

Climate Change Trends, Vulnerabilities, and Paleontology, Tule Springs Fossil Beds National Monument, Nevada

Patrick Gonzalez (U.S. National Park Service; University of California, Berkeley)

Whitney B. Reiner (University of California, Berkeley)

Natural Resource Stewardship and Science, U.S. National Park Service, Berkeley, California

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Climate Trends for the Area within Park Boundaries

- **Historical temperature** Average annual temperature in the park increased at the statistically significant rate of $1.7 \pm 0.3^{\circ}\text{C}$ per century ($3.1 \pm 0.5^{\circ}\text{F.}$) in the period 1950-2010 (Table 1, Figure 1).
- **Historical precipitation** Total annual precipitation increased in the period 1950-2010, but the rate was not statistically significant (Table 1, Figure 2).
- **Spatial patterns** At lower elevations the southern end of the park (Figure 3), historical temperature increases were greater (Figure 4). Historical precipitation increases were greater at the northern end of the park (Figure 5).
- **Projected temperature and precipitation** If the world does not reduce emissions from power plants, cars, and deforestation by 40-70%, models project substantial warming and changes in precipitation (Table 1, Figures 6, 7).
- **Projected precipitation** For projected average annual precipitation, climate models do not agree, with the average of all models projecting an increase, but many individual models projecting decreases.
- **Aridity** Even if precipitation increases, temperature increases may overcome any cooling effects of increased precipitation, leading to increased evapotranspiration and overall aridity.
- **Extreme heat** Projections under the highest emissions scenario project an increase of 25 to 30 more days per year with a maximum temperature $>35^{\circ}\text{C}$ (95°F.) (Kunkel et al. 2013).
- **Extreme storms** Projections under the highest emissions scenario project an increase in 20-year storms (a storm with more precipitation than any other storm in 20 years) to once every 5-6 years (Walsh et al. 2014).

Paleontology Research in the Park Relevant to Human Climate Change

- **Ancient desert wetlands** Analyses of sediments from 14 sites along the central axis of the park provided data to estimate groundwater discharge and broad land cover trends over the last 35 000 years (Springer et al. 2015). Desert wetlands once covered a substantial fraction of the area of the park 24 000 to 35 000 years ago. From 8200 to 11 700 years ago, the area became increasingly arid and wetlands dried up. Currently, the upper Las Vegas Wash, which runs directly through the park, runs only intermittently, draining storm water and runoff from the Las Vegas Valley toward Lake Mead (Bureau of Land Management 2011).

The paleohydrological research reveals the sensitivity of desert wetlands to climate (Springer et al. 2015). Although the absolute temperature and precipitation of the earlier time cannot be quantified, deposits showed cessation of groundwater discharge during warm periods, as shown in Greenland ice cores. Types of sediments and microfossils that indicate presence or absence of wetland vegetation indicate that extreme erosion occurred in arid periods, followed by the collapse of the entire wetland ecosystem and possible extirpation of some plant and animal species. The paleohydrologic research points to the possibility of desert wetlands in the park under wetter conditions and severe ecological changes when the climate becomes more arid.

- **Joshua trees** Across the southwestern U.S., woodrat (*Neotoma spp.*) middens and Shasta ground sloth (*Nothrotheriops shastensis*) dung from the late Pleistocene and early Holocene (10 000 to 40 000 years ago) shows very slow adaptive capacity of Joshua tree (migration ~1-2 meters per year) as its range contracted into its northern reaches when temperatures increased at the beginning of the Holocene (11 700 years ago) (Cole et al. 2011). Projection of the potential future range based on that adaptive capacity reveals potential loss of suitable habitat in the park and identifies new potential habitat at high elevations southwest of the park (Cole et al. 2011).
- **Desert woodrat** Across the western U.S., woodrat (*Neotoma spp.*) middens in the past 40 000 years show a decrease in body size as temperature increases (Smith and Betancourt 2006). The paleoecological evidence suggests that the evolutionary adaptive capacity of the species is sufficient to adapt to contemporary climate change.
- **Degradation of fossils and sub-fossils** Fossils and subfossils (partially mineralized animal and plant remains) in the park, especially those exposed to open air, are vulnerable to degradation from natural weathering in sunlight, wind, and rain and from wind and water erosion (Santucci et al. 2009). Any increase in the region of extreme storms under climate

change (Walsh et al. 2014) could increase erosion. Subfossils are more susceptible to breakage due to reduced mineral content and remnant collagen and are particularly sensitive to daily changes in relative humidity (Lacasa-Marquina et al. 2014). In general, rates of decomposition of biological material increase with humidity, so the vulnerability of subfossils in the park depends on whether projected temperature increases are high enough to increase aridity under the projected precipitation increases. Any degradation of fossils and subfossils under climate change could affect the types, numbers, and locations of fossils found in an area, affecting interpretation of the paleoecology of the region (Behrensmeyer et al. 2000).

