National Park Service
U.S. Department of the Interior

View of Cadillac Mountain from the Schoodic Peninsula (photo P. Gonzalez)

Climate Change Trends and Vulnerabilities in Acadia National Park, Maine

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Abstract

Greenhouse gas emissions from human activities have caused global climate change and widespread impacts on physical and ecological systems. To help the planning of management of Acadia National Park (N.P.) under climate change, this report presents results of original spatial analyses of historical and projected climate change trends and a review of published research on impacts and vulnerabilities. Spatial analyses of historical temperature and precipitation at 800 m spatial resolution show the changes that the area within the boundaries of Acadia N.P. has experienced. Average annual temperature from 1895 to 2010 increased at a statistically significant rate of 0.8 ± 0.2ºC (1.4 ± 0.4ºF.) per century (mean ± standard error [SE]), with the greatest increase in winter. Total annual precipitation from 1895 to 2010 increased at a statistically significant rate of 16 ± 5% per century, with the greatest increase in autumn. Temperature and precipitation did not show significant changes, however, for the period 1950-2010, when the weather station network was more stable. Only two analyses of field data from within or near the park have detected ecological changes that have been attributed to human climate change. At Bar Harbor, Maine, the closest tidal gauge to the park shows a rise in sea level at a statistically significant rate of 22 ± 0.8 cm (9 ± 0.3 in.) per century from 1947 to 2014. Regional analyses of bird counts from across the United States (U.S.), including the park, show that climate change shifted winter bird ranges northward 0.5 ± 0.3 km (0.3 ± 0.2 mi.) per year from 1974 to 2004. Projections of future climate under the four emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC) indicate annual average temperature increases from 2000 to 2100 of up to 5.1 ± 1.2ºC (9.2 ± 2.2º F.) (mean ± standard deviation [SD]) if the world does not reduce greenhouse gas emissions. Model projections show possible increases of total annual precipitation of 6 ± 6% to 14 ± 7% for the four scenarios. Published analyses for the area including the national park indicate numerous vulnerabilities to future climate change, including northward and upslope shifts of plant species, coastal flooding, damage to marine species, and range shifts of terrestrial mammals.

Introduction

Greenhouse gas emissions from power plants, motor vehicles, deforestation, and other human activities have increased temperatures around the world and changed other climate factors in the 20th and early 21st centuries (IPCC 2013). Field measurements show that climate change is fundamentally altering ecosystems by shifting biomes, contributing to species extinctions, and causing numerous other changes (IPCC 2014). To assist Acadia N.P. in the integration of climate change science into resource management, this report presents results of original spatial analyses of historical and projected climate change and a summary of published scientific findings on climate change impacts and vulnerabilities.

The historical analyses (Wang et al., in preparation) use previously published spatial climate data layers at 800 m spatial resolution, derived from point weather station measurements using the Parameter-elevation Relationships on Independent Slopes Model (PRISM; Daly et al. 2008). The area covered by the analyses is the area within park boundaries. The historical climate trends derive from linear regression of temperature and precipitation time series, with the statistical probability of significance corrected for temporal autocorrelation.

The analyses of future projections (Wang et al., in preparation) use output of all available general circulation models (GCMs) of the atmosphere in the Coupled Model Intercomparison Project Phase 5 (CMIP5) data set established for the most recent IPCC report (IPCC 2013). The coarse GCM output, often at spatial resolutions of up to 200 km, has been downscaled to 800 m spatial resolution using bias correction and spatial disaggregation (BCSD; Wood et al. 2004).

The information on climate change impacts and vulnerability comes from a search of scientific literature for published research that used field data from Acadia N.P. or spatial analyses of the area that includes Acadia N.P.

Historical Climate Changes

Mean annual temperature showed a statistically significant increase from 1895 to 2010 (Figure 1, Table 1). Changes in mean annual temperature from 1950 to 2010 were not, however, statistically significant (Figure 1, Table 1). The period 1950-2010 gives a more robust time series than the period 1895-2010 because the U.S. Government established a substantial number of weather stations in the late 1940s and the weather station network has been relatively stable since then. Spatial data from the longer period relies on fewer weather stations and a network that enlarged irregularly before the 1940s. None of the temperature trends for Acadia N.P. in the period 1950-2010 were statistically significant. The 1895-2010 trends show significant warming for winter, spring, and summer, with the greatest rate of warming in winter (Table 1). The highest rates of warming have occurred in the eastern half of Mount Desert Island (Figures 2, 3). The next highest rates of warming occurred on the Schoodic Peninsula.

The western half of Mount Desert Island and the Isle au Haut did not experience warming in the period 1950-2010 (Figure 3). Despite the warming of the eastern half of Mount Desert Island in the period 1950-2010, the slight cooling of the other areas produces a flat trend for the national park as a whole. The lack of a warming trend for the period 1950-2010 derives from anomalously lower temperatures in the 1960s that occurred across the eastern U.S. and much of the northern hemisphere (IPCC 2013) due to a cycle in ocean temperatures called the North Atlantic Oscillation (Hurrell 1995).

Total annual precipitation showed a statistically significant increase from 1895 to 2010 (Figure 4, Table 2). Autumn precipitation also increased significantly. The change in total annual precipitation from 1950 to 2010 was not statistically significant, although spring precipitation increased significantly (Figure 4, Table 2). Rates of precipitation tended to increase from inland to the coast (Figures 5, 6).

Climate change has increased the frequency of heat waves, heavy rainstorms, and other extreme events in some parts of the world (IPCC 2013). National Oceanic and Atmospheric Administration (NOAA) analyses of weather station data show an increase in the northeastern U.S. of heavy storms, with the decade 2001-2012 experiencing an increase of 50% in five-year storms (a storm with more precipitation than any other storm in five years), compared to the 1901-1960 average (Walsh et al. 2014). Furthermore, NOAA analyses show a 71% increase in the amount of precipitation falling in the heaviest 1% of all daily storm events from 1958 to 2012 in the northeastern U.S. (Walsh et al. 2014).

Historical Impacts

A search of scientific literature found only two published analyses of field data from within or near Acadia N.P. that detected changes that were attributed to human climate change. Mean sea level at the NOAA tidal gauge in Bar Harbor, Maine, just outside the national park, shows a statistically significant rise at a rate of 22 ± 0.8 cm per century from 1947 to 2014 (Figure 7). Analyses of tidal gauge measurements around the world have detected a statistically significant rise in global sea level with analyses of potential causal factors attributing the rise to human climate change (IPCC 2013).

Analyses of Audubon Christmas Bird Count data across the United States, including counts from Acadia N.P., 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 and not other factors (La Sorte and Thompson 2007). At the Mount Desert Island bird count circle, which covers parts of Acadia N.P., the range of the evening grosbeak (*Coccothraustes vespertinus*) seems to have shifted north out of the area.

Other research in Acadia N.P. or across the region has examined observations consistent with climate change. It is important to note that the changes, if observed, have not necessary been detected (shown statistically significantly different than historical variability) and they have not been attributed to climate change. Historical records of northern New England lakes, including lakes in mainland Maine, showed a nine-day advance of ice-out (melting of ice cover) dates from 1850 to 2000, consistent with climate change (Hodgkins et al. 2002). Several stream gauges in mainland Maine show a shift of peak stream flow to earlier in the spring from 1953 to 2002, resulting in lower stream flow later in the season, but stream gauges on the coast showed no significant trend (Hodgkins and Dudley 2006). Analyses of nutrient and water flows in Bass Harbor marsh estuary in Acadia N.P. seem to indicate that rising sea level is increasing oceanic inputs of water and nutrients, especially when island runoff reduces in the summer, and contributing to the growth of algae (Huntington et al. 2014). Analyses of citizen-reported bird observations indicated that 20 out of 105 migrating bird species monitored from 1994 to 2005 showed a relationship of earlier spring arrival to temperature (Wilson 2007). Analyses of visitation and temperature from 1979 to 2008 in 27 national parks found an overall shift of visitation to earlier in the year as warm temperatures arrived earlier, but found no significant correlation in Acadia N.P. (Buckley and Foushee 2012).

