

Anthropogenic Climate Change Trends in Kenai Fjords National Park, Alaska, USA

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Introduction

Human-caused climate change has increased temperatures in Alaska (IPCC 2013, USGCRP 2017), causing melting of glaciers and permafrost, earlier melting of snow, a lengthening of the growing season, and other impacts (Stone et al. 2002, Hinzman et al. 2005, Markon et al. 2018). Kenai Fjords National Park conserves unique ecosystems, biodiversity, and physical resources that are increasingly exposed to hotter conditions. This report presents results of spatial analyses of historical and projected climate trends for the area within park boundaries (Gonzalez et al. 2018)

Methods

Historical climate This report presents results of spatial analyses of historical climate trends (Gonzalez et al. 2018) that use climate data layers at 771 m spatial resolution produced by the University of Alaska Scenarios Network for Alaska and Arctic Planning (SNAP) (<http://ckan.snap.uaf.edu/dataset/historical-monthly-and-derived-temperature-products-771m-cru-ts>). SNAP used historical climate data layers previously published by the University of East Anglia Climate Research Unit (CRU; Harris et al. 2014) in which point measurements from weather stations from 1901 to 2009 were combined into pixels at 50 km spatial resolution. Parallel to that analysis, Oregon State University researchers used the Parameter-elevation Relationships on Independent Slopes Model (PRISM; Daly et al. 2008) to interpolate, with elevation and local topography, climate values in the spaces among weather stations from 1980 to 2010, producing climate data layers at 771 m spatial resolution. SNAP downscaled the 50 km CRU data using the 771 m PRISM data to produce time series of temperature and precipitation from 1901 to 2009 at 771 m spatial resolution. Spatial data after 2009 is not yet available.

Because the configuration of the U.S. weather station network stabilized only in the 1950s (Vose et al. 2014) and because time series for small areas such as parks can change when local stations change, trends for the period 1950-2009 are more strongly supported than trends for the

period 1901-2009.

This report summarizes results by giving trends for the area within the boundaries of the park. Linear regression of temperature and precipitation time series gives the historical climate trends, with the statistical probability of significance corrected for temporal autocorrelation. Analyses of monthly, seasonal, and annual climate were run for the periods 1901-2009 and 1950-2009.

Projected climate This report presents spatial analyses of future projections of climate (Gonzalez et al. 2018) that use output of all available general circulation models (GCMs) in the Coupled Model Intercomparison Project Phase 5 dataset developed for the most recent Intergovernmental Panel on Climate Change (IPCC) assessment report (IPCC 2013). The coarse-scale GCM output, at spatial resolutions of up to 200 km, has been downscaled to 800 m spatial resolution using the bias correction and spatial disaggregation method (Wood et al. 2004) and, as a base layer, the PRISM historical climate time series (Daly et al. 2008). Future projected changes are expressed as the change from the standard 1971-2000 historical baseline.

IPCC has coordinated numerous 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, no emissions reduction practices). Climate under each of the four scenarios was projected by up to 33 GCMs. The range of potential futures is defined first by the four emissions scenarios, then by the set of GCMs within an emissions scenario. Each scenario is characterized by the average and standard deviation of the GCM ensemble.

The report uses previously published future projections of snow, with the indicator being the fraction of days with precipitation falling as snow rather than rain (Littell et al. 2018). The projections of five GCMs were analyzed at 771 m spatial resolution for RCP4.5 and RCP8.5 for the period 2070-2090, relative to 1921-2000 (Littell et al. 2018).

Historical Climate Trends

Temperature In the area within the boundaries of Kenai Fjords National Park, average annual

temperature increased at a statistically significant rate of $1.2 \pm 0.5^{\circ}\text{C}$ per century (mean $\pm$ standard error) in the period 1901-2009 and $1.5 \pm 1^{\circ}\text{C}$ per century in the period 1950-2009 (Figure 1, Table 1) (Gonzalez et al. 2018). Seasonally, temperatures from 1901 to 2009 increased at the highest rate in winter (Table 1). December average temperature increased at statistically significant rates of $2.5 \pm 0.9^{\circ}\text{C}$ per century in the period 1901-2009 and $5.6 \pm 2.3^{\circ}\text{C}$ per century in the period 1950-2009. From 1901 to 2009, the period of above-freezing temperatures for the area of the park increased by approximately two weeks, mainly through an advance of warmth in the spring (Figure 2).

Temperature increases were highest in the northern part of the park (Figure 3). The spatial pattern of temperature change is consistent with previously published analyses of weather station measurements (Bieniek et al. 2014), U.S. National Climate Assessment spatial analyses (USGCRP 2017), and IPCC (2013) spatial analyses of the principal global temperature time series (Hansen et al. 2010, Morice et al. 2012, Vose et al. 2012).

Precipitation For the area within park boundaries, annual, seasonal, and monthly precipitation showed no statistically significant trends in the time periods starting in 1901 or 1950. (Table 2, Figure 4) (Gonzalez et al. 2018). Precipitation tended to decrease across most of the park for the period 1901-2009 (Figure 5). Previously published analyses also found a precipitation decrease in the region of the park (Harris et al. 2014, McAfee et al. 2014). Seasonally, decreases were greatest in summer.