Historical Impact in the Region Attributed to Human Climate Change

- **Bird range shifts** Analyses of Audubon Christmas Bird Count data across the United States, including counts in southern Nevada, detected a northward shift of winter ranges of a set of 254 bird species at an average rate of 0.5 ± 0.3 km per year from 1975 to 2004, attributable to human climate change and not other factors (La Sorte and Thompson 2007).

Future Vulnerabilities in the Region

- **Intermittent stream flows** The potential increased frequency of extreme storms (Walsh et al. 2014) could increase the flow in individual intermittent flow events in the dry wash that runs through the park. On the other hand, reduced snowfall and rainfall and increased temperature under all emissions scenarios could further reduce the sparse intermittent flow of courses in the wash (Garfin et al. 2014). The paleohydrological research in the park (Springer et al. 2015) that showed drying of ancient wetlands under arid conditions suggests vulnerability of plant and animal species under any projected future arid conditions in the region of the park.
- **Joshua trees** Under high emissions, warmer and drier conditions may eliminate the small area of suitable habitat for Joshua trees (*Yucca brevifolia*) in Tule Springs Fossil Beds National Monument (Cole et al. 2011). The slow dispersal rate shown in the paleoecological record indicates that Joshua trees may not be able to naturally colonize the higher elevation areas southwest of the park that may become newly suitable habitat.
- **Invasive species** Under high emissions, the region of the park could provide suitable habitat for the invasive salt cedar tree (*Tamarix spp.*) (Bradley et al. 2009, Perry et al. 2013). The range of the invasive yellow starthistle (*Centaurea solstitialis*) could expand in the region (Bradley et al. 2009).
- **Desert bighorn sheep** Research on desert bighorn sheep (*Ovis canadensis nelsoni*) across

southern California indicates that increased temperature and aridity may contract the potential range of the species (Epps et al. 2004), with higher-elevation areas providing some refugia (Epps et al. 2006, 2007). This suggests that the relatively low elevation of Tule Springs Fossil Beds National Monument (Figure 3) may not provide suitable habitat under climate change. Research in Death Valley National Park and Mojave National Preserve found that lower precipitation reduces forage quality and availability, forcing the sheep to expand their range (Oehler et al. 2009). Roads and off-highway vehicle use exacerbate the vulnerability of desert bighorns through habitat fragmentation that isolates populations, reducing physical and genetic connectivity (Ouren et al. 2007, Epps et al. 2005, 2006, 2007).

- **Desert woodrat** Paleoeological and contemporary data on desert woodrats (*Neotoma lepida*) in Death Valley National Park (Murray and Smith 2012, Smith et al. 2014) and on woodrats (*Neotoma spp.*) across the western U.S. (Smith and Betancourt 2006) indicate that high temperatures reduce body size and increase mortality. Recent research on desert woodrats and plant secondary compounds (toxins) in creosote bushes (*Larrea tridentata*) in the Mojave Desert found an association between elevated temperature and increased plant toxicity and reduced liver function in woodrats, translating to reduced tolerance to toxins (Kurnath et al. 2016). Changes in foraging behavior as a response to reduced tolerance to plant secondary compounds may increase predation risk. Desert woodrats in warmer temperatures can reduce their intake of toxic plants, but creosote bushes at the study site occupied up to 75% of diet and few alternatives to creosote bush exist, particularly during the warmest months when levels of plants are most toxic.

Research in Death Valley demonstrates relatively high water requirements for desert woodrats compared to other rodents (Murray and Smith 2012). Heat-stressed woodrats were observed coating portions of their body with saliva, which alleviates heat loads but also produces water deficits detrimental to fitness. Time spent foraging plants that provide water and energy was reduced by the restriction on activity outside the den driven by the need to conserve water.

- **Burrowing owls** Research on burrowing owls (*Athene cunicularia hypugaea*) in Albuquerque, NM, found statistically significant decreases in fledgling output, nest success, and breeding populations with increased aridity from a temperature increase of $1.3 \pm 0.6^{\circ}\text{C}$ ($2.3 \pm 1.1^{\circ}\text{F.}$) (Cruz-McDonnell and Wolf 2016), compared to the historical average annual temperature increase in the park of $1.7 \pm 0.3^{\circ}\text{C}$ per century ($3.1 \pm 0.5^{\circ}\text{F.}$) Each 1°C increase in temperature may reduce burrowing owl populations by a quarter. At the northernmost extent of the species'