Future Climate Projections

IPCC has coordinated research groups to project possible future climates under four defined greenhouse gas emissions scenarios, called representative concentration pathways (RCPs; Moss et al. 2010). The four emissions scenarios are RCP2.6 (reduced emissions from increased energy efficiency and installation of renewable energy), RCP4.5 (low emissions), RCP6.0 (high emissions, somewhat lower than continued current practices), and RCP8.5 (highest emissions due to lack of emissions reductions).

GCMs project increases in annual average temperature within park boundaries three to four times the amount of historical 20th century warming by 2050 (Table 3) and three to six times by 2100 (Table 4). Projected temperature increases become greater going away from the sea (Figure 8). Models project the greatest temperature increases in the winter. GCMs project increased precipitation under all emissions scenarios, with the greatest projected increases in winter (Tables 5, 6). Projected precipitation increases become greater going away from the sea (Figure 9). Taken together, the temperature and precipitation projections from 33 GCMs form a cloud of potential future climates (Figure 10). The mean of the GCM ensemble reflects the central tendency of the projections, but the uncertainty of any projection of the future can be large. Almost all GCMs project increased precipitation under all emissions scenarios.

Projections indicate potential changes in the frequency of extreme temperature and precipitation events. Modeling under emissions scenario RCP8.5 projects a temperature increase of 5ºC on the hottest days and a doubling of the frequency of five-year storms from 2000 to 2100 (Walsh et al. 2014). The relationship of North Atlantic hurricanes, which can produce storms that track up the coast to the area of Acadia N.P., and climate change is still unresolved (IPCC 2013).

Projected Vulnerabilities

Acadia N.P. lies at the transition between temperate broadleaf forests to the south and boreal conifer forest to the north. Analyses of historical 20th century climate trends and dynamic modeling of 21st century vegetation show that ecosystems in Acadia N.P. are highly vulnerable to a northward shift of the boreal conifer forest, temperate mixed forest, and temperate broadleaf forest biomes due to climate change under the warmest three emissions scenarios (Gonzalez et la. 2010). The shift results partly from potential increases in wildfire (Moritz et al. 2012). Other dynamic modeling of 21st century vegetation projects the same type of northward biome shift (Tang and Beckage 2010). Fragmentation of habitat due to urbanization exacerbates the vulnerability of ecosystems to biome shifts due to climate change (Eigenbrod et al. 2014).

Equilibrium niche modeling of suitable habitat for individual tree species across the eastern U.S. indicates that the potential habitat of boreal species, such as balsam fir (*Abies balsamea*) and red spruce (*Picea rubens*), could shift northward, with the northern edge moving away from the area of the park, and that the potential habitat of temperate species, such as red maple (*Acer rubrum*), could shift, with the southern edge moving towards the area of the park (Iverson et al. 2008). Niche modeling of individual tree species for the area that includes Acadia N.P. projects the same type of range shifts, with possible range decreases of 50% for 13 out of the 83 species examined and possible 200% range increases for 54 species (Fisichelli et al. 2014).

Modeling of the potential range of the hemlock woolly adelgid projects that the pest could move northward into the area of the park due to warming under climate change (Paradis et al. 2008, Dukes et al. 2009).

IPCC (2013) projects continued global sea level rise of 26 to 82 cm from 2005 to 2100 for the four emissions scenarios. Storm surge would occur over and above the projected sea level rise, with models projecting more frequent and intense coastal flooding (Horton et al. 2014). USGS analysis of Lidar data projects that a 60 cm sea level rise could cause substantial inundation in upland areas adjacent to 75 ha of salt marshes in 37 separate locations in Acadia N.P. (Nielsen and Dudley 2013). Many of the upland areas are currently freshwater wetlands, including 170 ha around the Northeast Creek and Bass Harbor marshes.

Concerning the vulnerability of marine ecosystems, increased precipitation and melting in the Arctic could reduce salinity in the Gulf of Maine (Greene et al. 2008), potentially causing a cascade of changes in the food web, including increases in phytoplankton, zooplankton, and herring (Jacobson et al. 2009). Warming sea temperatures could allow the invasive Asian shore crab (*Hemigrapsus sanguineus*) to colonize much of the Maine coast (Stephenson et al. 2009). These stresses would combine with the vulnerability of shellfish to dissolution of shells due to ocean acidification (IPCC 2014).

Individual animal species in Acadia N.P. are vulnerable to climate change. Three years of monitoring of 26 wetlands in the park indicate that higher temperatures may be contributing to ranavirus-caused death of frogs and other amphibians (Gahl and Calhoun 2010). A statewide survey of ecologists indicated concerns of high vulnerability for one-third of 442 species examined, due to habitat requirements, sensitivity, and adaptive capacity, especially in wetlands and high-elevation areas (Whitman et al. 2013). Niche modeling of numerous bird species projects continued northward shifts of many species, although not much change was projected for the area around Acadia N.P. (Rodenhouse et al. 2008). Analyses of the potential distributions of 213 mammal species under a doubling of atmospheric carbon dioxide, which translates to an increase in average annual temperature in Acadia N.P. of ~3ºC, project a possible loss of three species and influx of eight species into Acadia N.P. (Burns et al. 2003). One species vulnerable to local disappearance is the fisher (*Martes pennanti*).

Table 1. Historical average temperatures and temperature trends of the area within the boundaries of Acadia National Park. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \le 0.05$, ** $P \le 0.01$, *** $P \le 0.001$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	°C		°C century^{-1}			°C century^{-1}		
Annual	7.4	0.6	0.8	0.2	**	0.1	0.5	
December-February	-4.2	1.3	1.0	0.4	*	-0.4	1.1	
March-May	6.1	0.9	0.8	0.3	**	0.4	0.7	
June-August	18.6	0.7	0.9	0.3	**	0.4	0.5	
September-November	9.3	0.8	0.4	0.2		-0.3	0.5	
January	-5.7	2.3	0.1	0.6		-2.1	1.8	
February	-4.4	2.0	1.5	0.6	**	0.3	1.7	
March	0.2	1.5	0.5	0.4		0.5	0.8	
April	6.1	1.0	1.1	0.3	**	0.9	0.8	
May	11.9	1.2	0.7	0.3	*	-0.1	0.8	
June	16.7	1.0	1.0	0.3	**	0.2	0.6	
July	19.8	1.0	0.5	0.3		-0.1	0.7	
August	19.2	0.9	1.1	0.4	**	1.1	0.8	
September	14.9	1.0	0.4	0.3		1.2	0.8	
October	9.2	1.2	-0.1	0.4		-1.4	0.8	
November	3.7	1.5	1.0	0.4	**	-0.7	0.9	
December	-2.5	2.5	1.3	0.6	*	0.9	1.5	

