	0.6	
December-February	-0.5	1.5	0.8	0.5		1	1.5	
March-May	9.1	0.9	0.2	0.3		1.4	0.6	*
June-August	21.5	0.7	0.3	0.2		1.2	0.4	**
September-November	11.9	0.9	0.1	0.2		0.4	0.5	
January	-1.9	2.5	-0.2	0.7		-0.1	2.2	
February	-0.6	2.3	1.7	0.7	*	1.2	2.3	
March	3.6	1.4	0.4	0.5		2	0.9	*
April	9.1	1.2	0.7	0.3	*	1.2	0.9	
May	14.6	1.1	-0.4	0.3		1.1	0.8	
June	19.6	1	0.3	0.3		1	0.6	
July	22.8	0.9	0	0.3		0.8	0.7	
August	22	0.9	0.7	0.3	*	1.9	0.7	*
September	17.6	1	0	0.3		1.7	0.8	*
October	11.6	1.5	-0.5	0.4		-0.9	0.9	
November	6.5	1.5	0.7	0.3	*	0.5	0.8	
December	1	2.3	0.7	0.5		1.9	1.4	

Table 4. New Bedford Whaling National Historical Park. 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	1290	187	19	5	***	44	13	**
December-February	341	92	16	8	*	15	21	
March-May	324	85	24	9	**	57	21	**
June-August	305	101	16	9		59	23	*
September-November	318	83	23	8	**	49	20	*
January	119	62	11	14		24	43	
February	102	44	5	11		-12	28	
March	120	45	33	14	*	86	34	*
April	111	50	18	11		42	28	
May	94	36	21	15		35	39	
June	101	68	24	17		121	44	**
July	90	42	11	15		88	43	*
August	114	65	14	13		-14	37	
September	99	57	16	16		61	35	
October	101	43	27	14		95	37	*
November	119	54	25	12	*	0	28	
December	121	57	26	14		21	35	

Table 5. Roger Williams National Memorial. 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	1218	182	12	4	**	23	11	*
December-February	310	93	6	7	0.3914	1	20	
March-May	315	92	16	8	*	37	21	
June-August	279	88	7	9	0.4227	37	20	
September-November	314	81	20	8	*	21	18	
January	113	63	2	14		8	45	
February	90	38	-9	10		-25	25	
March	114	48	20	13		58	32	
April	107	52	12	11		24	28	
May	94	40	16	14		26	38	
June	89	68	18	16		98	40	*
July	87	36	-2	15		58	37	
August	103	53	6	14		-29	41	
September	98	52	8	15		34	33	
October	102	46	33	15	*	61	42	
November	114	54	20	12		-25	26	
December	107	59	20	13		9	35	

Table 6. New Bedford Whaling National Historical Park. 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	0.8	2.7	0.8	3	0.9	4.6	1
December-February	1.8	0.9	3	1.1	3.3	0.9	4.9	1.3
March-May	1.5	0.8	2.3	1.1	2.8	1	4.1	1.2
June-August	1.5	0.8	2.5	1	2.9	0.9	4.6	1.2
September-November	1.7	0.7	2.9	1.3	3.2	0.9	5	1.6
January	1.9	1.1	3.1	1.3	3.3	1	5.1	1.4
February	1.7	1.1	2.8	0.9	3.2	1.1	4.7	1
March	1.5	0.9	2.4	1.2	2.8	1.1	4.1	1.3
April	1.5	0.9	2.4	1.1	2.8	1.1	4.1	1.2
May	1.4	0.9	2.3	1.1	2.8	1	4	1.3
June	1.4	0.9	2.3	1.2	2.7	0.9	4.2	1.3
July	1.5	0.9	2.5	1.1	3	0.9	4.6	1.3
August	1.6	0.8	2.7	0.9	3.1	0.9	4.9	1.2
September	1.7	0.8	2.9	1.1	3.2	1	5.1	1.4
October	1.6	0.8	2.9	1.4	3.1	1	5	1.7
November	1.7	0.8	2.9	1.5	3.2	0.8	4.9	1.7
December	1.9	0.9	3.1	1.6	3.3	0.9	5	1.7

Table 7. Roger Williams National Memorial. 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	1.7	0.8	2.8	0.8	3.2	0.9	4.8	1
December-February	1.9	0.9	3.1	1.1	3.4	1	5.1	1.3
March-May	1.5	0.8	2.4	1.2	2.9	1	4.2	1.3
June-August	1.6	0.8	2.6	1	3.1	0.9	4.8	1.2
September-November	1.7	0.8	3	1.4	3.3	0.9	5.2	1.7
January	2	1.1	3.3	1.3	3.5	1	5.3	1.5
February	1.8	1.1	2.9	1	3.3	1.2	4.9	1.1
March	1.6	0.9	2.4	1.3	2.9	1.1	4.2	1.4
April	1.5	0.9	2.5	1.2	3	1.1	4.2	1.3
May	1.5	0.9	2.3	1.2	2.9	0.9	4.2	1.3
June	1.5	0.9	2.4	1.2	2.8	0.9	4.3	1.3
July	1.6	0.9	2.6	1.1	3.2	0.9	4.8	1.3
August	1.7	0.8	2.8	0.9	3.3	1	5.2	1.2
September	1.7	0.8	3	1.2	3.4	1	5.4	1.6
October	1.7	0.8	3	1.5	3.2	1	5.2	1.9
November	1.7	0.8	3	1.6	3.3	0.8	5	1.9
December	2	0.9	3.3	1.7	3.5	1	5.2	1.8

