



Rock Creek (photo P. Gonzalez)

Climate Change in Rock Creek Park, Washington, DC, USA

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Abstract

Greenhouse gas emissions from cars, power plants, and deforestation have caused global climate change and widespread impacts on physical and ecological systems. To assist in the integration of climate change science into resource management in Rock Creek Park, a national park that conserves natural ecosystems and historical sites across Washington, DC, this report presents information on climate change trends, historical impacts, future vulnerabilities, and carbon. Results on climate trends for the park come from original analyses at 800 meter spatial resolution. Information on historical impacts, future vulnerabilities, and carbon comes from a scientific literature review focusing on research that covers the Washington, DC, metropolitan area. For the area within park boundaries, annual average temperature increased at a statistically significant rate of $1.1 \pm 0.4^{\circ}\text{C}$ ($2 \pm 0.7^{\circ}\text{F.}$) per century (mean $\pm$ standard error) from 1950 to 2013, with the greatest increase in summer. Autumn average precipitation increased at a statistically significant rate of $48 \pm 21\%$ per century. Changes detected and attributed to human-caused climate change include a rise of sea level of 30 ± 1 cm in Washington, DC, from 1924 to 2016 and a northward shift of winter bird ranges of 0.5 ± 0.3 km (0.3 ± 0.2 mi.) per year (mean $\pm$ 95% confidence interval) across the lower 48 US states from 1975 to 2004. If the world does not reduce greenhouse gas emissions, modeling under the four emissions scenarios of the Intergovernmental Panel on Climate Change projects annual average temperature increases for the park of 1.7 to 4.9°C (3 to 9°F.) from 2000 to 2100 and increased precipitation. Increased heat in the winter could lead to less precipitation falling as snow and more as rain. Future vulnerabilities of park resources to continued climate change include increased stream flooding, increased shore flooding from sea level rise and storm surge, increases in invasive plants, northward shifts of tree and bird species, and sensitivity of salamanders and fish to warmer waters. Under the highest emissions scenario, floods of Rock Creek and its tributaries that in the past occurred once in 100 years and covered one-seventh of park area could occur once every 25 to 30 years. Forests in Rock Creek Park help reduce climate change by storing $98\,000 \pm 20\,000$ tons carbon in aboveground biomass at densities of up to 120 metric tons per hectare (54 tons per acre). An inventory of emissions from energy use, transportation, and waste generation in Rock Creek Park shows that operations account for one half and visitor cars account for one-third of the 1.4 billion tons per year of park carbon emissions, signaling opportunities for future reductions of the human cause of climate change.

Introduction

Greenhouse gas emissions from cars, power plants, deforestation, and other human activities have caused global climate change (IPCC 2013) and widespread impacts on ecosystems and human well-being (IPCC 2014). Field measurements show that climate change is fundamentally altering ecosystems by contributing to wildlife extinctions, shifting vegetation biomes, and causing other changes globally (IPCC 2014) and in U.S. national parks (Gonzalez 2017). In response, national parks are developing management strategies to conserve resources under changing conditions. To assist in the integration of climate change science into management of resources in Rock Creek Park (Figure 1), this report presents results of original spatial analyses of historical and projected climate change and an assessment of published research on historical impacts of climate change, future vulnerabilities, and carbon.

Methods

This report presents results of spatial analyses of historical climate trends (Wang et al., in preparation) that use previously published climate data layers at 800 meter (m) spatial resolution, derived from point weather station measurements using the Parameter-elevation Relationships on Independent Slopes Model (PRISM; Daly et al. 2008). PRISM uses elevation and topography to interpolate (calculate intermediate values) climate in the spaces among weather stations, which are the points in the data set tied to field measurements. This report summarizes results by giving trends for the entire area of the park, within its boundaries, as a single unit.

Linear regression of temperature and precipitation time series gives the historical climate trends, with the statistical probability of significance corrected for temporal autocorrelation. For small areas, such as Rock Creek Park, PRISM spatial climate data for the period starting in 1950 tends to give a more robust time series than the period starting in 1895. In the late 1940s, the U.S. Government established a substantial number of weather stations, most of which have operated continuously since then, creating a relatively stable configuration. In contrast, prior to the 1940s, fewer weather stations existed and the network changed irregularly. For a large area, such as the entire United States, the number of stations is sufficient for a robust analysis for the entire time series, but a smaller area such as Rock Creek Park has many fewer stations feeding into the spatial data.

Analyses were originally run for the period 1950-2010, the data available at the time of the original research. In addition, analyses of annual trends have since been run for the period 1950-2013.

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

This report also assesses information on historical impacts of climate change, future vulnerabilities of resources in Rock Creek Park, and carbon. The information comes from a search of the Thomson Reuters Web of Science scientific literature database for published research that used field data from the park or research that covered the park as part of a broader area of analysis.

Historical Climate Trends

Annual average annual temperature of the area within park boundaries increased at a statistically significant rate of $1.1 \pm 0.4^{\circ}\text{C}$ ($2 \pm 0.7^{\circ}\text{F.}$) per century (mean $\pm$ standard error) from 1950 to 2013 (Figure 2). The greatest increase has occurred in summer, in which seasonal average temperature has increased at a rate of $1.5 \pm 0.5^{\circ}\text{C}$ ($2.7 \pm 0.9^{\circ}\text{F.}$) per century from 1950 to 2013 (Table 1). In addition, monthly average temperature of the area within park boundaries showed statistically significant rates of increase for three months: March, $2.1 \pm 1^{\circ}\text{C}$ ($3.8 \pm 1.8^{\circ}\text{F.}$) per century; June, $1.4 \pm 0.6^{\circ}\text{C}$ ($2.5 \pm 1.1^{\circ}\text{F.}$) per century; and August $1.9 \pm 0.6^{\circ}\text{C}$ ($3.4 \pm 1.1^{\circ}\text{F.}$) (Table 1). National Airport hosts the weather station with the longest time series in the Washington, DC, metropolitan area. At National Airport, annual average temperature in the period 1946-2016 increased at the statistically significant rate of $1.7 \pm 0.3^{\circ}\text{C}$ ($3.1 \pm 0.5^{\circ}\text{F.}$) (Figure 2). Temperature increases were slightly higher in Glover-Archbold and Palisades Parks, but generally similar across Rock Creek Park (Figure 3).

The heat storing capacity of concrete, asphalt, and steel and other characteristics of a city create an urban heat island or area of higher temperature than unbuilt surrounding areas. The urban

heat island of Washington, DC, increases night-time temperatures by a maximum of $3.9 \pm 1.9^{\circ}\text{C}$ (Ramamurthy and Bou-Zeid 2017).

While annual average precipitation of the area within park boundaries increased from 1950 to 2013, the trend was not statistically significant (Figure 4). Seasonal total precipitation showed a statistically significant change for autumn, $48 \pm 21\%$ per century (mean $\pm$ standard error) from 1950 to 2010, while monthly total precipitation showed a statistically significant change for August, $-76 \pm 29\%$ per century (Table 2). Precipitation increases were slightly higher in the upper part of Rock Creek Park next to Maryland (Figure 5). At National Airport, annual average precipitation increased from 1946 to 2016, but the trend was not statistically significant (Figure 4). At National Airport, average annual snowfall was $420 \text{ mm} \pm 290 \text{ mm}$ (17 ± 11 inches) for the period 1946-2016 and snow decreased during that period, but the rate was not statistically significant (Figure 4).

Climate change is increasing the frequency of heavy downpours from rainstorms (IPCC 2013). National Oceanic and Atmospheric Administration (NOAA) analyses of weather station data show an increase of heavy storms in the region that includes the 12 northeastern U.S. states and the District of Columbia, with the decade 1991-2000 experienced a 50% increase 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). In addition, the heaviest storms in the region became even heavier, with a 71% increase in the amount of precipitation falling in the heaviest 1% of all storm days from 1958 to 2012 (Walsh et al. 2014).

Hurricanes or intense storm systems that originate as hurricanes occasionally reach the Washington, DC, area. While the intensity of North Atlantic hurricanes and the frequency of the strongest (Category 4 and 5) hurricanes have increased in the past 30 years, the relative contributions of human and natural causes remain unresolved (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 natural variability of tropical cyclone activity (IPCC 2013).

Historical Impacts

Changes detected in the area and attributed to human-caused climate change

Published research that includes the Washington, DC, metropolitan area has detected changes statistically significantly different from natural variation and attributed the cause of those changes to human-caused climate change more than other factors.

Sea level rise The mouth of Rock Creek, Thompson Boat Center, Georgetown Waterfront, and other parts of the park along the Potomac River are located on a coast where the water is at sea level. At the NOAA tidal gauge on the Southwest waterfront in Washington, DC, measurements show that sea level has increased 30 ± 1 cm (9 ± 0.4 in.) (mean $\pm$ standard error) from 1924 to 2016 (Figure 6). This tidal gauge has contributed to global analyses that have detected a statistically significant rise in global sea level from 1901 to 2010 (Church and White 2011, IPCC 2013). Analyses of potential causal factors attribute this rise to human-caused climate change, through runoff from the melting of glaciers and ice on land and the expansion of ocean water when it warms (Church and White 2011, IPCC 2013). Sea level along the US Northeast coast is rising at rates that are must faster than the global rate (Sallenger et al. 2012). At the Washington, DC, tidal gauge, the rate of sea level rise is a relative rate that includes the global rise in sea level, the regional fall in land level due to subsidence as the land rebounds from the melting of the continental ice sheet 20 000 years ago (Karegar et al. 2016), and the regional rise in sea level due to a weakening of the Gulf Stream (Ezer et al. 2013).

Bird range shifts Analyses of Audubon Christmas Bird Count data across the US, including the count in Washington, DC, detected a northward shift of winter ranges of a set of 254 bird species at a rate of 0.5 ± 0.3 km per year (mean $\pm$ 95% confidence interval) from 1975 to 2004, attributable more to climate change than other factors (La Sorte and Thompson 2007). Evening Grosbeak (*Coccothraustes vespertinus*) has been extirpated from many locations in the northern US and has not been seen since 1997 in the Washington, DC, Christmas Bird Count, which lies near the southern edge of its range (La Sorte and Thompson 2007). Additional analyses found northward shifts across the US from 1975 to 2011 of winter distributions of three raptor species listed by the NPS

Inventory and Monitoring Program (NPS 2017) as present in Rock Creek Park:
Red-tailed Hawk (*Buteo jamaicensis*), American Kestrel (*Falco sparverius*), Northern
Harrier (*Circus cyaneus*) (Paprocki et al. 2014).