The fraction of precipitation falling as snow has decreased in the lower 48 states since the 1920s (Kunkel et al. 2009). The trend has not been determined for Alaska, however, although higher temperatures generally reduce the fraction of precipitation falling as snow (Bintanja 2018, Legates and Bogart 2009).

Extreme precipitation events are increasing. For Alaska as a whole, the amount of precipitation in 5-year 2-day events (two days with more precipitation than any other two-day-period in five years) increased from 1958 to 2016, attributable in part to anthropogenic climate change (Easterling et al. 2017).

Future Climate Projections

Temperature Under the highest emissions scenario (RCP8.5), average annual temperature for the area of the park could increase $5.4 \pm 1.3^{\circ}\text{C}$ ($11.5 \pm 2.5^{\circ}\text{F.}$) by 2100, compared to the 1971-2000 baseline (Figure 6, Table 3) (Gonzalez et al. 2018, IPCC 2013). Emissions reductions (RCP2.6) could limit the annual average temperature increase to $2.1 \pm 0.9^{\circ}\text{C}$ by 2100. For the four emissions scenarios, the ensembles of GCMs produce a cloud of potential futures (Figure 6). Seasonally, GCMs project the highest temperature increases in winter (December to February).

Under continued climate change under the highest emissions scenario, the period of above-freezing temperatures could increase by approximately three months by 2100, starting earlier in the spring and ending later in autumn (Figure 2). Reduced carbon emissions from human activities could limit the increase in the warm period by two-thirds.

Precipitation For the area within the boundaries of the park, all GCMs project increased precipitation (Figure 6). For the highest emissions scenario, total annual precipitation for the area of the park could increase $24 \pm 8\%$ from 2000 to 2100 (Table 4). For the reduced emissions scenario, the increase would be $10 \pm 5\%$. Precipitation could increase most in autumn and winter.

Projected higher temperatures would reduce the fraction of precipitation falling as snow (Littell et al. 2018). For the area within park boundaries, the fraction of days from October to March in which precipitation would fall as snow (rather than rain) would decrease from $64 \pm 14\%$ (1970-1999) to $40 \pm 14\%$ under the low emissions scenario (RCP4.5, 2070-2090) or $28 \pm 12\%$ under the highest emissions scenario (RCP8.5, 2070-2090) (Table 5) (Littell et al. 2018).

The relative projected decrease in snow days from 1999 to 2090 for the area of the park is $58 \pm 9\%$ for the highest emissions scenario and $39 \pm 9\%$ for the low emissions scenario, showing the benefit of emissions reductions (Table 5) (Littell et al. 2018). The projected decrease in snow days varies by elevation and position relative to Pacific coast. Models project greater snow decreases at lower elevations toward the coast (Figure 7).

Figure 1. Average annual temperature, 1901-2009, for the area within the boundaries of Kenai Fjords National Park. The trends, calculated by linear regression, corrected for temporal autocorrelation, show a statistically significant increase for the period starting 1901, but not 1950.

