

Anthropogenic Climate Change in Sagamore Hill National Historic Site, New York

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Historical Climate Change Trends

- **Historical temperature** Greenhouse gas emissions from human activities have caused increases in temperatures and altered precipitation patterns globally (IPCC 2013), across the United States (USGCRP 2017), and in United States (US) national parks (Gonzalez et al. 2018). In the area within the boundaries of Sagamore Hill National Historic Site (NHS), temperature has increased at the statistically significant rate of $1.2 \pm 0.2^{\circ}\text{C}$ ($2.2 \pm 0.4^{\circ}\text{F.}$) per century from 1895 to 2016 (Table 1, Figure 1) (Gonzalez et al. 2018). Since 1950, the greatest warming has occurred in spring (Table 1). The rate of temperature increase becomes greater moving inland on Long Island (Figure 2).

For the historical time periods in the tables and figures, note that analyses of monthly, seasonal, and annual climate were originally run for the periods 1895-2010 (Table 1) and 1950-2010 (Table 1), the data available at the time of the original research (Gonzalez et al. 2018). Analyses of annual trends were later run for the period 1895-2016 when that data became available. In addition, climatologists use 1971-2000 (Table 1) as the standard baseline for comparing future projections with historical observations.

- **Historical precipitation** For the area within park boundaries, total annual precipitation showed no statistically significant change from 1895 to 2016 (Table 2, Figure 3) (Gonzalez et al. 2018). Autumn precipitation increased at a statistically significant rate of $17 \pm 9\%$ per century (1895-2010) (Table 2) (Gonzalez et al. 2018). Precipitation increases were greater going north from the park (Figure 4).
- **Extreme precipitation** For the northeastern US as a whole, the amount of precipitation in 20-year storms (a day with more precipitation than any other day in 20 years) increased in all four seasons from 1948 to 2015 (Easterling et al. 2017). In addition, the number of five-year storms (a two-day period with more precipitation than any other two-day period in five years) increased 74% from 1901 to 2016. These trends are attributable in part to anthropogenic climate change (Easterling et al. 2017).
- **Hurricanes** The maximum intensity of winds during the course of North Atlantic hurricanes has shown a statistically significant increase from 1982 to 2009 (Kossin et al. 2013), but the

number of North Atlantic hurricanes and the frequency of the strongest hurricanes (Categories 4 and 5) did not change significantly from 1970 to 2014 (Klotzbach and Landsea 2015). The surface tracking speed of North Atlantic hurricanes over land showed a statistically significant 20% decrease from 1949 to 2016, suggesting that slower hurricanes contributed to the increased precipitation in the eastern US (Kossin 2018). While anthropogenic climate change contributes to increased hurricane intensity, the relative contributions of anthropogenic climate change and natural variability in causing hurricane trends remain unresolved due to changing historical methods of tracking hurricanes, incomplete understanding of physical mechanisms, and natural variability of tropical cyclone activity (IPCC 2013, USGCRP 2017).

- **Tornadoes** The area around Nassau County, New York, recorded a tornado every two to three years in the period 1950-1986 (Leathers 1993), although tornadoes are much more common in the midwestern US than the northeastern US (Agee et al. 2016). Analyses of historical records of US tornadoes from 1954 to 2013 indicate that the total number of tornadoes in the country has shown no statistically significant trend (Brooks et al. 2014). The numbers of days with over 30 tornadoes, however, has increased in the US (Brooks et al. 2014, Elsner et al. 2015) and the number of tornadoes per tornado outbreak has increased (Moore 2017, Tippet and Cohen 2016). Moreover, tornado power, a function of wind speed, tornado path area, and air density, has increased $5\% \pm 1\%$ per year from 1994 to 2016 for the US (Elsner et al. 2019). Changes in methods for recording the numbers of tornadoes over time prevent attribution of the causes of tornado increases, so they cannot be definitively attributed to climate change (Brooks et al. 2014).

Historical Impacts Attributed in Part to Anthropogenic Climate Change

- **Sea level rise** At the National Oceanic and Atmospheric Administration (NOAA) tidal gauge at Kings Point, New York, on Long Island west of the park, measurements show that sea level increased 22 ± 2 cm (9 ± 1 in.) (mean $\pm$ standard error) from 1931 to 2019 (NOAA 2019; Figure 5). Analyses of the global tidal gauge network detected a statistically significant rise in global sea level from 1901 to 2012 (Church and White 2011, Dangendorf et al. 2017, IPCC 2013). Analyses of potential causal factors attribute this rise to human-caused climate change through runoff from the melting of glaciers and other land ice and the expansion of ocean water when it warms (IPCC 2013, Slangen et al. 2016).
- **Bird range shifts** Analyses of Audubon Christmas Bird Count data across the US, including

the count circle in northern Nassau County, New York, detected a northward shift of winter ranges of a set of 254 bird species an of 15 km (9 mi.) from 1975 to 2004, attributable in part to anthropogenic climate change (La Sorte and Thompson 2007). Across much of the US, including in northern Nassau County, New York, the evening grosbeak (*Coccothraustes vespertinus*) has been extirpated, with its range shifting north to colder areas in Canada. Further analyses found northward shifts in winter distributions of six raptor species across the US from 1975 to 2011 (Paprocki et al. 2014), including the American Kestrel (*Falco sparverius*) and the rough-legged hawk (*Buteo lagopus*), which have decreased in the northern Nassau County count, and the red-tailed Hawk (*Buteo jamaicensis*), which has increased in the northern Nassau County count.

Projected Climate Change Trends

- **Projected temperature** Without reductions of greenhouse gas emissions from power plants, cars, and other human sources, the set of general circulation models (GCMs) of global climate in IPCC (2013) (up to 33 GCMs) project additional heating of the area within park boundaries of $4.8 \pm 0.9^{\circ}\text{C}$ ($8.6 \pm 1.6^{\circ}\text{F.}$) by 2100 under the highest emissions scenario (representative concentration pathway [RCP] 8.5). The temperature increase could be kept to $1.7 \pm 0.7^{\circ}\text{C}$ ($3.1 \pm 1.3^{\circ}\text{F.}$) under a scenario of emissions reductions (RCP2.6) (Tables 3, 4, Figure 6, Gonzalez et al. 2018). GCMs project the highest temperature increases in autumn.
- **Projected precipitation** With continued greenhouse gas emissions, the set of GCMs in IPCC (2013) (up to 33 GCMs) project future increases in total annual precipitation in the park $14 \pm 9\%$ per century by 2100 under the highest emissions scenario (RCP8.5), but $7 \pm 7\%$ under a scenario of emissions reductions (RCP2.6) (Tables 5, 6; Figures 6, 7; Gonzalez et al. 2018). From 1895 to 2010, the precipitation cycle shifted to a cycle with no peak in precipitation in August. Under continued climate change, precipitation would increase most in spring and autumn (Figure 7).
- **Projected snow** Almost all GCMs project increases in total precipitation for the park (Figure 5), but warmer temperatures would reduce the fraction of winter precipitation falling as snow and increase the fraction falling as rain. On Long Island, New York, the fraction of precipitation falling as snow in January could decrease from ~60% (1981-2000) to ~20% (2081-2100) under the highest emissions scenario (RCP8.5) and to ~40% under the low emissions scenario (RCP4.5) (Ning and Bradley 2015). On Long Island, New York, the

number of days with snowfall >1 cm (greater than half an inch) could decrease by up to 75% from 2000 to 2100 under a high emissions scenario (Notaro et al. 2014).