Changes consistent with, but not formally attributed to human climate change

Other research has found changes consistent with human-caused climate change, but either not detected as statistically significantly different than historical variability or, if detected, not analyzed to formally attribute the cause of the change.

Increased stream flow The US Geological Survey stream gauge on Rock Creek at Sherrill Drive shows that annual average stream flow in Rock Creek increased at a statistically significant rate of $40 \pm 15\%$ per century from 1930 to 2016 (Figure 7). Stream flow has increased in all seasons, but most in the autumn (Schmit 2011).

Across the Mid-Atlantic region (generally, District of Columbia, Maryland, Pennsylvania, and Virginia), stream flow between 1881 to 2008 and the peak magnitude of floods from 1940 to 2013 showed statistically significant increases (Archfield et al. 2016, Armstrong et al. 2014, Hirsch and Ryberg 2012). While these trends are consistent with increased precipitation due to climate change, that is just one factor contributing to the stream flow increases in Rock Creek and elsewhere. A combination of urbanization and increased precipitation has increased runoff along much of the US East Coast (Yang et al. 2015) and the expansion of built-up and paved areas in Washington, DC, and Montgomery County, MD, would tend to increase runoff. Analyses found no simple correlation of stream flow to atmospheric carbon dioxide (Hirsch and Ryberg 2012) but that the increases result from a complex combination of precipitation changes due to human-caused climate change and the natural variability of the North Atlantic Oscillation cycle (Armstrong et al. 2014).

Earlier cherry tree blooming Monitoring of tree blooming in Washington, DC, and Baltimore, Maryland, showed a statistically significant advance of cherry tree blooming by a week from 1970 to 1999 (Abu-Asab et al. 2001). This is an example of a change in phenology, the timing of life events. While blooming dates vary from year to year, the long-term trend shows earlier blooming. In flowering trees, heat triggers the break from winter dormancy. Earlier cherry blooming is consistent with the hotter temperatures caused by

climate change. In Kyoto, Japan, records show that cherry trees are blooming earlier than they ever have in 1200 years (Primack et al. 2009). An acceleration of blooming in the past century coincides with increasing temperatures due to climate change and to expansion of the urban heat island of the city.

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).

If we do not reduce greenhouse gas emissions from human activities by 40-70%, GCMs project substantial warming and slight increases in precipitation in the park by 2100. The temperature and precipitation projections from 33 GCMs form a cloud of potential future climates (Figure 8). GCMs project potential increases in annual average temperature of the area within park boundaries by 1.7 to 2.8°C (3 to 5°F.) by 2050 (Table 3) and 1.7 to 4.9°C (3 to 9°F.) by 2100 (Table 4). Models project the greatest temperature increases in the autumn (Tables 3, 4). Projected temperature increases are similar across the park (Figure 9).

The average of the ensemble of GCMs projects increased precipitation under all emissions scenarios (Tables 5, 6). For the area within park boundaries, almost all GCMs project increased precipitation (Figure 8). Furthermore, the ensemble averages and standard deviations for all emissions scenarios project increased precipitation (Figure 8). GCMs project the greatest increases in winter (Tables 5, 6), although increased heat in the winter would lead to less precipitation falling as snow and more as rain (Demaria et al. 2016, Ning and Bradley 2015). Under low emissions (RCP4.5), the snow season in Washington, DC could contract from the period December–March to January–February (Ning and Bradley 2015). Under highest emissions (RCP8.5), snowfall could disappear entirely (Ning and Bradley 2015). Projected precipitation increases are similar across the park (Figure 10). Even if precipitation increases,

temperature increases may overcome any cooling effects and lead to increased evapotranspiration of up to 4% in the Mid-Atlantic region (Naz et al. 2016).

Projections indicate potential changes in the frequency of extreme temperature and precipitation events. For the District of Columbia, under the highest emissions scenario, models project up to 21 more days per year with a maximum temperature $>35^{\circ}\text{C}$ (95°F.) (Kunkel et al. 2013), up to 22 fewer days below freezing (Kunkel et al. 2013), and an increase in 20-year storms (a storm with more precipitation than any other storm in 20 years) to once every five to six years (Walsh et al. 2014). Models project an increase in North Atlantic 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 Vulnerabilities

If we do not reduce greenhouse gas emissions from human activities, continued climate change could increase the vulnerability of park resources (IPCC 2013). Published research on the Mid-Atlantic region or on resources found in Rock Creek Park has identified numerous vulnerabilities.

Physical Resources

Stream flow changes and flooding Under the highest emissions scenario (RCP8.5), in the Mid-Atlantic region, hotter winters would melt snow cover earlier, causing an advance in spring peak stream runoff up to 10 days and a 10% increase in flow by 2095 (Demaria et al. 2016). Stream flow would tend to increase most in autumn and winter, up to 15% by 2050 (Naz et al. 2016). Under a low emissions scenario (RCP4.5), spring peak runoff timing could occur up to 10 days later, though still with a 10% increase in flow by 2095. Under low emissions, the increase in potential evapotranspiration could reduce the lowest stream flows in the summer up to 20% by 2100 in the North Branch of Rock Creek, upstream of the park in Maryland (Hejazi and Moglen 2007). Under the highest emissions scenario (RCP8.5), the lowest stream flows could decrease by 5% by 2050 in the Mid-Atlantic region (Naz et al. 2016).

Under historical climate, the Federal Emergency Management Agency (FEMA 2017) has delineated areas with a flood hazard of 1% or a flood that has historically occurred once in 100 years (a 100-year flood). This flood analysis assumes stationarity, that flood probabilities do not change during the period of analysis. Stationarity does not exist, however, under climate change since climate change is altering the probabilities of heavy storms and other key factors influencing flooding (Milly et al. 2008). A nonstationary flood frequency analysis of the Little Patuxent River in Columbia, Maryland, northeast of the park, estimated a 30% increase in stream flow for a 100-year flood under medium emissions (scenario A1B) by 2100 (Gilroy and McCuen 2012).

An original spatial analysis indicates that 14% of the area of Rock Creek Park is covered by the FEMA 100-year flood zone (Figure 11). This zone includes extensive areas on either side of Rock Creek and areas in Glover-Archbold, Klinge Valley, Melvin Hazen, and Soapstone Valley Parks. Under the highest emissions scenario (RCP8.5), models project a 300 to 400% increase in the frequency of 20-year storms in the Mid-Atlantic region (Walsh et al. 2014). If flood frequency also experiences that increase, that area of Rock Creek Park that had been estimated to experience flooding once in 100 years could experience flooding once every 25 to 30 years under climate change.

Any projected increase in flooding increases the vulnerability to damage of Beach Drive, the old Klinge Road, and many trails and historical buildings located next to Rock Creek and other water courses, including Pierce Mill (Figure 12). Increased stream flow can increase erosion of river banks (Yellen et al. 2015), making any buildings on river banks vulnerable.

Sea level rise and flooding If the world does not reduce emissions from human activities, climate change under the highest emissions scenario (RCP 8.5) may increase sea level 80 cm (2 feet, 7 inches) by 2100 at Rock Creek Park (IPCC 2013, Caffrey et al. in press). A scenario of reduced carbon emissions (RCP2.6) could keep the increase in sea level to 53 cm (1 foot, 9 inches). The major future vulnerability to sea level rise is the direct inundation of land. Sea level rise of 90 cm (3 ft.) could flood parts of Georgetown Waterfront Park, but other parts of Rock Creek Park are generally at higher elevation and not immediately vulnerable to that rise in sea level (Sweet et al. 2017).

Storm surge and flooding Storm surge would occur over and above the projected sea level rise, with models projecting more frequent and intense coastal flooding. A category 4 hurricane can currently cause flooding of Georgetown Waterfront Park, Thompson Boat House, and the lower reach of Rock Creek (Caffrey et al. in press).

Vegetation

Invasive plants Climate change tends to favor invasive alien plants in temperate zones like the Mid-Atlantic region for three main reasons:

1. Carbon dioxide (CO₂) enrichment – Invasive alien plants generally exploit atmospheric CO₂ more efficiently than native species, an ability that also explains the higher growth rates of invasive alien plants (Davidson et al. 2011, Liu et al. 2017)
2. Warmer, moister conditions – Increasing warmth and moisture due to climate change increase the suitability of temperate zone ecosystems to plants from sub-tropical and tropical zones, their ability to out-compete temperate zone plants, and their tendency to become invasive (Hellmann et al. 2008, Theoharides et al. 2007).
3. Disturbance – Invasive alien plants often proliferate in disturbed sites (Hellmann et al. 2008, Theoharides et al. 2007). Climate change can increase disturbances, particularly biome shifts and wildfire changes, increasing the risk of invasion from alien plants (Early et al. 2016).

Under high emissions, the Washington, DC, metropolitan area is moderately to highly vulnerable to invasive species under climate change (Early et al. 2016). Under high emissions, the area continues to be highly favorable for the invasive plants kudzu (*Pueraria lobata*) and privet (*Ligustrum sinense*) (Bradley et al. 2010) and Japanese honeysuckle (*Lonicera japonica*) (Kilkenny and Galloway 2016) and increasingly favorable for cogongrass (*Imperata cylindrica*) (Bradley et al. 2010). Freezing temperatures easily damage Japanese knotweed (*Fallopia japonica*), so climate change favors its survival and spread (Baxendale and Tessier 2015). Earlier flowering under higher temperatures further increase the invasiveness of numerous non-native plants, including climbing nightshade (*Solanum dulcamara*), coltsfoot (*Tussilago farfara*), curly dock (*Rumex crispus*), garlic mustard (*Alliaria petiolata*), ground ivy (*Glechoma hederacea*), narrowleaf plantain (*Plantago lanceolata*), and ivyleaf speedwell (*Veronica hederifolia*) (Hulme 2011). An increase of climbing vines such as kudzu in Rock Creek Park trees could reduce tree

growth and increase tree mortality (Matthews et al. 2016). Experimental increases of atmospheric carbon dioxide in a North Carolina forest (Mohan et al. 2006) indicate that the increase of carbon dioxide that causes climate change could increase the growth and toxicity of poison ivy (*Toxicodendron radicans*), a species common in Rock Creek Park.