Table 2. Historical average precipitation totals and precipitation trends of the area within the boundaries of Acadia National Park. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	mm y^{-1}		% $century^{-1}$			% $century^{-1}$		
Annual	1400	180	16	5	***	21	11	
December-February	370	100	12	7		-20	15	
March-May	360	100	14	8		41	21	*
June-August	260	60	11	9		41	25	
September-November	380	90	26	8	**	27	16	
January	130	60	-3	13		-21	36	
February	100	40	7	10		-24	29	
March	130	50	0	14		56	27	*
April	120	50	18	11		37	27	
May	110	60	27	14	*	30	38	
June	100	40	22	13		86	32	**
July	90	40	2	10		37	27	
August	70	40	7	14		-9	42	
September	110	60	9	12		22	26	
October	120	50	34	15	*	77	39	
November	140	70	31	12	**	-9	23	
December	130	60	29	11	**	-15	24	

Table 3. Projected temperature increases (ºC), 2000 to 2050, for the area within the boundaries of Acadia N.P., from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.8	0.8	2.3	0.6	2.0	0.6	2.9	0.7
December-February	2.0	0.9	2.6	1.0	2.1	0.8	3.3	1.1
March-May	1.8	0.9	1.9	1.1	1.9	0.8	2.5	1.1
June-August	1.8	0.8	2.1	0.8	1.9	0.6	2.8	0.8
September-November	1.9	0.7	2.4	1.1	2.0	0.5	3.0	1.2
January	2.2	0.9	2.8	1.3	2.1	1.0	3.5	1.3
February	1.8	1.0	2.3	0.8	2.1	1.0	3.1	0.8
March	1.9	1.1	2.0	1.1	2.0	1.0	2.7	1.2
April	1.7	0.9	1.9	1.1	1.9	0.9	2.4	1.2
May	1.7	0.8	1.9	1.0	1.7	0.7	2.4	1.1
June	1.6	0.8	1.9	0.9	1.8	0.6	2.5	0.9
July	1.9	0.9	2.2	0.9	2.0	0.7	2.9	0.9
August	1.8	0.8	2.3	0.7	2.0	0.6	2.9	0.8
September	1.9	0.7	2.3	0.9	2.1	0.6	3.0	1.0
October	1.9	0.8	2.3	1.3	1.8	0.6	3.0	1.4
November	1.8	0.7	2.5	1.3	2.0	0.5	3.0	1.4
December	2.0	0.9	2.7	1.5	2.2	0.8	3.4	1.6

Table 4. Projected temperature increases (°C), 2000 to 2100, for the area within the boundaries of Acadia N.P., from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.8	0.9	2.9	0.9	3.3	1.0	5.1	1.2
December-February	2.1	1.0	3.4	1.2	3.7	1.1	5.6	1.4
March-May	1.7	1.0	2.6	1.2	3.1	1.2	4.5	1.4
June-August	1.7	0.9	2.8	1.0	3.3	1.1	5.0	1.3
September-November	1.7	0.8	3.0	1.4	3.3	1.0	5.2	1.7
January	2.2	1.2	3.6	1.5	3.8	1.1	5.9	1.6
February	2.0	1.1	3.1	1.0	3.6	1.2	5.4	1.2
March	1.7	1.1	2.7	1.3	3.1	1.3	4.7	1.5
April	1.7	1.0	2.6	1.2	3.1	1.3	4.5	1.4
May	1.6	0.9	2.4	1.2	3.0	1.0	4.4	1.3
June	1.6	0.9	2.5	1.1	3.0	1.1	4.6	1.3
July	1.7	1.0	2.8	1.1	3.4	1.2	5.1	1.4
August	1.7	1.0	2.9	1.0	3.4	1.1	5.4	1.3
September	1.8	0.9	3.0	1.1	3.4	1.1	5.4	1.6
October	1.7	0.9	2.9	1.5	3.2	1.1	5.2	1.9
November	1.8	0.9	3.0	1.6	3.3	0.9	5.1	1.9
December	2.1	1.0	3.5	1.7	3.7	1.1	5.5	1.9

Table 5. Projected precipitation changes (%), 2000 to 2050, for the area within the boundaries of Acadia N.P., from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

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

Table 6. Projected precipitation changes (%), 2000 to 2100, for the area within the boundaries of Acadia N.P., from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	6	6	9	6	10	6	14	7
December-February	8	10	14	10	15	10	24	14
March-May	7	8	10	10	10	8	18	11
June-August	5	10	9	13	7	14	8	15
September-November	3	8	5	9	8	7	7	11
January	11	18	16	17	15	15	28	22
February	5	11	14	15	15	10	22	15
March	6	15	14	14	12	14	24	18
April	10	10	9	13	12	12	17	17
May	7	15	7	14	6	13	12	15
June	2	12	7	13	8	16	10	18
July	8	16	9	18	6	16	7	16
August	6	13	11	21	8	16	8	24
September	1	12	2	12	3	12	-1	14
October	3	15	3	13	2	10	4	20
November	5	11	11	15	18	11	16	16
December	9	13	13	10	18	16	24	18

Figure 1.