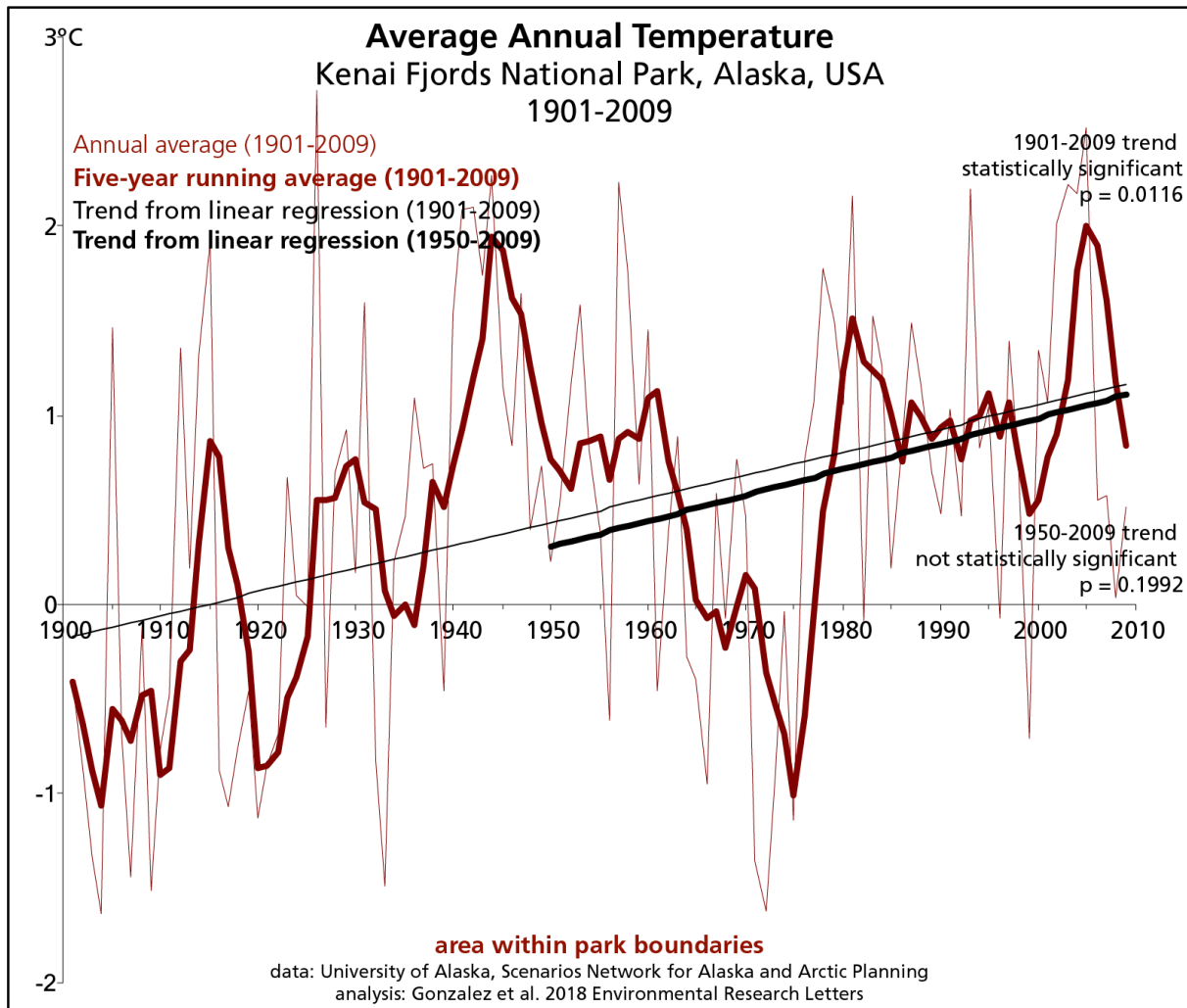


Figure 2. Monthly average temperatures, historical and projected, for the area within the boundaries of Kenai Fjords National Park. From 1901 to 2009, the period of above-freezing temperatures increased by approximately two weeks. Under continued climate change under the highest emissions scenario, the period of above-freezing temperatures could increase by approximately three months by 2100, starting earlier in the spring and ending later in autumn. Reduced carbon emissions from human activities could limit the increase in the warm period by two-thirds.

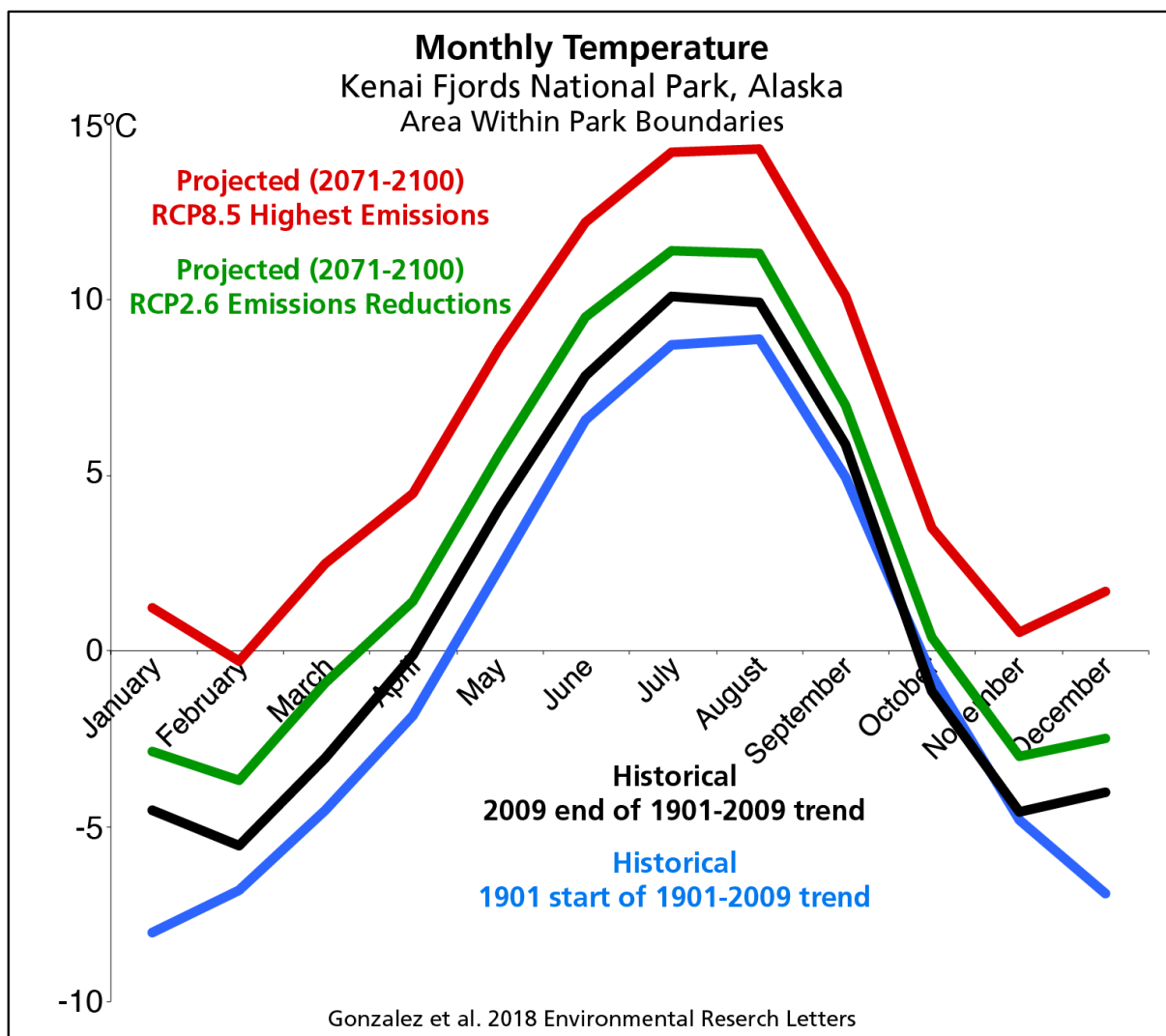


Figure 3. Trend in annual average temperature, 1901-2009, at 800 m spatial resolution, from linear regression, corrected for temporal autocorrelation.