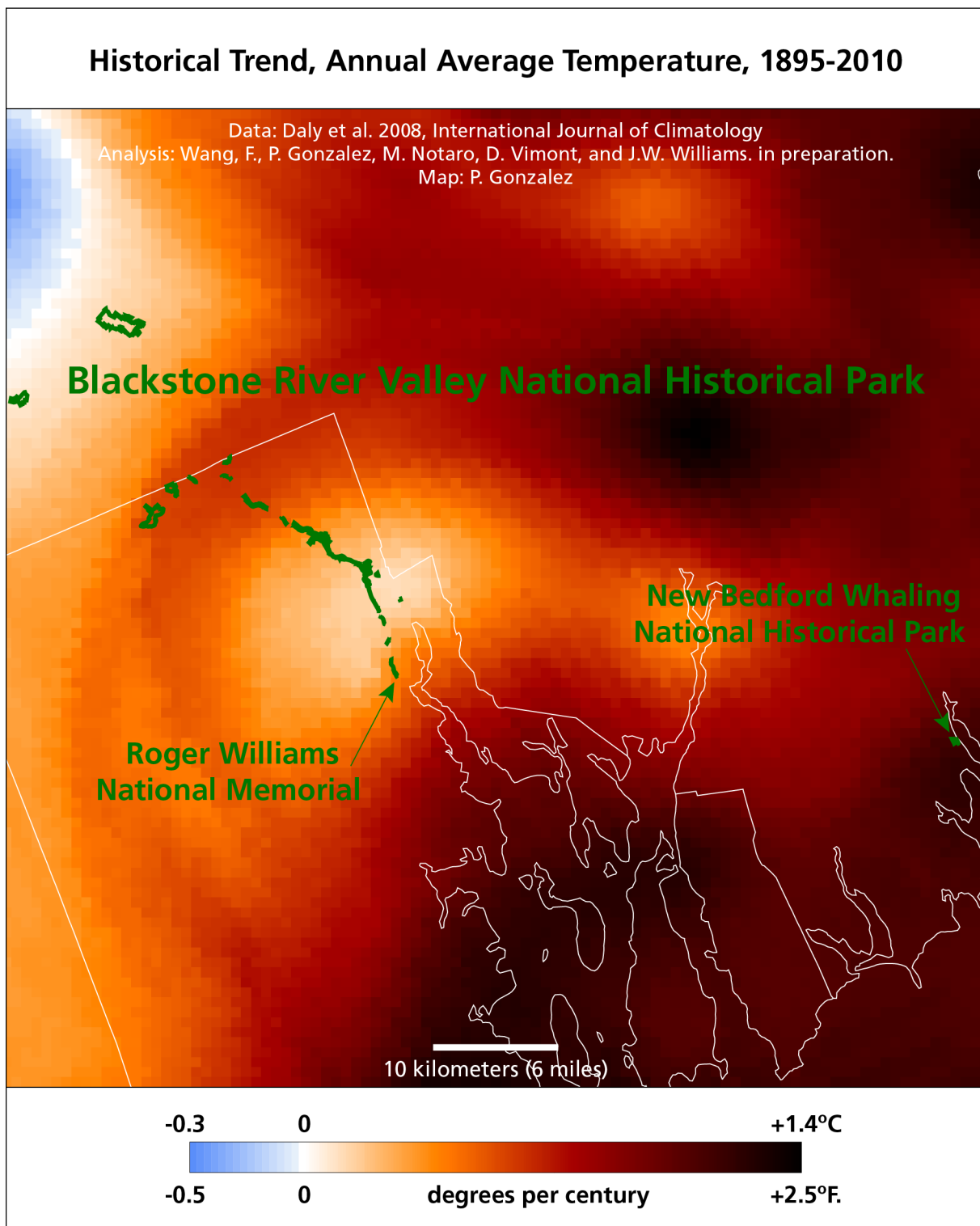
Table 8. New Bedford Whaling National Historical Park. Projected precipitation changes (%), 2000 to 2100, for the area within the boundaries of the park, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard 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	6	6	9	6	10	6	13	8
December-February	8	9	15	9	16	8	25	14
March-May	6	8	9	9	9	8	15	10
June-August	7	14	10	16	9	17	9	19
September-November	3	8	4	9	5	9	4	11
January	10	18	19	17	17	16	33	22
February	6	11	15	14	15	11	21	13
March	9	13	13	11	13	11	22	16
April	7	14	9	17	7	13	14	18
May	3	15	4	12	6	13	10	12
June	6	20	10	21	8	27	12	24
July	7	16	8	19	11	18	7	21
August	8	17	11	23	9	20	9	31
September	2	10	3	14	3	13	0	18
October	2	18	0	16	-2	16	0	22
November	6	11	8	14	13	12	12	15
December	9	12	13	11	17	15	22	16

Table 9. Roger Williams National Memorial. 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)

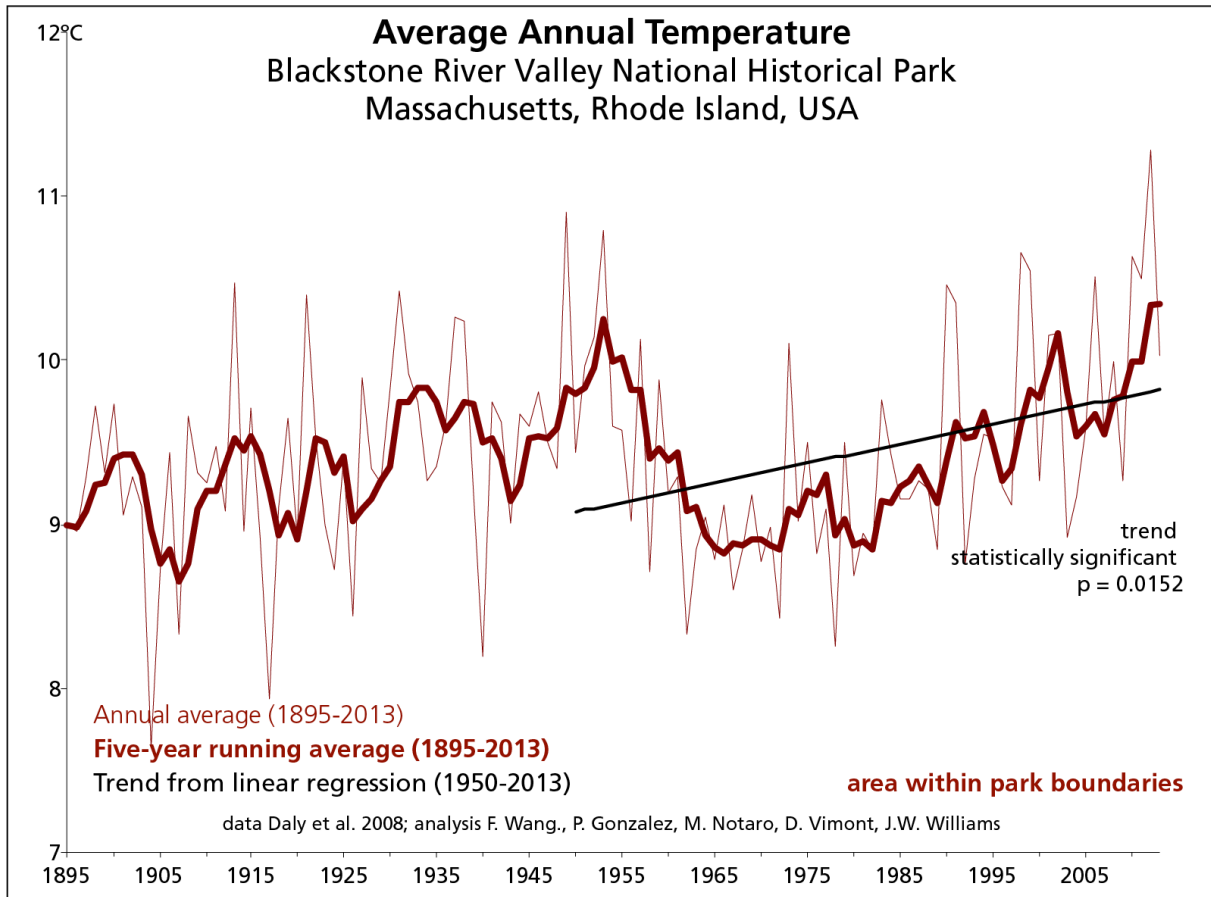
	Emissions Scenarios							
	Reductions		Low		High		Highest	
	RCP2.6		RCP4.5		RCP6.0		RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	6	6	10	6	10	6	15	8
December-February	8	9	16	9	17	8	26	14
March-May	7	8	9	9	10	7	16	10
June-August	7	13	11	14	9	15	12	17
September-November	3	7	4	9	6	8	5	11
January	11	19	20	17	19	16	34	23
February	6	11	15	15	16	11	22	14
March	9	13	14	12	14	11	21	15
April	7	14	10	17	8	12	15	18
May	5	15	4	11	7	13	12	11
June	6	19	11	20	9	24	13	22
July	8	15	9	17	10	17	9	18
August	8	17	14	25	10	19	14	32
September	3	11	4	14	4	12	1	18
October	2	18	0	15	-2	15	1	21
November	6	10	8	13	14	12	13	15
December	9	13	13	10	18	15	23	16

Figure 1.