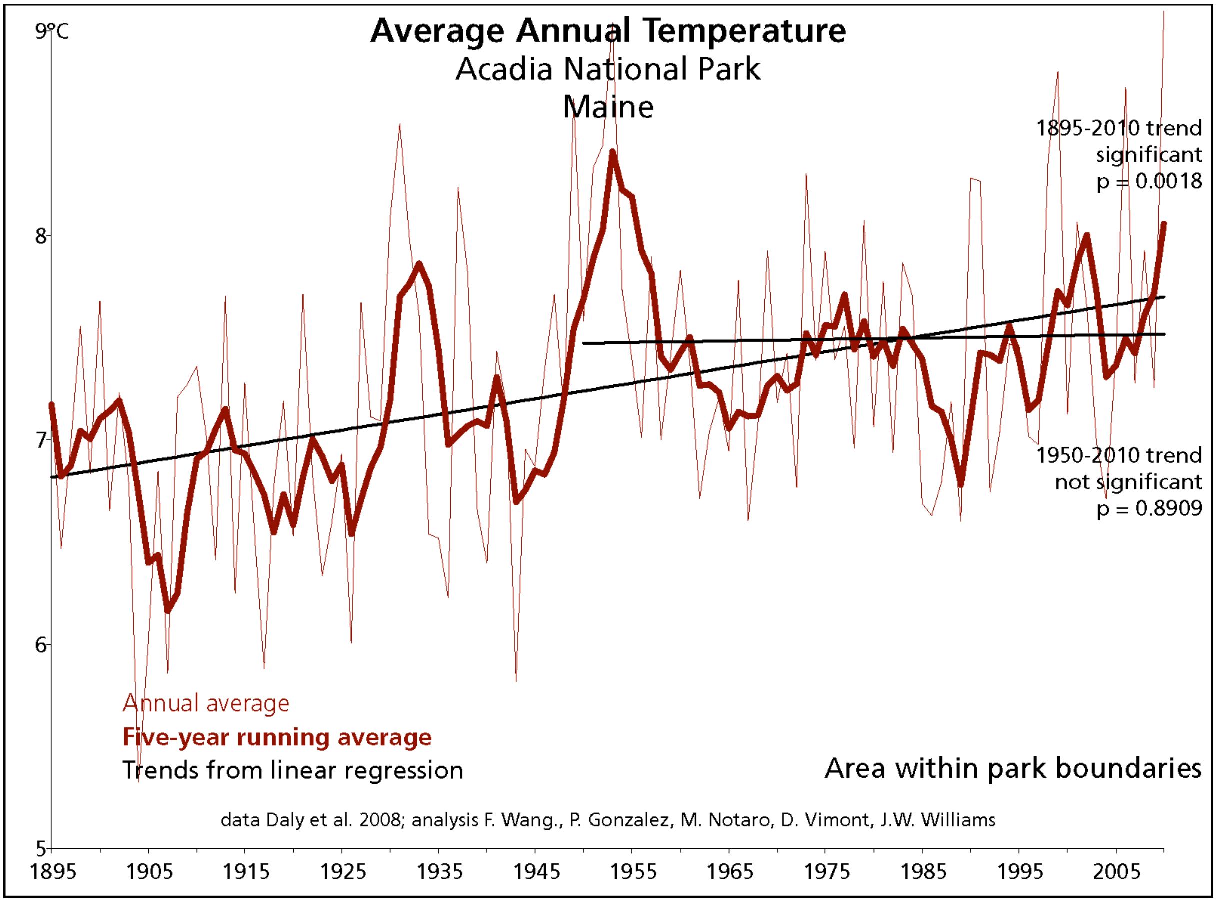

Average Annual Temperature
Acadia National Park
Maine
9°C
8
7
6
5
1895-2010 trend
significant
p = 0.0018
1950-2010 trend
not significant
p = 0.8909
Annual average
Five-year running average
Trends from linear regression
Area within park boundaries
data Daly et al. 2008; analysis F. Wang., P. Gonzalez, M. Notaro, D. Vimont, J.W. Williams
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
1995
2005

Figure 2.

Map width = 70 km

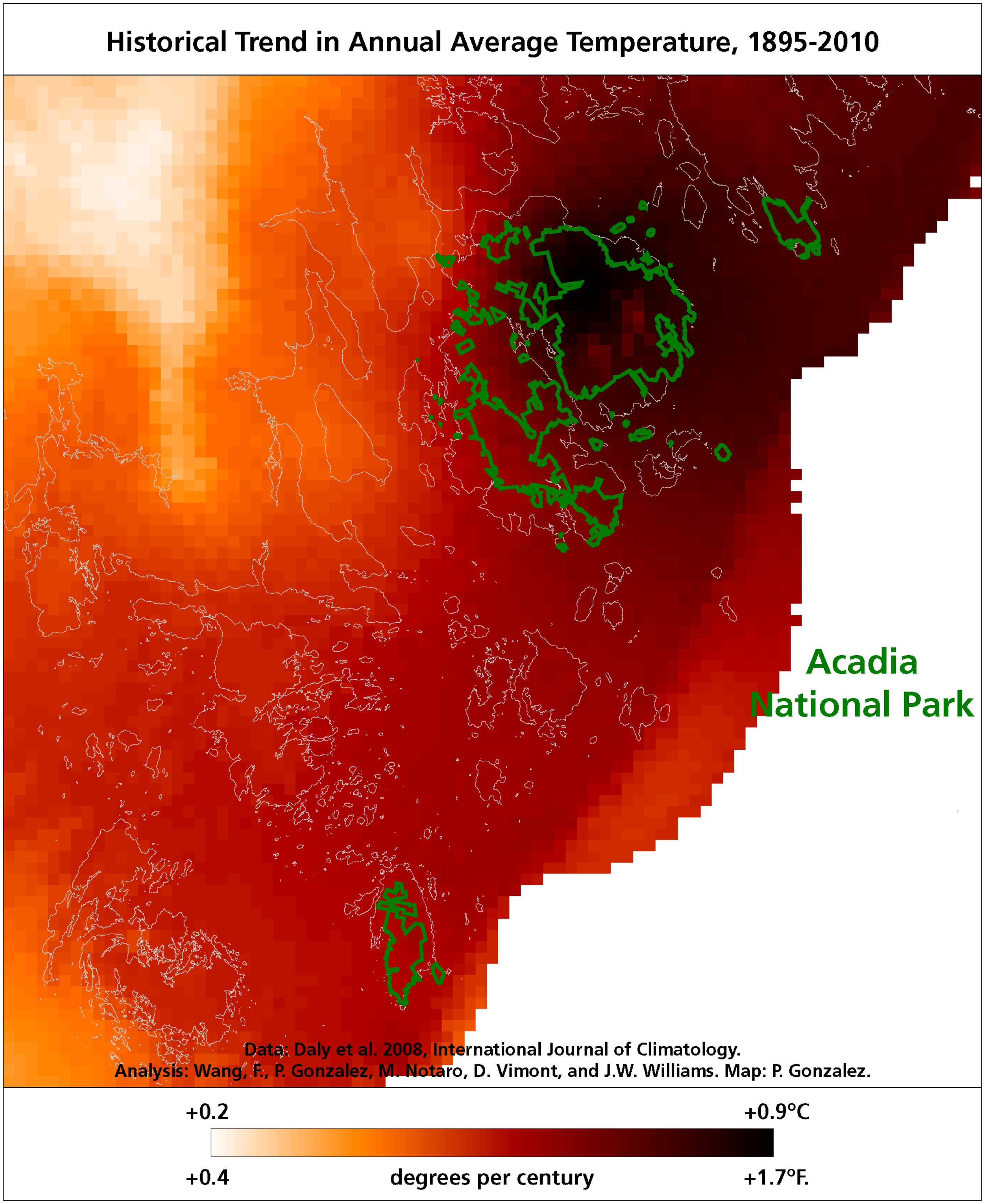


Figure 3.