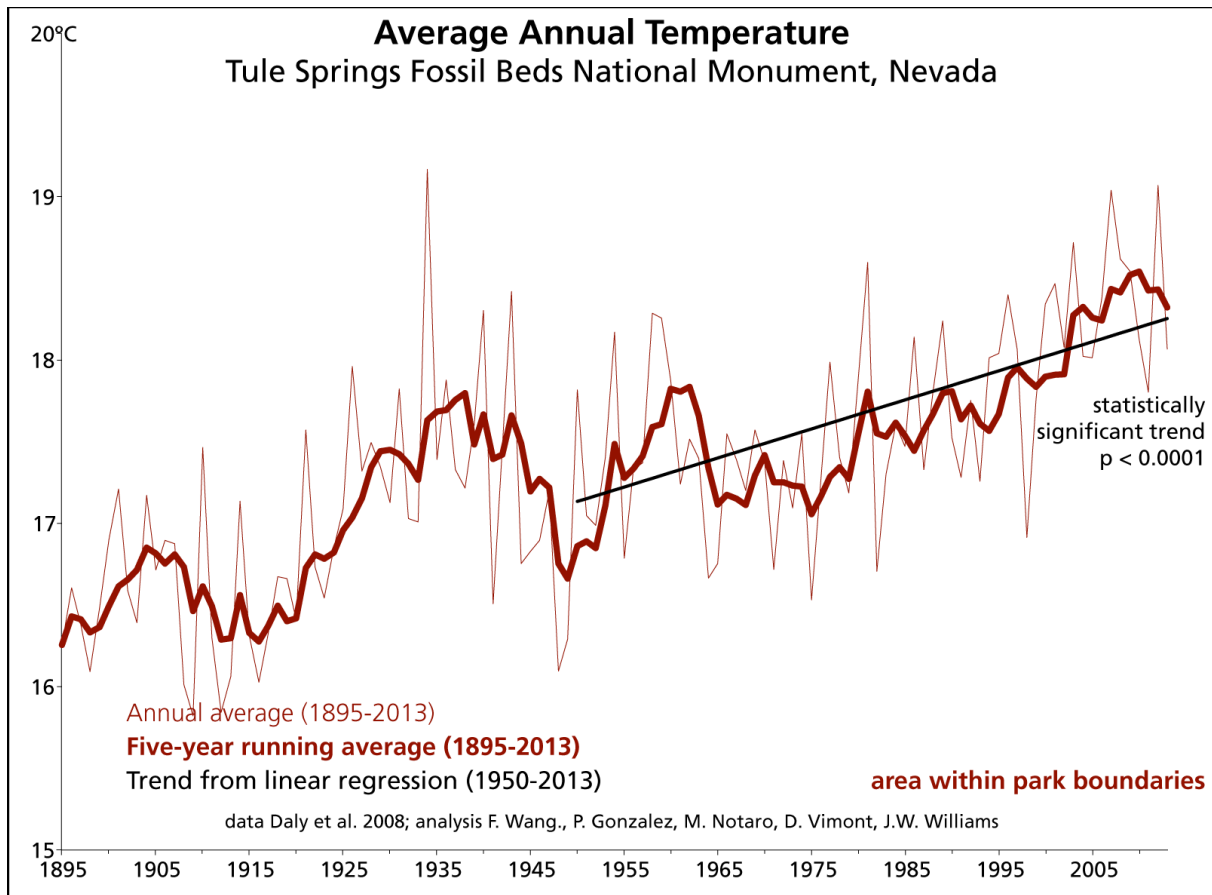
range, populations have already decreased (Cruz-McDonnell and Wolf 2016).

- **Desert tortoise** Research on the desert tortoise (*Gopherus agassizii*) in Joshua Tree National Park (Barrows 2011, Lovich et al. 2014), on Bureau of Land Management land in Kern County, California (Jennings and Berry 2015), and in Fort Irwin (Mack et al. 2015) and other Mojave Desert military bases (McCoy et al. 2011) indicates that the tortoise is vulnerable to increased mortality and range contraction under climate change due to heat stress (Barrows 2011, Mack et al. 2015), lack of water (Barrows 2011, Lovich et al. 2014), reduced forage (Jennings and Berry 2015), and increased predation (Lovich et al. 2014).
- **Gila monster** Tracking of gila monsters (*Heloderma suspectum*) near Lake Mead found that these lizards frequent desert tortoise burrows in search of desert tortoise eggs, an important source of food for the lizard (Gienger and Trancy 2008). Gila monster dependence on tortoise eggs for nutrition suggests a link of the population dynamics of the Gila monster to the population dynamics of the desert tortoise, which are highly vulnerable to climate change.

Table 1. Historical rates of change and projected future changes per century in annual average temperature and annual total precipitation for the park as a whole (data Daly et al. 2008, IPCC 2013; analysis Wang et al. in preparation). The table gives the historical rate of change per century calculated from data for the period 1950-2013. The U.S. weather station network was more stable for the period starting 1950 than for the period starting 1895. The table gives central values with standard errors (historical) and standard deviations (projected).