Main conclusion: Temperature increased across the area of the parks.

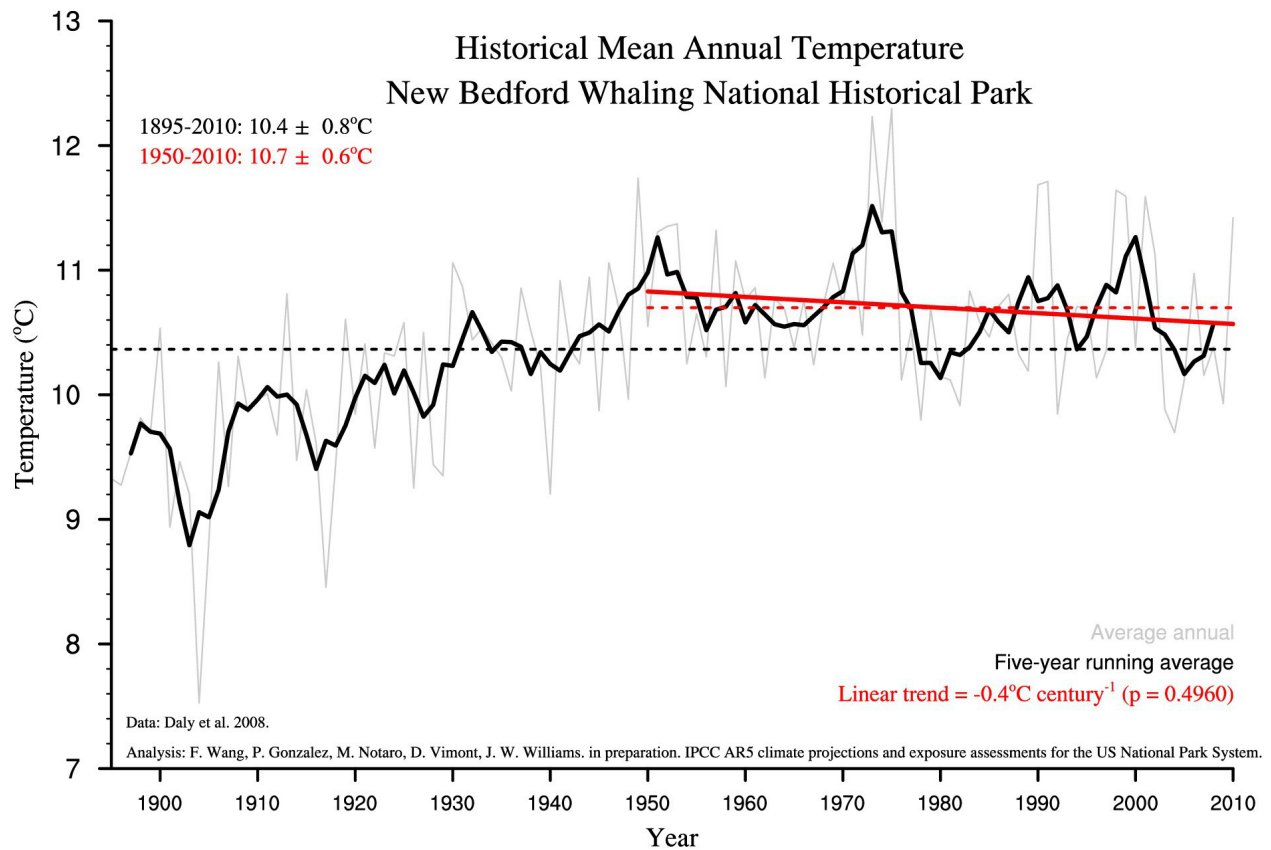
Figure 2.



Main conclusion: Temperature increased at a statistically significant rate.

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).

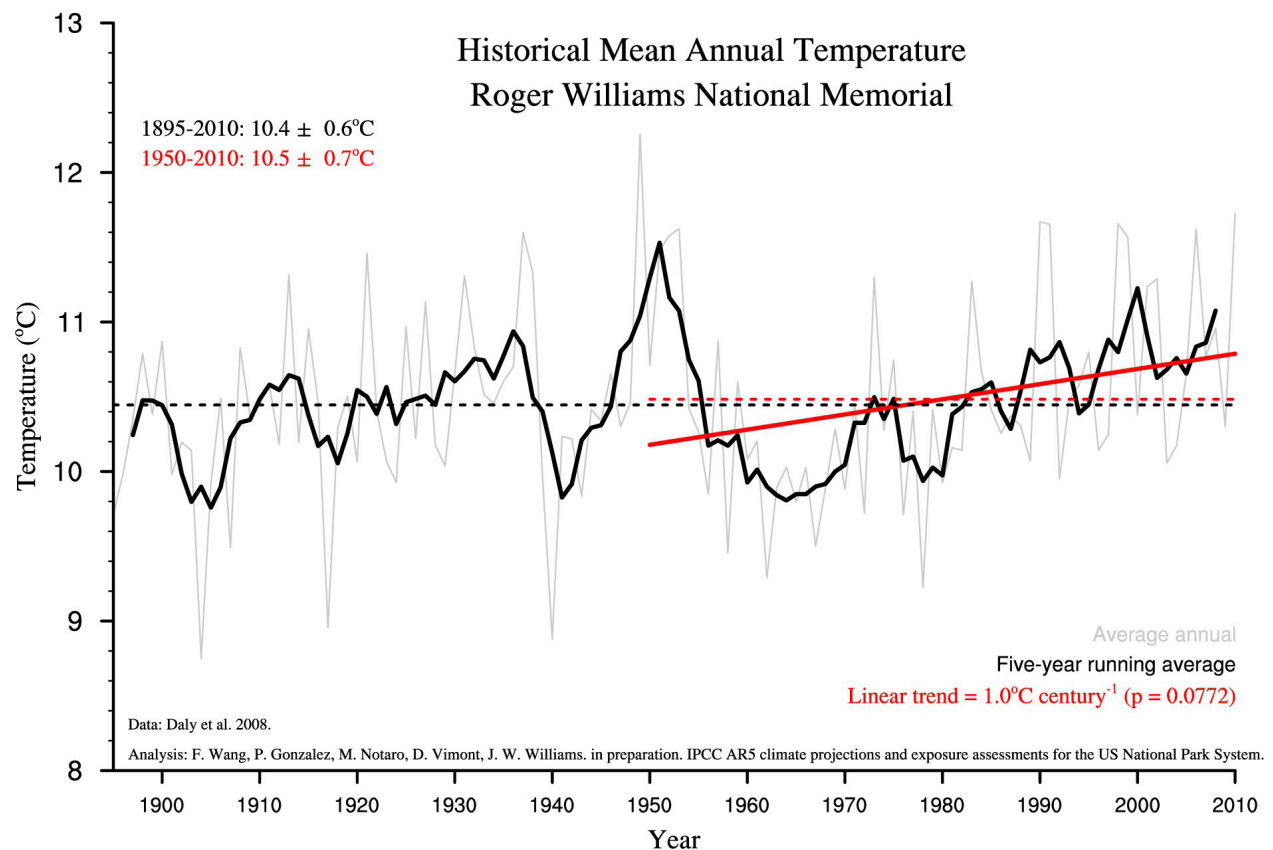
Figure 3.