Map width = 70 km

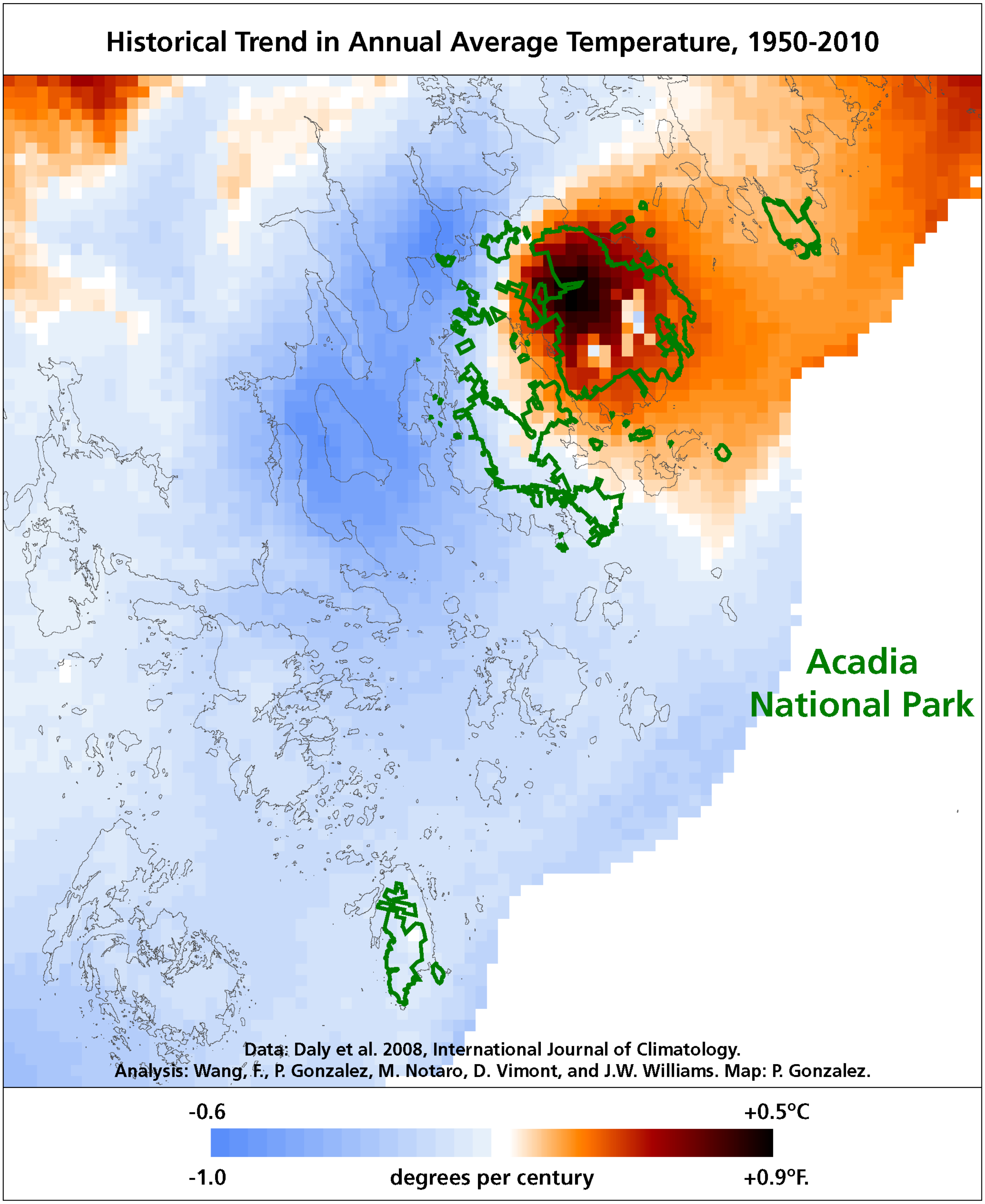


Figure 4.

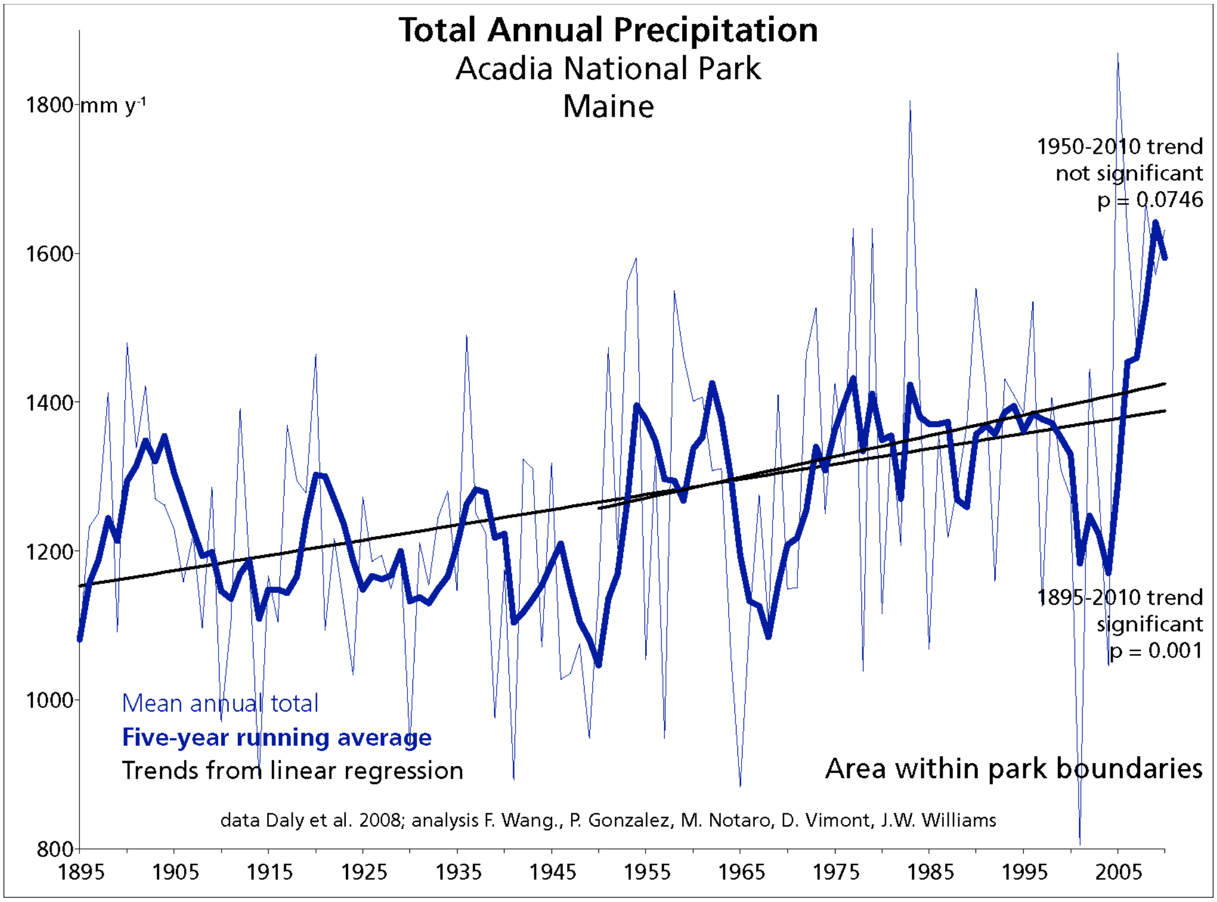

Total Annual Precipitation
Acadia National Park
Maine
mm y-1
1800
1600
1400
1200
1000
800
1950-2010 trend
not significant
p = 0.0746
1895-2010 trend
significant
p = 0.001
Mean annual total
Five-year running average
Trends from linear regression
Area within park boundaries
data Daly et al. 2008; analysis F. Wang., P. Gonzalez, M. Notaro, D. Vimont, J.W. Williams
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
1995
2005

Figure 5.