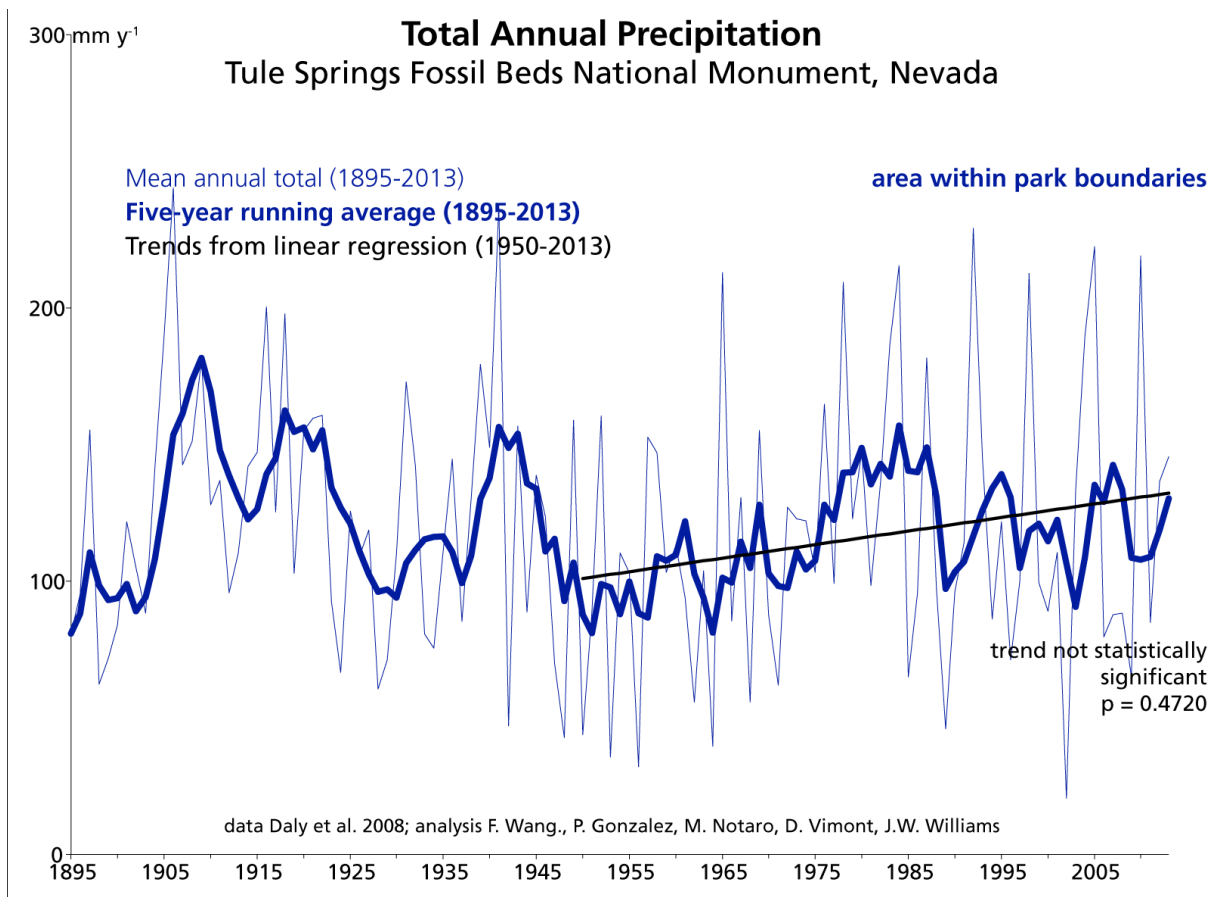
	1950-2013	2000-2100
Historical		
temperature	+1.7 ± 0.3°C per century (3.1 ± 0.5°F.)	
precipitation	+47 ± 21% per century	
Projected (compared to 1971-2000)		
Reduced emissions (IPCC RCP2.6)		
temperature	+1.6 ± 0.7°C per century (+2.9 ± 1.3°F.)	
precipitation	+9 ± 12% per century	
Low emissions (IPCC RCP4.5)		
temperature	+2.8 ± 0.7°C per century (+5 ± 1.3°F.)	
precipitation	+5 ± 10% per century	
High emissions (IPCC RCP6.0)		
temperature	+3.2 ± 0.8°C per century (+5.8 ± 1.4°F.)	
precipitation	+5 ± 12% per century	
Highest emissions (IPCC RCP8.5)		
temperature	+5.0 ± 0.9°C per century (+9 ± 1.6°F.)	
precipitation	+7 ± 18% per century	

Figure 1.



Main conclusion: Temperature increased at a statistically significant rate in the park.