Tree range shifts Under continued climate change, hotter temperatures will tend to shift the ranges of eastern US tree species northward (Iverson et al. 2008, Rogers et al. 2017). In the Washington, DC, metropolitan area, eastern hemlock (*Tsuga canadensis*), eastern white pine (*Pinus strobus*), and other conifer species are most vulnerable due to their colder temperature requirements (Lanza and Stone 2016). Among deciduous species, climate change could shift the potential ranges of red maple (*Acer rubrum*), tulip tree (*Liriodendron tulipifera*), and white oak (*Quercus alba*) north (Iverson et al. 2008) as hickories and other southern species shift from the south (Fisichelli et al. 2014). Other deciduous trees vulnerable to a range shift include American basswood (*Tilia americana*), pin oak (*Quercus palustris*), and sugar maple (*Acer saccharum*) (Lanza and Stone 2016).

In Rock Creek Park, potential tree species changes under climate change would occur in the context of a historical shift of early successional trees, including Virginia pine (*Pinus virginiana*) and black cherry (*Prunus serotina*) to later successional trees, including American beech (*Fagus grandifolia*) (Matthews and Nortrup 2013). In addition, scarlet oak (*Quercus coccinea*), black oak (*Quercus velutina*), and other oaks have been declining (Matthews and Nortrup 2013) due to the suppression of all fires, which favor eastern oak species (Nowacki and Abrams 2008).

Wildfire slight increase Fire suppression in eastern US forests, including Rock Creek Park, has created moister and shadier conditions and less flammable fuel beds that favor mesic tree species such as American beech (*Fagus grandifolia*) and red maple (*Acer rubrum*) and disfavor xeric fire-adapted species such as chestnut oak (*Quercus prinus*) and scarlet oak (*Quercus coccinea*) (Nowacki and Abrams 2008). Under climate change, high moisture throughout the year could keep wildfire ignition low in the Washington, DC, area, leading to unchanging or only slightly increasing potential wildfire frequency (Clark et al. 2014, Moritz et al. 2012).

Flooding Increased flooding could change the form and ecology of Rock Creek, its floodplain, and adjacent upland areas. Potential changes include altered distribution of riparian vegetation and upland vegetation, changes habitat for fish and invertebrates, and changes in habitat for wildlife that use the edge of the floodplain (Death et al. 2015).

Earlier cherry tree blooming Continued warming could advance peak bloom of Tidal Basin cherry trees by a week (medium emissions scenario A1B) to a month (high emissions scenario A2) by 2100 (Chung et al. 2011).

Wildlife

Bird range shifts Climate change could continue to shift the ranges of bird species northward across the US and in the Mid-Atlantic (Langham et al. 2015). Projections using Breeding Bird Survey and Christmas Bird Count data indicate that, under low emissions (scenario B2), the District of Columbia would become less suitable for 10 to 28 bird species and more suitable for 23 to 37 species, a potential net gain of 9 to 13 species (Langham et al. 2015). Under high emissions (scenario A2), the projections indicate lower suitability for 12 to 34 bird species and higher suitability for 30 to 45 species, a potential net gain of 11 to 18 species. Follow-up analyses (Wu in preparation) indicate a loss of suitable climate in the park for 19 species in summer and 7 species in winter, a gain of suitable habitat for 24 species in summer and 49 species in winter, a possible net gain by 2050, under the highest emissions scenario (RCP8.5). One species, the house finch (*Haemorrhous mexicanus*), might possibly lose suitable habitat in both summer and winter under high emissions (Wu in preparation).

Bat sensitivity White nose syndrome is a deadly disease of bats caused by an invasive fungus (*Pseudogymnoascus destructans*), found across the eastern US, but not in the District of Columbia (US Fish and Wildlife Service <<https://www.whitenosesyndrome.org>>). It has killed bats of three species found by NPS Inventory and Monitoring (NPS 2017) in Rock Creek Park: big brown bats (*Eptesicus fuscus*), little brown bats (*Myotis lucifugus*), and Northern long-eared bats (*Myotis septentrionalis*), listed as threatened under the Endangered Species Act. White nose syndrome exhibits particular climate requirements: annual temperature range (difference between maximum and minimum) of 38 to 40°C (100-104°F.) mean temperature of the wettest quarter less than 18°C (64°), precipitation

frequency of 30% of days with any precipitation, and precipitation during the wettest month less than 100 mm (Flory et al. 2012). The disease is found in areas that are higher in elevation and drier than Rock Creek Park and, under projected climate scenarios, the park would continue to provide unsuitable climate. The speed and severity of the historic spread of white nose syndrome suggests that factors other than climate, such as accidental human transmission, are more influential in its expansion.

Increasing aridity can reduce bat reproduction (Adams and Hayes 2008). Bats may be disproportionately affected by increased aridity relative to other mammals because small body size and a large surface area-to-volume ratio predisposes them to dehydration through evaporative loss (Adams 2010). This suggests vulnerability of bats under scenarios where evapotranspiration increases.

Monitoring in Wisconsin of little brown bats (*Myotis lucifugus*), a species found in Rock Creek Park, found one potential phenology mismatch (Meyer et al. 2016). As temperature increases, bats may emerge earlier from hibernacula, before insect prey become abundant.

The Indiana bat (*Myotis sodalis*), found in Maryland north and west of the park and listed as endangered under the Endangered Species Act, is vulnerable to a range shift under continued climate change. Under high emissions, hotter temperatures may shift the range for the Indiana Bat north and east due to a loss of suitable summer climate for maternity colonies (Loeb and Winters 2013).

Hotter streams In upper branches of the Anacostia River, northeast of Rock Creek, runoff from surrounding urban areas after a rainstorm can raise water temperatures 3.5°C (6°F.) for 3 hours (Nelson and Palmer 2007). Continued urbanization and climate change under low emissions (scenario B2), could double the number of summer days that water temperature could exceed 28°C (82°F.) (Nelson and Palmer 2007).

Salamander sensitivity Sampling of northern dusky salamander (*Desmognathus fuscus*), northern two-lined salamander (*Eurycea bislineata*), and northern red salamander (*Pseudotriton ruber*) in streams in Rock Creek Park, Chesapeake and Ohio Canal National Historical Park, and Prince William Forest Park found sensitivity of the species to water

temperature (Grant et al. 2014). Statistical analyses of water temperature and water quality variables indicated that stream water temperature most limits occupancy. *D. fuscus* and *P. ruber*, salamanders that favor headwater streams, were found mainly in areas of water temperature less than ~15°C (59°F.). This sensitivity increases the vulnerability of the headwater salamanders to climate change. *E. bislineata* was less sensitive, still abundant in areas at 22°C (72°F.)

Fish sensitivity Fish species that require cold waters are vulnerable to climate change across much of the US (Lynch et al. 2016). Two fish species that migrate annually from the Atlantic Ocean up into Rock Creek to spawn, alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*), collectively called river herring, are particularly vulnerable to projected climate change (Lynch et al. 2015, Tommasi et al. 2015). Under medium emissions (scenario A1B), hotter ocean waters off the Mid-Atlantic coast could reduce spring habitat and populations of alewife by one-third and fall habitat and populations of blueback herring by two-thirds (Lynch et al. 2015). In the Potomac River, the hatching and survival of juvenile alewives are most sensitive to May water temperature, while juvenile blueback herring are most sensitive to May and peak autumn river flows (Tommasi et al. 2015).

Eastern tent caterpillar starvation Climate change could create a phenology mismatch in Washington, DC, of the eastern tent caterpillar (*Malacosoma americanum*) and its main food plant, black cherry (*Prunus serotina*) (Abarca and Lill 2015). Laboratory and field studies found that, under higher temperatures, caterpillar hatching can occur earlier than tree budburst and optimal foliage quality, leading to increased starvation of caterpillars.

Monarch butterfly sensitivity The monarch butterfly (*Danaus plexippus*) has been declining for two decades due to loss of milkweed (*Asclepias spp.*) from herbicide use in the US, where it breeds in the summer, and loss of forests to logging in Mexico, where it seeks refuge in the winter (Thogmartin et al. 2017). Under climate change, increasing summer heat in the US can reduce butterfly populations and increased heat and aridity in Mexico can reduce the extent of oyamel fir (*Abies religiosa*), the preferred tree species of the monarch butterfly (Sáenz-Romero et al. 2012).

Carbon

Growing vegetation naturally removes carbon from the atmosphere, reducing the magnitude of climate change. Conversely, deforestation, wildfire, and other agents of tree mortality emit carbon to the atmosphere, exacerbating climate change.

Analyses of Forest Service inventory plots and MODIS remote sensing across the forests and woodlands of the lower 48 US states provides spatial estimates of carbon in aboveground biomass (Wilson et al. 2013). Forests in Rock Creek Park contain carbon in aboveground biomass at densities up to 120 tons per hectare (54 tons per acre) (Figure 13), among the highest densities in the Mid-Atlantic. Spatial analysis of the carbon results from Wilson et al. (2013) gives a total stock of carbon in aboveground biomass of $98\,000 \pm 20\,000$ tons. Conservation of these forests keeps the carbon from going into the atmosphere and reduces climate change through any net growth and removal of carbon from the atmosphere.

Monitoring of forest plots at the Smithsonian Environmental Research Center, east of Washington, DC, on Chesapeake Bay, found an increase in aboveground biomass between 1987 and 2009 (McMahon et al. 2010). This growth is consistent with, but not formally attributed to, increased warmer temperatures due to climate change and increased atmospheric carbon dioxide, which can enhance photosynthesis.

As part of the NPS Climate Friendly Parks program, Rock Creek Park has conducted an inventory of greenhouse gas emissions from fossil fuel use in energy, transportation, and waste generation by park operations and visitors (NPS 2012). The analysis estimated total emissions in 2009 of 1.4 billion tons carbon, of which 45% came from park operations. Visitors driving passenger vehicles accounted for 36% of total emissions. The *Rock Creek Park Action Plan* (NPS 2012) identified energy conservation, renewable energy, reduced use of vehicles, and other actions to cut the emissions that cause climate change.