- **Extreme temperatures** For Long Island, New York, under the highest emissions scenario (RCP8.5), models project an increase of 10 to 20 more days per year with a maximum temperature >32°C (90°F.), an increase of 2–3°C (4–6°F.) in the hottest temperature of the year, and a decrease of 20 to 30 fewer days per year below freezing (0°C, 32°F.), from 1990 to 2050 (Vose et al. 2017).
- **Extreme storms** For the northeastern US as a whole, models project an increase in five-year storms (a two-day period with more precipitation than any other two-day period in five years) to once every two years (low emissions scenario, RCP4.5) or every year (highest emissions scenario, RCP8.5) (Easterling et al. 2017). In addition, models project a 22% increase in the amount of precipitation in 20-year storms (a storm with more precipitation than any other storm in 20 years) under the highest emissions scenario (RCP8.5) (Easterling et al. 2017).
- **Hurricanes** Models project an increase in North Atlantic hurricane intensity and rainfall rates under continued climate change, although projections of the total number of North Atlantic hurricanes under climate change do not agree (IPCC 2013, USGCRP 2017). Under low emissions (RCP4.5), the maximum intensity of winds during the course of North Atlantic hurricanes could increase 4% and rainfall rates increase 15% to 20% by 2100 (Knutson et al. 2015).
- **Tornadoes** With continued climate change, the potential for severe thunderstorms that provide conditions for tornadoes may increase substantially (Diffenbaugh et al. 2013, Gensini and Mote 2015). Under the highest emissions scenario, models project a 40% increase from 2000 to 2100 of the number of days in spring with severe thunderstorms that could produce tornadoes in the eastern US (Diffenbaugh et al. 2013).

Future Projected Vulnerabilities

- **Sea level rise and storm surge** Without reductions of greenhouse gas emissions from human activities, climate change under the highest emissions scenario (RCP 8.5) would increase sea level at the park ~80 cm (~31 in.) by 2100 (Caffrey et al. 2018) (Figures 8, 9). A scenario of reduced carbon emissions (RCP2.6) could limit the increase in sea level to ~50 cm (~20 in.) by 2100 (Caffrey et al. 2018). Over and above projected sea level rise, daily high tides and storm surge would increase the potential total sea level rise during storms. A category 4 hurricane at mean tide could create a storm surge of 7.5 m (25 ft.) (Caffrey et al.

2018) (Figure 10). Sea level rise could permanently inundate the entire low-lying coastal part of the park while storm surge could even flood part of the higher part of the park. The combination of sea level rise and storm surge could increase erosion and loss of coastal land (Dupigny-Giroux et al. 2018).

- **Stream flooding** On Long Island, New York, peak spring streamflow could increase 10 to 20% due to earlier snow melt under climate change (Demaria et al. 2016).
- **Invasive plants** Under high emissions, hotter and moister conditions would make the area more favorable to the invasive plants kudzu (*Pueraria lobata*) and privet (*Ligustrum sinense*) (Bradley et al. 2010). Climate change tends to favor invasive alien plants in temperate zones for three main reasons: (1) Invasive alien plants generally exploit atmospheric carbon dioxide more efficiently than native species (Davidson et al. 2011, Liu et al. 2017), (2) Increasing warmth and moisture due to climate change increase the suitability of temperate zone ecosystems to plants from sub-tropical and tropical zones (Hellmann et al. 2008, Theoharides and Dukes 2007), and (3) Invasive alien plants often proliferate in disturbed sites (Hellmann et al. 2008, Theoharides and Dukes 2007) and climate change can increase disturbances, particularly biome shifts and wildfire changes (Early et al. 2016).
- **Emerald ash borer** The emerald ash borer, an exotic and invasive insect that has killed ash trees (*Fraxinus spp.*) across the eastern US, had not yet invaded Long Island in May 2017 <<http://www.dec.ny.gov/animals/7253.html>>. The area of the park is in the currently suitable range of the insect and will remain in its potential range under a range of climate change emissions scenarios (Liang and Fei 2014).
- **Tree range shifts** For one GCM under very high emissions, models project potential losses of serviceberry (*Amelanchier spp.*) and pitch pine (*Pinus rigida*) by 2100 from the 16 000 km² area that includes the park (Fisichelli et al. 2014). In New York as a whole, climate change could reduce red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), and white ash (*Fraxinus americana*), as southern tree species shift up from the south (Iverson et al. 2008).
- **Bird range changes** Climate change could continue to shift the ranges of bird species northward across the US (Langham et al. 2015). Modeling of suitable climate for bird species in 2050 indicates that, under the highest emissions scenario (RCP8.5), the park and a 10 km wide area around the park may gain suitable climate for 35 bird species not currently present in winter and 18 species not currently present in summer but lose suitable climate for five species in winter and 17 species in summer (Wu et al. 2018). One species vulnerable to extirpation is the black-capped chickadee (*Parus atricapillus*). One potential colonizer is the

black vulture (*Coragyps atratus*). The full list of species changes is at <https://s3.amazonaws.com/audubon-filehost/SagamoreHillNationalHistoricSite.pdf>.

- **Lyme Disease** The warmer and moister winter conditions of climate change would tend to increase the populations of the blacklegged tick (*Ixodes scapularis*), a carrier of lyme disease (Lieske and Lloyd 2018).
- **Surface ozone** The formation of ground-level ozone, a pollutant hazardous to people, increases as temperature increases. Under high emissions (RCP6.0), ground-level ozone concentrations on Long Island could increase 5-10 parts per billion by 2050 (Meehl et al. 2018). Under low emissions (RCP4.5), the number of episodes on Long Island with ground-level ozone >75 parts per billion could increase one to six days by 2050 (Shen et al. 2016).

Scientific Abbreviations

GCM	<u>general circulation models</u> of global climate
P	<u>probability</u> that a phenomenon is due to random chance, a value <0.05 denotes statistical significance
RCP	<u>representative concentration pathway</u> , a scenario of future greenhouse gas emissions based on a storyline of potential future population, energy use, and economic conditions
SD	<u>standard deviation</u> , statistical measure of the variability of a sample of observations, such that 68% of the observations are one standard deviation or less from the average value
SE	<u>standard error</u> , statistical measure of the variability of sample averages drawn from a population of observations, such that 68% of the averages are one standard error or less from the average value, used here for historical trends

Table 1. Historical average temperatures and temperature trends (Gonzalez et al. 2018) of the area within the boundaries of Sagamore Hill NHS. Historical average and standard deviation (SD) given for a standard historical period (1971-2000). Historical trends, standard errors (SE), and statistical significance (sig.) given for longer periods. Statistical significance gives the probability (P) that a trend is random. The lower the probability, the more significant the trend. * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	°C		°C century ⁻¹			°C century ⁻¹		
Annual	11.6	0.6	1.1	0.2	***	1.4	0.5	**
December-February	0.9	1.4	1.6	0.5	**	1.6	1.4	
March-May	10.1	0.9	1	0.3	***	1.9	0.7	**
June-August	22.3	0.6	1.2	0.2	***	1.5	0.4	***
September-November	13.2	0.8	0.8	0.2	**	0.7	0.5	
January	-0.4	2.4	0.5	0.7		0.9	2	
February	0.4	2.2	2.3	0.7	**	1.3	2.2	
March	4.6	1.4	1.3	0.5	**	2.7	0.9	**
April	10	1	1.4	0.3	***	1.8	0.8	*
May	15.5	1.2	0.4	0.3		1.3	0.9	
June	20.6	1	1.1	0.3	***	1.4	0.5	*
July	23.6	1	0.9	0.2	***	1.1	0.6	
August	22.9	0.8	1.5	0.3	***	1.8	0.7	**
September	19	0.9	0.6	0.3		1.3	0.7	
October	12.9	1.5	0.3	0.4		-0.6	0.9	
November	7.8	1.4	1.5	0.3	***	1.3	0.8	
December	2.5	2.2	1.8	0.5	**	2.4	1.3	

Table 2. Historical average precipitation totals and precipitation trends (Gonzalez et al. 2018) of the area within the boundaries of Sagamore Hill NHS. Historical average and standard deviation (SD) given for a standard historical period (1971-2000). Historical trends, standard errors (SE), and statistical significance (sig.) given for longer periods. Statistical significance gives the probability (P) that a trend is random. The lower the probability, the more significant the trend. * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

	1971-2000		1895-2010			1950-2010	
	mean	SD	trend	SE		trend	SE
	mm y ⁻¹		% century ⁻¹			% century ⁻¹	
Annual	1221	184	4	5		17	14
December-February	279	85	-6	7		0	19
March-May	338	112	11	9		17	26
June-August	301	78	-5	8		22	19
September-November	302	87	17	9	*	28	22
January	100	56	-4	16		29	50
February	78	32	-25	10	*	-37	23
March	112	47	6	11		7	28
April	109	55	15	12		21	36
May	117	64	12	16		23	47
June	91	56	14	15		90	39
July	105	52	-9	13		26	27
August	105	54	-16	15		-38	44
September	102	52	17	15		61	33
October	91	49	15	18		69	52
November	109	54	20	12		-38	27
December	102	53	5	12		-1	33

Table 3. Projected temperature increases (°C), 2000 to 2050 (Gonzalez et al. 2018), for the area within the boundaries of Sagamore Hill NHS, from the average of all available general circulation model projections (up to 33) in IPCC (2013) for the four emissions scenarios (RCPs = representative concentration pathway). The lower the standard deviation (SD), the closer together the model projections within and emissions scenario.