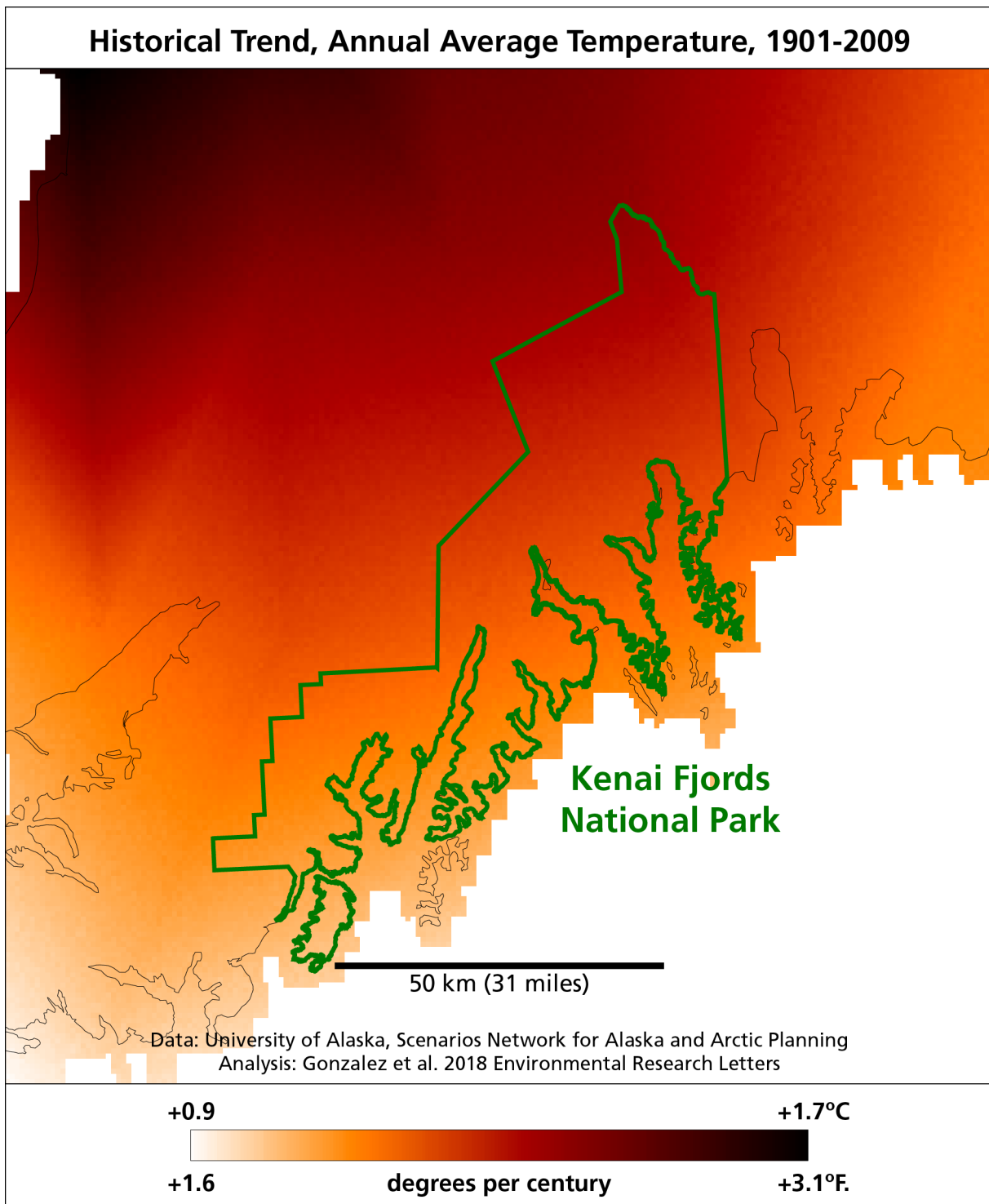


Figure 4. Total annual precipitation, 1901-2009, for the area within the boundaries of Kenai Fjords National Park. The trends, calculated by linear regression corrected for temporal autocorrelation, show no statistically significant long-term change.