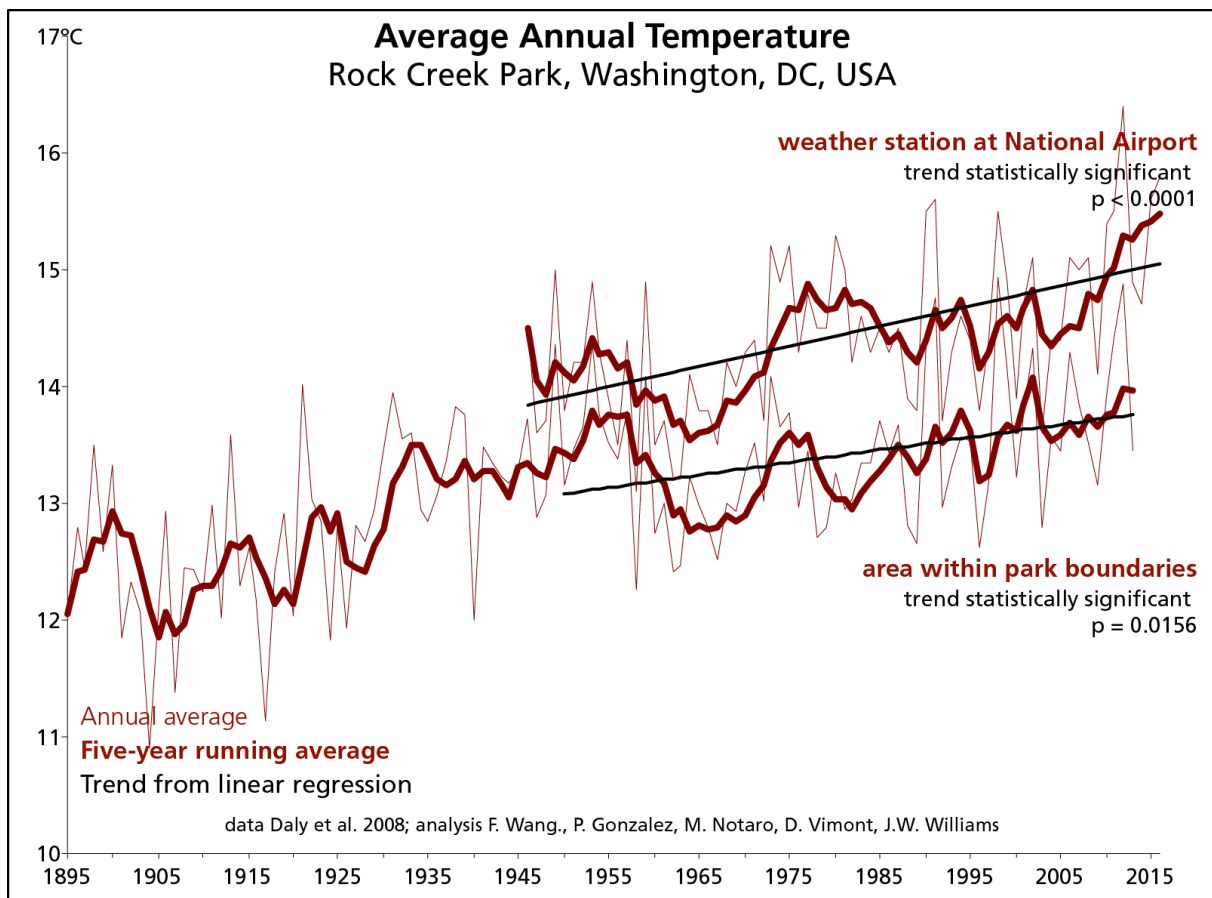
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Figure 1.

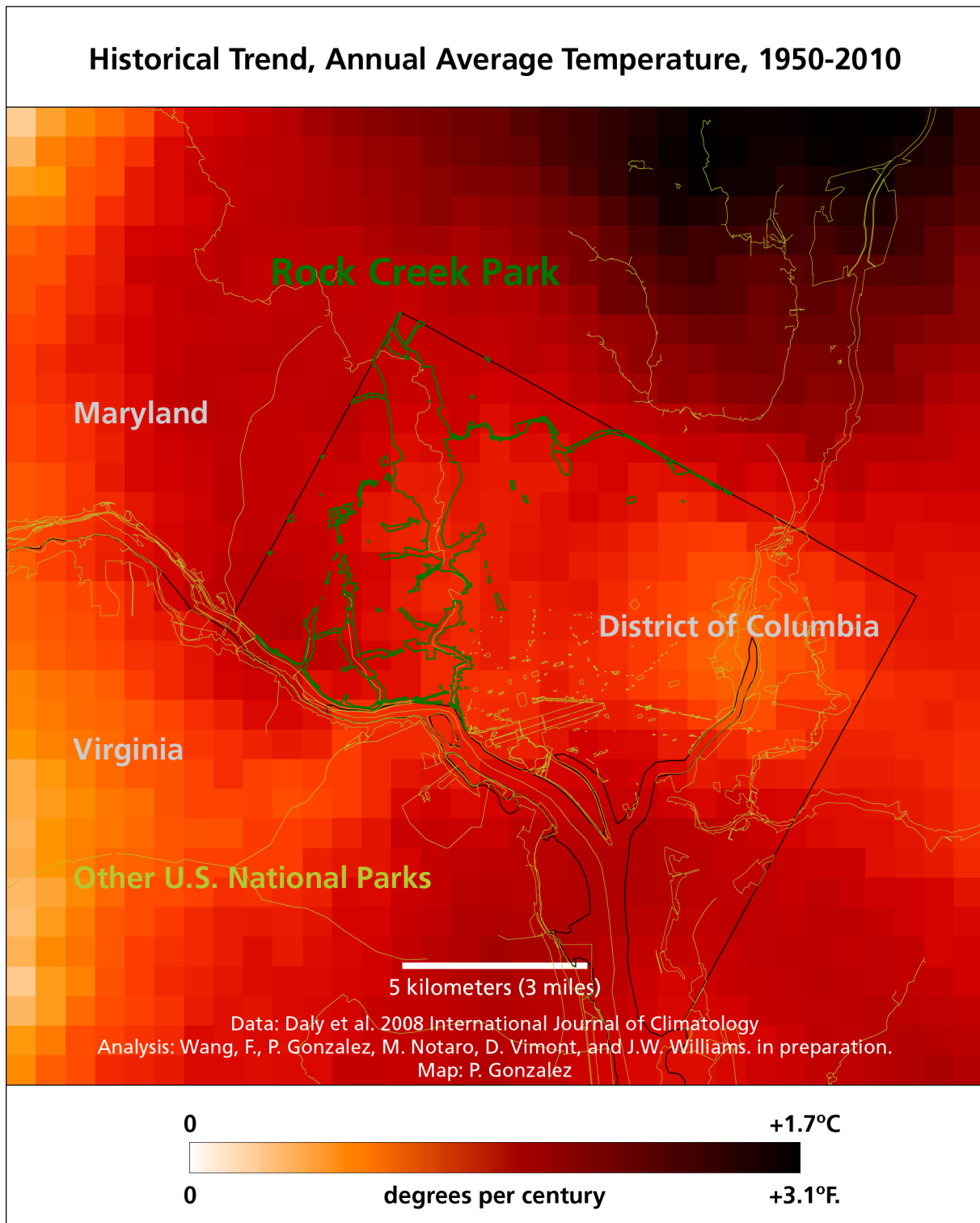


Figure 2.



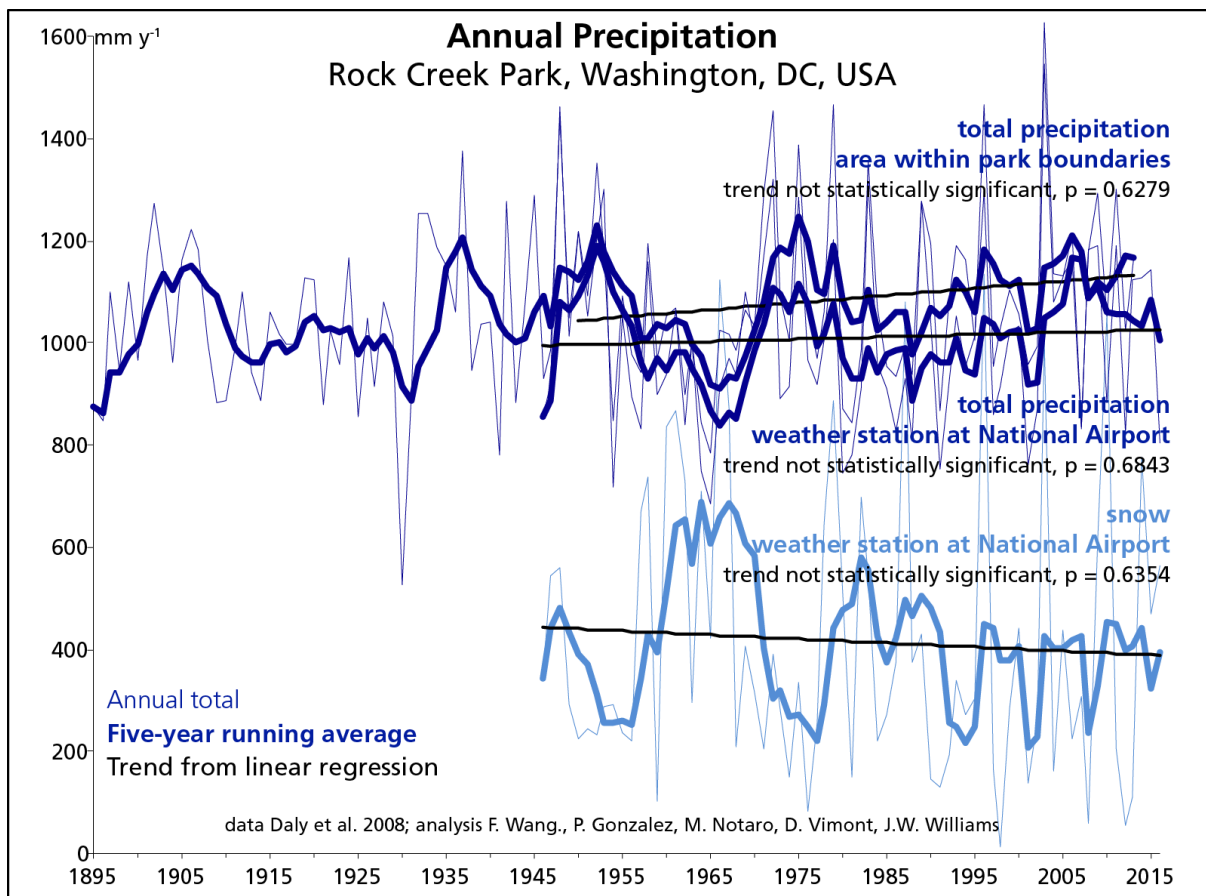
Main conclusion: Average annual temperature has increased at statistically significant rates in Rock Creek Park and at National Airport

Figure 3.