	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	0.6	2.2	0.5	1.9	0.5	2.8	0.6
December-February	1.8	0.8	2.4	1	1.9	0.7	3	1
March-May	1.6	0.8	1.8	1.1	1.7	0.7	2.3	1.1
June-August	1.7	0.6	2.1	0.8	1.9	0.5	2.7	0.7
September-November	1.9	0.6	2.4	1.2	2	0.5	3	1.3
January	2	0.8	2.5	1.2	1.8	0.9	3.1	1.2
February	1.7	1	2.1	0.9	1.8	0.9	2.7	0.9
March	1.7	0.9	1.8	1.1	1.8	0.9	2.4	1.2
April	1.6	0.7	1.8	1.2	1.7	0.7	2.3	1.1
May	1.5	0.8	1.8	1.1	1.7	0.6	2.3	1.1
June	1.5	0.7	1.9	1.1	1.8	0.5	2.5	1
July	1.7	0.7	2.1	0.9	2	0.6	2.8	0.9
August	1.8	0.7	2.2	0.6	2.1	0.6	2.9	0.6
September	1.9	0.7	2.5	0.9	2.2	0.7	3	1.1
October	2	0.7	2.4	1.4	1.9	0.6	3.1	1.5
November	1.8	0.6	2.5	1.4	1.9	0.5	2.9	1.4
December	1.8	0.8	2.6	1.5	2	0.7	3.1	1.6

Table 4. Projected temperature increases (°C), 2000 to 2100 (Gonzalez et al. 2018), for the area within the boundaries of Sagamore Hill NHS, from the average of all available general circulation model projections (up to 33) in IPCC (2013) for the four emissions scenarios (RCPs = representative concentration pathway). The lower the standard deviation (SD), the closer together the model projections within and emissions scenario.

	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	0.7	2.8	0.7	3.2	0.8	4.8	0.9
December-February	1.9	0.9	3	1.1	3.3	1	5	1.3
March-May	1.5	0.7	2.4	1.2	2.9	0.9	4.1	1.3
June-August	1.6	0.8	2.6	0.9	3.2	0.9	4.9	1.1
September-November	1.7	0.8	3	1.4	3.3	0.9	5.2	1.7
January	1.9	1.1	3.1	1.3	3.3	1	5.1	1.5
February	1.8	1.1	2.8	1	3.3	1.2	4.8	1.1
March	1.5	0.9	2.4	1.3	2.8	1.1	4.1	1.4
April	1.5	0.8	2.4	1.2	2.9	1	4.2	1.3
May	1.5	0.8	2.3	1.2	2.9	0.8	4.2	1.3
June	1.5	0.8	2.4	1.2	2.9	0.9	4.4	1.3
July	1.6	0.8	2.6	1	3.3	0.9	4.9	1.2
August	1.7	0.8	2.9	0.9	3.4	1	5.3	1.1
September	1.7	0.8	3.1	1.2	3.5	1	5.4	1.5
October	1.7	0.8	3.1	1.6	3.3	1	5.3	1.9
November	1.8	0.8	3	1.6	3.3	0.8	5	1.9
December	1.9	0.9	3.2	1.8	3.4	1	5.1	1.9

Table 5. Projected precipitation changes (%), 2000 to 2050 (Gonzalez et al. 2018), for the area within the boundaries of Sagamore Hill NHS, from the average of all available general circulation model projections (up to 33) in IPCC (2013) for the four emissions scenarios (RCPs = representative concentration pathway). The lower the standard deviation (SD), the closer together the model projections within and emissions scenario.

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

Table 6. Projected precipitation changes (%), 2000 to 2100 (Gonzalez et al. 2018), for the area within the boundaries of Sagamore Hill NHS, from the average of all available general circulation model projections (up to 33) in IPCC (2013) for the four emissions scenarios (RCPs = representative concentration pathway). The lower the standard deviation (SD), the closer together the model projections within and emissions scenario.

	Emissions Scenarios							
	Reductions		Low		High		Highest	
	RCP2.6		RCP4.5		RCP6.0		RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	7	7	10	7	11	7	14	9
December-February	8	10	16	9	18	10	26	15
March-May	7	9	10	9	11	9	15	9
June-August	9	13	11	15	10	18	9	20
September-November	4	8	5	9	6	8	7	12
January	10	19	20	17	19	16	33	23
February	6	11	15	15	16	13	23	15
March	6	12	13	11	13	12	19	13
April	8	13	11	17	10	11	16	16
May	8	18	6	14	10	14	12	13
June	6	13	7	17	5	16	6	17
July	9	16	11	19	11	22	8	24
August	12	19	14	23	14	26	12	33
September	5	14	7	16	6	13	5	19
October	3	18	1	18	1	17	3	19
November	6	10	8	13	12	12	13	15
December	10	14	14	12	20	17	24	17

Figure 1. Average annual temperature, 1895-2016, for the area within park boundaries. The trend, calculated by linear regression, corrected for temporal autocorrelation, shows a statistically significant long-term increase (Gonzalez et al. 2018) due to human-caused climate change (IPCC 2013, USGCRP 2017).