Main conclusion: 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).

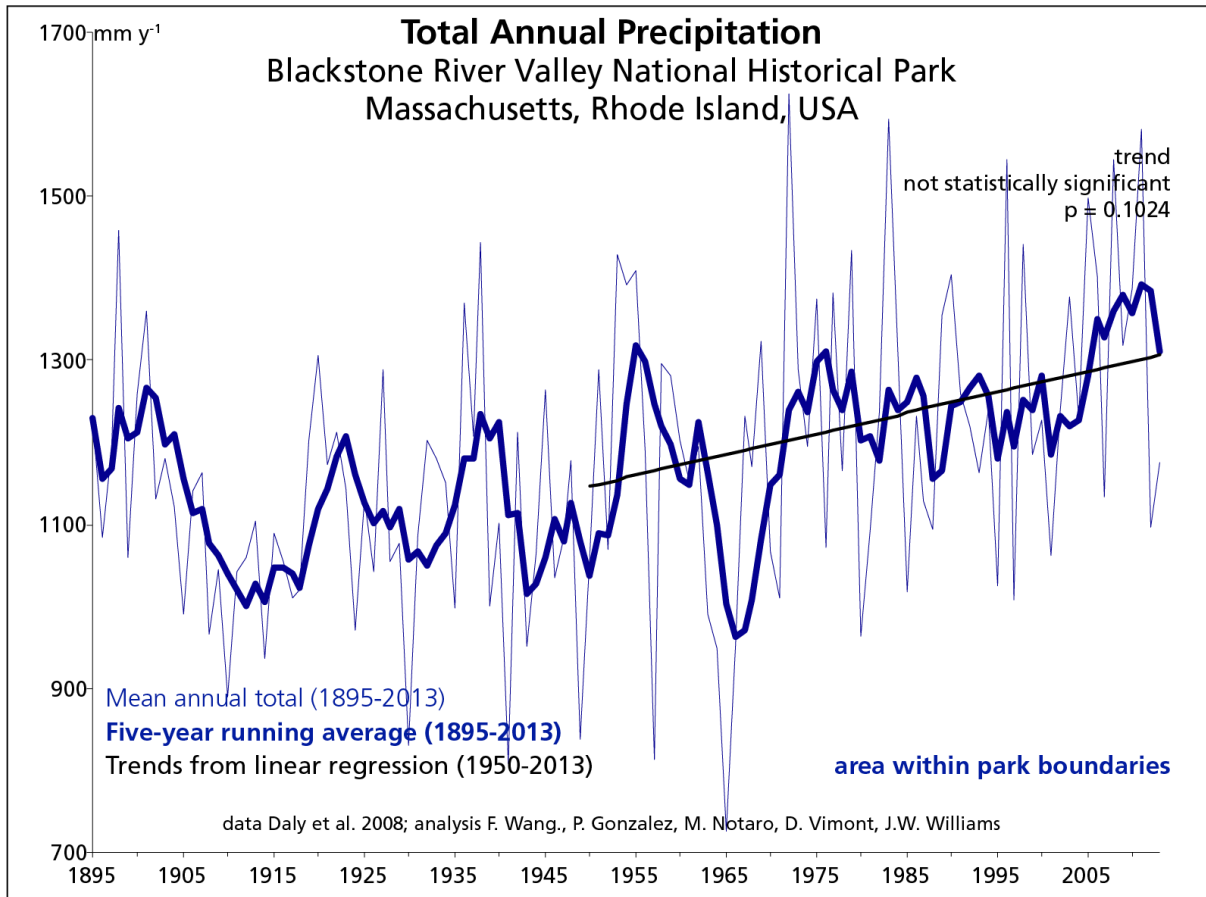
Figure 4.



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).

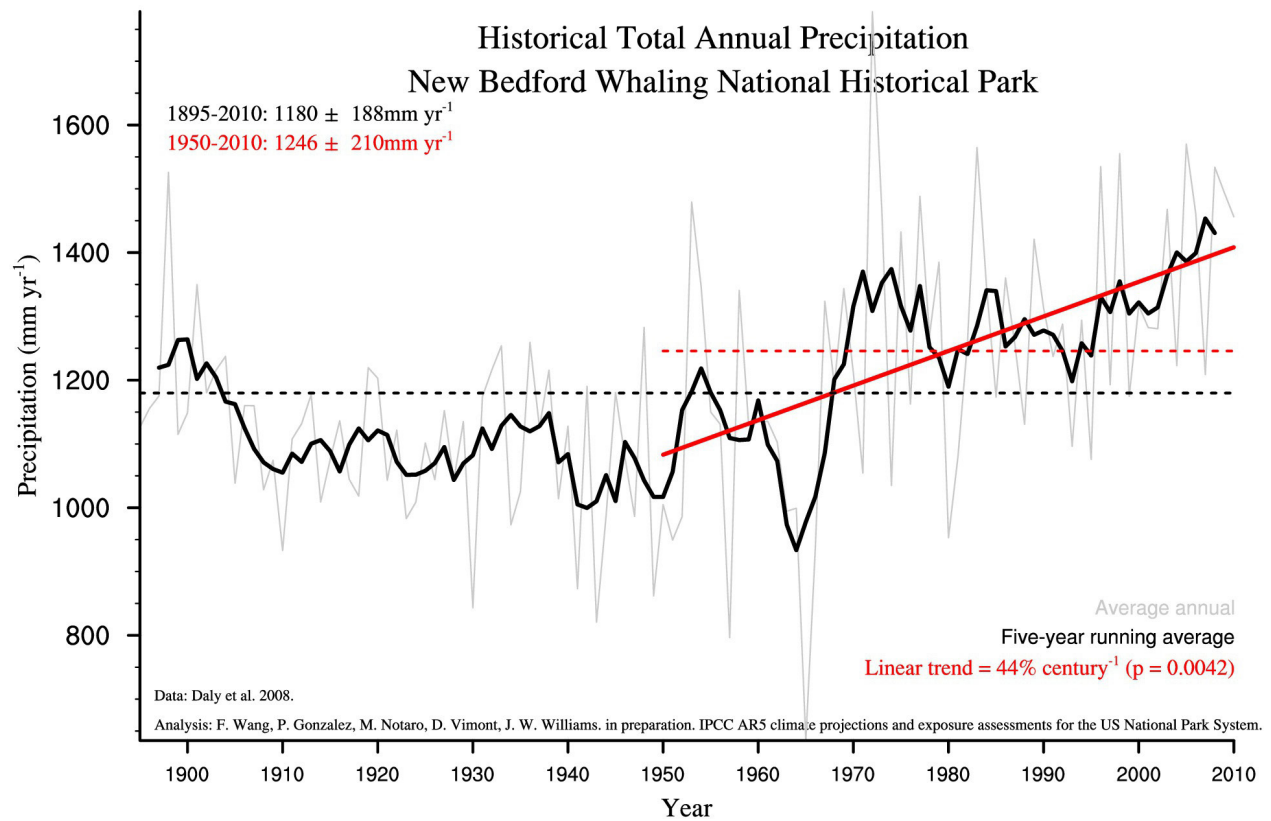
Figure 5.