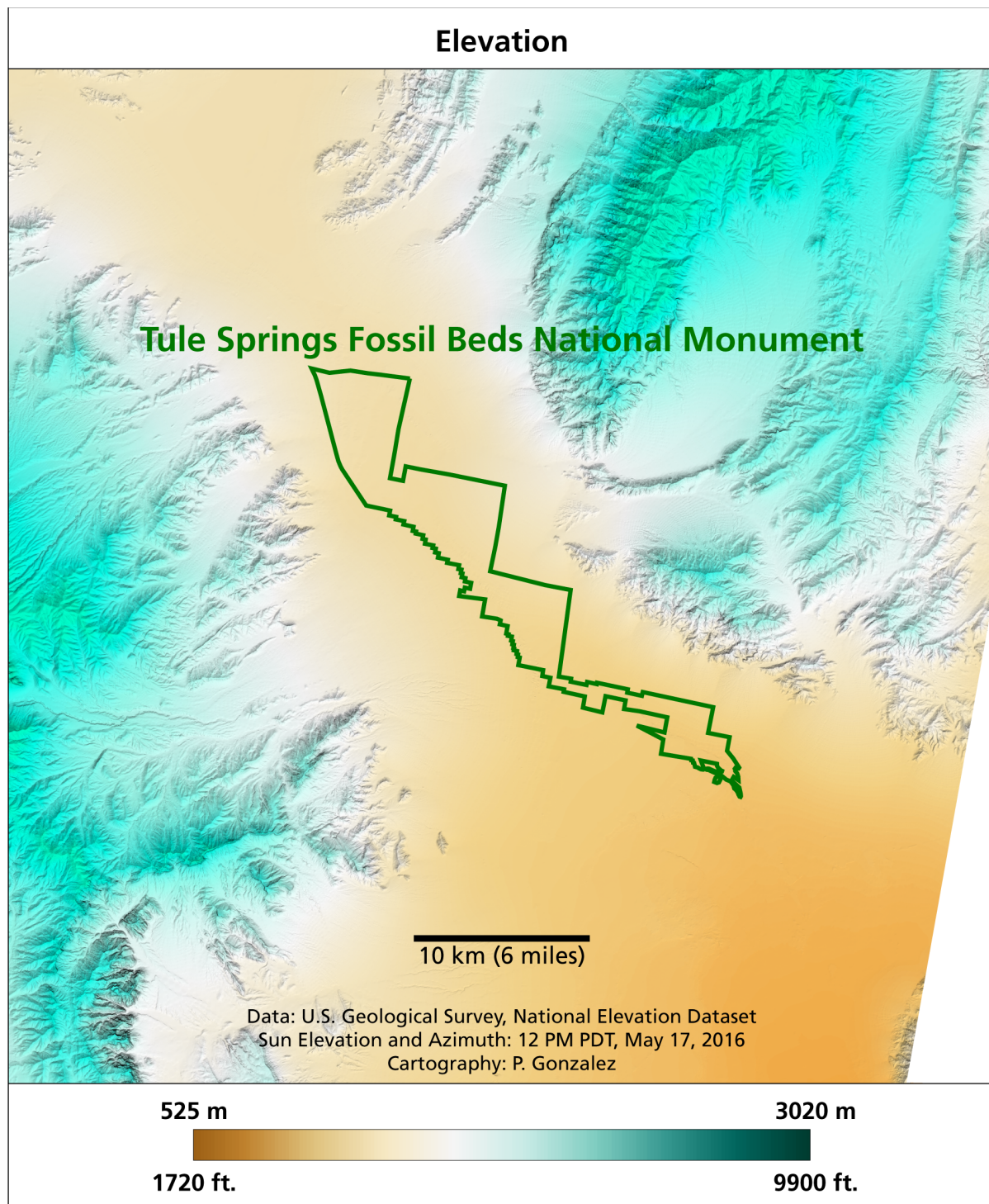
Note that the U.S. weather station network was more stable for the period starting 1950 than for the period starting 1895. (Data: National Oceanic and Atmospheric Administration, Daly et al. 2008. Analysis: Wang et al. in preparation, University of Wisconsin and U.S. National Park Service).

Figure 2.

Main conclusion: Precipitation increased at a statistically significant rate in the park.