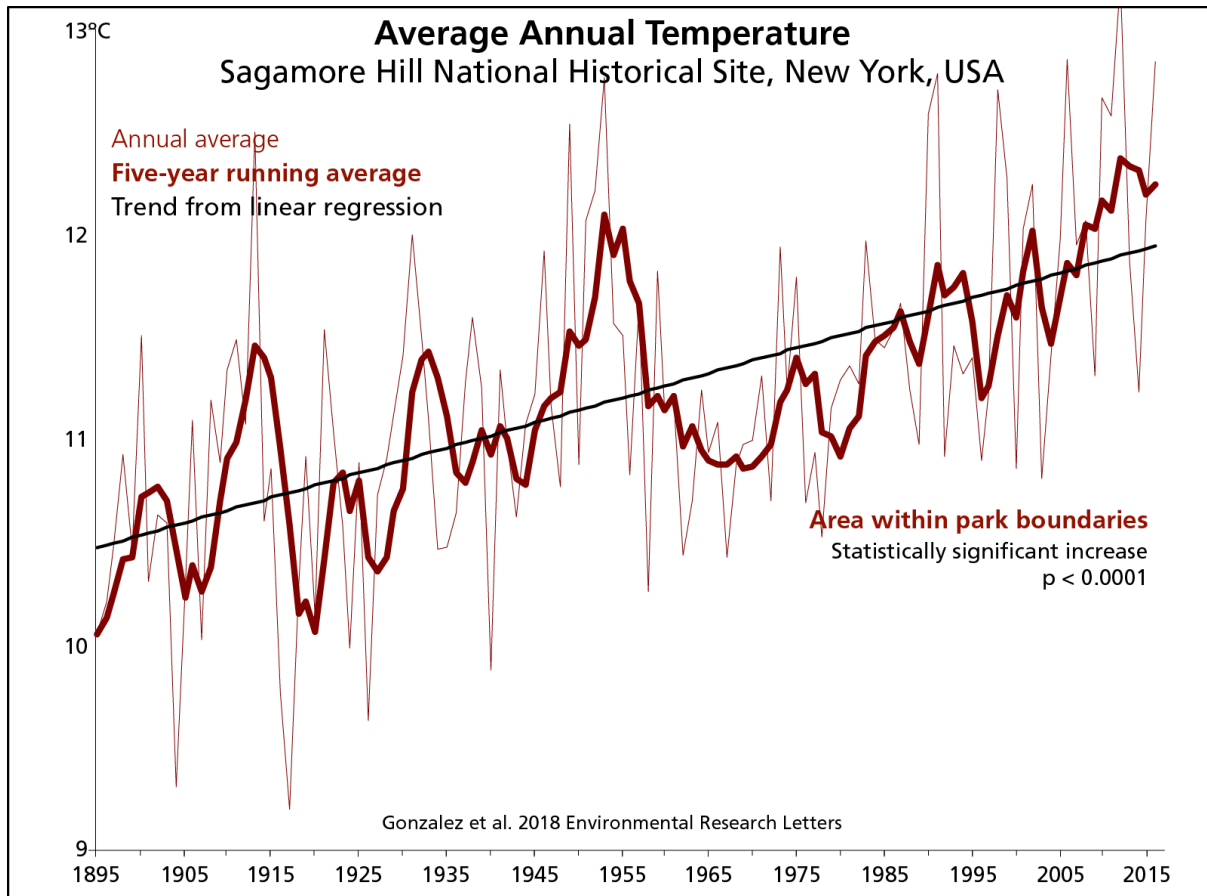


Figure 2. Trend in annual average temperature, 1895-2016, at 800 m spatial resolution, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

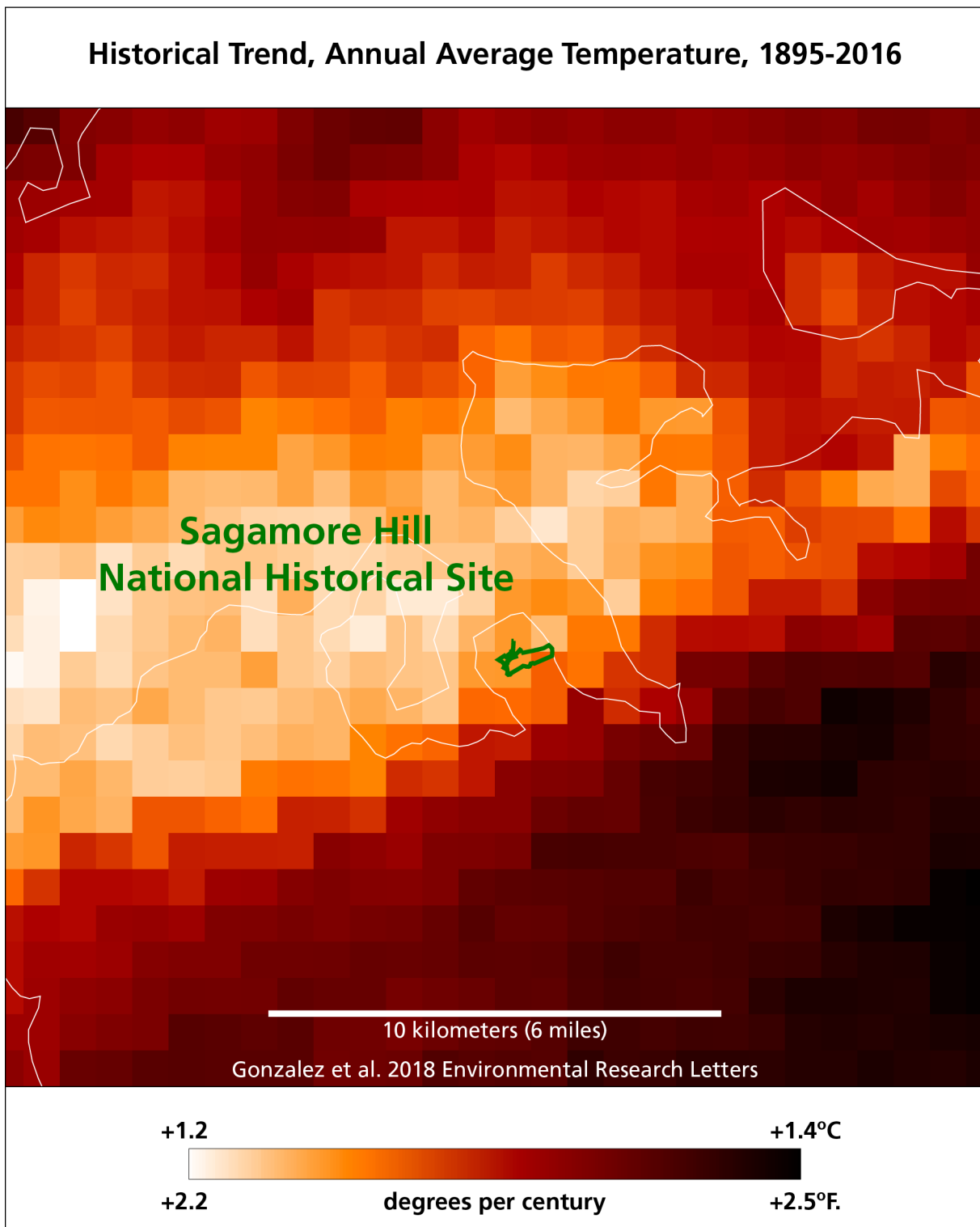


Figure 3. Total annual precipitation, 1895-2016, for the area within park boundaries. The trend, calculated by linear regression corrected for temporal autocorrelation, shows no statistically significant long-term change (Gonzalez et al. 2018)..