Map width = 70 km

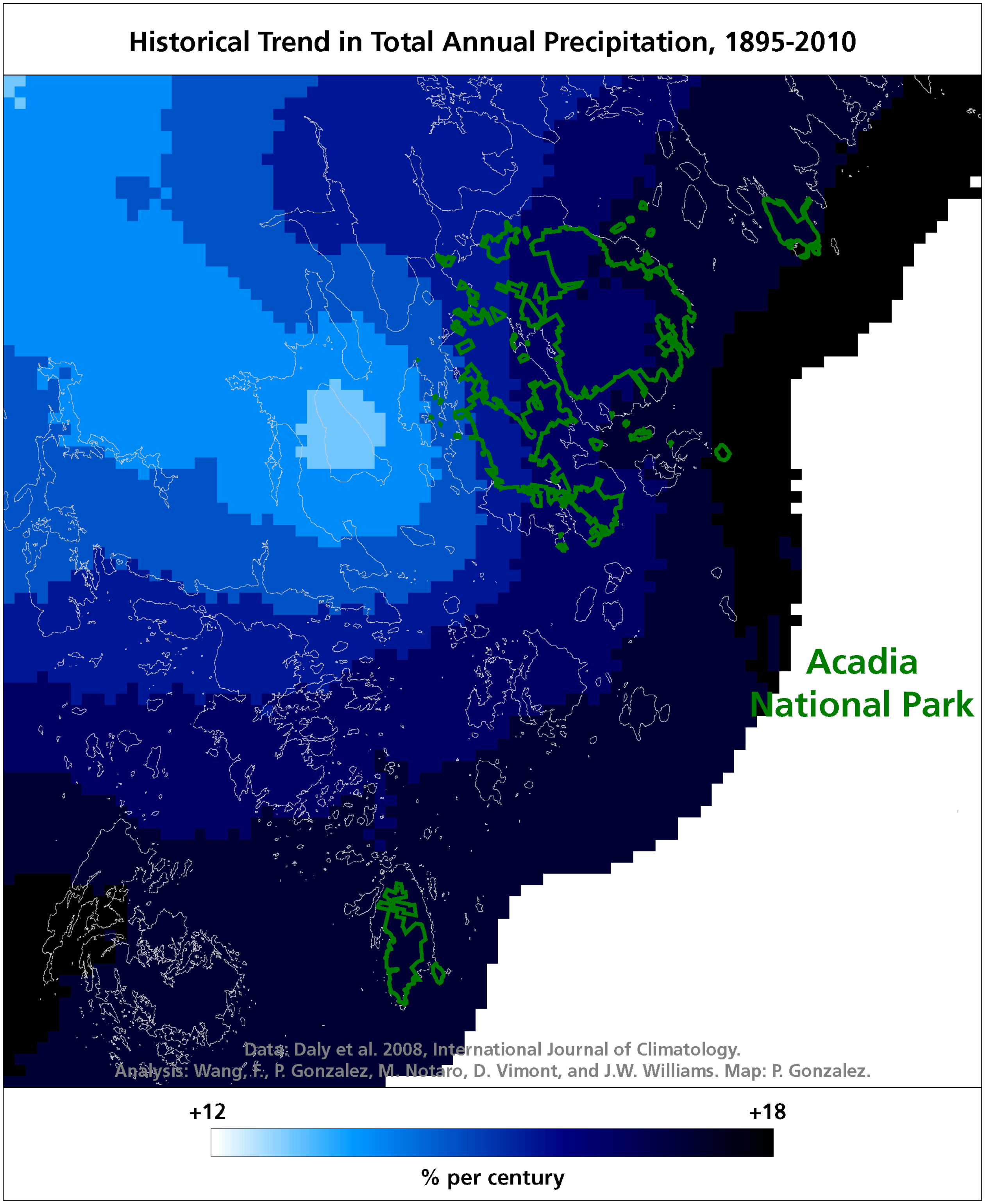


Figure 6.

Map width = 70 km

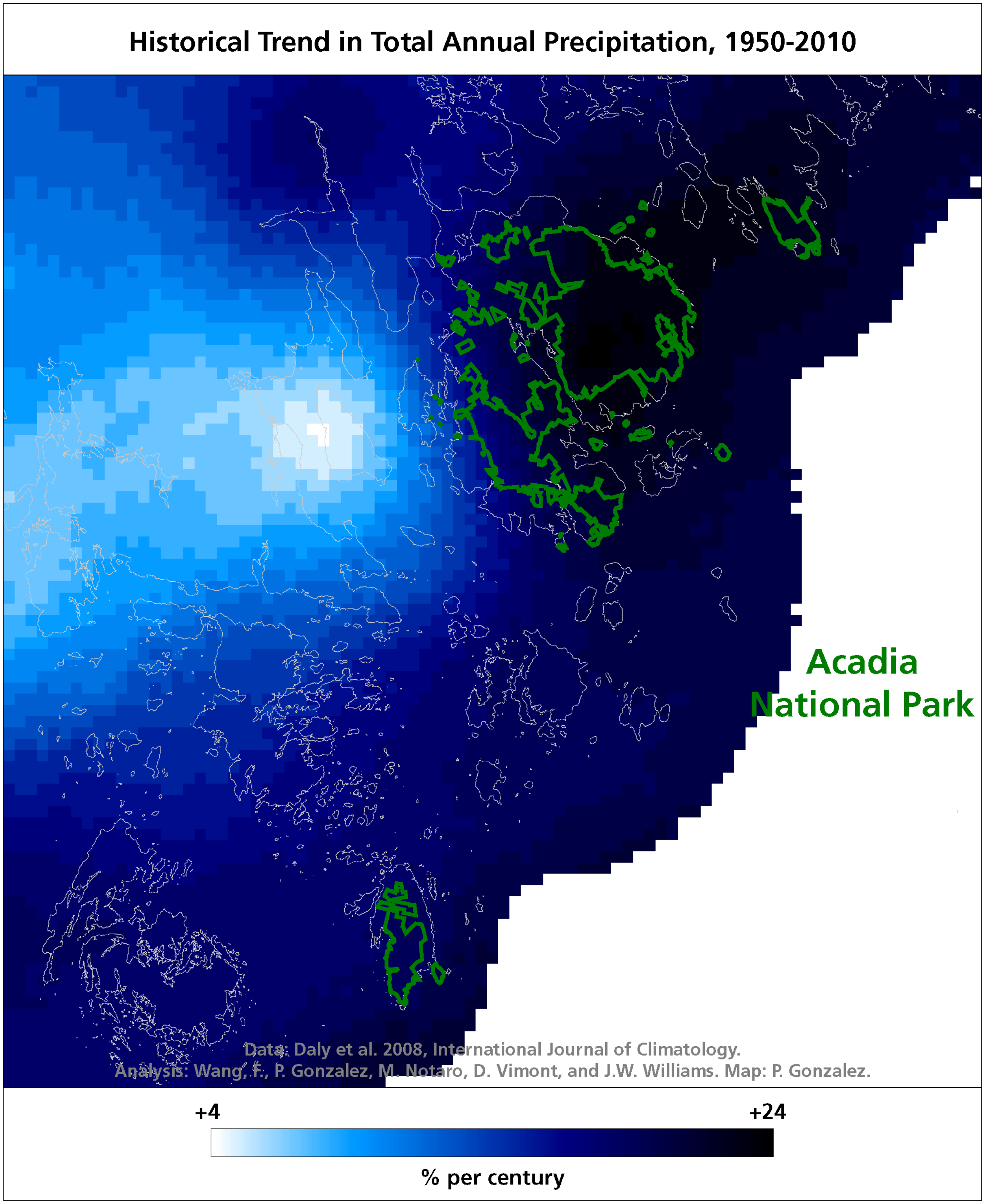


Figure 7.