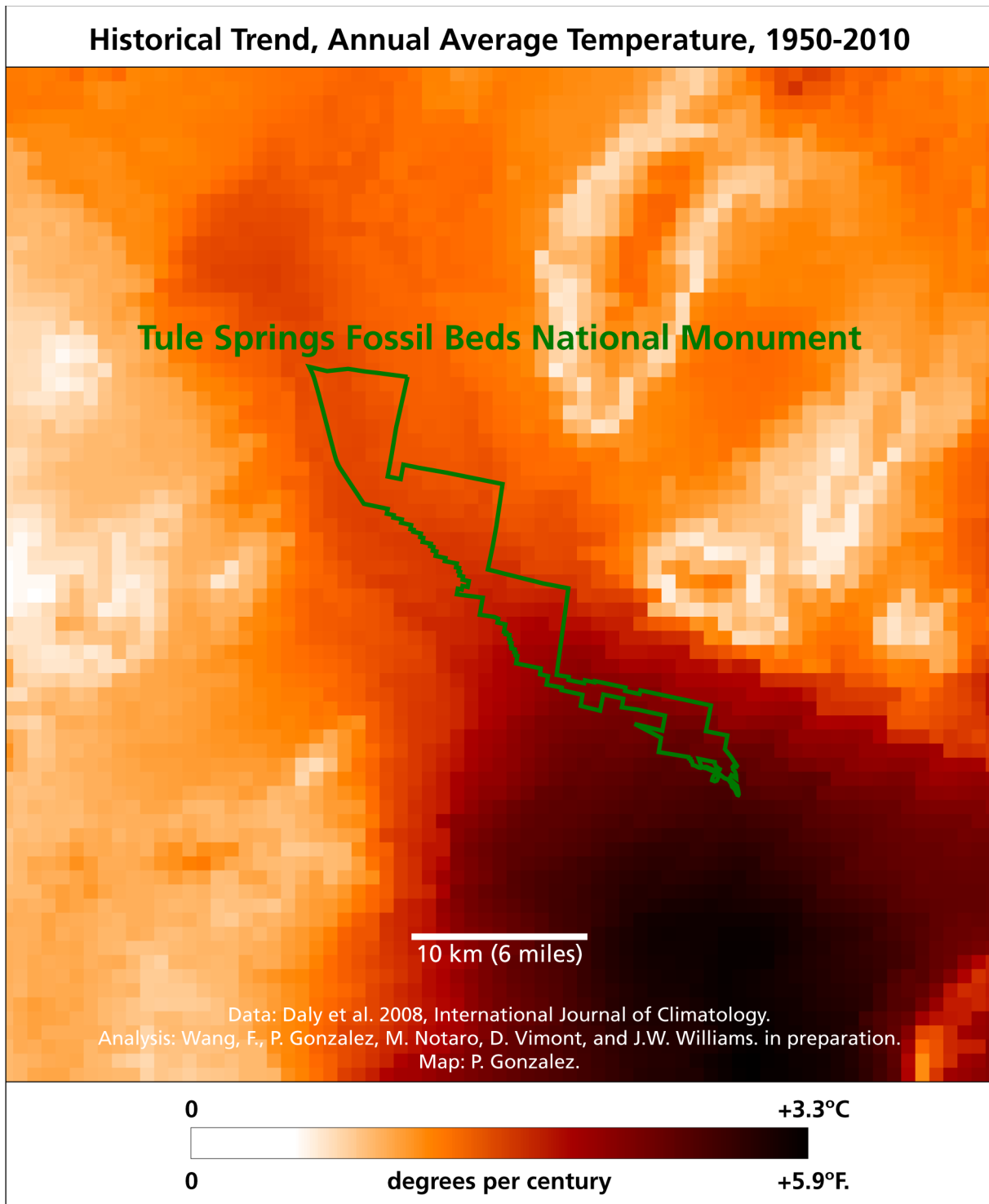
Note that the U.S. weather station network was more stable for the period starting 1950 than for the period starting 1895. (Data: National Oceanic and Atmospheric Administration, Daly et al. 2008. Analysis: Wang et al. in preparation, University of Wisconsin and U.S. National Park Service).

Figure 3.



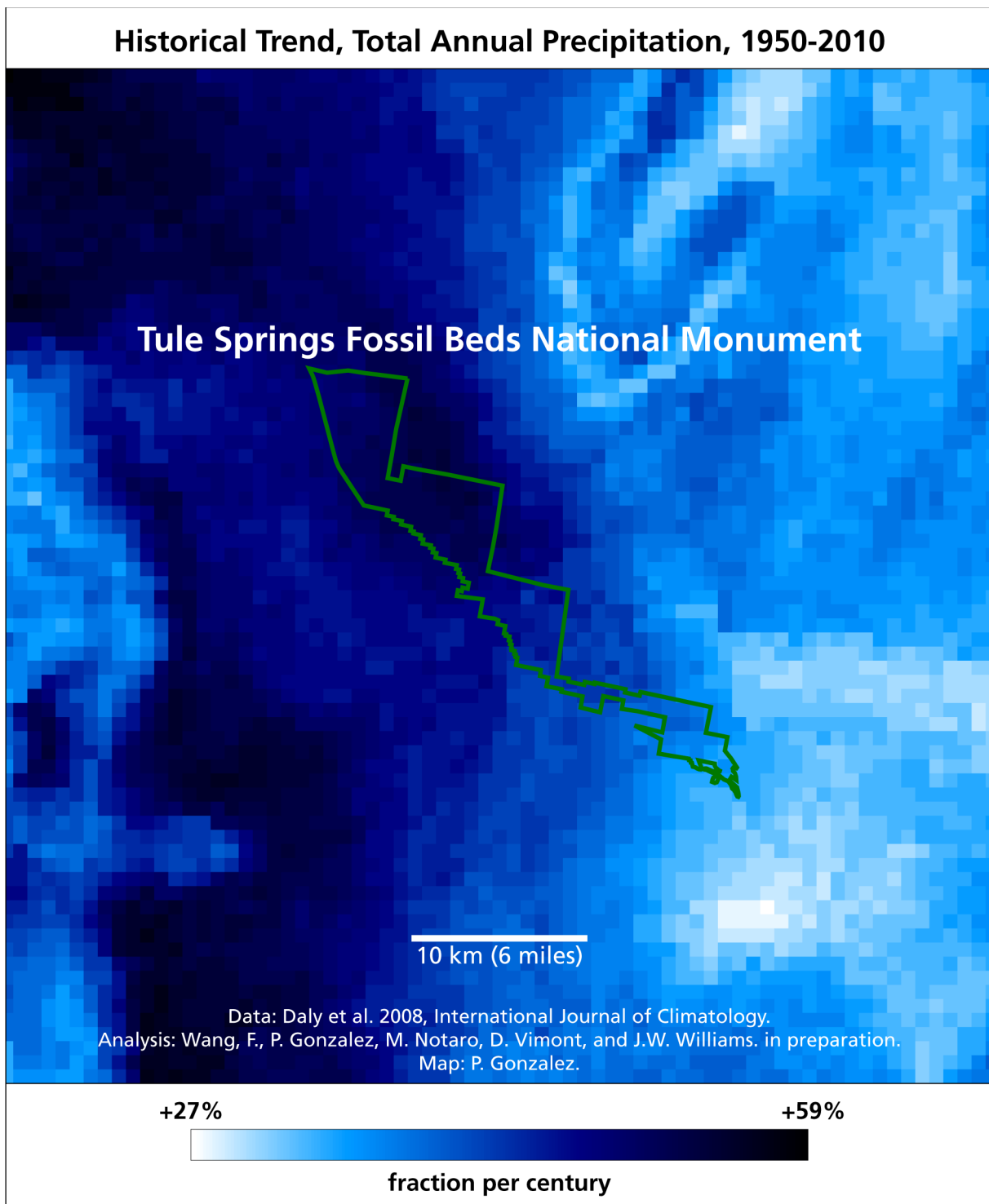
Main conclusion: Elevation in the park ranged from 640 m in the south to 1010 m in the north.