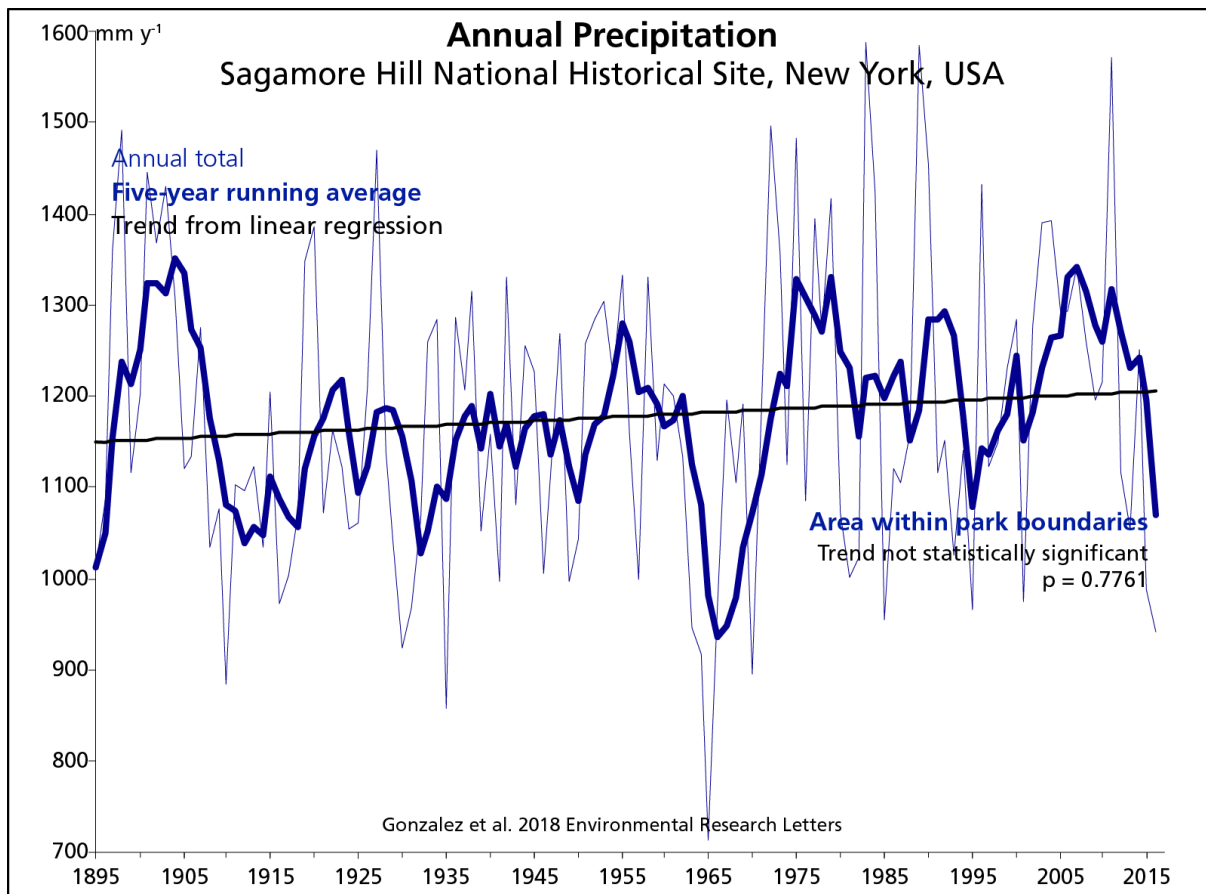


Figure 4. Trend in total annual precipitation, 1895-2016, at 800 m spatial resolution, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

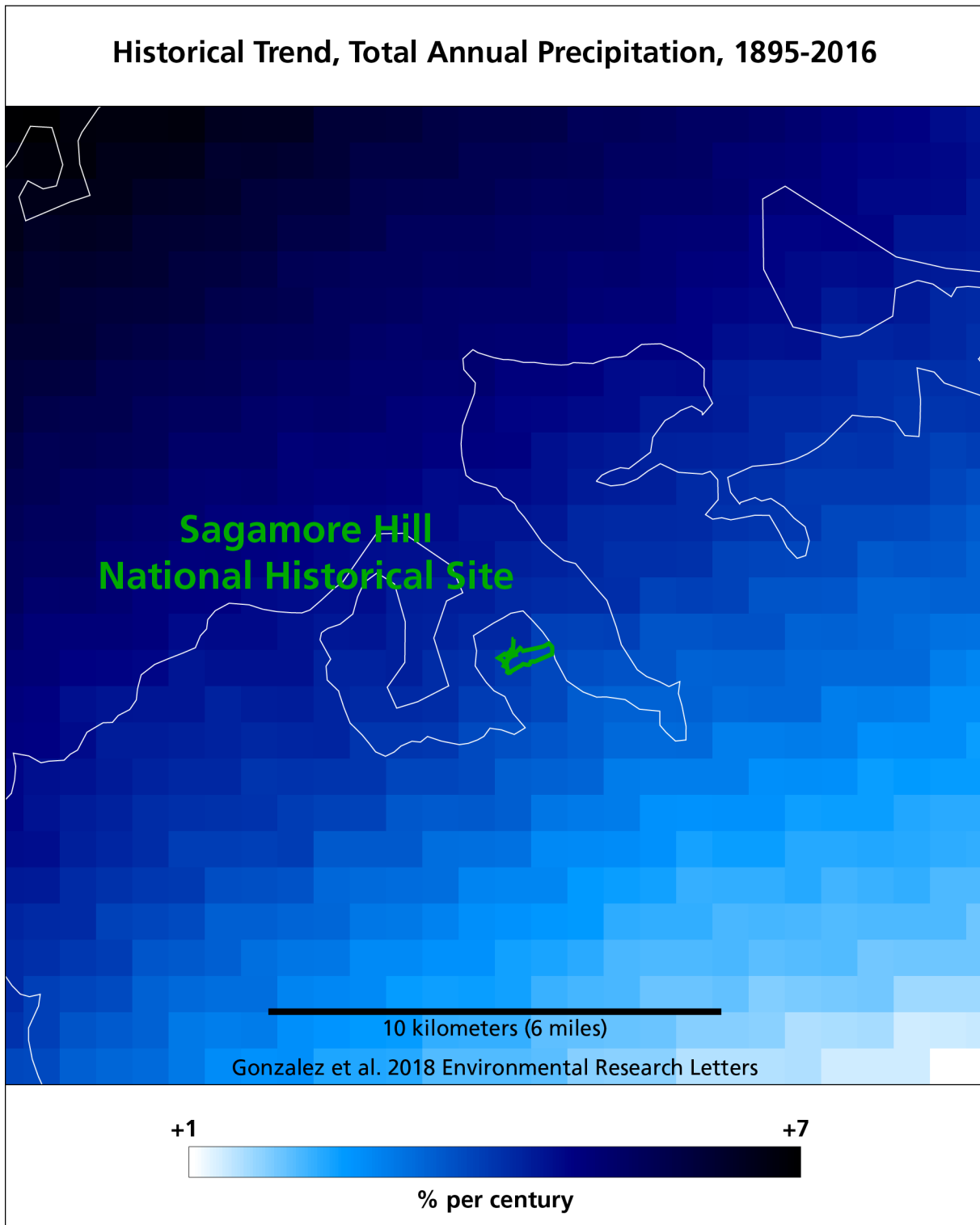


Figure 5. Sea level rise at the Kings Point, New York, tidal gauge, 1931-2019 (NOAA 2019). Sea level is shown relative to the 1983-2001 average.

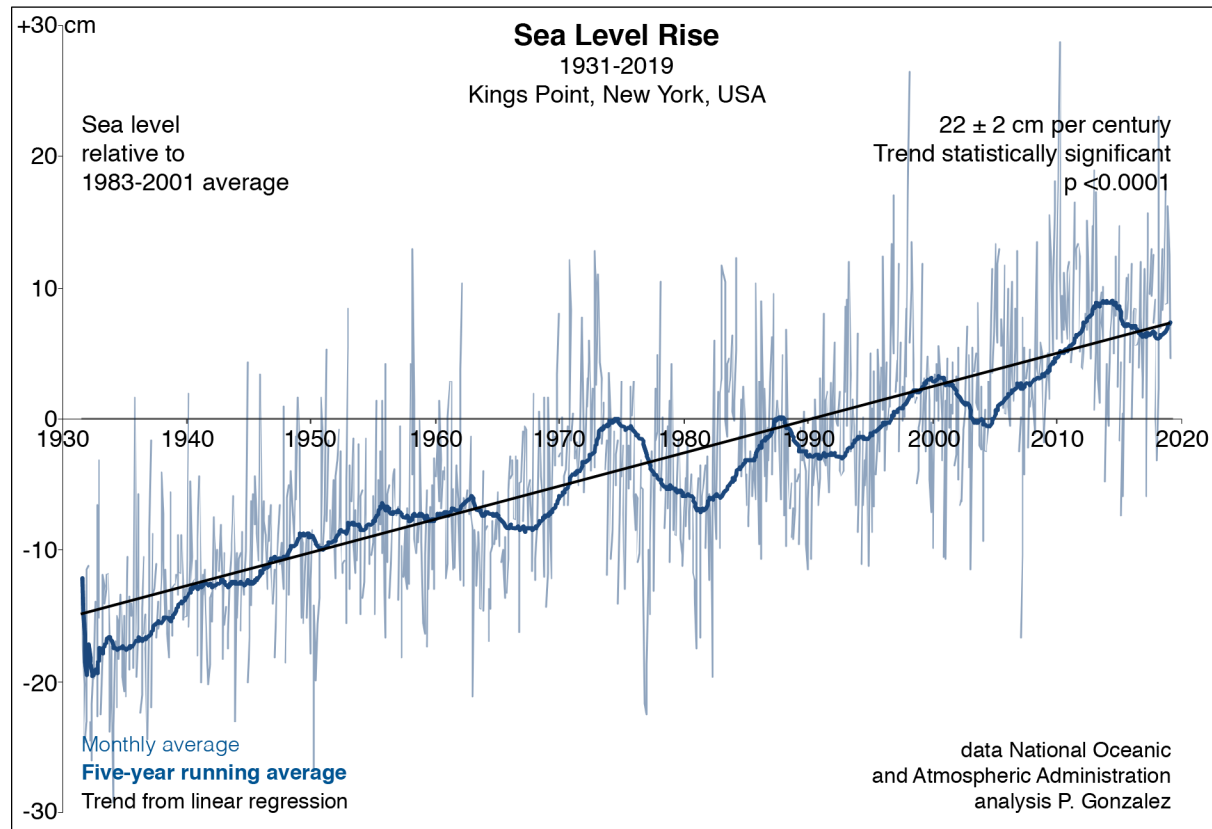


Figure 6. Projections of future climate change due to human causes, for the area within park boundaries, relative to 1971-2000 average values. Each small dot is the output of a single GCM. The large color dots are the average values for the four IPCC emissions scenarios. The crosses are the standard deviations of the average values. Most models project increased temperature and precipitation.