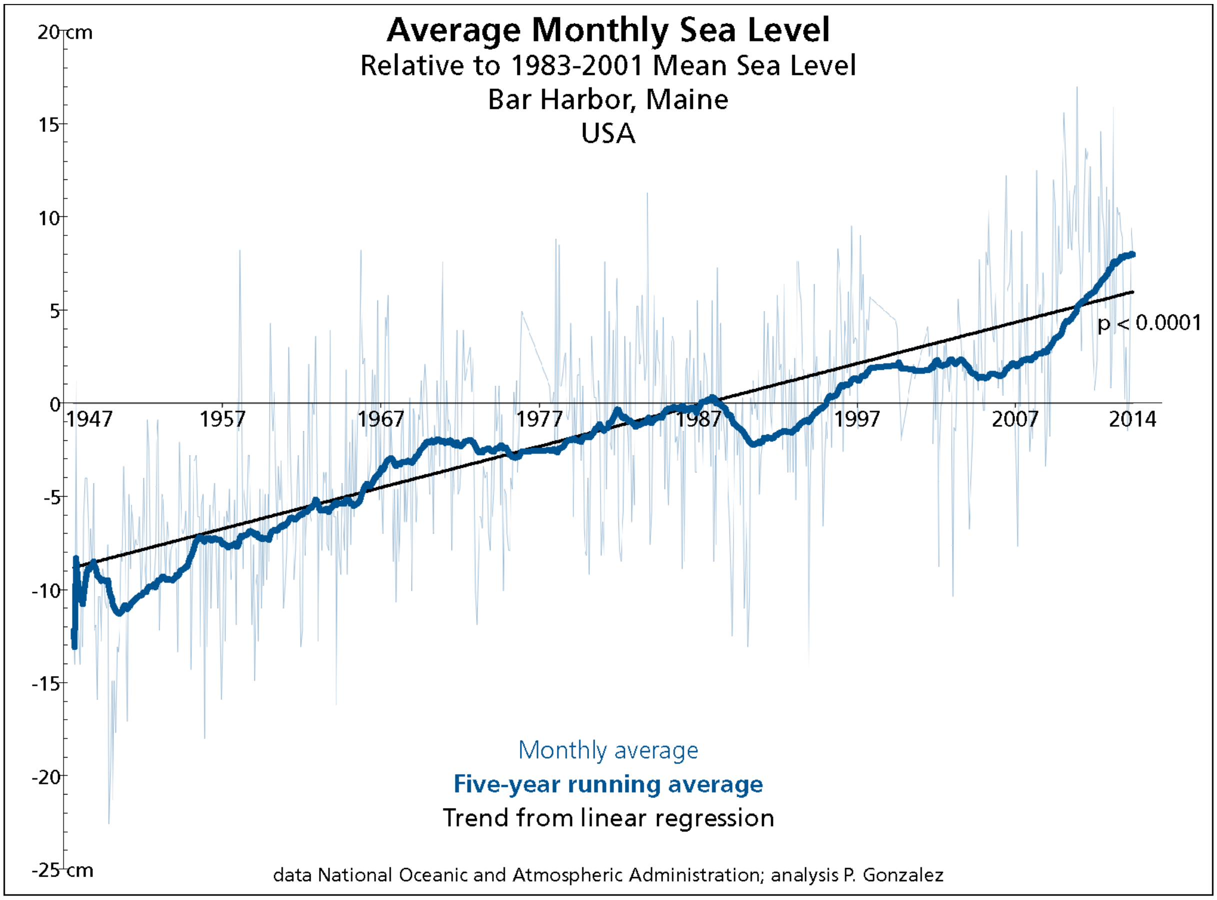

Average Monthly Sea Level
Relative to 1983-2001 Mean Sea Level
Bar Harbor, Maine
USA
20 cm
15
10
5
0
-5
-10
-15
-20
-25 cm
1947
1957
1967
1977
1987
1997
2007
2014
p < 0.0001
Monthly average
Five-year running average
Trend from linear regression
data National Oceanic and Atmospheric Administration; analysis P. Gonzalez

Figure 8.

Map width = 70 km

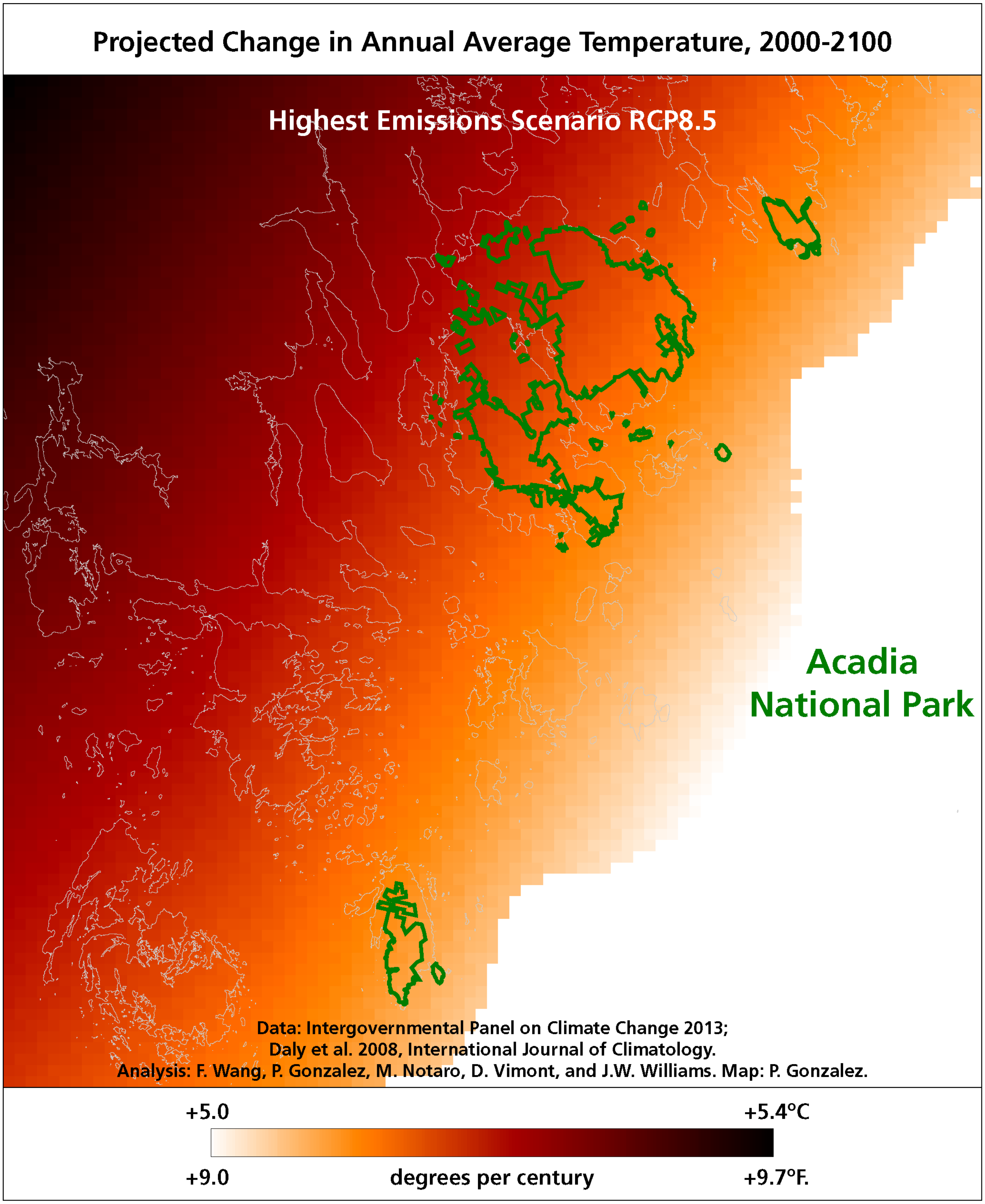


Figure 9.

