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Mt. Tammany, above the Delaware Water Gap, New Jersey and Pennsylvania (photo P. Gonzalez)

Climate Change Trends, Vulnerabilities, and Hydrology in Delaware Water Gap National Recreation Area, USA

Patrick Gonzalez, Ph.D.

Natural Resource Stewardship and Science
U.S. National Park Service
130 Mulford Hall
University of California, Berkeley
Berkeley, CA 94720-3114 USA

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Abstract

Greenhouse gas emissions from human activities have caused global climate change and widespread impacts on physical systems, ecosystems, and biodiversity. To assist in the integration of climate change science into resource management in Delaware Water Gap National Recreation Area (NRA), particularly the proposed restoration of wetlands at Watergate, this report presents: (1) results of original spatial analyses of historical and projected climate trends at 800 m spatial resolution, (2) results of a systematic scientific literature review of historical impacts, future vulnerabilities, and carbon, focusing on research conducted in the park, and (3) results of original spatial analyses of precipitation in the Vancampens Brook watershed, location of the Watergate wetlands. Average annual temperature from 1950 to 2010 increased at statistically significant rates of 1.1 ± 0.5ºC (2 ± 0.9ºF.) per century (mean ± standard error) for the area within park boundaries and 0.9 ± 0.4ºC (1.6 ± 0.7ºF.) per century for the Vancampens Brook watershed. The greatest temperature increase in the park was in spring. Total annual precipitation from 1950 to 2010 showed no statistically significant change. Few analyses of field data from within or near the park have detected historical changes that have been attributed to human climate change, although regional analyses of bird counts from across the United States (U.S.) show that climate change shifted winter bird ranges northward 0.5 ± 0.3 km (0.3 ± 0.2 mi.) per year from 1975 to 2004. With continued emissions of greenhouse gases, projections under the four emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC) indicate annual average temperature increases of up to 5.2 ± 1ºC (9 ± 2º F.) (mean ± standard deviation) from 2000 to 2100 for the park as a whole. Climate models project increases of total annual precipitation of 8% to 15% on average, with almost all models agreeing on increasing precipitation. Under high emissions, twenty-year storm years could triple in frequency. Published analyses for the mid-Atlantic and northeastern U.S. identify numerous future vulnerabilities to climate change, including continued loss of eastern hemlock (*Tsuga canadensis*) from infestations of hemlock woolly adelgid (*Adelges tsugae*), upslope and northward vegetation shifts at the biome and species levels, increases in invasive plant species, potential loss of some populations of brook trout (*Salvelinus fontinalis*), and negative effects on wood turtles (*Glyptemys insculpta*) and other species. National park ecosystems can help to naturally reduce climate change by storing carbon. Broadleaf forests in the park store 140 ± 50 tons per hectare, with the carbon in each hectare equivalent to the annual emissions of 25 ± 9 Americans. Fossil fuel burning for park operations and visitor driving emitted 5200 tons of carbon in 2004, with 85% coming from visitors' automobiles.

Introduction

Greenhouse gas emissions from power plants, motor vehicles, deforestation, and other human activities have increased temperatures around the world and caused other changes in climate in the 20th and early 21st centuries (IPCC 2013). Field measurements show that climate change is fundamentally altering ecosystems by shifting vegetation biomes, contributing to species extinctions, and causing numerous other changes (IPCC 2014). To assist Delaware Water Gap NRA in the integration of climate change science into resource management, particularly a proposed restoration of the Watergate wetlands, 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, vulnerabilities, and ecosystem carbon.

Delaware Water Gap NRA straddles the Delaware River northeastern Pennsylvania and northwestern New Jersey in the mid-Atlantic region of North America (Figure 1). The Watergate wetland restoration area covers 34 ha (84 ac.), including ponds and a length of Vancampens Brook (Figure 2), with the watershed covering 16 km^2 (6 sq. mi.) from the outlet of the main pond up the ravine, entirely within the park (Figure 3). The National Park Service proposes to restore wetlands at Watergate to a more natural state, possibly by removing dams and other structures, a septic field, and a mowed lawn. Under such a proposal, the National Park Service would investigate how to design the alignment, width, and flow regime of the brook, extent of the flooded area, and other aspects of a wetlands ecosystem for potential future conditions under climate change, rather than attempting to return the area to a past state that may not be possible to maintain under climate change. So, while the proposed project would restore a wetlands ecosystem, it would not necessarily restore a past state.

Possible goals of a proposed restoration:

1. Establish a wetlands ecosystem with robust functions under potential future climate change, that will provide a high quality water supply and habitat for native Eastern North American species.
2. Facilitate an orderly ecological transition over time, minimizing probabilities of catastrophic simplification of ecological structure and species composition under climate change.

The proposed restoration project would comprise a climate change adaption measure at the landscape scale. Any increase of trees and organic wetlands soils could also increase carbon storage, naturally reducing climate change. Finally, the project can reduce greenhouse gas emissions in replacing a grass lawn, which requires maintenance that uses gasoline-powered engines, by natural vegetation.

Methods

The historical climate analyses (Wang et al., in preparation) used 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 National Weather Service stations at Stroudsburg, Pennsylvania (southwest of the park) and Aeroflex Andover Airport, New Jersey (east of the park) have contributed to this data layer. The weather station at Walpack Center, New Jersey, in the park, was established in 2004 and does not provide a time series long enough to assess climate change. The PRISM data set uses weather station measurements and interpolates between weather stations based on elevation and topography. Spatial analyses were completed for: (1) the area within park boundaries, and (2) the area of Vancampens Brook watershed above Watergate. Linear regression of temperature and precipitation time series gives the historical climate trends, with the statistical probability of significance corrected for temporal autocorrelation. The period starting in 1950 gives a more robust time series than the period starting in 1895 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 changed irregularly before the 1940s.

The spatial 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 the Thomson Reuters Web of Science scientific literature database for published research that used field data from Delaware Water Gap NRA or analyses of the region that includes the park.

Historical Climate Changes

For Delaware Water Gap NRA as a whole, average annual temperature showed a statistically significant increase in the period 1950-2010 (Figure 4, Table 1). The 1950-2010 trends show statistically significant warming in spring and summer with the greatest rate of warming in spring (1.4 ± 0.6ºC).

For Vancampens Brook watershed, average annual temperature also showed a statistically significant increase in the period 1950-2010 (Figure 4, Table 2). The time series for the watershed is very similar to that for the park as a whole (Figure 4).

Mean annual temperature decreases with increasing elevation (Figure 5). Temperature increases for the period 1950-2010 were greatest at the Delaware Water Gap in the south end of the park and Dingman's Ferry in the northern section of the park (Figure 6). In the northeastern U.S., the length of the frost-free season (period from first to last occurrence of temperature <0ºC [32ºF.]) increased by 10-14 days between the periods 1901-1960 and 1991-2012 (Walsh et al. 2014).

For Delaware Water Gap NRA as a whole and for the Vancampens Brook watershed, total annual precipitation for the periods 1895-2010 and 1950-2010 showed no statistically significant trends, with precipitation slightly increasing (Figure 7, Table 3). Total annual precipitation is relatively greater in the Vancampens Brook watershed and across the southern section of the park (Figure 8). The greatest precipitation increases in the period 1950-2010 occurred at the Delaware Water Gap in the south end of the park (Figure 9). National Oceanic and Atmospheric Administration (NOAA) analyses of weather station data show an increase in the northeastern U.S. of heavy storms, with a 71% increase in the amount of precipitation falling in the heaviest 1% of all daily storm events from 1958 to 2012 (Walsh et al. 2014).

Historical Impacts

Changes detected in Delaware Water Gap NRA and attributed to human climate change

The search of published scientific literature found no research using field data from the park that detected ecological changes attributed to human climate change.

Changes detected in the region and attributed to human climate change Analyses of

Audubon Christmas Bird Count data across the U.S. detected a northward shift of winter ranges of a set of 254 bird species at an average rate of 0.5 ± 0.3 km per year from 1975 to 2004, attributable to human climate change (La Sorte and Thompson 2007). For the count circle (sample area) that covers the park (Dingman's Ferry, Pennsylvania), counts only started in 1993, so it was not included in the analysis of La Sorte and Thompson (2007), although older count circles in the region were included.

Changes consistent with, but not formally attributed to human climate change The northward and upslope spread of hemlock woolly adelgid (*Adelges tsugae*) and widespread mortality of eastern hemlock (*Tsuga canadensis*) due to adelgid infestations is consistent with temperatures that have increased above the cold tolerance level of the pest (Parker et al. 1998, Skinner et al. 2003, Dukes et al. 2009). These observations are consistent with, but not formally attributed to, human climate change.

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 the world does not reduce emissions from power plants, cars, and deforestation by 40-70%, GCMs project substantial warming and slight increases in precipitation. The temperature and precipitation projections from 33 GCMs form a cloud of potential future climates (Figure 10). GCMs project potential increases in annual average temperature within park boundaries four to thirteen times historical warming by 2100 (Table 4), with the greatest temperature increases in autumn. Projected temperature increases do not show much spatial variation across the park (Figure 11).

The average of the ensemble of GCMs projects increased precipitation under all emissions scenarios (Table 5). The average of the ensemble reflects the central tendency of the projections, but the uncertainty of any single model of future climate can be large. For the area of the park, almost all GCMs project increased precipitation (Figure 10). Confidence in the projections of a precipitation increase is high (since the ensemble averages, even considering the standard deviations, are greater than zero). Projected precipitation increases do not show much spatial variation across the park (Figure 12).

Projections indicate potential changes in the frequency of extreme temperatures and precipitation events. For eastern Pennsylvania and northern New Jersey, under the highest emissions scenario, models project 20-21 fewer days per year with a minimum temperature below freezing, leading to less snow and freezing conditions and six to nine more days per year with a maximum temperature >35ºC (95ºF.) (Kunkel et al. 2013). The number of winter days with snow on the ground could decrease by 10 days by 2100 (Hayhoe et al. 2007). In the northeastern U.S., models project an increase of the length of the frost-free season (period from first to last occurrence of temperature <0ºC [32ºF.]) of 20-40 days for the low to high emissions scenarios between the periods 1971-2000 and 2070-2099 (Walsh et al. 2014).

For eastern Pennsylvania and northern New Jersey, under the highest emissions scenario, models project an increase in the frequency of 20-year storms (a storm with more precipitation than any other storm in 20 years) to once every 5-6 years (Kunkel et al. 2013).