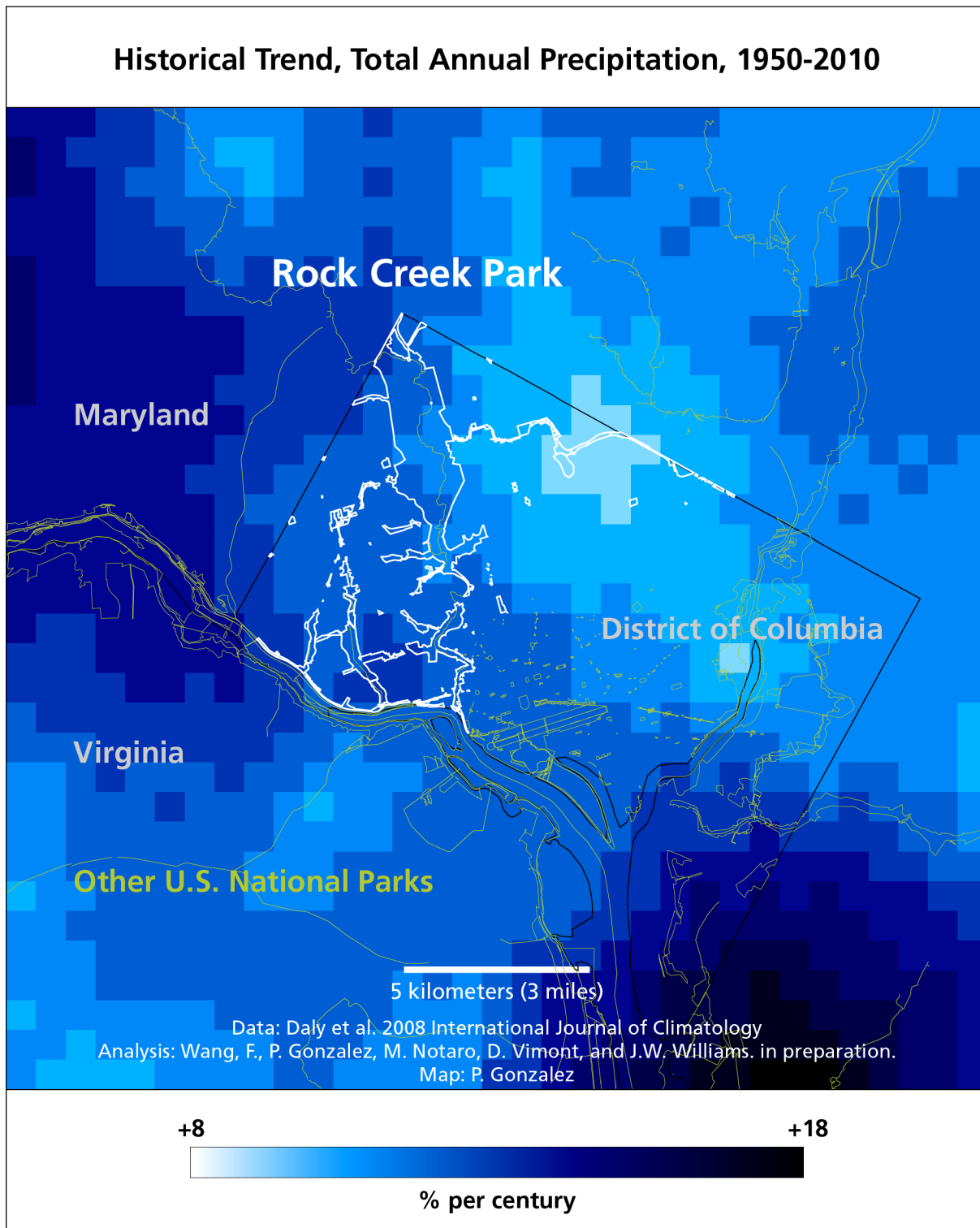
Main conclusion: Temperature has increased across the entire park.

Figure 4.

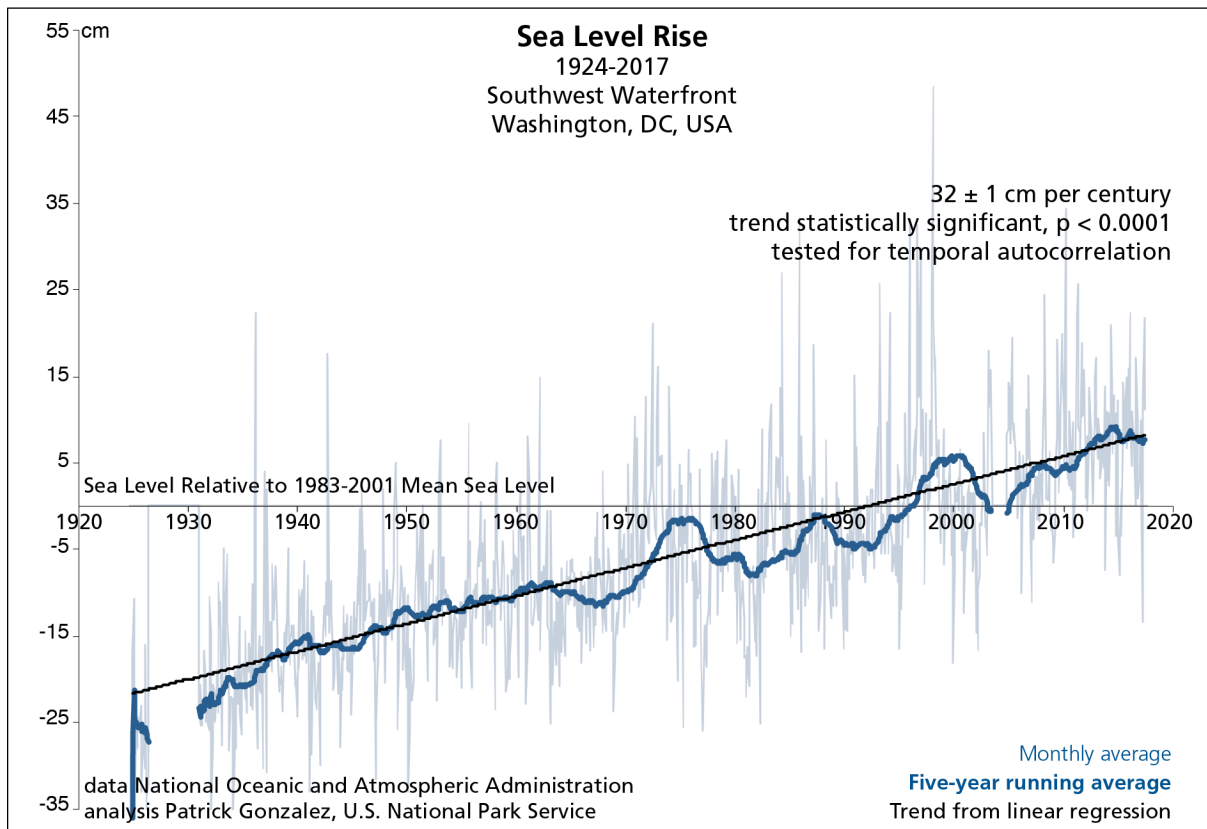


Main conclusion: Precipitation has increased and snow has decreased, but the rates have not been statistically significant.

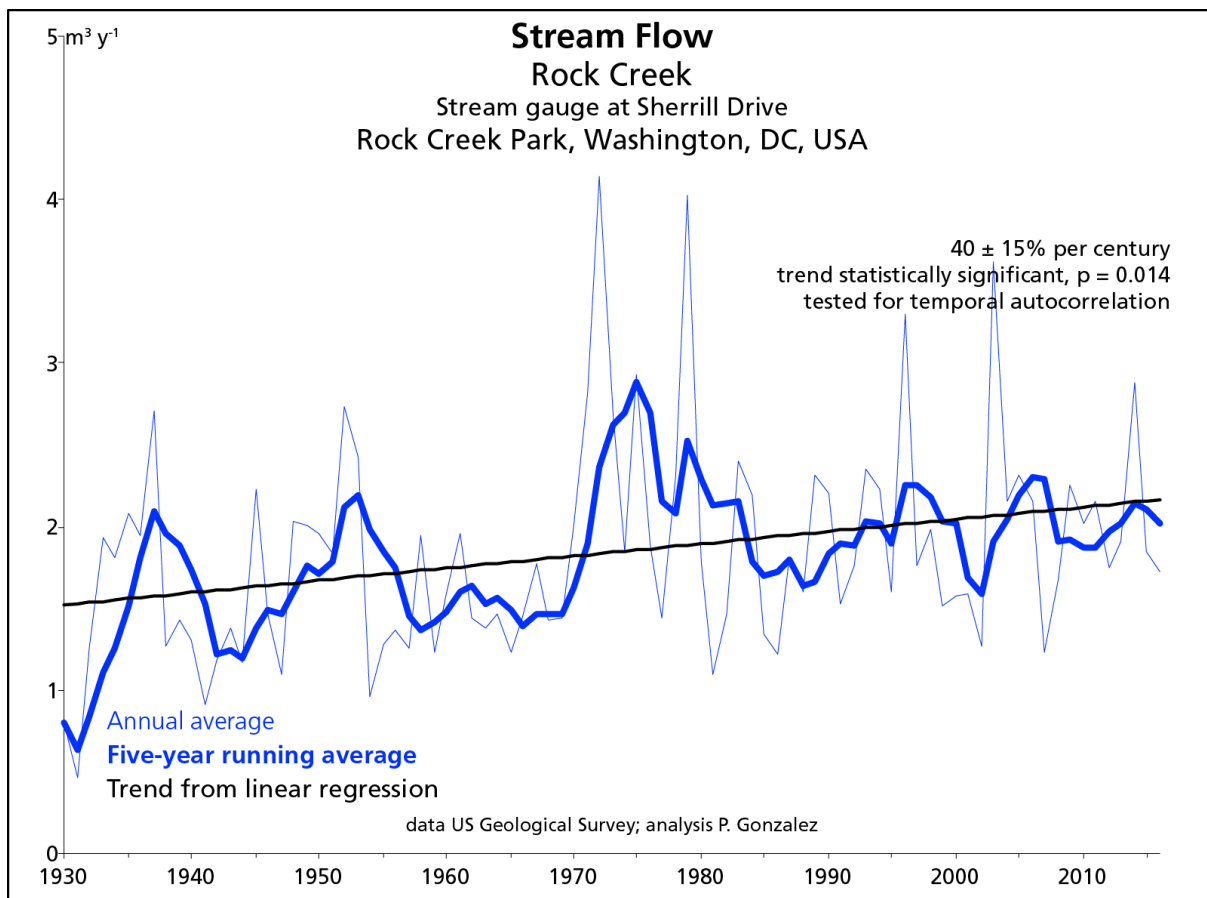
Figure 5.



Main conclusion: Precipitation has increased across the entire park.