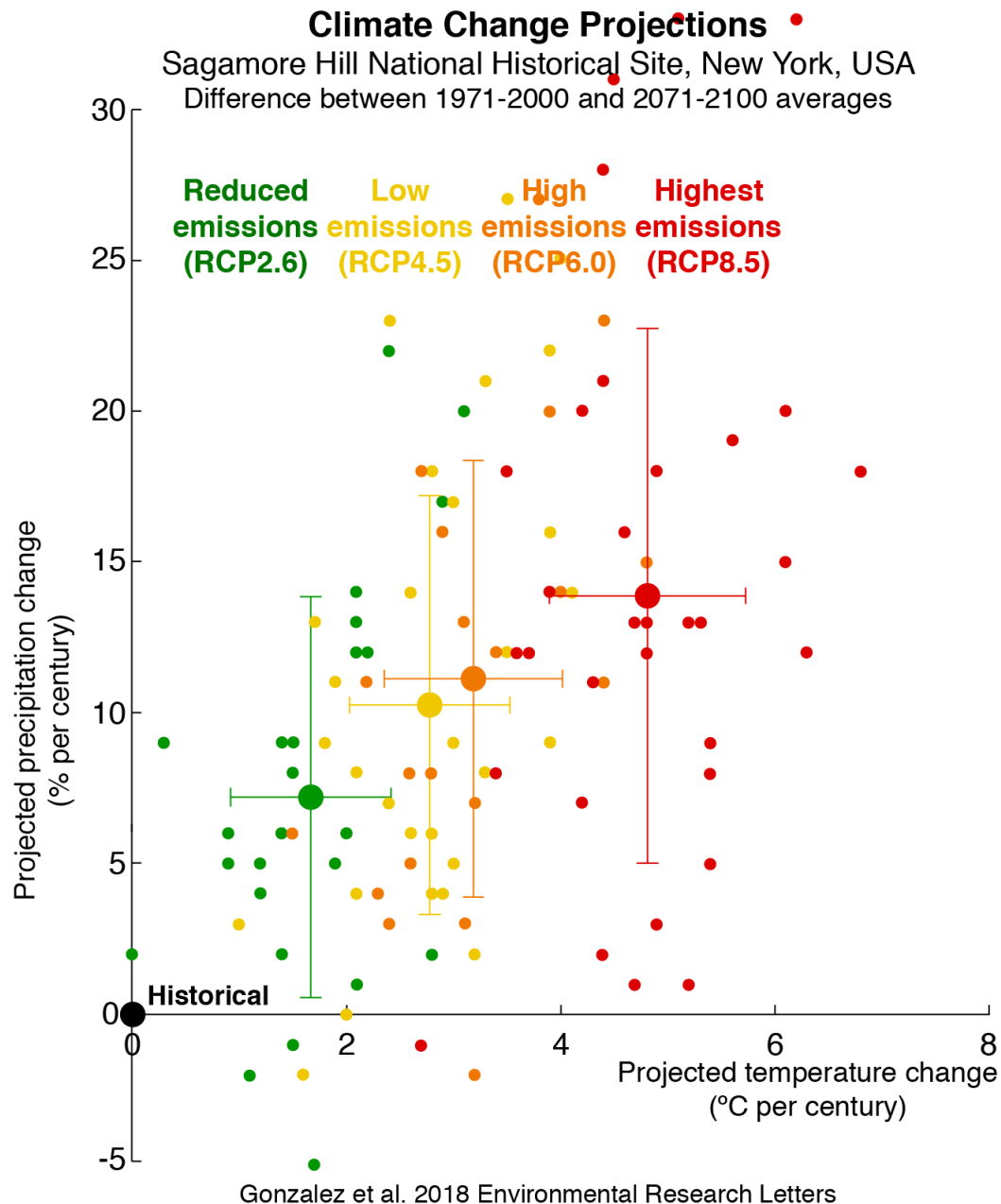


Figure 7. Monthly precipitation for the area within park boundaries. The blue line denotes the average values at the beginning of the period 1895-2010 while the black line denotes the average values at the end of the period 1895-2010. The green and red lines indicate projections under the lowest and highest emissions scenarios. Historically, precipitation has reduced in summer. Under continued climate change, precipitation would increase most in spring and autumn.