For the Vancampens Brook watershed, the 1895-2013 historical data (Figure 13, grey bars) show a normal probability distribution of total annual precipitation (Figure 13, black curve). The annual average is 1200 ± 170 mm (47 ± 7 in.) per year and twenty-year storm years (total precipitation occurring only once in 20 years) had ≥ 1500 mm (59 in.) per year (Figure 13, black area under the curve). Under the scenario of the greatest emissions reductions (RCP2.6), the probability distribution could shift to greater precipitation amounts (Figure 13, orange curve) and the former twenty-year storm years could double in frequency (Figure 13, orange area under the curve). Under the worst scenario (RCP8.5), former twenty-year storm years could triple in frequency (Figure 13, red area under the curve).

For Delaware Water Gap NRA as a whole, the 1895-2013 historical data show that the seasonal distribution of precipitation has changed. At the beginning of the historical period (Figure 14, blue line), precipitation peaked in July, the middle of summer. By the end of the period (Figure 14, black line), precipitation showed a bi-modal distribution, with peaks in June and September, and a notable decrease in February. Under the scenario of the greatest sustainability improvements (RCP2.6) (Figure 14, orange line) and the worst scenario (RCP8.5) (Figure 14, red line), total annual precipitation could be higher than historical, but monthly precipitation could be lower than historical for July and October. The relative low point in February could persist.

Future Vulnerabilities

With continued emissions from power plants, cars, and deforestation, continued climate change could increase the vulnerability of species, ecosystems, and physical, cultural, and infrastructure resources (IPCC 2013). Published research in Delaware Water Gap NRA and in the mid-Atlantic and northeast U.S. has identified numerous vulnerabilities to climate change.

Vegetation shifts Continued climate change may shift biomes (major vegetation formations) poleward and upslope, with temperate conifer tree species in the region of the park decreasing and temperate broadleaf tree species increasing (Gonzalez et al. 2010). The area of the park is highly vulnerable to this biome shift due to climate change. Eastern larch (*Larix laricina*) at Watergate is particularly vulnerable to increased mortality because it is a boreal conifer species requiring cooler temperatures than temperate conifers. Under the highest emissions scenario, climate change could shift the ranges of numerous individual tree species northward, reducing potential densities of red maple (*Acer rubrum*) more than many other species (Iverson et al. 2008). Due to high fragmentation of natural habitat by agriculture, towns and cities, roads, and power lines, the region of the park shows high habitat loss due to land cover change (Eigenbrod et al. 2015). The park is highly vulnerable to the combined effects of biome shifts due to climate change and habitat loss due to land cover change (Figure 20; Eigenbrod et al. 2015).

Hemlock woolly adelgid (*Adelges tsugae*) Because low temperatures limit the spread of hemlock woolly adelgid (Parker et al. 1998, Skinner et al. 2003, Dukes et al. 2009), which is causing widespread mortality of eastern hemlock (*Tsuga canadensis*), continued climate change would exacerbate hemlock woolly adelgid infestation, increase mortality of hemlock trees, and extend the range of infestations further north (Dukes et al. 2009). Hemlock mortality causes changes in nitrogen cycling (see following section) and reduced habitat for certain wildlife species (see sections below).

Emerald ash borer (*Agrilus planipennis*) While the Emerald ash borer, an exotic and invasive insect that has killed extensive areas of ash trees (*Fraxinus spp.*) in the midwestern U.S., has not yet invaded the park, the region 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).

Nitrogen In southern Pennsylvania, dieback of eastern hemlock due to hemlock woolly adelgid has increased leaching of nitrate from forest soils to surface waters (Cessna and Nielsen 2012), a process that could increase under climate change (Campbell et al. 2009), increasing the risk of eutrophication. Climate change may also increase wet and dry nitrogen deposition in the eastern U.S. from air pollution (Civerolo et al. 2008).

Wetland hydrology In the Susquehanna River Valley, west of the park, hydrologic modeling under a high emissions scenario indicates that, even with increased precipitation, hotter temperatures could increase evapotranspiration and otherwise create dry periods in freshwater upland wetlands (US EPA 2013, Yu et al. 2015). This possibility is relevant to adaptive management under climate change of the proposed wetlands at Watergate.

Birds In Delaware Water Gap NRA, dieback of eastern hemlock due to hemlock woolly adelgid tends to reduce habitat for the Acadian flycatcher (*Empidonax virescens*), blue-headed vireo (*Vireo solitarius*), black-throated green warbler (*Dendroica virens*), and Blackburnian warbler (*Dendroica fusca*) (Ross et al. 2004). In eastern Pennsylvania and northern New Jersey, climate change may reduce populations of temperate zone and neotropical migrant bird species (Rodenhouse et al. 2008).

Wood turtles (*Glyptemys insculpta*) Severe floods in Massachusetts increased the mortality of wood turtles (Jones and Sievert 2009), which are also found in Delaware Water Gap NRA, suggesting possible vulnerability if the frequency of extreme storm events increases in the park.

Amphibians In Delaware Water Gap NRA, a survey of three frog and one newt species and epidemiological analyses found two pathogens, a ranavirus and mesomycetozoan (Glenney et al. 2010). Extinction of amphibians in Costa Rica due to drier conditions due to climate change and to a pathogenic fungus (Pounds et al. 2006) suggest a vulnerability of amphibians in areas of Delaware Water Gap NRA that may experience increased drying under climate change.

Because most models project increased precipitation in the park, increased drying would only occur when temperature increases would raise evapotranspiration of an area.

Brook trout (*Salvelinus fontinalis*) In southwestern Pennsylvania, brook trout, which favor cooler water, are vulnerable to higher stream temperatures under climate change (Argent and Kimmel 2013). In Delaware Water Gap NRA, native brook trout (*Salvelinus fontinalis*) and exotic brown trout (*Salmo trutta*) were two to three times as prevalent in hemlock forest than hardwood forest streams (Ross et al. 2003). In Pennsylvania, the thermal sensitivity of small streams, such as Vancampens Brook, is closely related to base water flow, with higher sensitivity at low flows (Kelleher et al. 2012). The U.S. Geological Survey is conducting research on brook trout in Delaware Water Gap NRA similar to research in Shenandoah National Park, Virginia, which used measured air–water temperature relationships to analyze groundwater influences on thermal sensitivity and vulnerability of brook trout to higher stream temperatures under climate change (Snyder et al. 2015). Preliminary results for Delaware Water Gap NRA indicate potential loss of some brook trout populations under climate change.

Invasive plants Under high emissions, eastern Pennsylvania and northern New Jersey could become more favorable to the growth of the invasive plants kudzu (*Pueraria lobata*) and privet (*Ligustrum sinense*) (Bradley et al. 2010). Under high emissions, hotter temperatures and increased precipitation will continue to make the park suitable for the invasive tree species tree-of-heaven (*Ailanthus altissima*) (Clark et al. 2014). In Delaware Water Gap NRA, canopy decline due to hemlock woolly adelgid infestations can increase invasion by garlic mustard (*Alliaria petiolata*), Japanese barberry (*Berberis thunbergii*), and Japanese stiltgrass (*Microstegium vimineum*) (Eschtruth et al. 2006, Eschtruth and Battles 2009).

Other plants In Delaware Water Gap NRA, dieback of eastern hemlock due to hemlock woolly adelgid led to increases in the number and species richness of bryophytes, such as montane dicranum moss (*Dicranum montanum*) (Cleavitt et al. 2008). In Ontario, northward migration of the range of the native orchid Nodding Ladies'-tresses (*Spiranthes cernua*), an orchid found in Delaware Water Gap NRA, suggests that temperature may change the occurrence of the orchid in the park (Catling and Oldham 2011).

Other insects In eastern Pennsylvania and northern New Jersey, climate change may shift the range of the poisonous brown recluse spider (*Loxosceles reclusa*) into the region from the central U.S. (Saupe et al. 2011). In eastern Pennsylvania and northern New Jersey, climate change could shift the range of the Asian tiger mosquito (*Aedes albopictus*), vector of the disease chikungunya, into the region from the south (Rochlin et al. 2013). In Delaware Water Gap NRA, aquatic invertebrate species richness was higher and more even in streams draining hemlock forests than streams draining mixed hardwood forests (Snyder et al. 2002), suggesting a reduction with dieback of eastern hemlock due to hemlock woolly adelgid.

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.

Twenty-eight USDA Forest Service Forest Inventory and Analysis program plots in broadleaf forest in the Adams Creek, Dingman's Falls, and Little Bushkill watersheds, partly in the western section of the national park, provided data to quantify forest carbon stocks and changes (Xu et al. 2016). The carbon density of all carbon pools (above- and belowground, biomass and dead matter) increased from 110 ± 40 tons per hectare (mean ± standard deviation) in the period 2001-2003 to 140 ± 50 tons per hectare in the period 2012-2014. The 2012-2014 carbon in each hectare of forest was equivalent to the annual emissions of 25 ± 9 Americans (Gonzalez et al. 2015). Although the plots showed a tendency to increase in carbon due to growth of mid-successional stands, the change was not statistically significant. The largest 10% of the trees accounted for 40% of the carbon. Red maple (*Acer rubrum*) and white pine (*Pinus strobus*) showed the greatest net carbon increases, while white oak (*Quercus alba*) and chestnut oak (*Quercus prinus*) showed the greatest net decreases (Xu et al. 2016).

Delaware Water Gap NRA has conducted an inventory of greenhouse gas emissions from fossil fuel use in buildings and vehicles (NPS 2005) as part of the NPS Climate Friendly Parks program to reduce park fossil fuel emissions. The carbon equivalent of emissions from buildings and vehicles in the park, electricity imported from outside the park, and visitor driving was 5200 tons in 2004, with 85% coming from visitors' automobiles. The park's annual emissions are equivalent to the emissions from burning 40 ±10 hectares of the park's broadleaf forest.