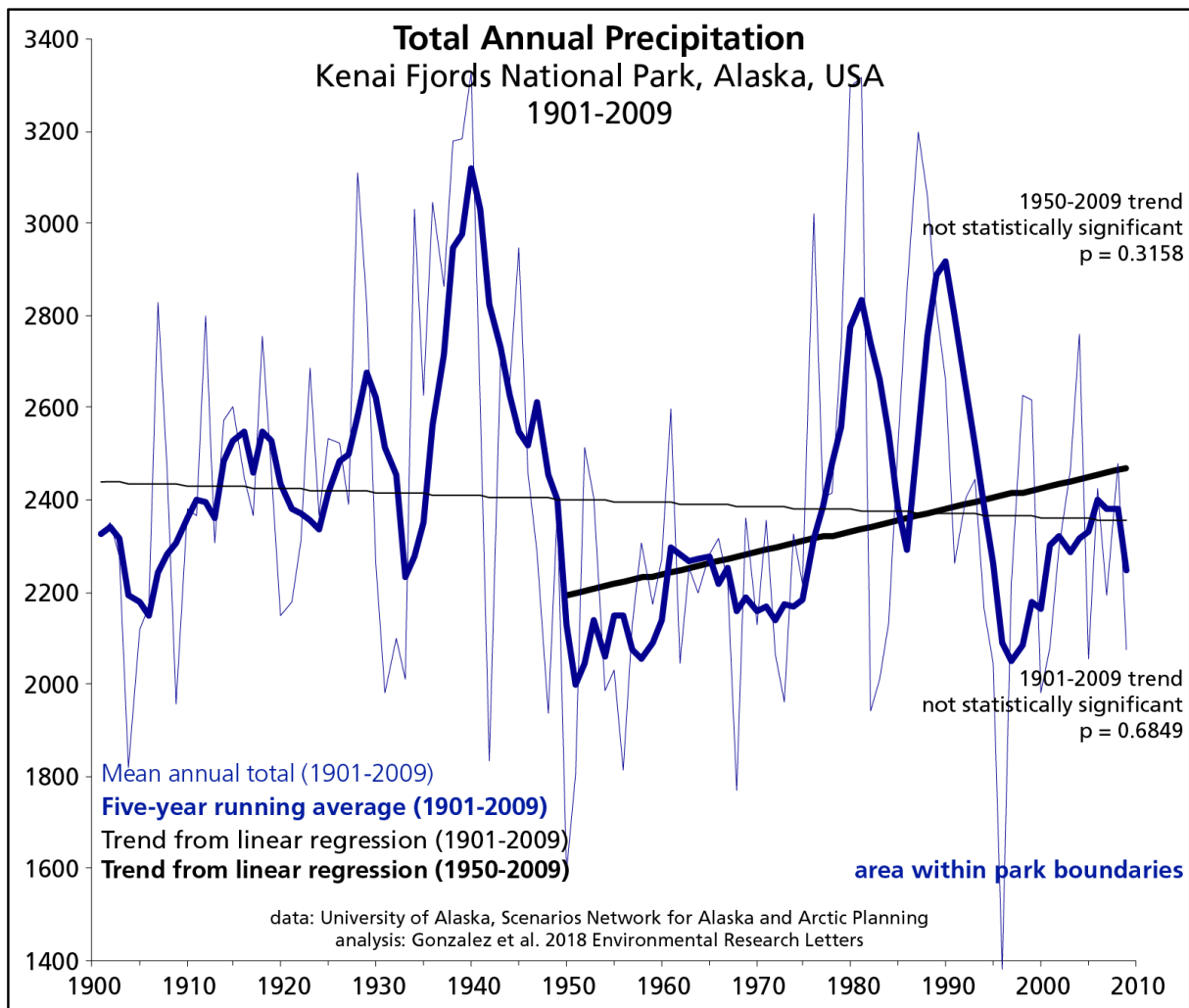


Figure 5. Trend in total annual precipitation, 1901-2009, at 800 m spatial resolution, from linear regression, corrected for temporal autocorrelation.