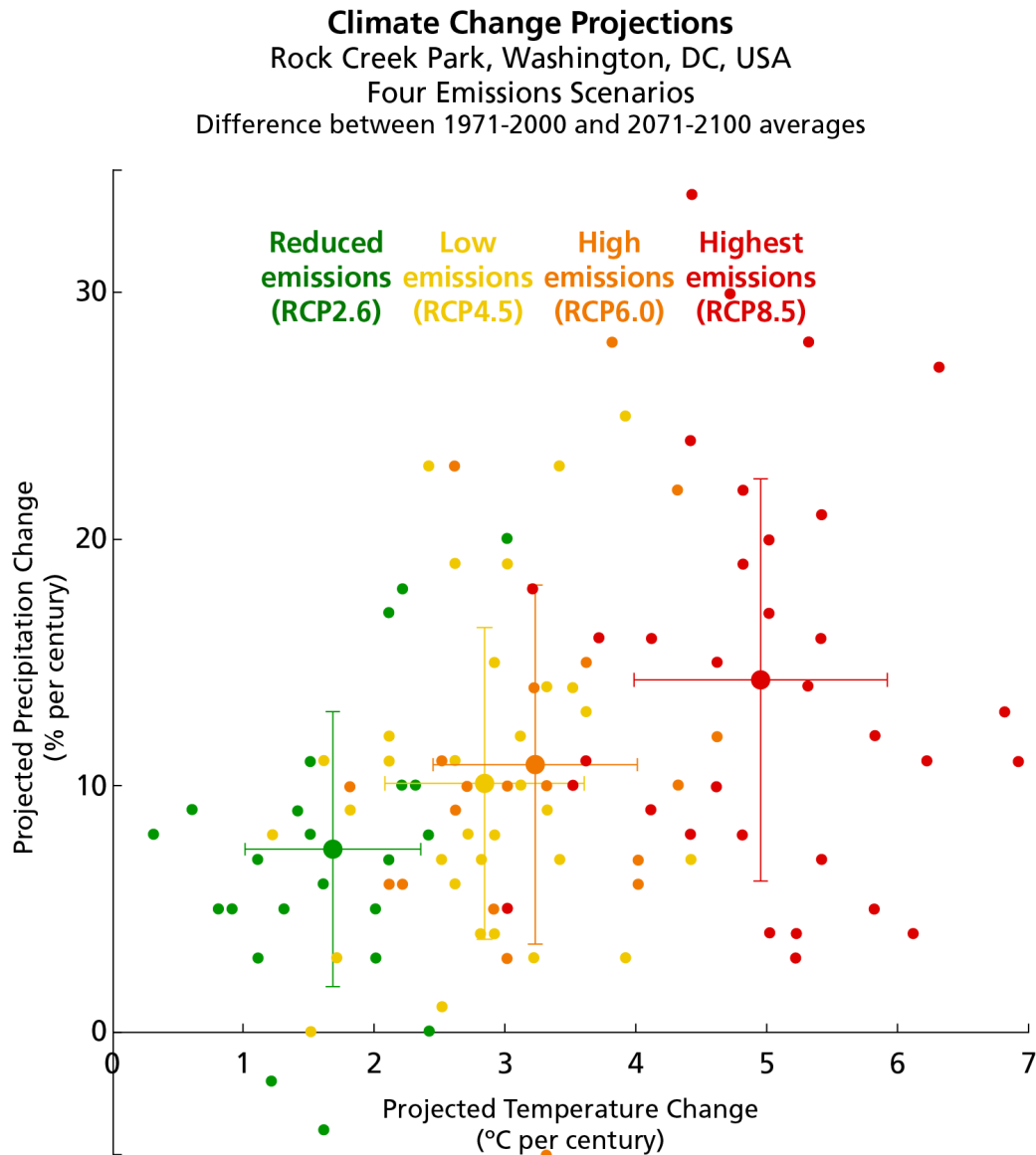
Figure 6.

Main conclusion: Sea level has risen at a statistically significant rate since 1924.

Figure 7.

Main conclusion: Stream flow has risen at a statistically significant rate since 1930.

Figure 8.

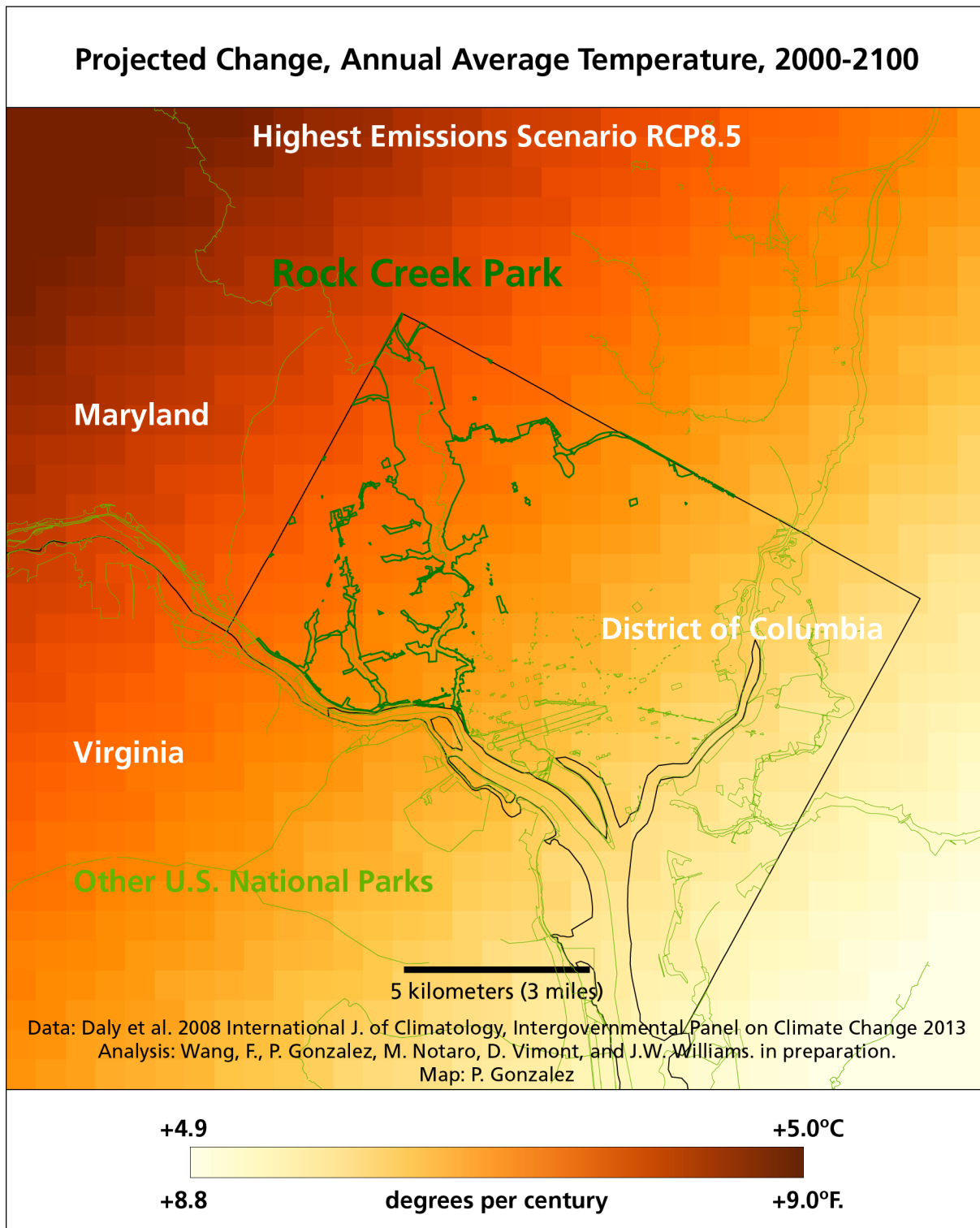


Data: Intergovernmental Panel on Climate Change 2013, Daly et al. 2008
Analysis: F. Wang, P. Gonzalez, M. Notaro, D. Vimont, J.W. Williams; Graph P. Gonzalez

Main conclusion: All models project increased temperature and most project increased precipitation.

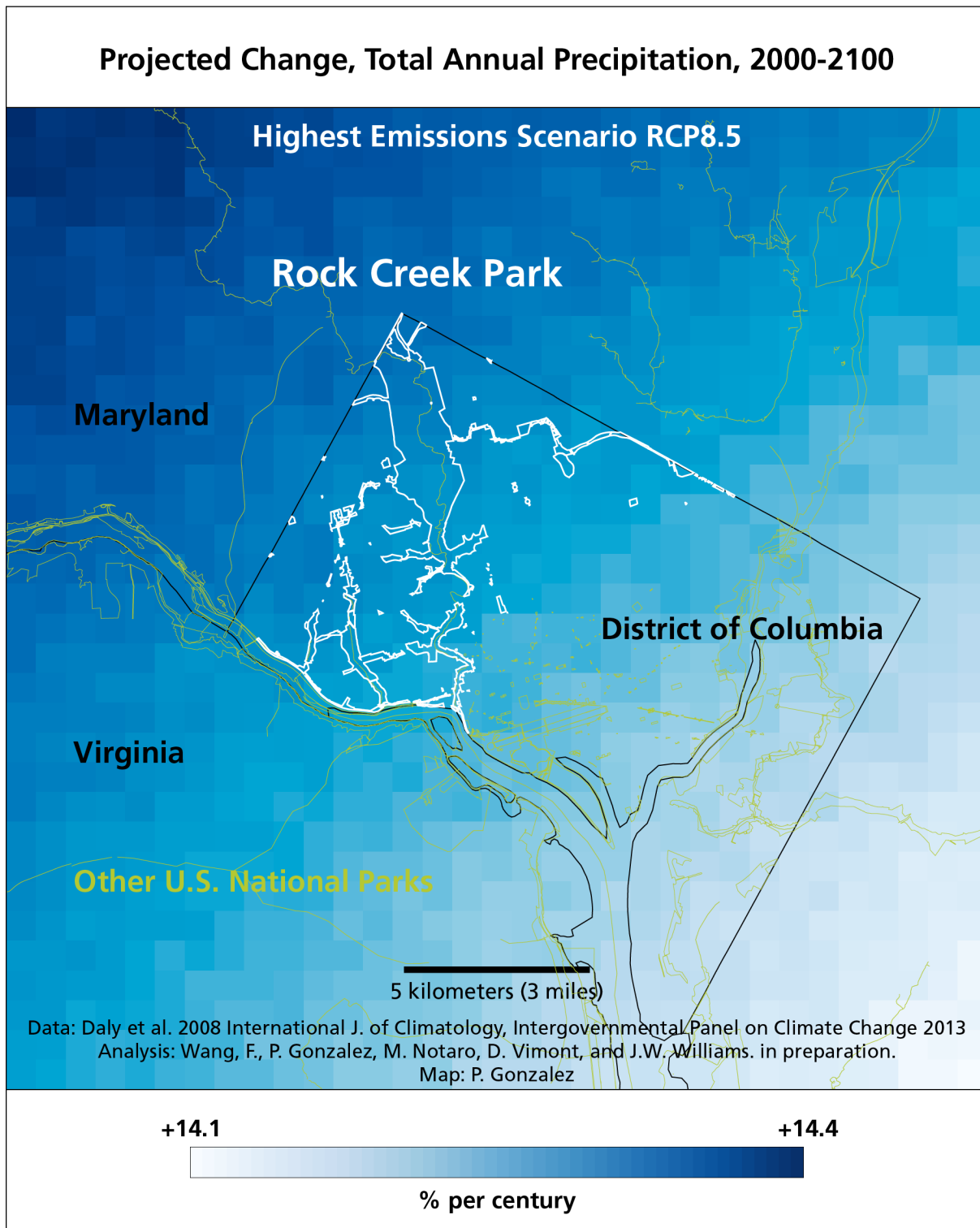
Projections of future climate for the area within park boundaries, relative to 1971-2000 average values. Each small dot is the output of a single GCM. The large color dots are the average values for the four IPCC emissions scenarios. The crosses are the standard deviations of each emissions scenario average. (Data: IPCC 2013, Daly et al. 2008; Analysis: F. Wang, P. Gonzalez, M. Notaro, D. Vimont, J.W. Williams).