Main conclusion: Precipitation 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).

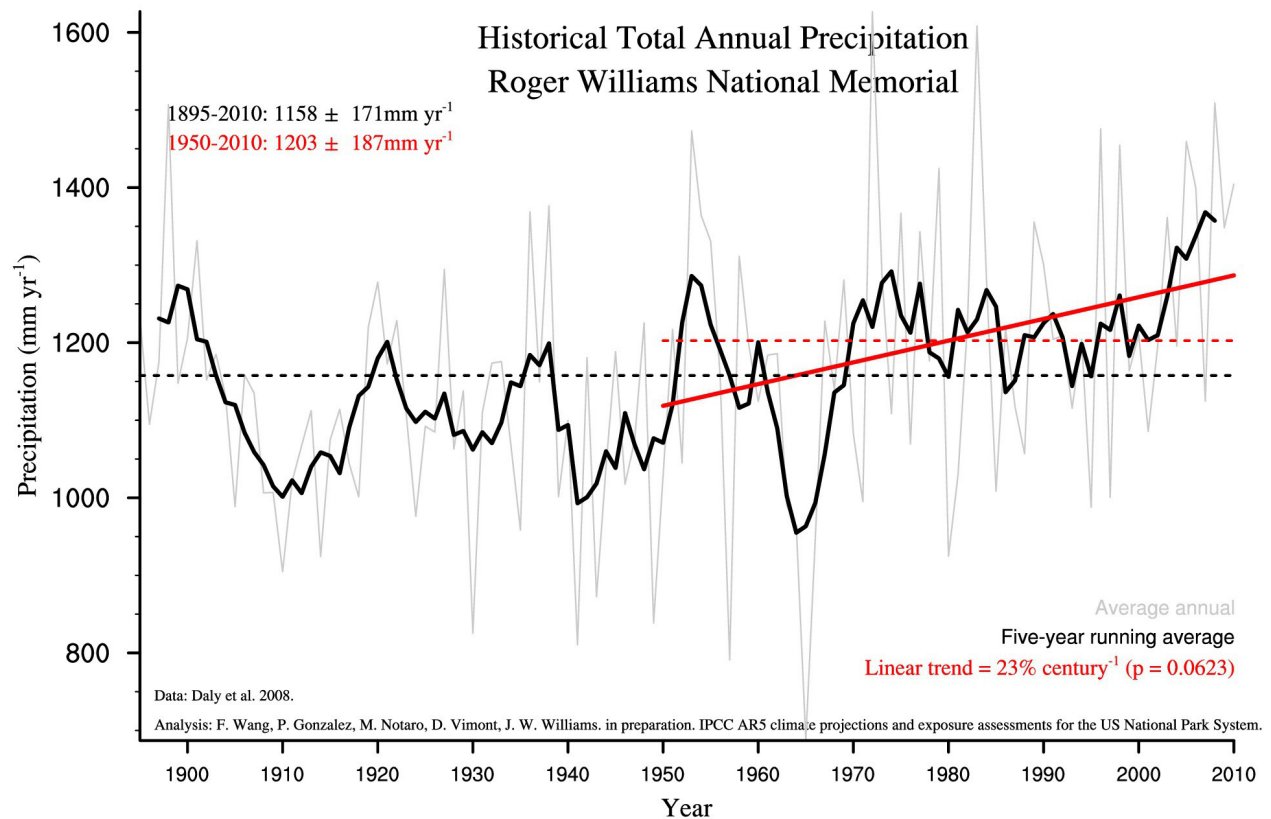
Figure 6.



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).

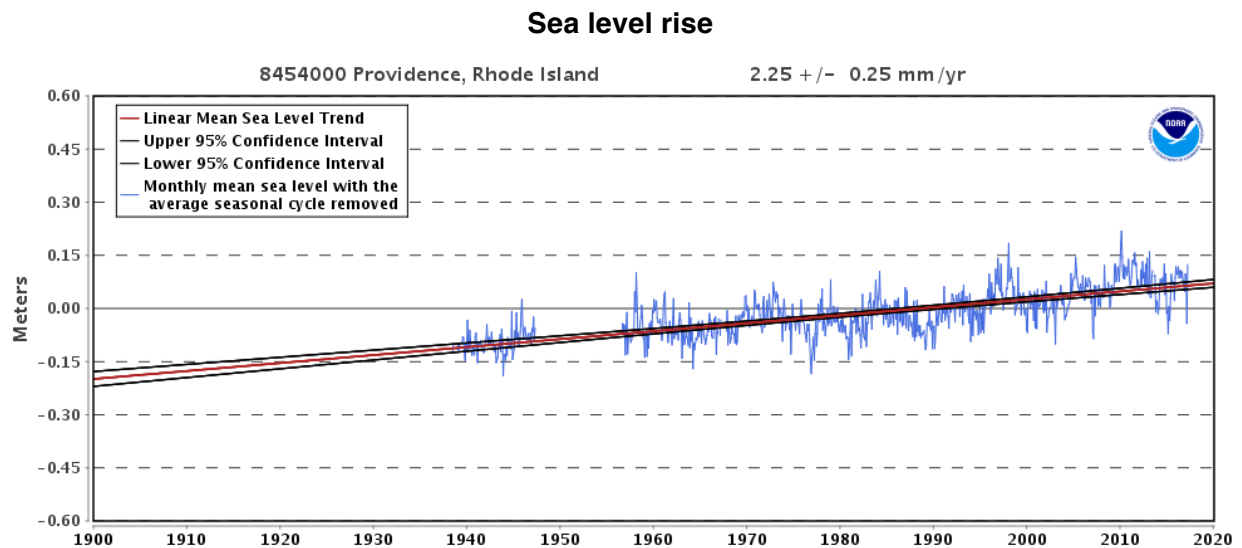
Figure 7.



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).