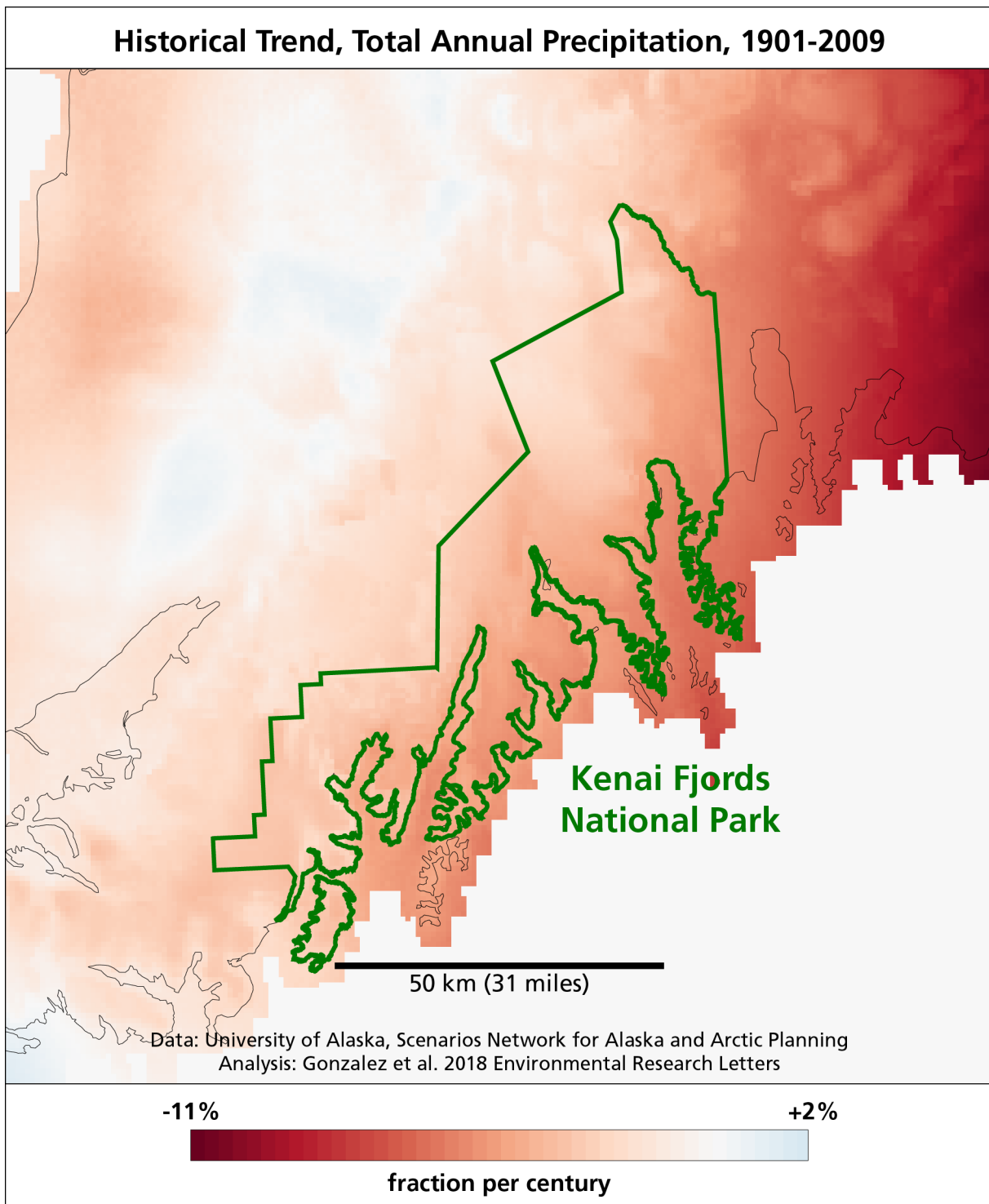
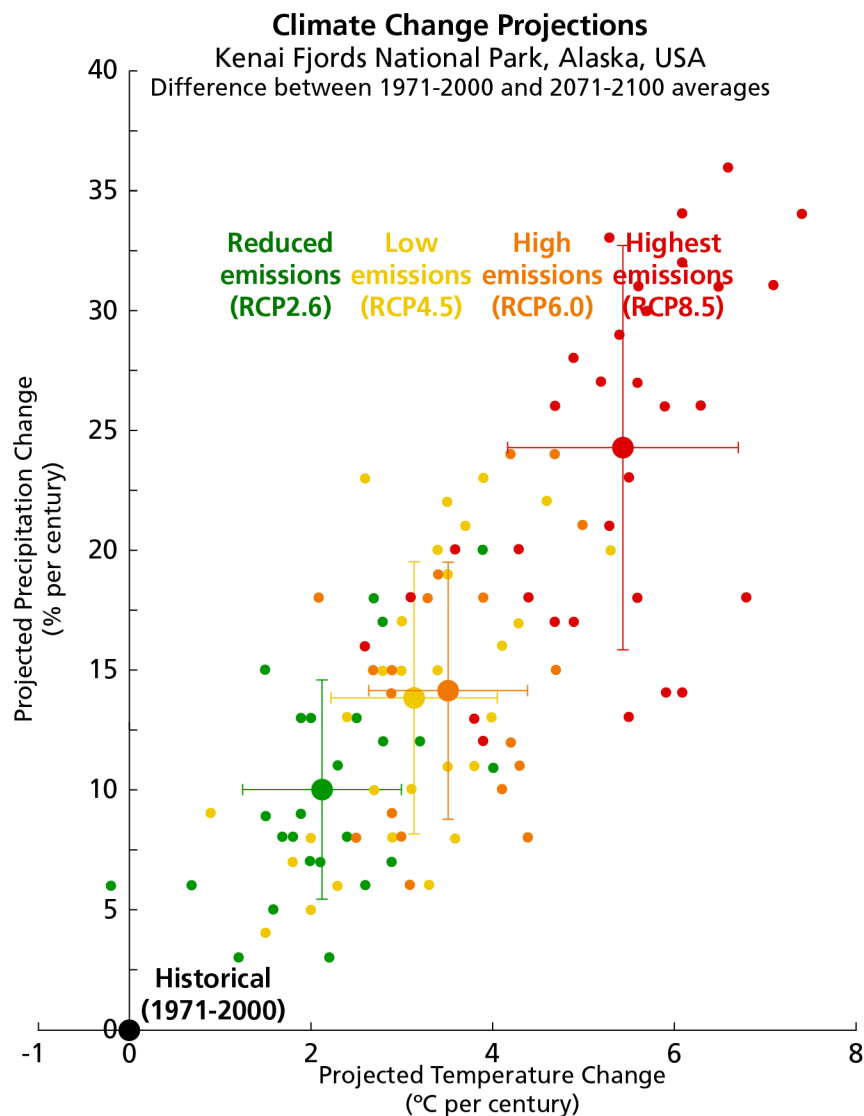


Figure 6. Projections of future climate for the area within the boundaries of Kenai Fjords National Park, relative to 1971-2000 average values. Each small dot is the output of a single general circulation model. The large color dots are the average values for the four IPCC emissions scenarios. The crosses are the standard deviations of the average values. All models project increased temperature and precipitation.