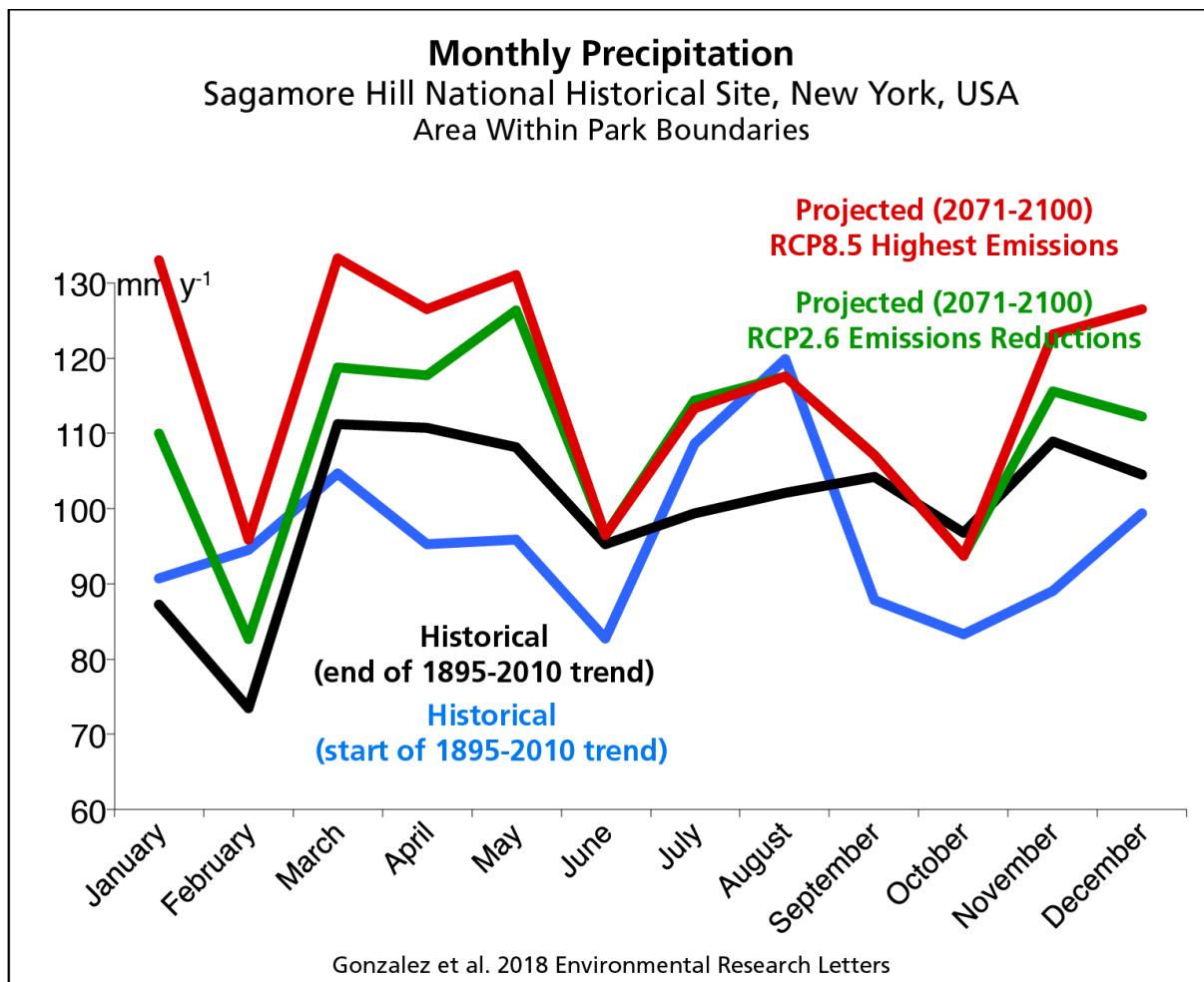


Figure 8. Aerial image of Sagamore National Historic Site, from <<https://maps.nps.gov/slr>>, showing current conditions. The lowest elevation parts of the park are the beach and marsh at the east end.



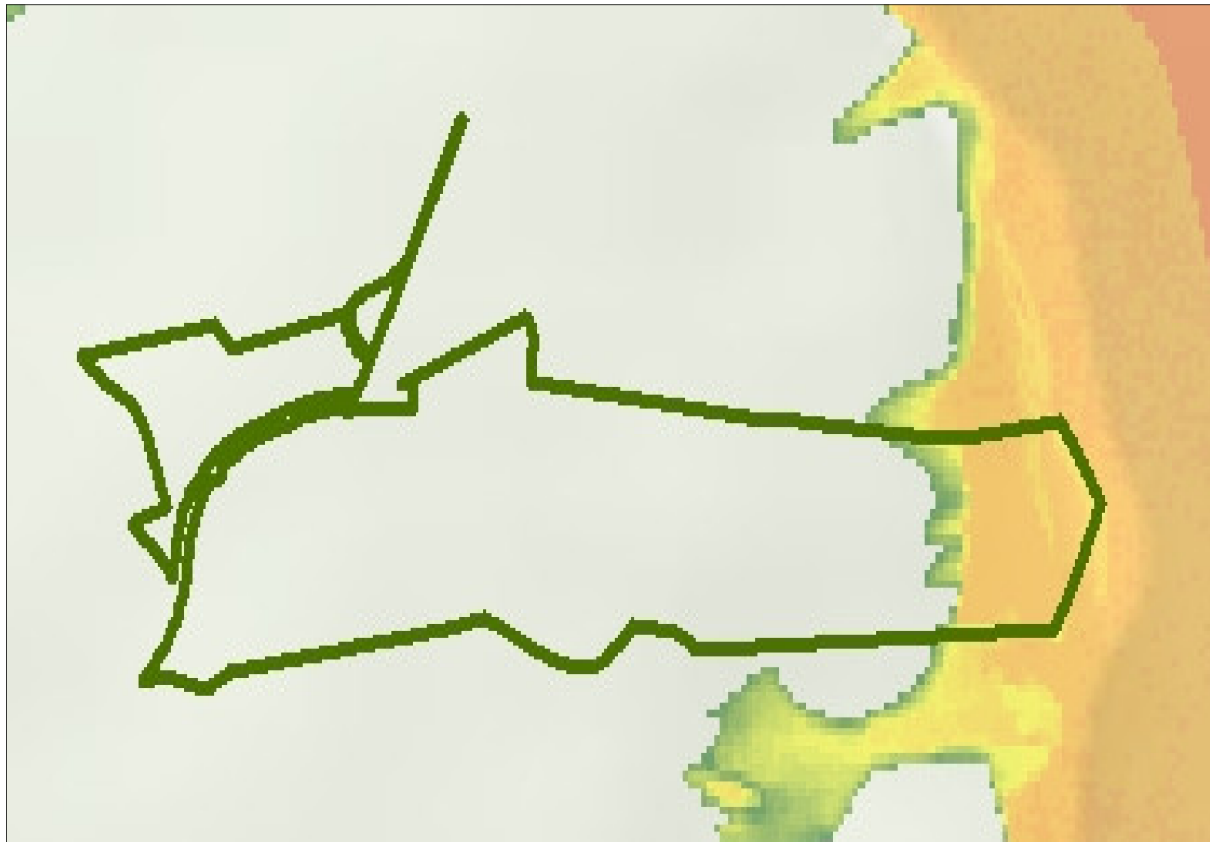
Figure 9. Projected sea level under the highest emissions scenario (RCP8.5) (Caffrey et al. 2018). Sea level is shown at the highest tide, known as Mean Higher High Water, the 1983-2001 average of the higher high water height of each tidal day. Image from <<https://maps.nps.gov/slr>>



Figure 10. Potential storm surge for a category 4 hurricane at mean tide (Caffery et al. 2018).

Other storm surge maps are available at

<https://www.flickr.com/photos/125040673@N03/sets/72157645661546267>.



References

- Agee, E., J. Larson, S. Childs, and A. Marmo. 2016. Spatial redistribution of U.S. tornado activity between 1954 and 2013. *Journal of Applied Meteorology and Climatology* 55: 1681-1697.
- Archfield, S.A., R.M. Hirsch, A. Viglione, and G. Blöschl. 2016. Fragmented patterns of flood change across the United States. *Geophysical Research Letters* 43: 10 232-10 239.
- Bradley, B.A., D.S. Wilcove, and M. Oppenheimer. 2010. Climate change increases risk of plant invasion in the Eastern United States. *Biological Invasions* 12: 1855-1872.
- Brooks, H.E., G.W. Carbin, and P.T. Marsh. 2014. Increased variability of tornado occurrence in the United States. *Science* 346: 349-352.
- Caffrey, M.A., R.L. Beavers, and C.H. Hoffman. 2018. Sea level rise and storm surge projections for the National Park Service. Report NPS/NRSS/NRR—2018/1648. National Park Service, Fort Collins, CO.
- Church, J.A. and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st Century. *Surveys in Geophysics* 32: 585-602.
- Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology* 28: 2031-2064.
- Dangendorf, S., M. Marcos, G. Wöppelmann, C.P. Conrad, T. Frederikse, and R. Riva. 2017. Reassessment of 20th century global mean sea level rise. *Proceedings of the National Academy of Sciences of the USA* 2017 114: 5946-5951.
- Davidson, A.M., M. Jennions, and A.B. Nicotra. 2011. Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. *Ecology Letters* 14: 419-431.
- Demaria, E.M.C., R.N. Palmer, J.K. Roundy. 2016. Regional climate change projections of streamflow characteristics in the Northeast and Midwest U.S. *Journal of Hydrology: Regional Studies* 5: 309-323.
- Diffenbaugh, N.S., M. Scherer, and R.J. Trapp. 2013. Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proceedings of the National Academy of Sciences of the USA* 110: 16 361-16 366.
- Dupigny-Giroux, L.A., E.L. Mecray, M.D. Lemcke-Stampone, G.A. Hodgkins, E.E. Lentz, K.E. Mills, E.D. Lane, R. Miller, D.Y. Hollinger, W.D. Solecki, G.A. Wellenius, P.E. Sheffield, A.B. MacDonald, and C. Caldwell. 2018. Northeast. In U.S. Global Change Research Program (USGCRP). *Impacts, Risks, and Adaptation in the United States: Fourth National*