Map width = 70 km

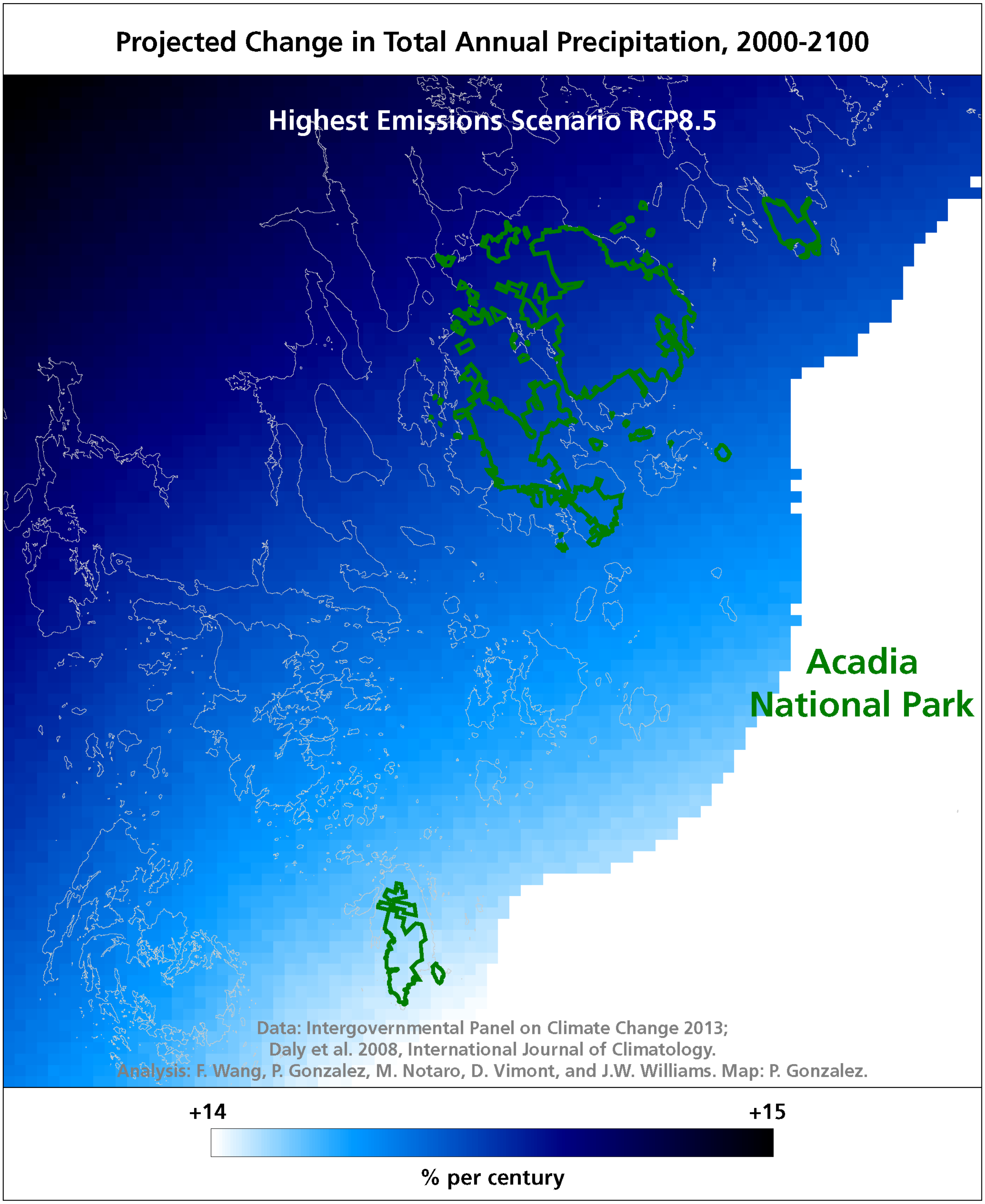
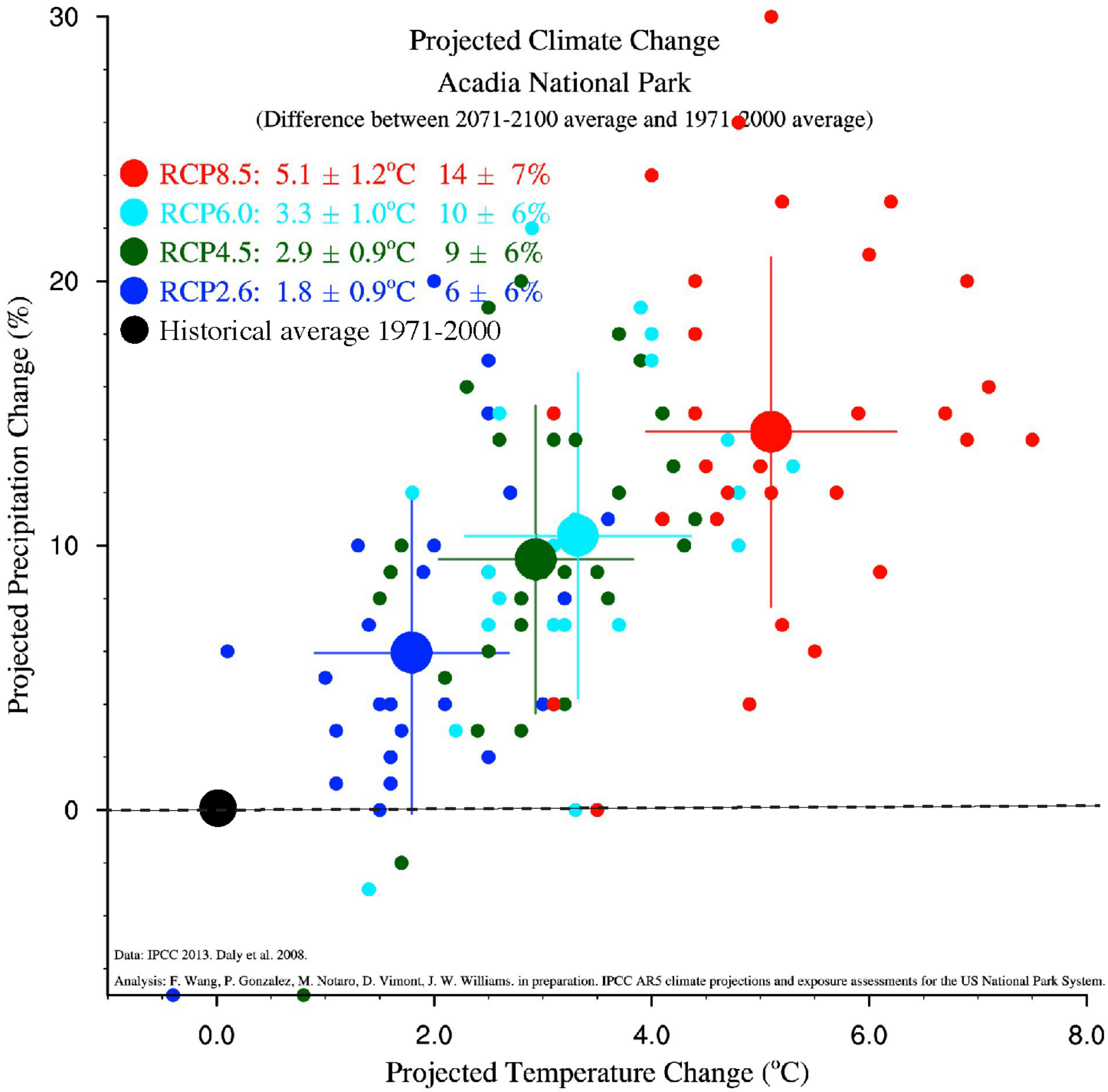


Figure 10. Projections of future climate for the area within park boundaries. The large black dot is the current combination of temperature and precipitation. Each small dot is the output of a single GCM. The large color dots are the average values for the four IPCC emissions scenarios. The lines are the standard deviations of each average value. (Data: IPCC 2013, Daly et al. 2008; Analysis: F. Wang, P. Gonzalez, M. Notaro, D. Vimont, J.W. Williams).



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