Table 1. **Delaware Water Gap NRA.** Historical average temperatures and trends of the area within park boundaries. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	°C		°C century^{-1}			°C century^{-1}		
Annual	9.4	0.6	0.4	0.2		1.1	0.5	*
December-February	-2.3	1.5	1	0.5	*	1.3	1.5	
March-May	8.7	1	0.3	0.3		1.4	0.6	*
June-August	20.6	0.7	0.3	0.2		1.1	0.4	*
September-November	10.6	0.8	0	0.2		0.5	0.5	
January	-3.7	2.6	-0.2	0.7		0.6	2.1	
February	-2.4	2.4	1.8	0.8	*	1.1	2.5	
March	2.6	1.7	0.7	0.6		2.4	1	*
April	8.6	1.2	0.5	0.3		1.1	0.9	
May	14.7	1.3	-0.3	0.4		0.8	0.9	
June	19.1	1	0.2	0.3		1	0.6	
July	21.8	1	0	0.2		0.7	0.6	
August	20.8	1	0.6	0.3		1.6	0.7	*
September	16.6	0.9	-0.4	0.4		1	0.8	
October	10.4	1.6	-0.6	0.4		-1.1	1	
November	4.9	1.5	0.9	0.3	*	1.5	0.8	
December	-0.9	2.4	1	0.5		2.2	1.4	

Table 2. **Vancampens Brook watershed**, from Watergate upstream. Historical averages and historical and projected rates of change in annual average temperature and annual total precipitation (data Daly et al. 2008, IPCC 2013; analysis Wang et al. in preparation). Note that the U.S. weather station network was more stable for the period starting 1950 than for the period starting 1895. The table gives mean values with standard errors (historical) and standard deviations (projected).

Historical (1895-2010)	
temperature average	9 ± 0.6°C (48 ± 1°F.)
temperature trend	+0.3 ± 0.2°C (+0.5 ± 0.4°F.) per century
precipitation average	1200 ± 170 mm (47 ± 7 in.) per year
precipitation trend	+6 ± 4% per century
Historical (1950-2010)	
temperature average	9 ± 0.6°C (48 ± 1°F.)
temperature trend	+0.9 ± 0.4°C (+1.6 ± 0.7°F.) per century
precipitation average	1200 ± 180 mm (47 ± 7 in.) per year
precipitation trend	+7 ± 7% per century

Projected (2000-2100)	
Reduced emissions (IPCC RCP2.6)	
temperature	+1.8 ± 0.7°C (+3.2 ± 1.3°F.) per century
precipitation	+8 ± 6% per century
Low emissions (IPCC RCP4.5)	
temperature	+3 ± 0.8°C (+5.4 ± 1.4°F.) per century
precipitation	+11 ± 6% per century
High emissions (IPCC RCP6.0)	
temperature	+3.4 ± 0.9°C (+6.1 ± 1.6°F.) per century
precipitation	+11 ± 7% per century
Highest emissions (IPCC RCP8.5)	
temperature	+5.2 ± 0.8°C (+9.4 ± 1.4°F.) per century
precipitation	+15 ± 8% per century

Table 3. **Delaware Water Gap NRA.** Historical average precipitation totals and trends of the area within park boundaries. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	mm y^{-1}		% $century^{-1}$			% $century^{-1}$		
Annual	1209	169	7	5		17	14	
December-February	258	76	1	8		3	20	
March-May	318	76	10	7		3	22	
June-August	325	77	-2	7		20	18	
September-November	306	88	22	8	**	39	21	
January	95	55	5	15		21	47	
February	74	31	-20	11		-27	26	
March	96	39	4	10		3	25	
April	104	48	12	12		-14	33	
May	118	56	13	15		22	42	
June	116	55	13	12		78	33	
July	104	47	-15	12		1	30	
August	104	41	-4	12		-19	36	
September	116	59	24	11	*	61	26	*
October	93	45	23	16		89	44	
November	98	45	20	12		-35	30	
December	91	53	10	13		4	37	

Table 4. **Delaware Water Gap NRA.** Projected temperature increases (ºC per century), 2000 to 2100, for the area within park boundaries, average of all available general circulation model projections for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation. **Bold type** = season or month with greatest increase.

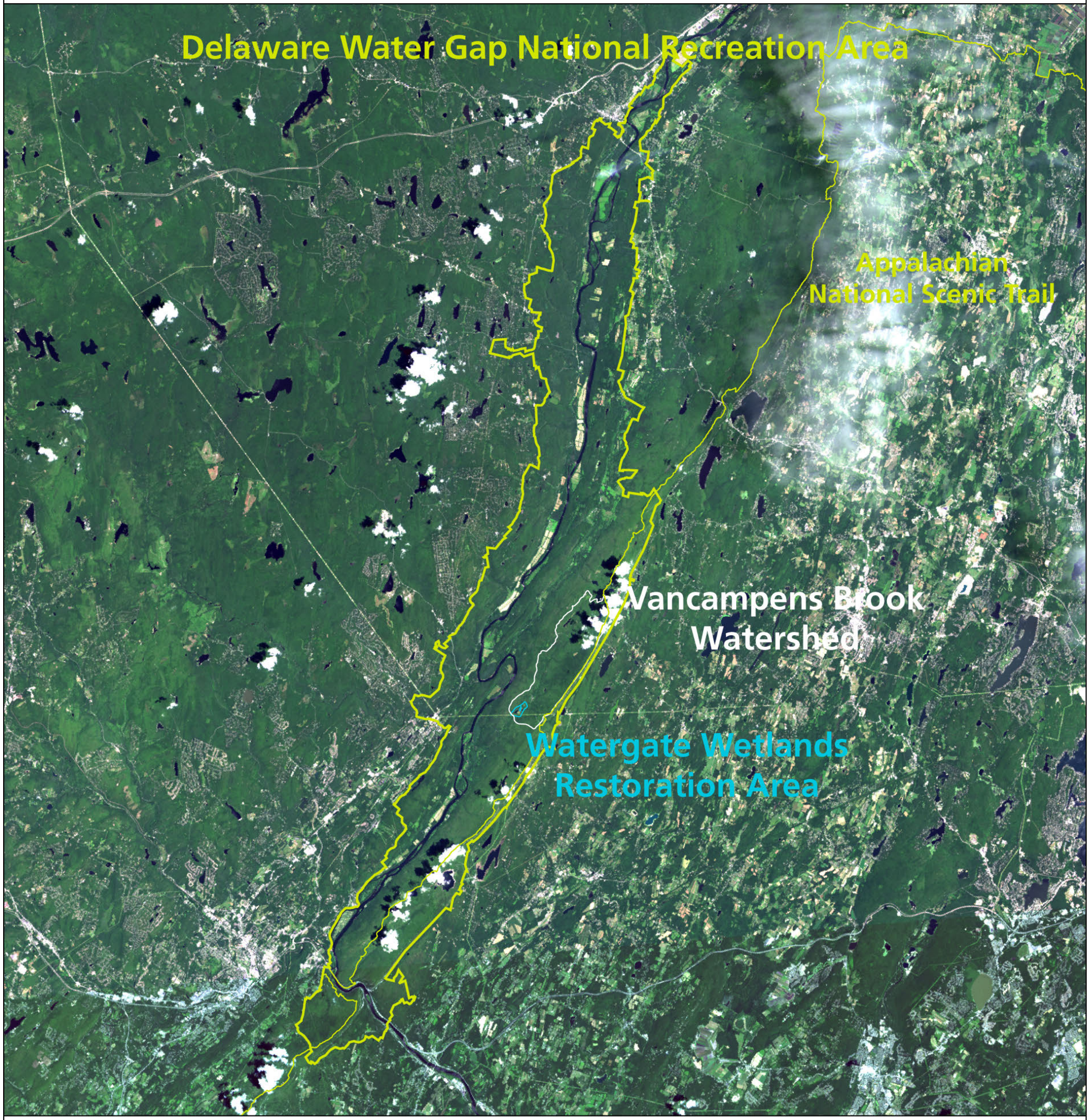
	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.8	0.7	3	0.8	3.4	0.9	5.2	1
December-February	2	0.9	3.2	1.2	**3.6**	**1**	5.3	1.4
March-May	1.6	0.7	2.5	1.3	3.1	0.9	4.4	1.4
June-August	1.7	0.8	3	1	3.6	1.1	5.4	1.2
September-November	**1.8**	**0.8**	**3.3**	**1.7**	3.5	1	**5.6**	**2.1**
January	2	1.2	3.4	1.4	3.6	1	5.5	1.6
February	1.9	1.2	3	1.1	3.5	1.3	5.1	1.1
March	1.6	0.9	2.4	1.6	3	1.1	4.2	1.6
April	1.6	0.9	2.6	1.4	3.1	0.9	4.5	1.5
May	1.6	0.8	2.5	1.2	3.1	0.8	4.5	1.4
June	1.6	0.7	2.6	1.2	3.3	0.9	4.8	1.3
July	1.8	0.8	3	1	3.7	1.1	5.5	1.3
August	1.8	0.9	3.3	1.1	3.8	1.3	**6**	**1.6**
September	1.9	0.9	**3.4**	**1.6**	**3.8**	**1.2**	6	2
October	1.8	0.9	3.3	1.9	3.4	1.1	5.7	2.3
November	1.8	0.8	3.1	1.9	3.4	0.9	5.2	2.1
December	**2**	**1**	3.4	2	3.6	1.2	5.4	2.1

Table 5. **Delaware Water Gap NRA.** Projected precipitation changes (% per century), 2000 to 2100, for the area within park boundaries, average of all available general circulation model projections 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	8	6	11	6	11	7	15	8
December-February	9	9	17	10	19	10	27	16
March-May	9	9	11	8	14	9	17	8
June-August	9	10	11	12	9	16	11	18
September-November	4	7	5	9	5	7	7	11
January	11	18	21	18	20	16	34	24
February	8	12	17	17	19	13	25	16
March	7	10	12	9	13	11	19	11
April	10	12	13	14	16	11	19	14
May	9	17	8	14	12	14	13	11
June	8	12	7	14	6	13	6	13
July	8	15	10	15	7	20	9	20
August	10	17	17	21	12	25	17	34
September	5	12	8	17	6	13	5	17
October	3	17	1	16	-1	17	4	20
November	5	10	7	11	11	13	12	14
December	10	13	16	12	21	17	25	18