- Climate Assessment, Volume II. [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)] USGCRP, Washington, DC.
- Early, R., B.A. Bradley, J.S. Dukes, J.J. Lawler, J.D. Olden, D.M. Blumenthal, P. Gonzalez, E.D. Grosholz, I. Ibañez, L.P. Miller, C.J.B. Sorte, and A.J. Tatem. 2016. Global threats from invasive alien species in the twenty-first century and national response capacities. *Nature Communications* 7: 12485. doi:10.1038/ncomms12485.
- Easterling, D.R., J.R. Arnold, T. Knutson, K.E. Kunkel, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner. 2017. Precipitation change in the United States. In U.S. Global Change Research Program (USGRP). *Climate Science Special Report. Fourth National Climate Assessment, Volume I*. [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)] USGCRP, Washington, DC.
- Elsner, J.B., S.C. Elsner, and T.H. Jagger. 2015. The increasing efficiency of tornado days in the United States. *Climate Dynamics* 45: 651-659.
- Elsner, J.B., T. Fricker, and Z. Schroder. 2019. Increasingly powerful tornadoes in the United States. *Geophysical Research Letters* 46: 392-398.
- Fisichelli, N.A., S.R. Abella, M.P. Peters, and F.J. Krist Jr. 2014. Climate, trees, pests, and weeds: Change, uncertainty, and biotic stressors in eastern U.S. national park forests. *Forest Ecology and Management* 327: 31-39.
- Gensini, V.A. and T.L. Mote. 2015. Downscaled estimates of late 21st century severe weather from CCSM3. *Climatic Change* 129: 307-321.
- Gonzalez, P., F. Wang, M. Notaro, D.J. Vimont, and J.W. Williams. 2018. Disproportionate magnitude of climate change in United States national parks. *Environmental Research Letters* 13: 104001. doi:10.1088/1748-9326/aade09.
- Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes. 2008. Five potential consequences of climate change for invasive species. *Conservation Biology* 22: 534-543.
- Intergovernmental Panel on Climate Change (IPCC). 2013. *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, Cambridge, UK.
- Iverson, L.R., A.M. Prasad, S.N. Matthews, and M. Peters. 2008. Estimating potential habitat for 134 eastern US tree species under six climate scenarios. *Forest Ecology and Management* 254: 390-406.
- Klotzbach, P.J. and C.W. Landsea. 2015. Extremely intense hurricanes: Revisiting Webster et al. (2005) after 10 years. *Journal of Climate* 28: 7621-7629.
- Knutson, T.R., J.J. Sirutis, M. Zhao, R.E. Tuleya, M. Bender, G.A. Vecchi, G. Villarini, and D.

- Chavas. 2015. Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate* 28: 7203-7224.
- Kossin, J.P. 2018. A global slowdown of tropical-cyclone translation speed. *Nature* 558: 104-107.
- Kossin, J.P., T.L. Olander, and K.R. Knapp. 2013. Trend analysis with a new global record of tropical cyclone intensity. *Journal of Climate* 26: 9960-9976.
- Kunkel, K.E., M. Palecki, L. Ensor, K.G. Hubbard, D. Robinson, K. Redmond, and D. Easterling. 2009. Trends in Twentieth-Century U.S. snowfall using a quality-controlled dataset. *Journal of Atmospheric and Oceanic Technology* 26: 33–44.
- Kunkel, K.E., D.A. Robinson, S. Champion, X. Yin, T. Estilow, and R.M. Frankson. 2016. Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change Reports* 2: 65–73.
- La Sorte, F.A. and F.R. Thompson. 2007. Poleward shifts in winter ranges of North American birds. *Ecology* 88: 1803-1812.
- Langham, G.M., J.G. Schuetz, T. Distler, C.U. Soykan, and C. Wilsey. 2015. Conservation status of North American birds in the face of future climate change. *PLoS One* 10: e0135350. doi:10.1371/journal.pone.0135350.
- Leathers, D.J. 1993. A synoptic climatology of northeastern united states tornadoes. *Physical Geography* 14: 171-190.
- Liang, L. and S. Fei. 2014. Divergence of the potential invasion range of emerald ash borer and its host distribution in North America under climate change. *Climatic Change* 122: 735-746.
- Lieske, D.J. and V.K. Lloyd. 2018. Combining public participatory surveillance and occupancy modelling to predict the distributional response of *Ixodes scapularis* to climate change. *Ticks and Tick-borne Diseases* 9: 695-706.
- Liu, Y., A.M.O. Oduor, Z. Zhang, A. Manea, I.M. Tooth, M.R. Leishman, X. Xu, and M. van Kleunen. 2017. Do invasive alien plants benefit more from global environmental change than native plants? *Global Change Biology* 23: 3363-3370.
- Meehl, G.A., C. Tebaldi, S. Tilmes, J.F. Lamarque, S. Bates, A. Pendergrass, and D. Lombardozzi. 2018. Future heat waves and surface ozone. *Environmental Research Letters* 13: 064004. doi:10.1088/1748-9326/aabdc.
- Moore, T.W. 2017. On the temporal and spatial characteristics of tornado days in the United

- States. *Atmospheric Research* 184: 56-65.
- National Oceanic and Atmospheric Administration (NOAA). 2019. Relative Sea Level Trend 8516945 Kings Point, New York.
https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8516945.
- Ning, L. and R.S. Bradley. 2015. Snow occurrence changes over the central and eastern United States under future warming scenarios. *Scientific Reports* 5: 17073.
doi:10.1038/srep17073.
- Notaro, M., D. Lorenz, C. Hoving, and M. Schummer. 2014. Twenty-First-Century projections of snowfall and winter severity across central-eastern North America. *Journal of Climate* 27: 6526–6550.
- Paprocki, N. 2014. Regional distribution shifts help explain local changes in wintering raptor abundance: Implications for interpreting population trends. *PLOS One* 9: e86814.
doi:10.1371/journal.pone.0086814.
- Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P. Giovannetone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe, C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B. Silva, B.C. Stewart, A.V. Vecchia, G. Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D. Wuebbles. 2013. Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society* 94: 821-834.
- Rupp, D.E., P.W. Mote, N.L. Bindoff, P.A. Stott, and D.A. Robinson. 2013. Detection and attribution of observed changes in Northern Hemisphere spring snow cover. *Journal of Climate* 26: 6904-6914.
- Shen, L., L.J. Mickley, and E. Gilleland. 2016. Impact of increasing heat waves on U.S. ozone episodes in the 2050s: Results from a multimodel analysis using extreme value theory. *Geophysical Research Letters* 43: 4017-4025. doi:10.1002/2016GL068432.
- Slangen, A.B.A, J.A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter. 2016. Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change* 6: 701-705.
- Theoharides, K.A. and J.S. Dukes. 2007. Plant invasion across space and time: Factors affecting nonindigenous species success during four stages of invasion. *New Phytologist* 176: 256-273.
- Tippett, M.K. and J.E. Cohen. 2016. Tornado outbreak variability follows Taylor's power law of

fluctuation scaling and increases dramatically with severity. *Nature Communications* 7: 10668. doi:10.1038/ncomms10668.

U.S. Global Change Research Program (USGCRP). 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC.

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang. 2013. *Observations: Cryosphere*. In *Intergovernmental Panel on Climate Change. Climate Change 2013: The Physical Science Basis*. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)] Cambridge University Press, Cambridge, UK.

Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner. 2017. *Temperature changes in the United States*. In U.S. Global Change Research Program (USGRP). *Climate Science Special Report. Fourth National Climate Assessment, Volume I*. [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)] USGCRP, Washington, DC.

Wu, J.X., C.B. Wilsey, L. Taylor, and G.W. Schuurman. 2018. Projected avifaunal responses to climate change across the U.S. National Park System. *PLoS One* 13 e0190557 doi:10.1371/journal.pone.0190557.

Yang, Q., H. Tian, M.A.M. Friedrichs, M. Liu, X. Li, and J. Yang. 2015. Hydrological responses to climate and land-use changes along the North American East Coast: A 110-year historical reconstruction. *Journal of the American Water Resources Association* 51: 47-67.