Figure 4.



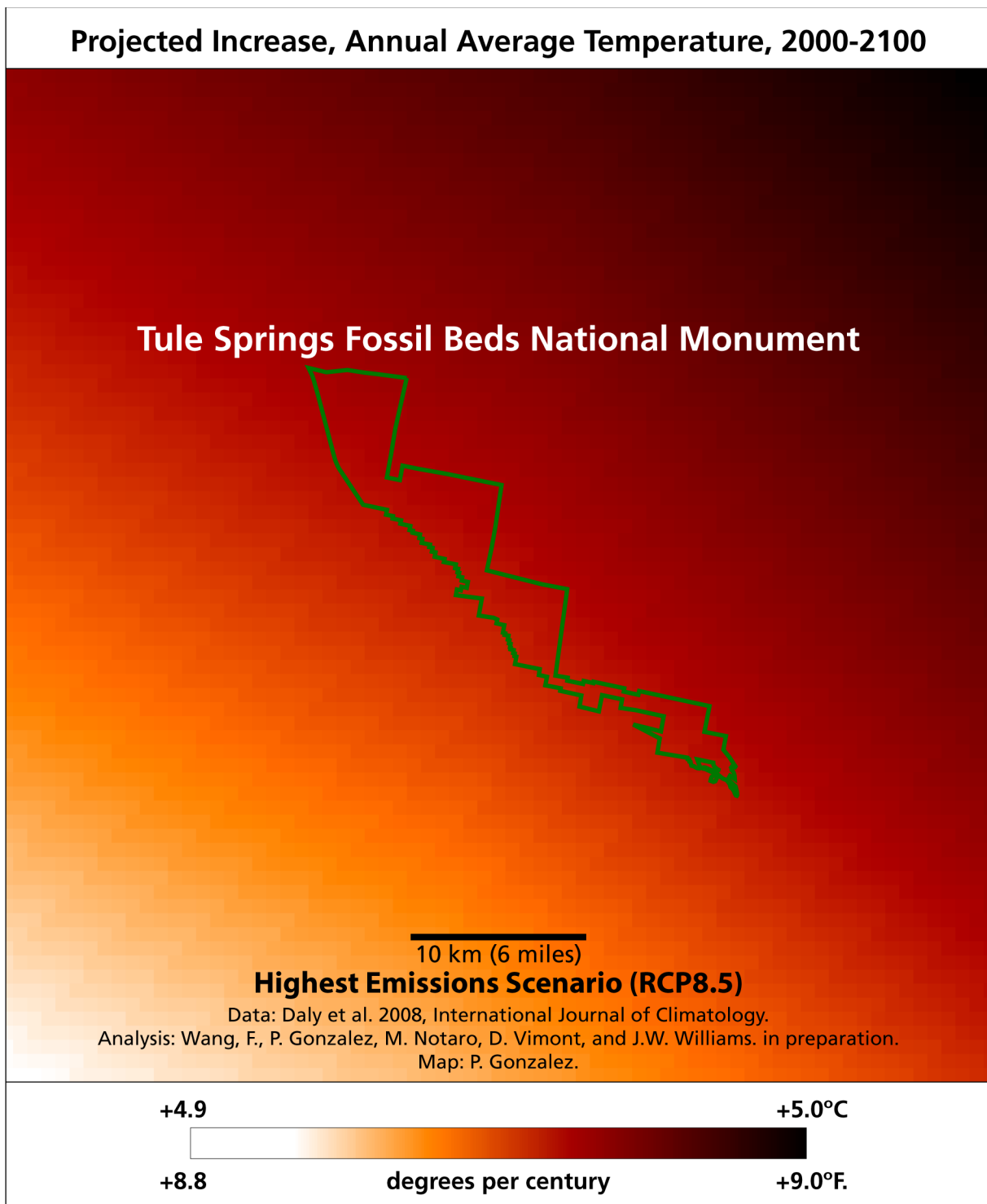
Main conclusion: Temperature increases are greatest in the southern end of the park.