Figure 1

Delaware Water Gap, Pennsylvania, New Jersey

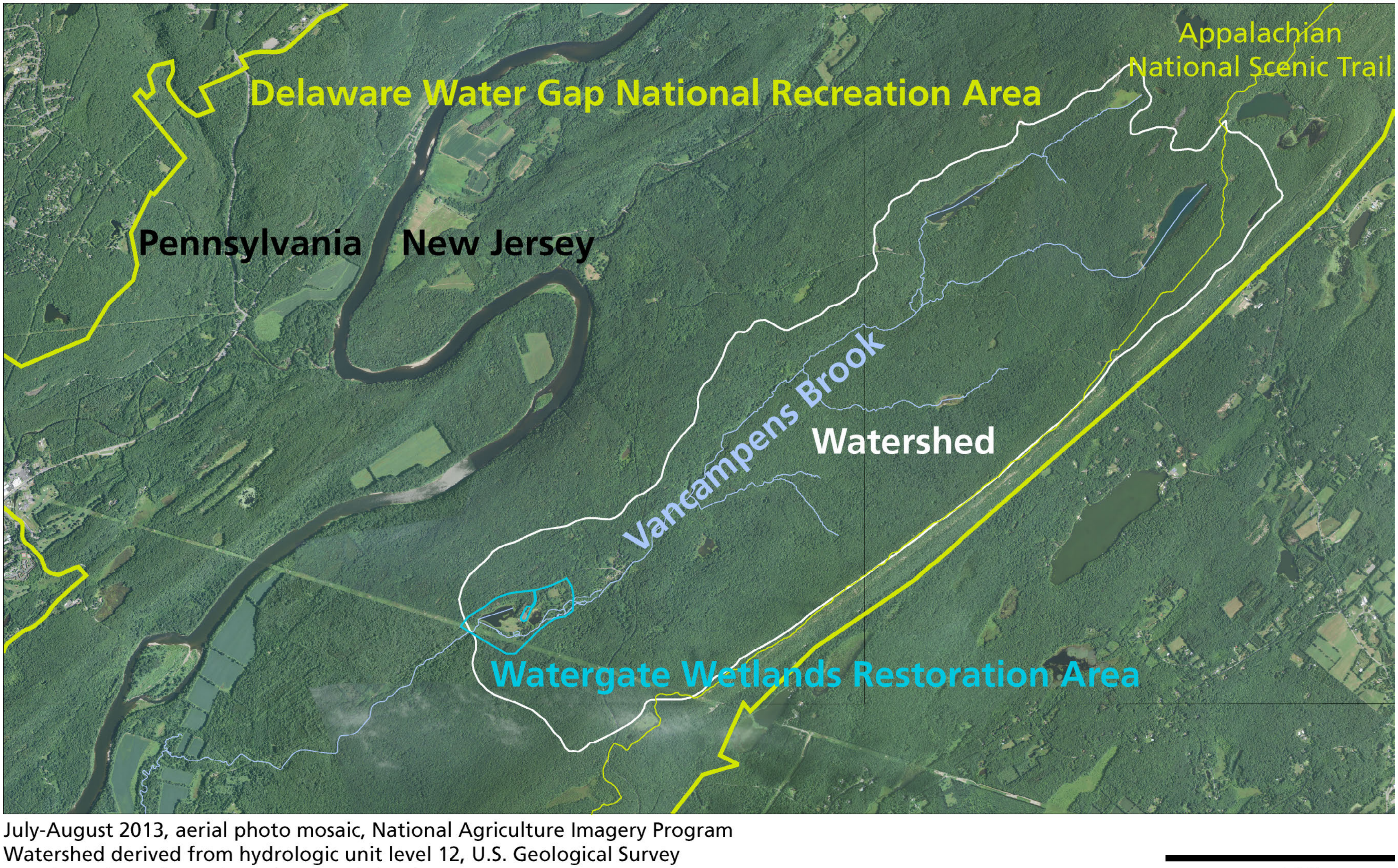


July 25, 2015

Data: Landsat 8, U.S. Geological Survey.
Analysis: P. Gonzalez.

Figure 2

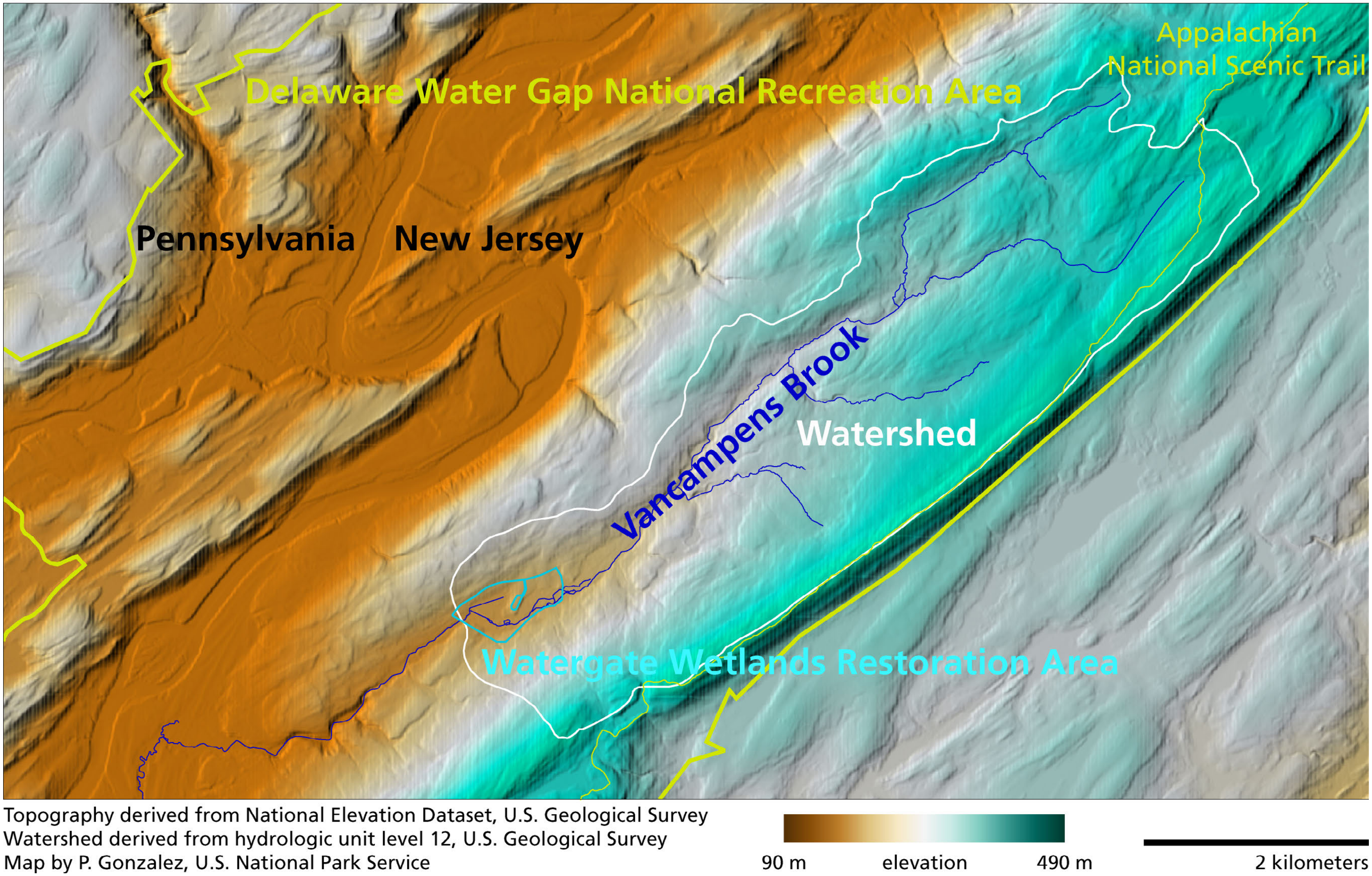
Watergate Wetlands Restoration



July-August 2013, aerial photo mosaic, National Agriculture Imagery Program
Watershed derived from hydrologic unit level 12, U.S. Geological Survey
Map by P. Gonzalez, U.S. National Park Service