Data: Intergovernmental Panel on Climate Change 2013
Analysis: Gonzalez et al. 2018 Environmental Research Letters

Figure 7. Projected change in the fraction of days from October to March in which precipitation would fall as snow (Littell et al. 2018).

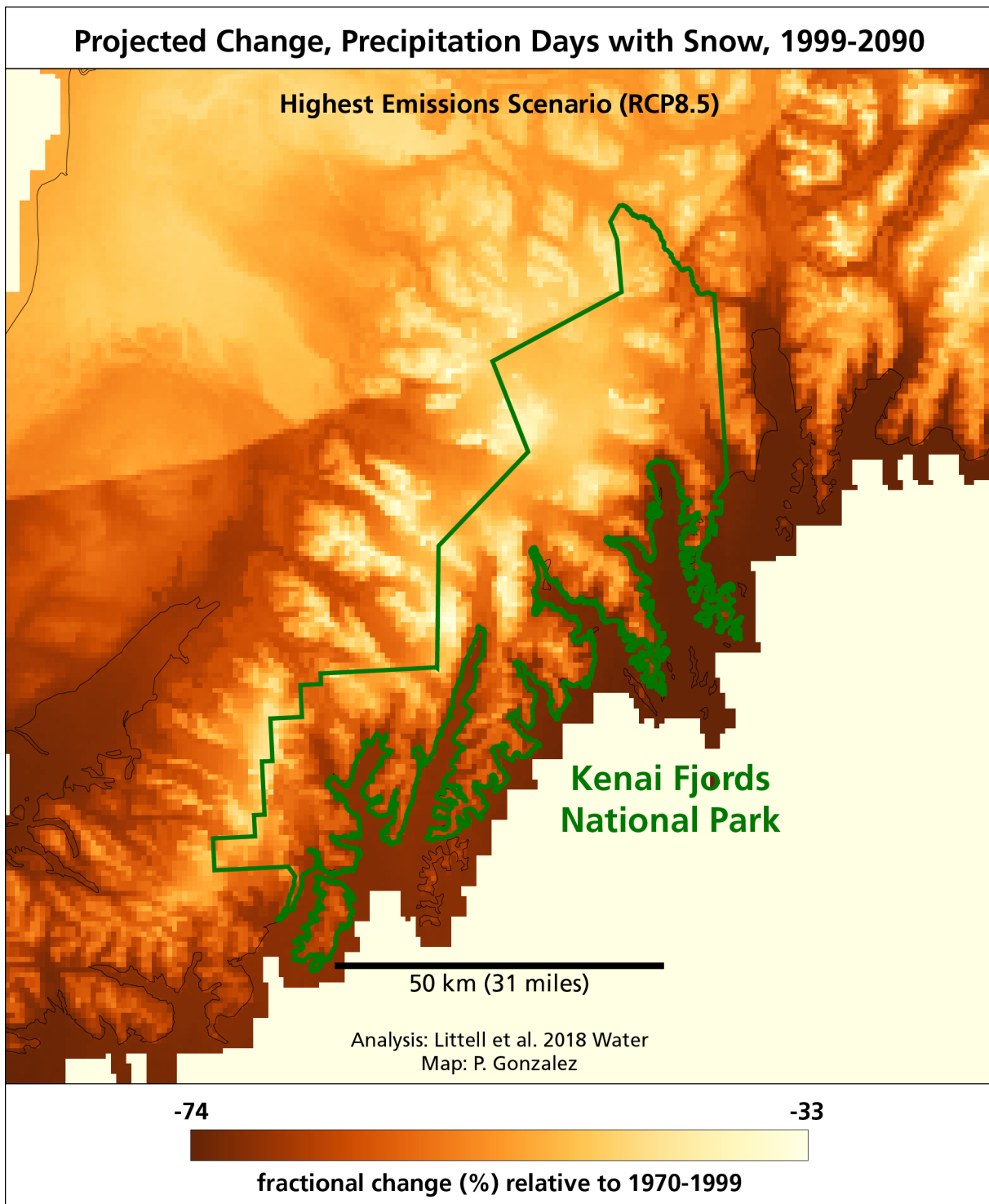


Table 1. Historical average temperatures and temperature trends of the area within the boundaries of Kenai Fjords National Park. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