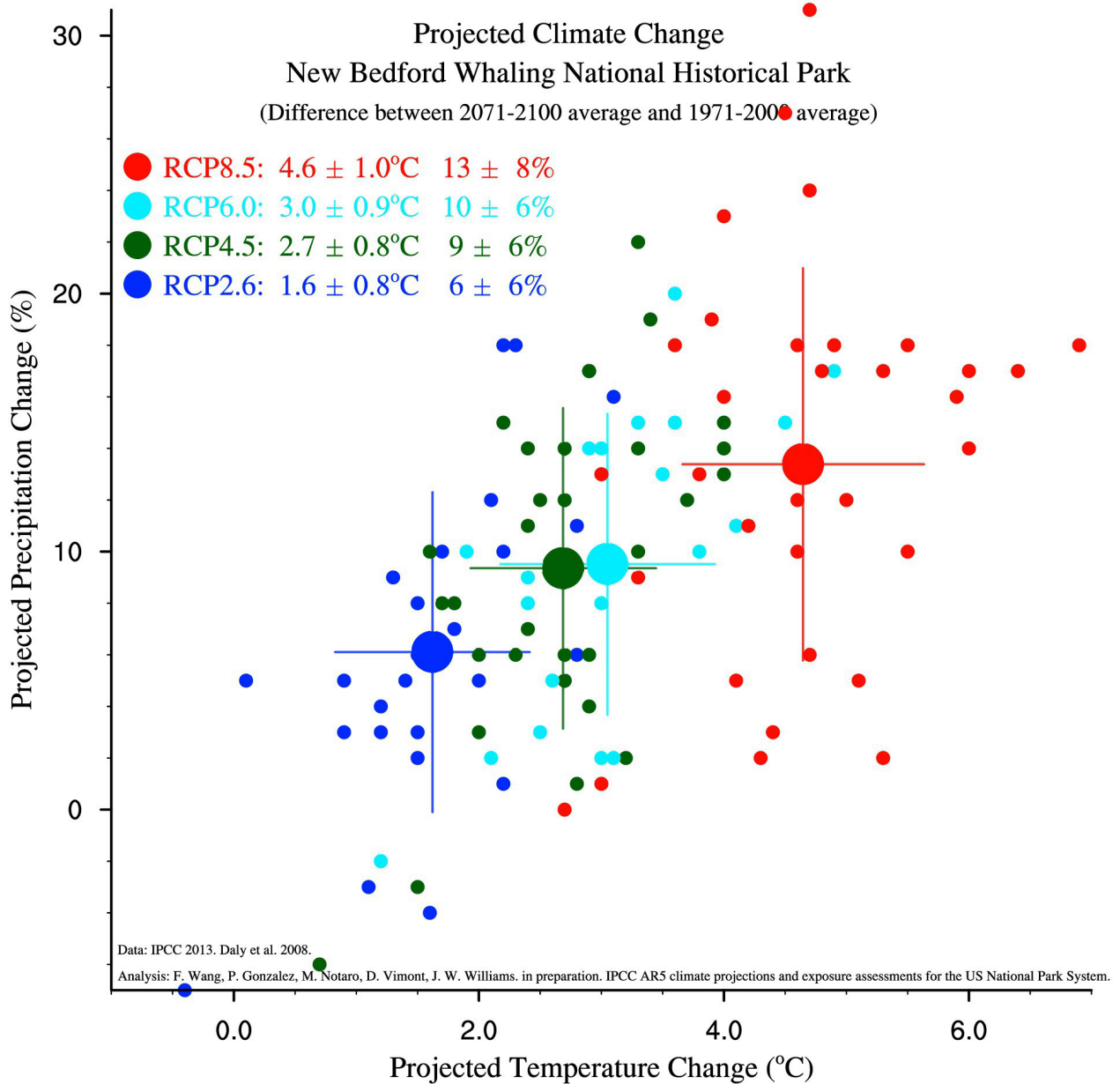
Figure 8.



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

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

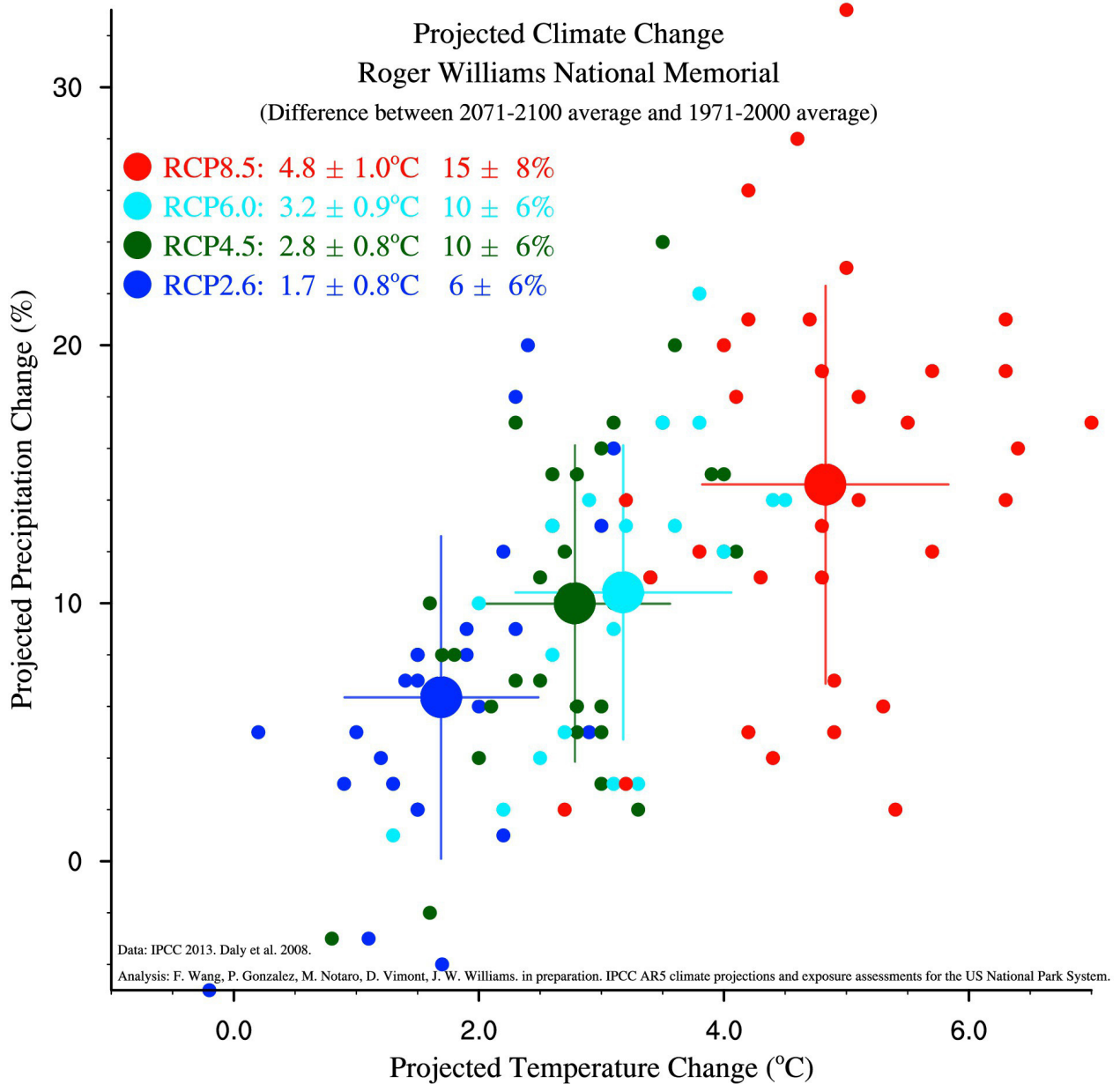
Figure 9.



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 10.