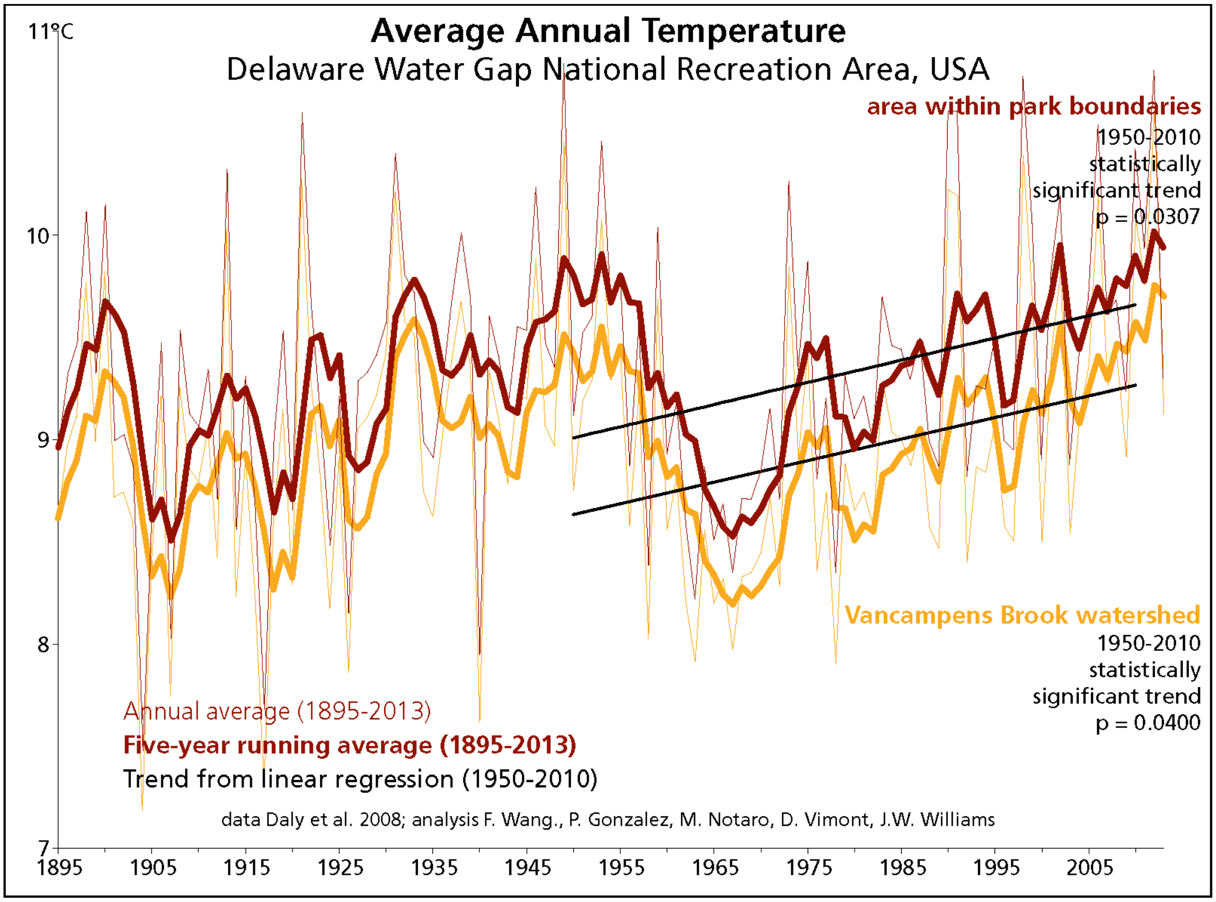
Figure 3

Watergate Wetlands Restoration



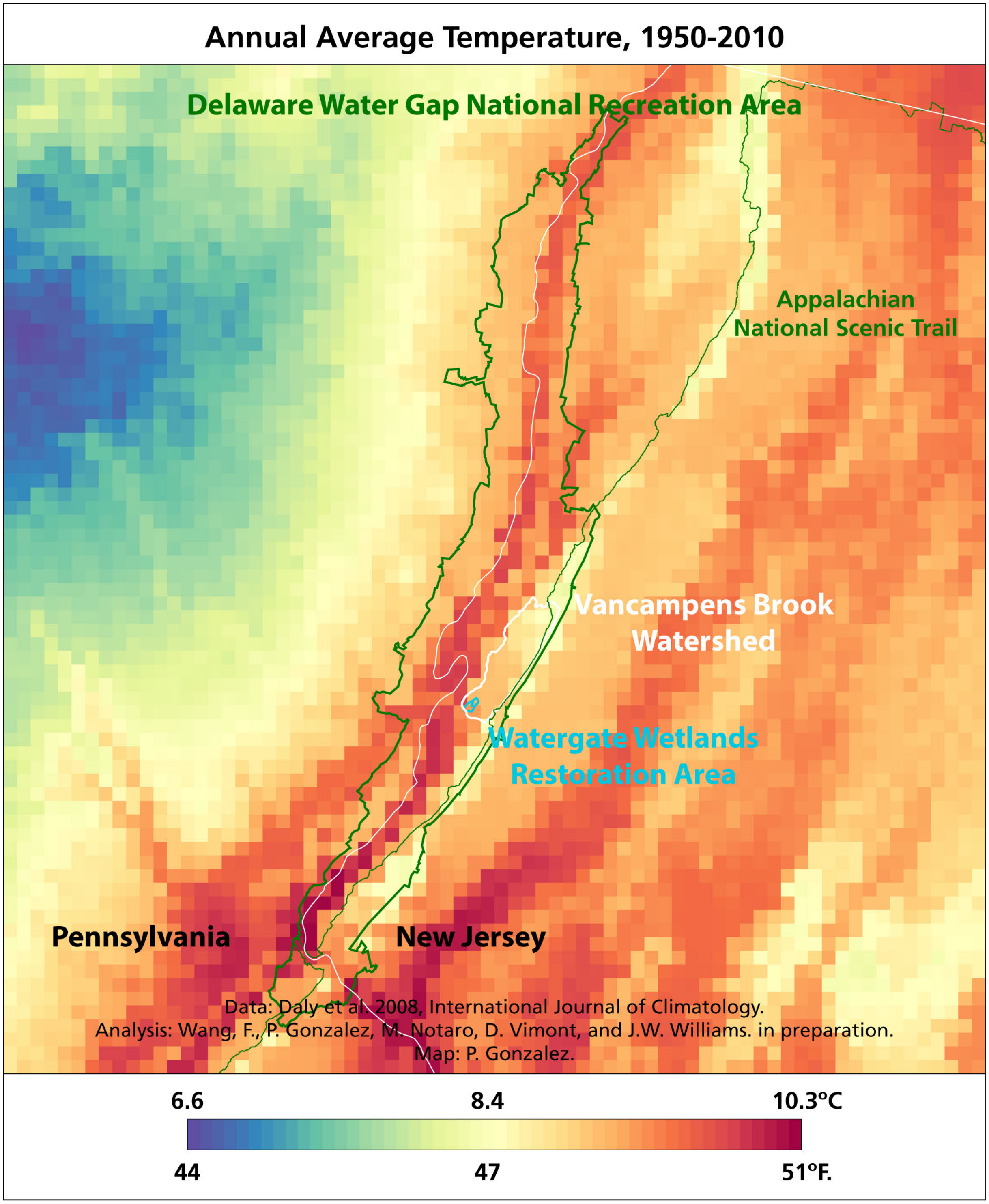
Topography derived from National Elevation Dataset, U.S. Geological Survey
Watershed derived from hydrologic unit level 12, U.S. Geological Survey
Map by P. Gonzalez, U.S. National Park Service

Figure 4



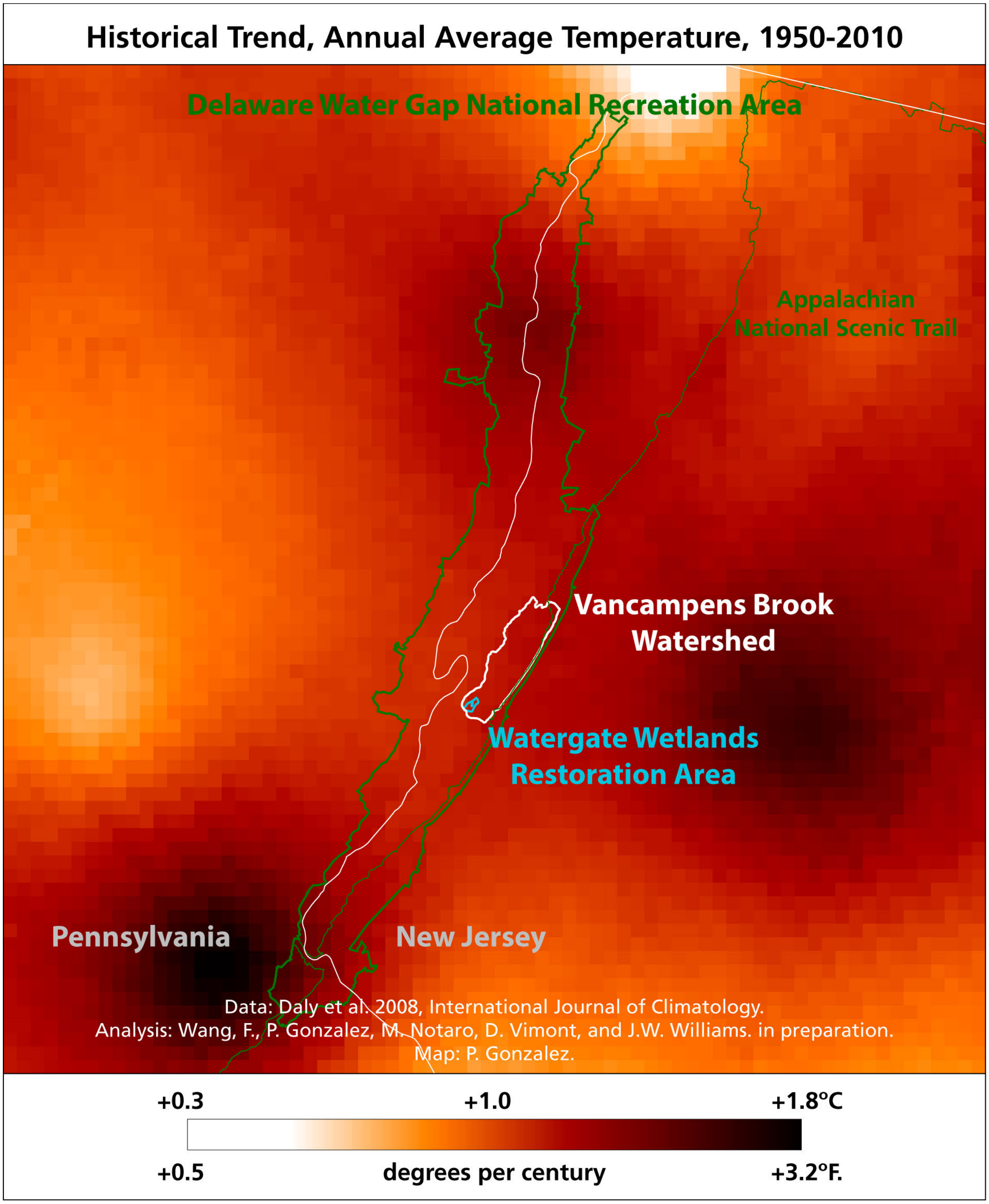
Main conclusion: Temperature increased at statistically significant rates in the park and watershed.

Figure 5



Main conclusion: Average temperatures decrease as elevation increases.