Figure 9.



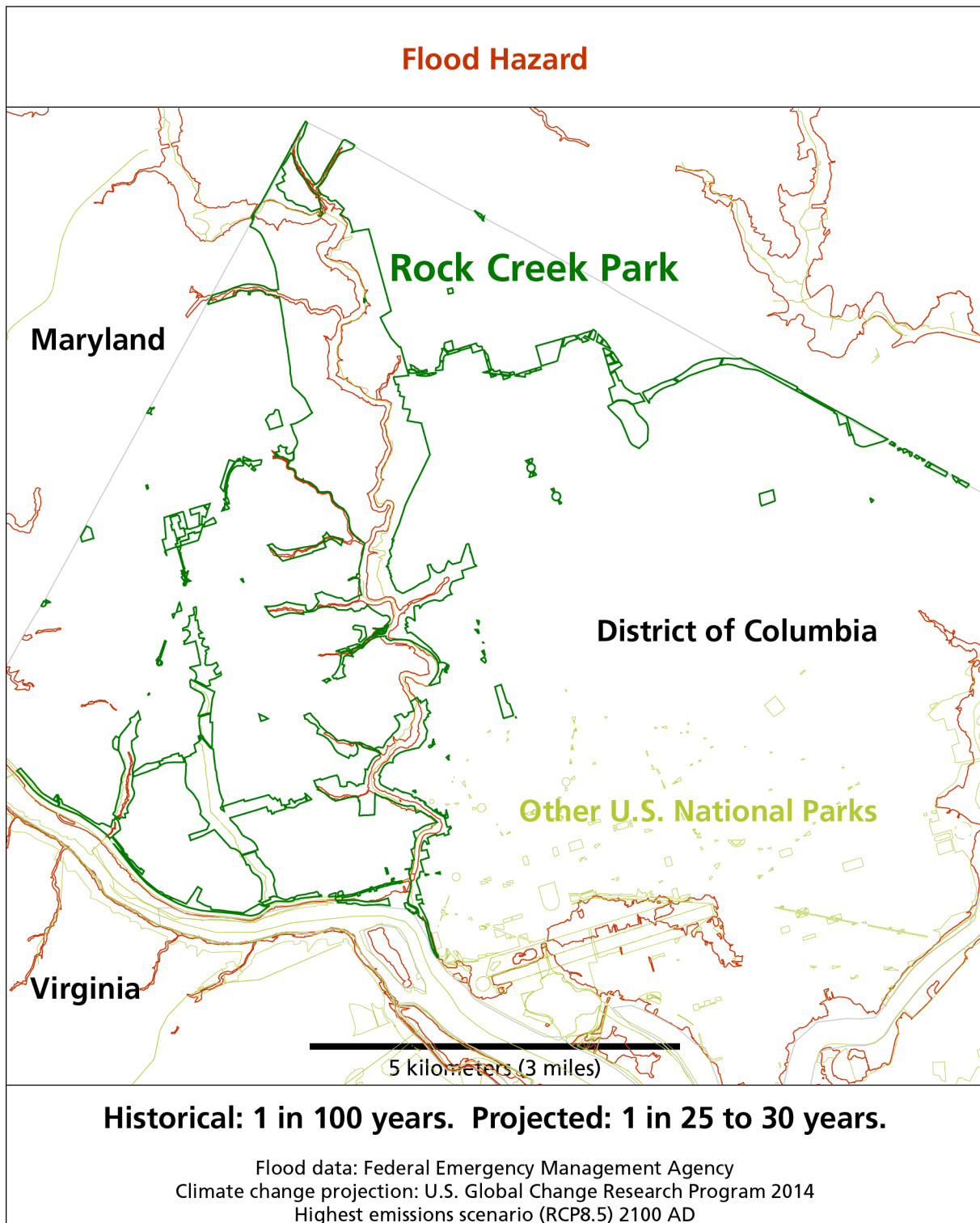
Main conclusion: Projected temperature increases are similar across the park.

Figure 10.



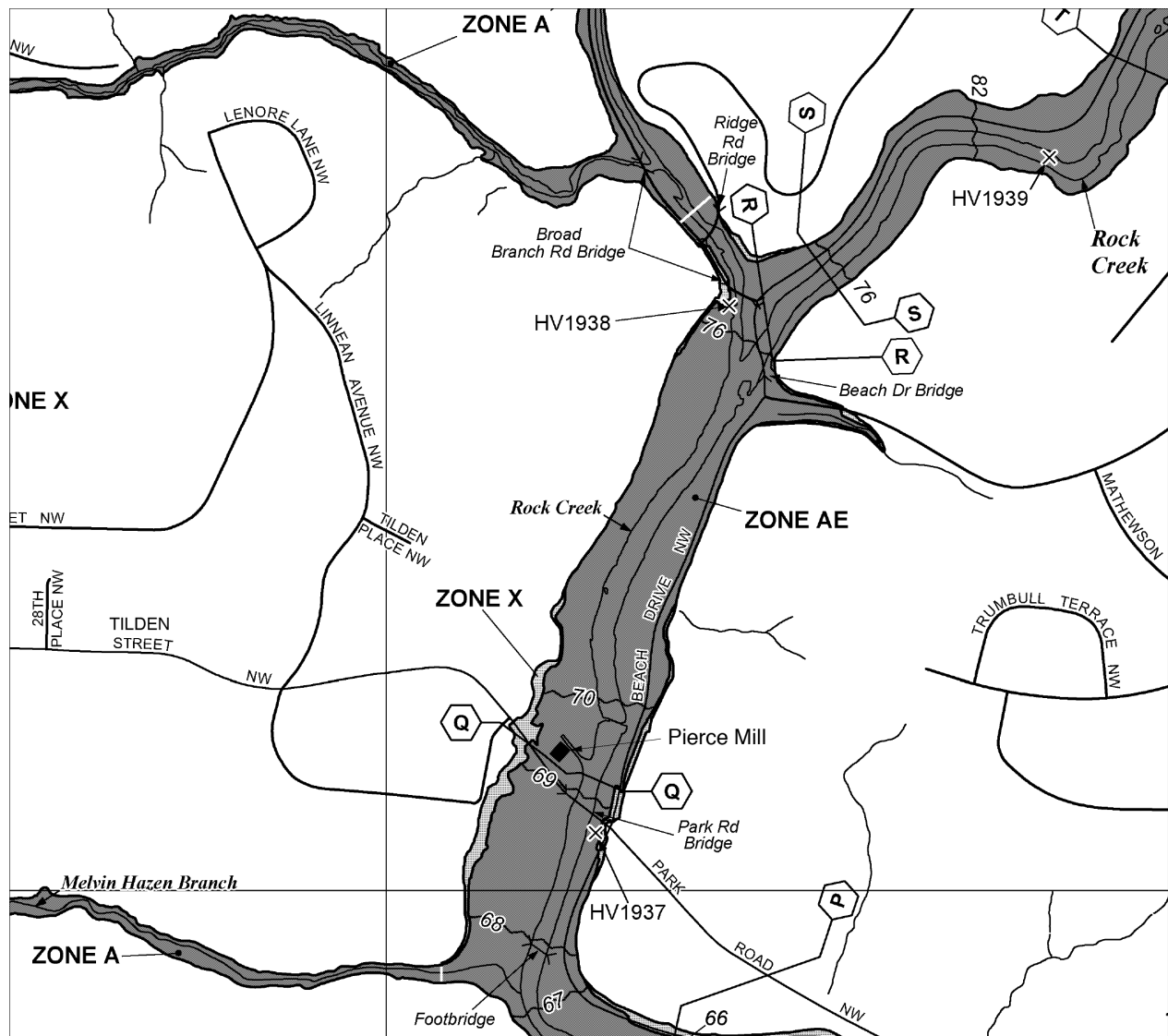
Main conclusion: Projected precipitation increases are similar across the park.

Figure 11.



Main conclusion: A 100-year flood (FEMA 2017) could occur every 25 to 30 years under high emissions.