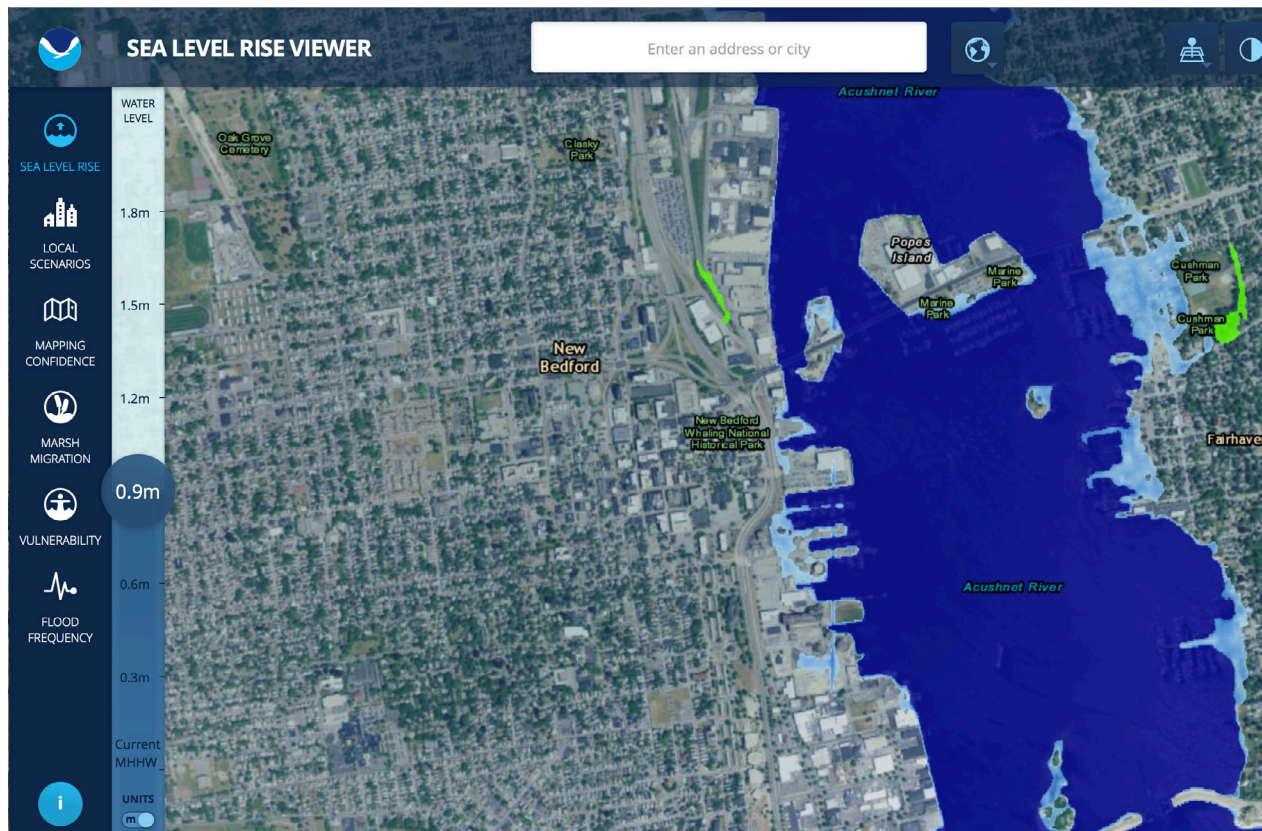


Main conclusion: Models agree on projection of temperature increases and total precipitation increases in the park.

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 11.

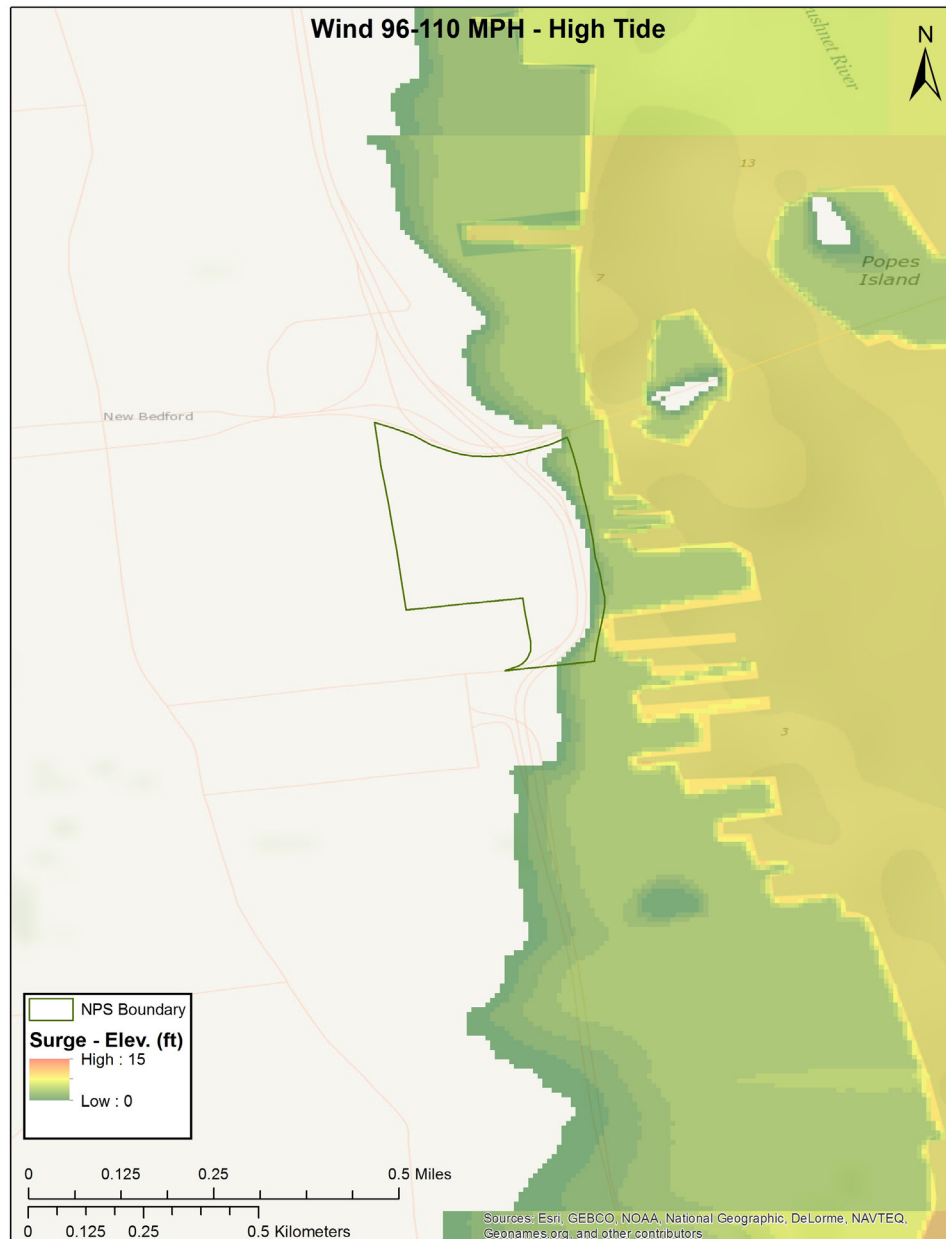
Projected sea level rise of 90 cm (3 ft.) at New Bedford Whaling National Historical Park



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

Figure 12.