Figure 6

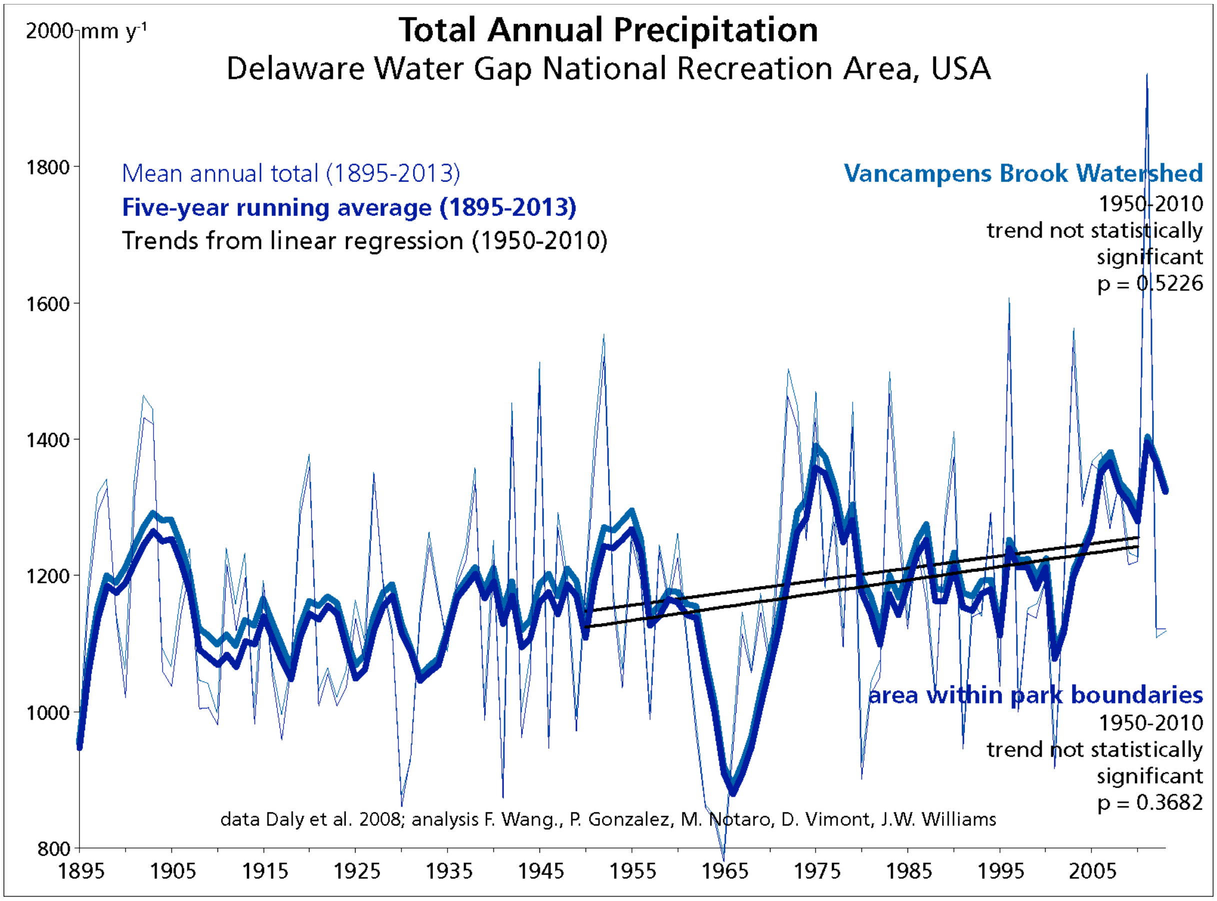


Historical Trend, Annual Average Temperature, 1950-2010

Data: Daly et al. 2008, International Journal of Climatology.
Analysis: Wang, F., P. Gonzalez, M. Notaro, D. Vimont, and J.W. Williams. in preparation.
Map: P. Gonzalez.

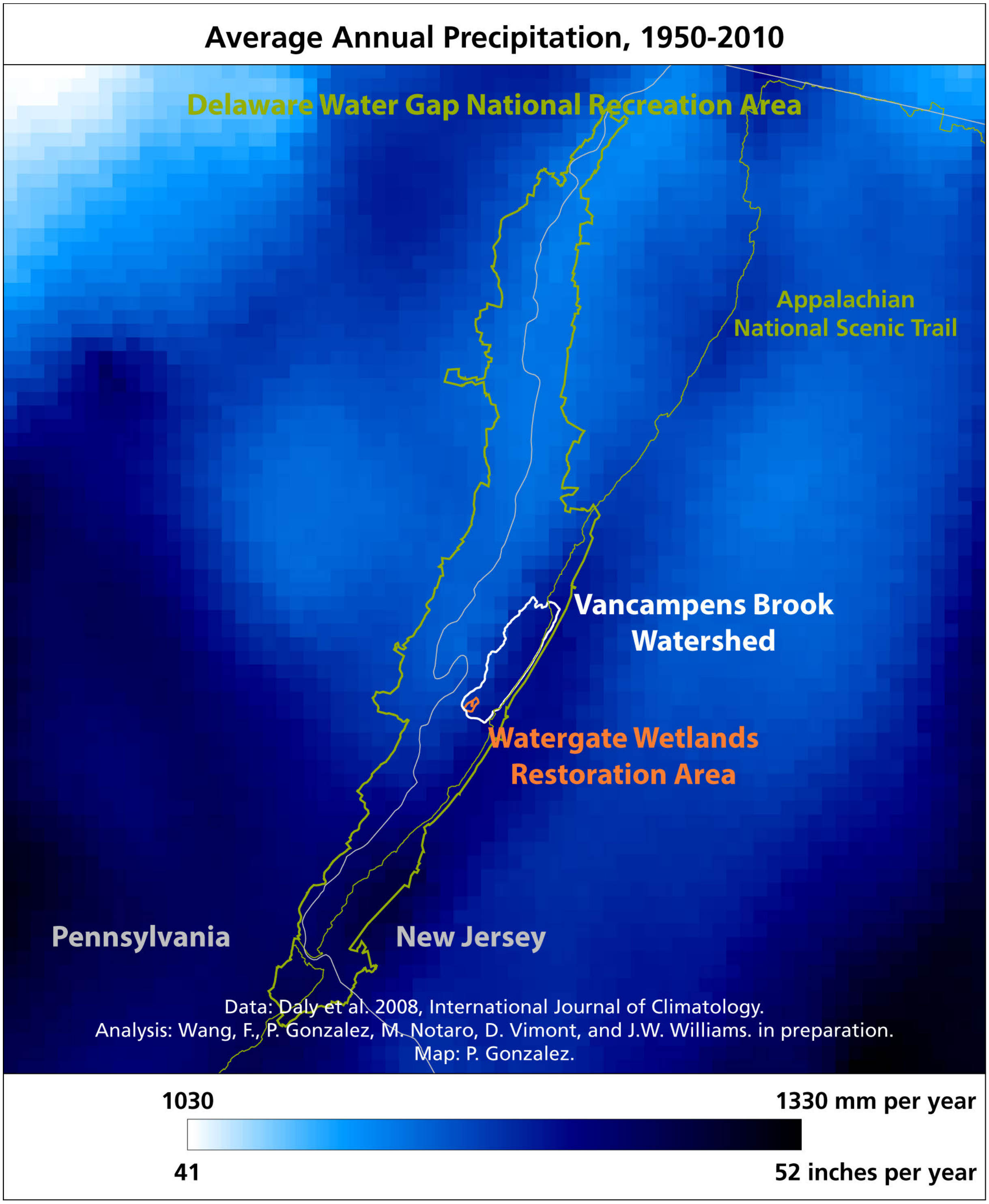
Main conclusion: Temperature increases are greatest at the Delaware Water Gap.

Figure 7



Main conclusion: Precipitation has increased, but the change has not been statistically significant.

Figure 8

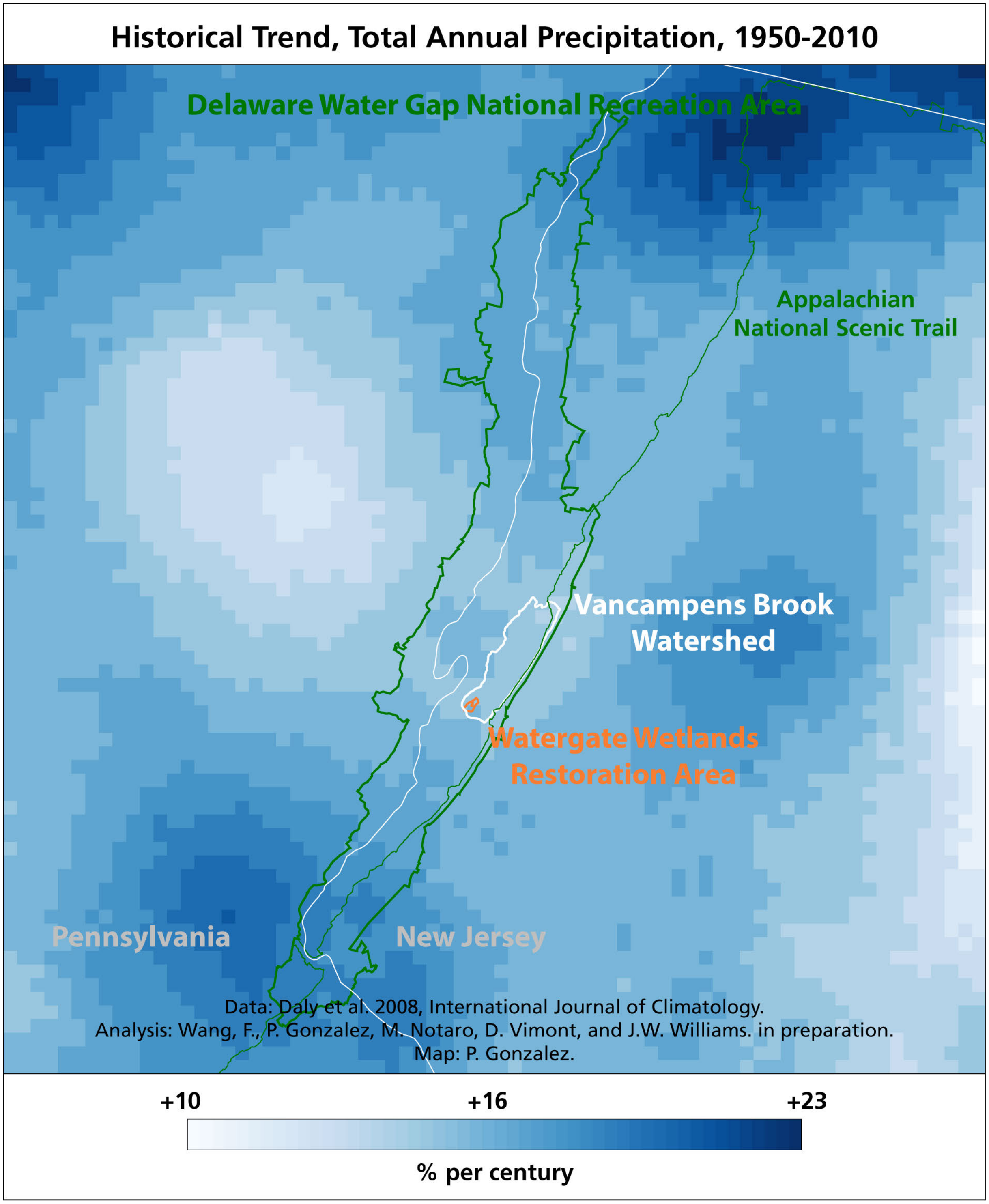


Average Annual Precipitation, 1950-2010

Data: Daly et al. 2008, International Journal of Climatology.
Analysis: Wang, F., P. Gonzalez, M. Notaro, D. Vimont, and J.W. Williams. in preparation.
Map: P. Gonzalez.

Main conclusion: Precipitation is greatest in the south of the park and the Vancampens Brook watershed.