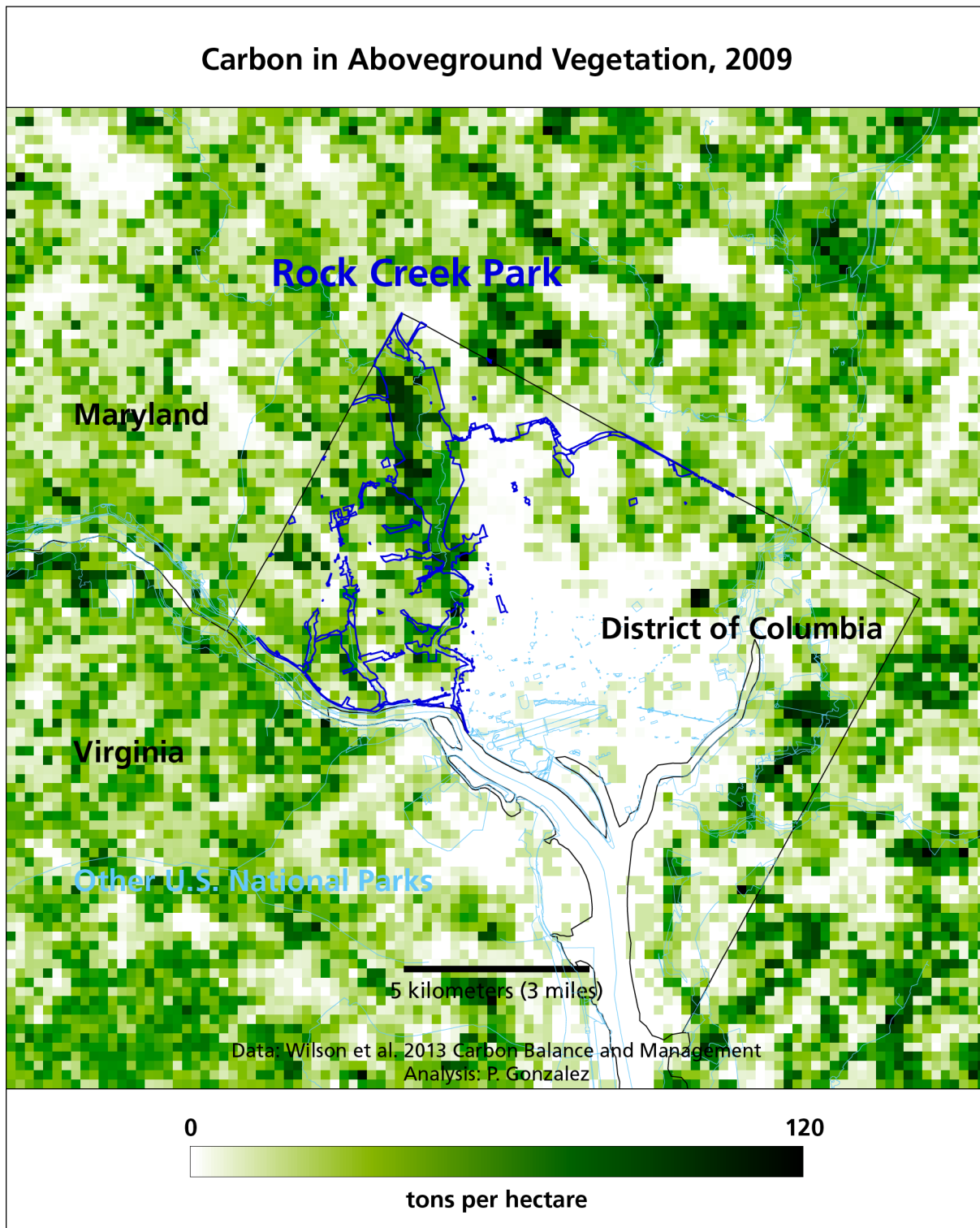
Figure 12.



Main conclusion: In a major flood, Rock Creek can overflow to 4-5 times its regular width, flooding historic structures like the Pierce Mill and other resources.

Flood hazard (FEMA 2017) for the section of Rock Creek around the historic Pierce Mill. The dark gray (Zones A and AE) denotes the area of historical 100-year floods, potentially increasing to 25- to 30-year floods under climate change.

Figure 13.



Main conclusion: Forests in Rock Creek Park contain carbon in aboveground biomass at densities up to 120 tons per hectare (54 tons per acre).

Table 1. Historical average temperatures and temperature trends of the area within the boundaries of Rock Creek 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.
	°C		°C century ⁻¹			°C century ⁻¹		
Annual	13.4	0.6	1.1	0.2	***	1.1	0.4	*
December-February	2.5	1.5	1.5	0.5	**	0.3	1.4	
March-May	12.7	1	1	0.3	***	1	0.5	
June-August	24.1	0.7	1.3	0.3	***	1.5	0.5	**
September-November	14.4	0.9	0.9	0.3	**	0.6	0.5	
January	1	2.6	0.3	0.8		-0.4	2.3	
February	2.8	2.4	2.2	0.9	*	0.1	2.3	
March	7.4	1.6	1	0.5		2.1	1	**
April	12.8	1.3	1.5	0.4	***	0.7	0.9	
May	18	1.4	0.6	0.3		0.1	0.8	
June	22.7	1.1	1.4	0.4	***	1.4	0.6	*
July	25.3	1.1	1.1	0.3	**	1.2	0.8	
August	24.4	1.1	1.5	0.3	***	1.9	0.6	**
September	20.6	1.1	0.7	0.4		1	0.8	
October	14.1	1.6	0.5	0.4		-0.6	1	
November	8.5	1.7	1.3	0.4	***	1.5	0.9	
December	3.5	2.4	1.6	0.6	**	1	1.4	

Table 2. Historical average precipitation totals and precipitation trends of the area within the boundaries of Rock Creek Park. No trends were statistically significant.

SD = standard deviation, SE = standard error.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE		trend	SE	
	mm y ⁻¹		% century ⁻¹			% century ⁻¹		
Annual	1104	183	8	5		12	12	
December-February	245	75	-1	7		12	20	
March-May	290	77	12	8		11	23	
June-August	296	73	-7	7		-16	18	
September-November	273	95	33	9	***	48	21	*
January	88	44	-8	15		27	44	
February	72	39	-10	13		-13	36	
March	98	44	10	12		-5	32	
April	83	38	0	12		1	34	
May	108	44	25	14		35	38	
June	91	55	2	12		13	36	
July	106	43	-4	13		18	32	
August	99	44	-19	11		-76	29	**
September	104	71	31	16		62	38	
October	86	48	28	16		65	44	
November	83	43	41	17	*	15	44	
December	85	46	8	12		4	35	

Table 3. Projected temperature increases (°C), 2000 to 2050, for the area within Rock Creek 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	1.7	0.6	2.2	0.6	1.9	0.5	2.8	0.6
December-February	1.7	0.7	2.2	0.9	1.7	0.6	2.8	1
March-May	1.6	0.6	1.8	1.1	1.8	0.5	2.3	1.2
June-August	1.8	0.6	2.3	0.7	2.1	0.7	2.9	0.7
September-November	1.9	0.7	2.6	1.4	2	0.6	3.1	1.5
January	1.8	0.7	2.4	1.3	1.5	0.9	2.9	1.2
February	1.6	1	1.9	0.9	1.7	0.8	2.5	0.9
March	1.6	0.8	1.8	1.2	1.7	0.8	2.3	1.4
April	1.6	0.7	1.9	1.3	1.7	0.6	2.4	1.1
May	1.5	0.7	1.9	1.1	1.8	0.5	2.4	1.1
June	1.6	0.5	2	0.9	1.8	0.5	2.7	0.9
July	1.8	0.6	2.3	0.9	2.1	0.7	3	0.9
August	1.9	0.7	2.4	0.8	2.2	0.9	3.2	0.9
September	2	0.8	2.7	1.2	2.3	0.9	3.3	1.4
October	2	0.7	2.5	1.6	1.9	0.7	3.2	1.7
November	1.7	0.7	2.5	1.5	1.8	0.5	2.8	1.5
December	1.7	0.8	2.5	1.6	1.9	0.8	2.9	1.7

Table 4. Projected temperature increases (°C), 2000 to 2100, for the area within Rock Creek 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	1.7	0.7	2.8	0.8	3.2	0.8	4.9	1
December-February	1.7	0.8	2.8	1	3.1	0.9	4.7	1.2
March-May	1.5	0.6	2.4	1.2	2.9	0.7	4.3	1.3
June-August	1.7	0.7	2.9	0.9	3.4	1	5.3	1.2
September-November	1.7	0.8	3.1	1.6	3.4	0.9	5.5	1.9
January	1.7	1.1	2.8	1.3	3.1	0.9	4.6	1.5
February	1.6	1	2.7	1	3.1	1.1	4.4	1
March	1.5	0.8	2.2	1.4	2.7	0.9	3.8	1.4
April	1.6	0.7	2.6	1.2	3	0.8	4.3	1.3
May	1.5	0.7	2.5	1.1	3.1	0.7	4.6	1.3
June	1.6	0.6	2.6	1.1	3.2	0.8	4.9	1.2
July	1.8	0.7	2.9	1	3.5	1	5.3	1.2
August	1.8	0.9	3.2	1.2	3.6	1.3	5.8	1.6
September	1.8	0.9	3.3	1.5	3.6	1.1	5.8	1.9
October	1.7	0.9	3.2	1.8	3.3	1.1	5.6	2.1
November	1.7	0.8	2.9	1.8	3.1	0.8	5	1.9
December	1.8	1	3	1.8	3.2	1	4.9	1.9

Table 5. Projected precipitation changes (%), 2000 to 2050, for the area within Rock Creek 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	8	5	9	5	7	6	9	6
December-February	11	11	11	9	11	11	14	11
March-May	7	8	9	7	7	8	9	8
June-August	9	12	8	12	6	13	8	14
September-November	6	7	7	9	6	8	6	10
January	16	16	13	12	14	15	16	16
February	9	14	13	18	11	15	17	17
March	4	10	8	9	7	11	13	11
April	10	13	11	13	6	11	9	12
May	8	14	9	13	7	11	6	13
June	5	13	4	14	4	14	6	15
July	9	16	7	16	7	19	7	19
August	12	16	12	17	6	17	11	18
September	8	15	7	17	4	13	7	14
October	6	14	7	16	6	18	3	15
November	5	13	7	18	8	14	8	14
December	10	16	10	12	10	12	11	14

Table 6. Projected precipitation changes (%), 2000 to 2100, for the area within Rock Creek 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	7	6	10	6	11	7	14	8
December-February	7	9	15	11	15	12	24	15
March-May	7	8	10	8	11	7	14	9
June-August	9	11	10	14	12	19	12	20
September-November	6	10	7	10	6	9	8	11
January	8	15	16	17	13	15	28	20
February	8	13	17	20	18	19	25	21
March	5	9	10	12	12	11	17	12
April	10	12	12	11	15	11	17	15
May	8	13	8	17	8	11	9	15
June	7	12	5	14	9	16	6	16
July	8	15	11	18	10	22	13	23
August	11	15	15	20	16	29	17	28
September	8	15	10	16	6	14	10	22
October	5	20	2	18	3	17	3	19
November	5	13	8	17	8	14	12	14
December	8	14	13	14	17	16	21	17

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