Figure 5.



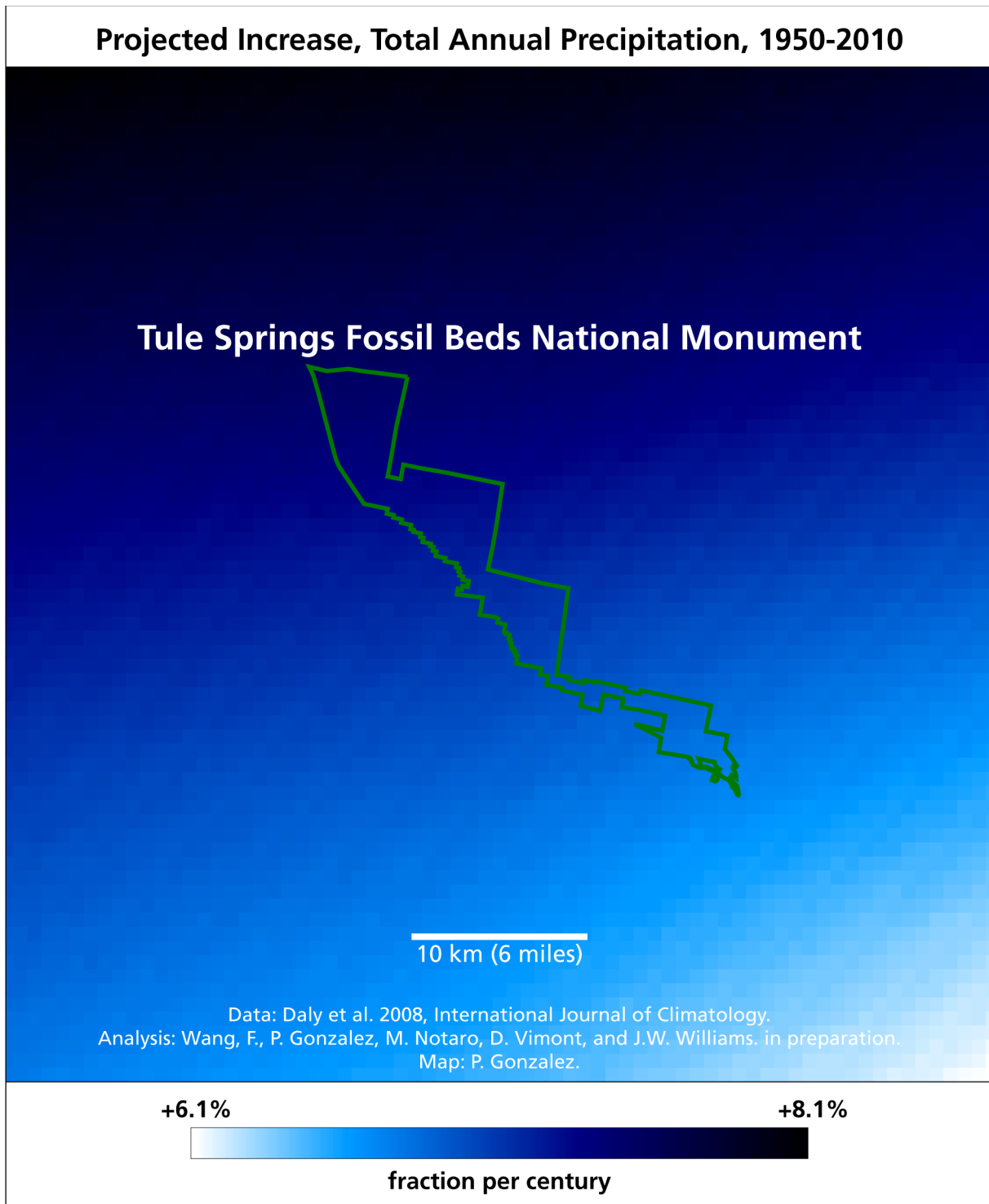
Main conclusion: Precipitation increases are greatest in the northern end of the park.

Figure 6.



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

Figure 7.



Main conclusion: Projected precipitation increases are slightly greater in the northern end of the park.

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