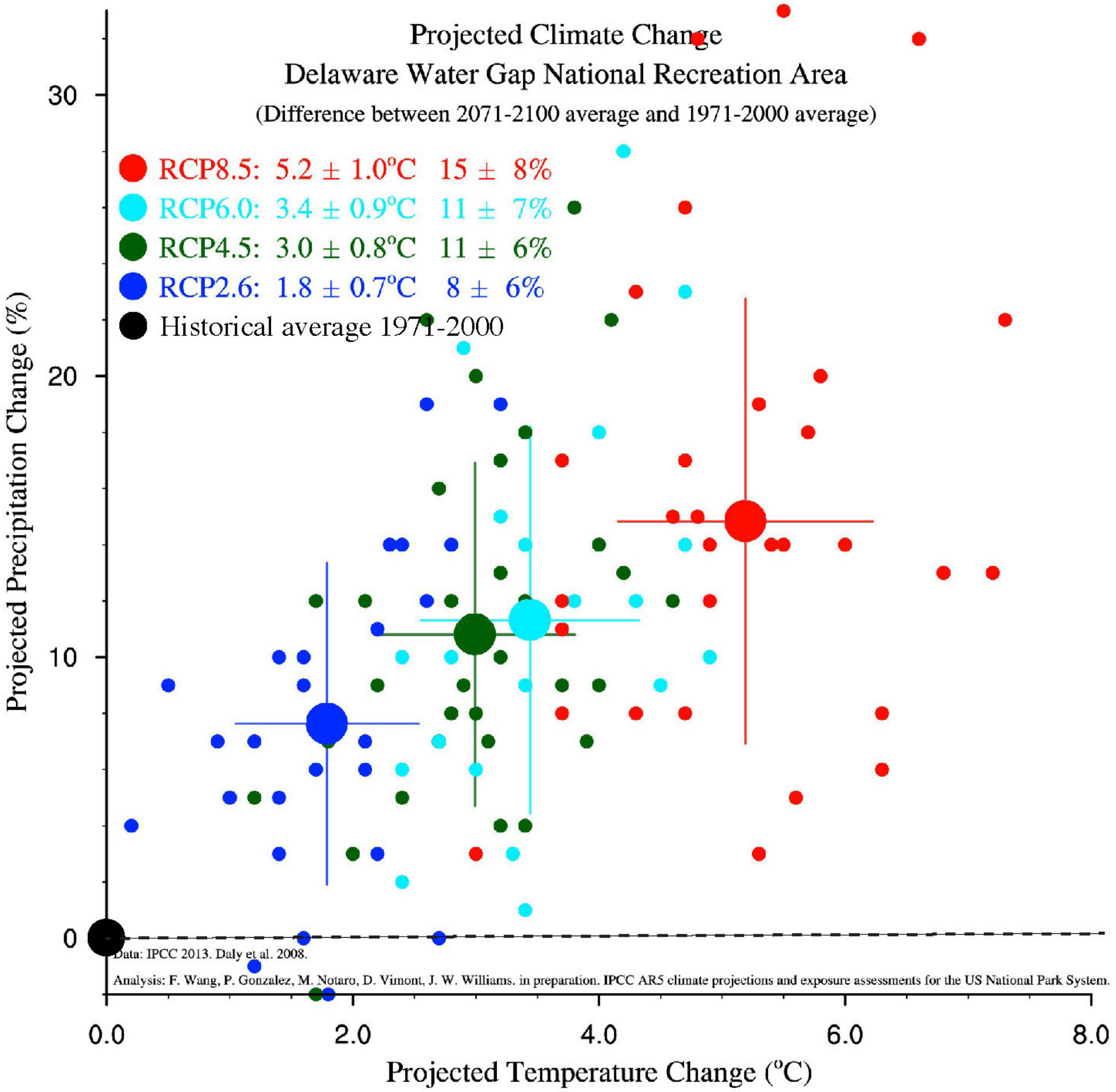
Figure 9



Data: Daly et al. 2008, International Journal of Climatology.
Analysis: Wang, F., P. Gonzalez, M. Notaro, D. Vimont, and J.W. Williams. in preparation.
Map: P. Gonzalez.

Main conclusion: Precipitation increases are greatest at the north and south ends of the park.

Figure 10



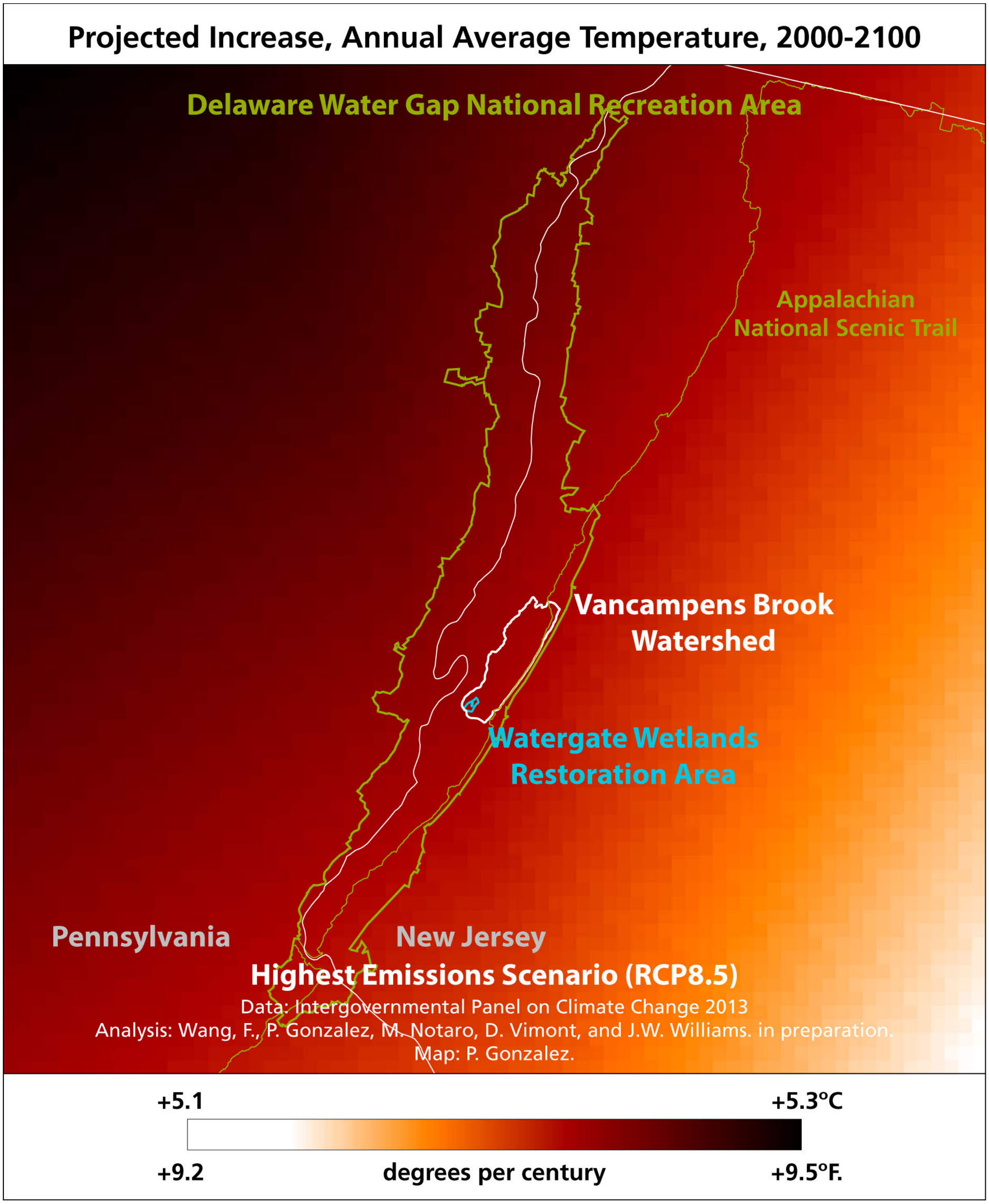
Data: IPCC 2013. Daly et al. 2008.

Analysis: F. Wang, P. Gonzalez, M. Notaro, D. Vimont, J. W. Williams. in preparation. IPCC AR5 climate projections and exposure assessments for the US National Park System.

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

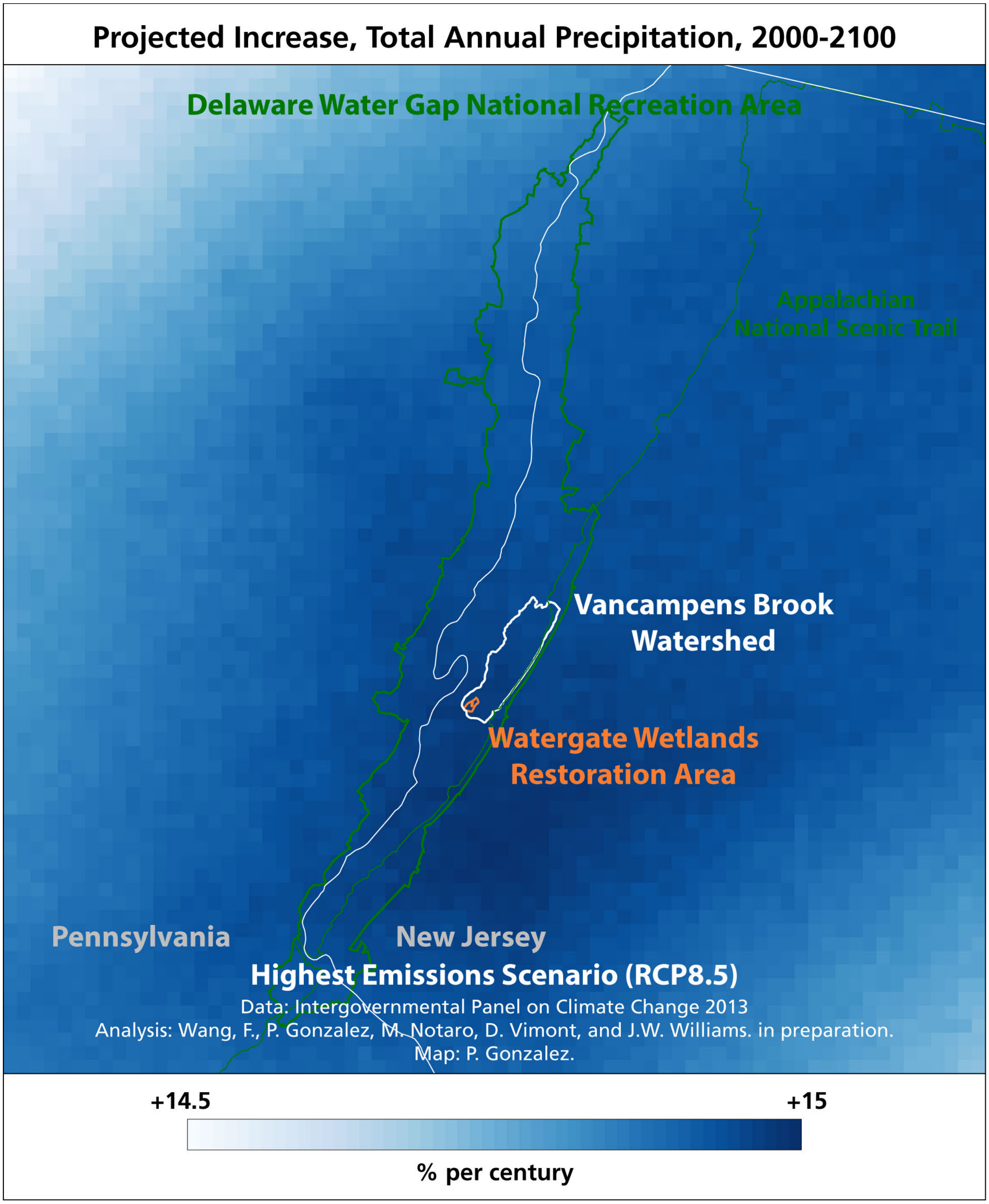
Projections of future climate for the area within park boundaries, relative to 1971-2000 average values. Each small dot is the output of a single GCM. The large color dots are the average values for the four IPCC emissions scenarios. The lines are the standard deviations of each emissions scenario average.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