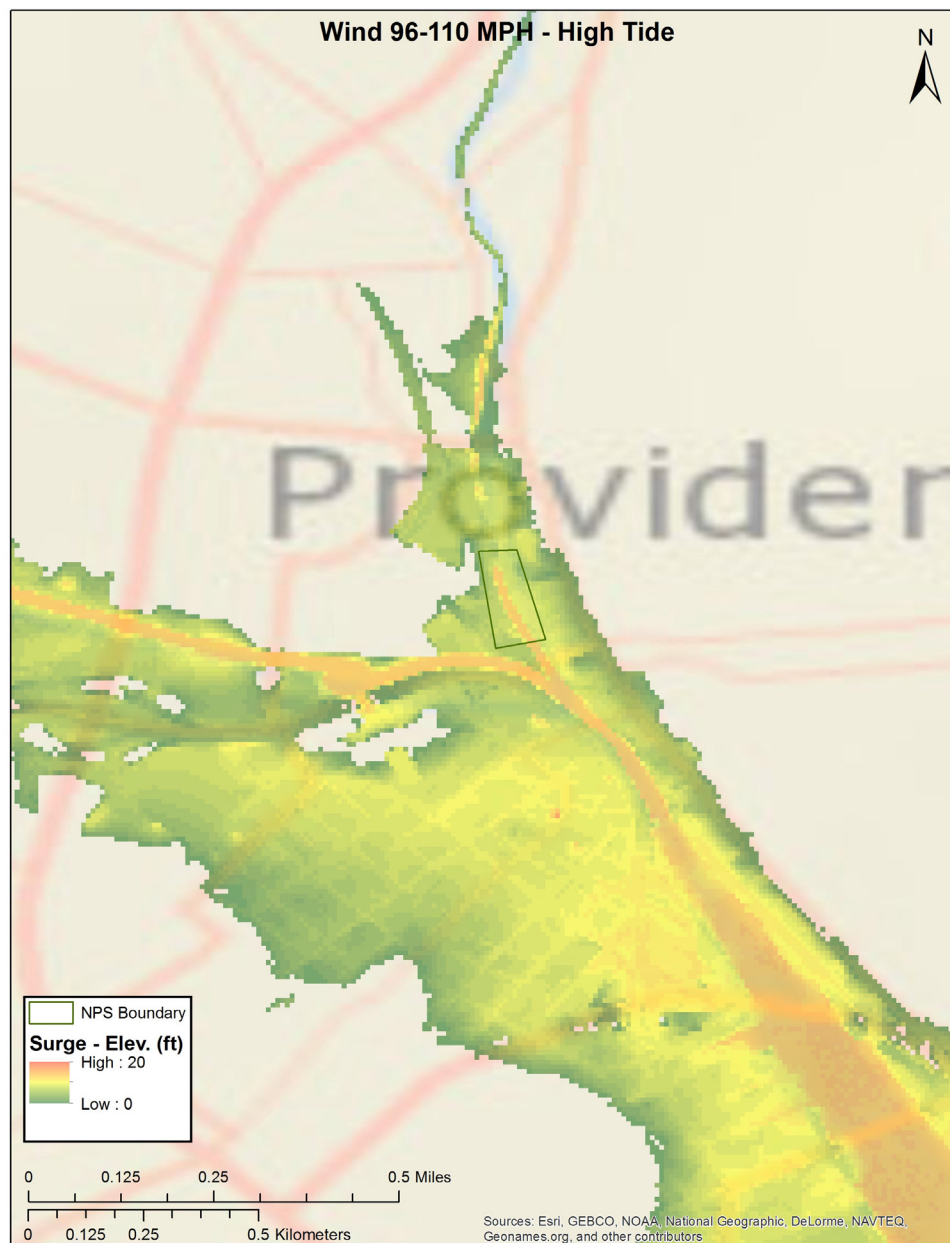
**Modeled storm surge of a Category 2 storm at high tide
at New Bedford Whaling National Historical Park**



Data and map: Caffrey et al. (in press)

Figure 13.

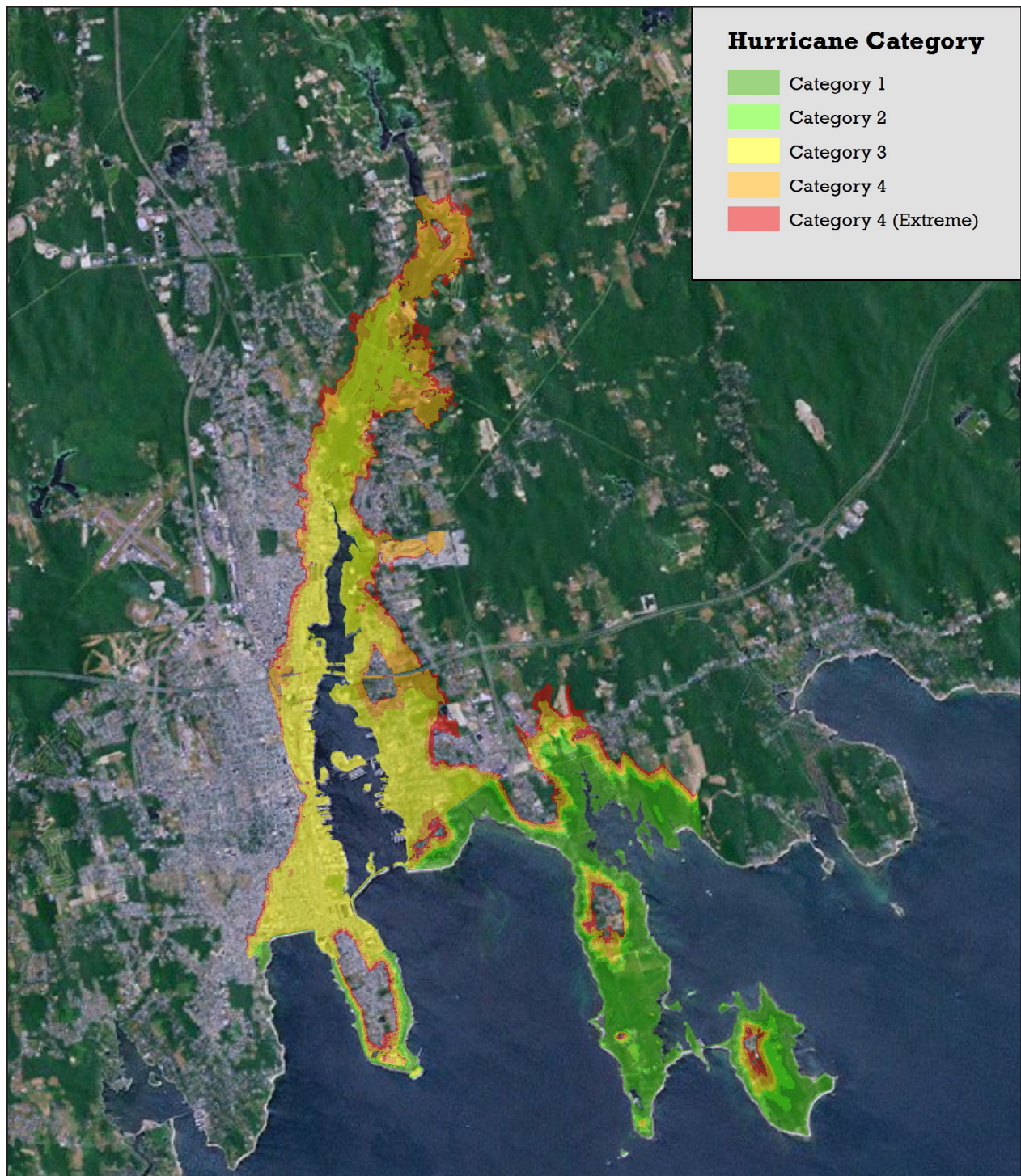
Modeled storm surge of a Category 2 storm at high tide at Roger Williams National Memorial



Data and map: Caffrey et al. (in press)

Figure 14.

**Modeled flooding of New Bedford, MA, with storm surges from hurricanes over and above
60 cm (2 ft.) of sea level rise**



Data and map: Longley and Lipsky (2014)

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