	1971-2000		1901-2009			1950-2009		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	°C		°C century ⁻¹			°C century ⁻¹		
Annual	0.6	1	1.2	0.5	*	1.3	1	
December-February	-5.7	2.3	2.2	0.8	**	4.4	2.1	*
March-May	-0.2	1.5	1.4	0.5	**	1.6	1.2	
June-August	8.8	0.7	1.1	0.4	**	-0.1	0.8	
September-November	-0.4	1.3	0.2	0.4		-0.5	0.9	
January	-5.6	4	3	1.3	*	4.4	3.6	
February	-6.5	3.4	1.1	1.1		3.1	2.3	
March	-3.3	2.5	1.3	0.7		2.1	1.8	
April	-0.7	1.8	1.5	0.6	*	1.5	1.4	
May	3.5	1.1	1.5	0.5	**	1.3	1.1	
June	7.3	0.9	1.1	0.4	**	0	0.9	
July	9.5	0.7	1.2	0.4	**	0.1	0.8	
August	9.5	0.9	0.9	0.3	**	-0.4	0.8	
September	5.3	1.1	0.8	0.4	*	-0.7	0.7	
October	-1.4	1.5	-0.4	0.6		0.1	1.2	
November	-5	2.6	0.2	0.7		-0.9	1.9	
December	-4.7	3	2.5	0.9	**	5.6	2.3	*

Table 2. Historical average precipitation totals and precipitation trends of the area within the boundaries of Kenai Fjords National Park. No trends were statistically significant.

SD = standard deviation, SE = standard error.

	1971-2000		1901-2009		1950-2009	
	mean	SD	trend	SE	trend	SE
	mm y ⁻¹		% century ⁻¹		% century ⁻¹	
Annual	2448	452	-3	8	20	20
December-February	655	248	-2	13	60	35
March-May	517	198	-4	11	14	26
June-August	413	111	-6	8	-16	22
September-November	863	268	-1	8	16	19
January	232	141	-1	20	83	64
February	173	97	-12	16	28	34
March	176	104	20	17	91	45
April	162	99	-9	17	-38	40
May	179	87	-20	14	-9	30
June	116	47	11	16	-9	36
July	120	63	-3	16	-18	47
August	177	74	-18	13	-20	34
September	305	109	22	12	61	32
October	315	146	-23	16	-17	40
November	243	160	3	14	6	39
December	250	130	0	18	54	43

Table 3. Projected temperature increases (°C), 2000 to 2100, for the area within Kenai Fjords National Park boundaries, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions		Low		High		Highest	
	RCP2.6		RCP4.5		RCP6.0		RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	2.1	0.9	3.1	0.9	3.5	0.9	5.4	1.3
December-February	2.6	1.1	3.8	1.3	4.2	1.2	6.5	1.7
March-May	2.2	0.9	3	1.2	3.4	0.9	5.4	1.5
June-August	1.9	0.9	2.7	1.1	3.2	1.1	4.8	1.4
September-November	1.8	0.7	3	1.3	3.2	0.8	5.1	1.6
January	2.7	1.2	4	1.5	4.5	1.5	6.8	1.7
February	2.8	1.1	3.7	1.6	4.3	1.2	6.2	1.8
March	2.4	1.1	3.3	1.1	3.7	0.8	5.8	1.5
April	2.1	1	2.9	1.1	3.3	1	5.2	1.5
May	2.1	1	2.9	1.5	3.4	1.4	5.1	2
June	2.2	1.2	2.8	1.6	3.4	1.3	4.9	1.8
July	1.9	0.9	2.6	1.1	3.1	1	4.7	1.3
August	1.8	0.8	2.7	0.9	3.2	1	4.8	1.4
September	1.7	0.8	2.7	1.2	3	0.8	4.8	1.6
October	1.8	0.8	2.9	1.4	3.2	0.8	4.9	1.7
November	2	0.9	3.3	1.4	3.4	0.9	5.5	1.7
December	2.2	1.7	3.8	1.4	3.8	1.2	6.4	1.9

Table 4. Projected precipitation changes (%), 2000 to 2100, for the area within Kenai Fjords National Park boundaries, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions		Low		High		Highest	
	RCP2.6		RCP4.5		RCP6.0		RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	10	5	14	6	14	5	24	8
December-February	13	8	18	10	18	12	32	17
March-May	10	6	15	9	14	7	27	16
June-August	7	6	10	6	8	6	16	8
September-November	9	6	12	7	14	6	21	10
January	11	11	16	13	21	17	33	18
February	15	9	17	11	19	11	28	21
March	11	14	18	12	17	11	34	23
April	11	10	14	13	13	12	27	19
May	9	13	14	14	12	14	20	16
June	11	15	14	16	5	13	18	17
July	7	9	12	11	10	9	16	14
August	5	8	7	9	10	10	15	12
September	8	9	9	12	12	8	14	14
October	9	12	12	13	16	10	22	15
November	10	11	15	11	14	10	28	13
December	13	16	20	16	15	17	33	24

Table 5. Projected changes in snow for the area within the boundaries Kenai Fjords National Park (Littell et al. 2018). The indicator is the fraction of days from October to March with precipitation falling as snow rather than rain. Historical values are derived from weather stations. Projections are the averages of the outputs five GCMs for two emissions scenarios. The relative change is the decrease from 1970-1999 to 2070-2090, as a fraction of the 1970-1999 value. RCP = representative concentration pathway, SD = standard deviation.

	Fraction of precipitation days with snow (%)						Projected change (%)			
	1970-1999			2070-2090			1999-2090			
	RCP4.5		RCP8.5		RCP4.5		RCP8.5		RCP8.5	
	average	SD	average	SD	average	SD	average	SD	average	SD
Park	63	14	40	14	28	12	-39	9	-58	9

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