Figure 11



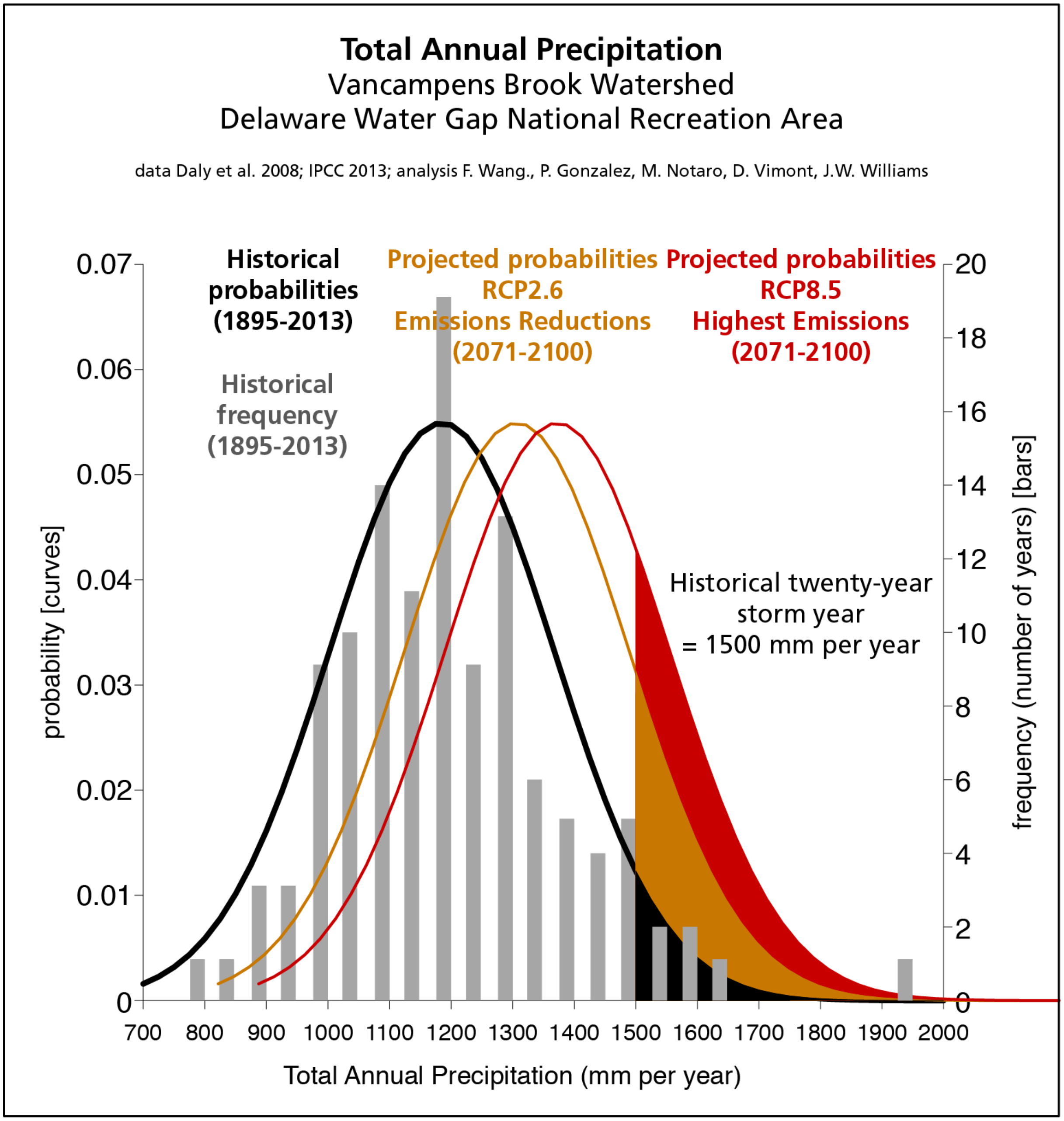
Main conclusion: Projected temperature increases are similar across the park.

Figure 12



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

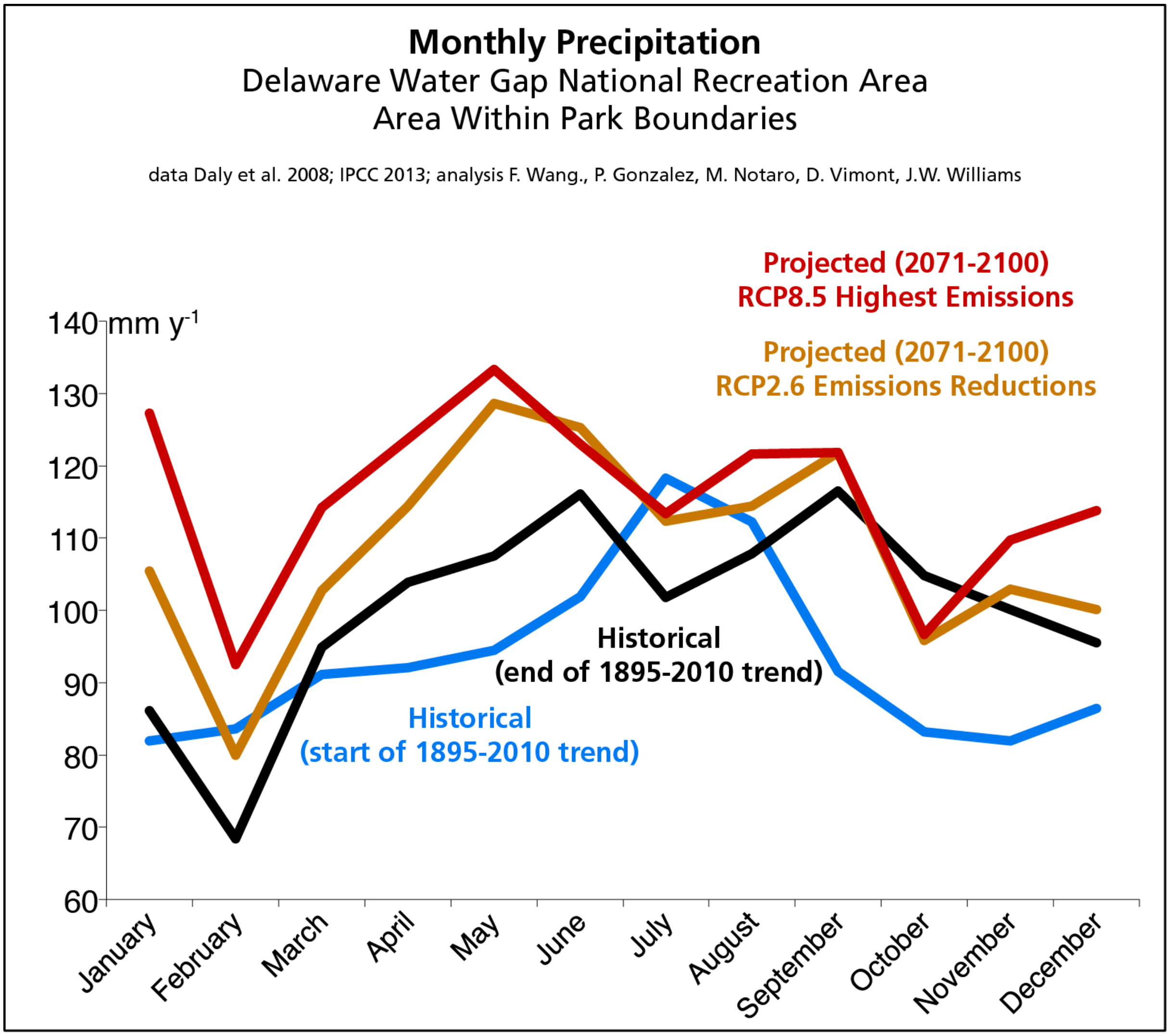
Figure 13



Main conclusion: Climate change may increase extreme storm years.

For the Vancampens Brook watershed, the 1895-2013 historical data (grey bars) show a normal probability distribution of total annual precipitation (black curve). The annual average was 1200 ± 170 mm (47 ± 7 in.) per year and twenty-year storm years (total precipitation occurring only once in 20 years) had ≥ 1500 mm (59 in.) per year (black area under the curve). Under the scenario of sustainability improvements (RCP2.6), the probability distribution could shift to higher precipitation (orange curve) and the former twenty-year storm years could double in frequency (orange area under the curve). Under the worst scenario (RCP8.5), former twenty-year storm years could triple in frequency (red area under the curve).

Figure 14



Main conclusion: Climate change is changing the seasonal distribution of precipitation.

For Delaware Water Gap NRA as a whole, data for the 1895-2013 historical period show that the seasonal distribution of precipitation has changed. At the beginning of the historical period (Figure 14, blue line), precipitation peaked in July, the middle of summer. By the end of the period (Figure 14, black line), precipitation showed a bi-modal distribution, with peaks in June and September, and a notable decrease in February. Under the scenario of the greatest sustainability improvements (RCP2.6) (Figure 14, orange line) and the worst scenario (RCP8.5) (Figure 14, red line), total annual precipitation could be higher than historical, but monthly precipitation could be lower than historical for July and October. The relative low point in February could persist.

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