# Historic & Projected Climate Change in the Greater Yellowstone Ecosystem

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Evidence of the Earth's shifting climate patterns has become more perceptible from sea and surface temperature monitoring, satellite technology, and improvements in climate modeling. At a relevant human scale, these changes are highlighted by recent hurricane events, glacial retreat, and droughts at new, unprecedented frequencies and magnitudes that have begun to reshape the landscapes. Within the Greater Yellowstone Ecosystem (GYE), regional managers and citizens have already experienced major disturbance events that have changed the system's ecology, such as increased mountain pine beetle attacks, wildfire events, and reduced annual snowpack. The fifth annual Intergovernmental Panel for Climate Change (IPCC) report and the latest U.S. National Climate Assessment report a decadal global temperature increase of 1-1.2°F and a continuing upward trend.

From paleoclimate records of the GYE, changing climate has occurred before due to the natural variability of the Earth's position relative to the sun. The last major warm period occurred during the late Pleistocene and early Holocene (12,000-8,000 years ago), when the world saw the end of the last glacial maximum. The first major vegetation to move in was Engelmann spruce, followed by subalpine fir and whitebark pine, creating a widespread subalpine forest across the region. As conditions grew warmer and glaciers reached their minimum (9,500-7,500 years ago), the region became characterized by drier and warmer conditions than present day. At this period, lodgepole pine and Douglas-fir moved in from southern landscapes, pushing sub-alpine species to higher elevations (Whitlock and Bartlein 2004). Around 5,000 years ago, temperatures dropped and precipitation increased, converging towards the climate we recognize the GYE as having today.

## How Has Climate Changed Within the GYE?

The Greater Yellowstone Ecosystem is a complex and fascinating region to study climate. The GYE area encompasses approximately 58,000 square miles with an elevational gradient from 1,713–13,800 ft representing 14 mountain ranges. Due to the complex mountain topography and steep elevational gradients, weather is highly variable across the region, allowing events where specific mountain ranges can encounter snowfall in one area while another experiences warm, clear skies. The region is home to some of the longest running records of temperature and precipitation anywhere in the U.S., with some weather stations initiated in 1895! Interest in snow science and variability across these mountain landscapes led to the installation of 92 active SNOwpack TELemetry (SNOTEL) stations across the GYE region. SNOTEL stations are automated climate and snowpack sensors distributed across sites within the western U.S. and operated by the Natural Resource Conservation Service. These sites provide scientists with some of the highest density records of long-term weather data of anywhere in the U.S.

Although weather stations provide excellent information regarding their local site, scientists often need to know what the weather was like at higher elevation sites, in shaded valleys, or other places different from where the weather stations are established. We draw on two separate datasets called the Parameter-elevation Relationships on Independent Slopes Model (PRISM) (Daly 2002), and TopoWx ("Topography Weather") (Oyler et al. 2014) to characterize past climate for the GYE. PRISM and TopoWx use mathematical equations based on the relationship between weather to elevation, aspect, and other factors to estimate the temperature and precipitation that occurred in locations without weather stations. The result is a weather dataset of temperature and precipitation every month since 1895 (PRISM) and 1948 (TopoWx) for every 800m square (grid) in the continental U.S.  We use this data to calculate the mean annual temperatures and precipitation since the earliest available period in the GYE. Using these two gridded climate datasets, we are able to utilize their individual strengths and summarize climate for sub-areas of interest within the GYE.

Since 1948, annual temperatures across the GYE have averaged 37.4°F (figure 1) with an annual precipitation of 21.4 in/year (figure 2). Current trends indicate annual temperatures have increased by 0.31°F/decade, echoing the increasing temperature changes seen globally. Similarly, mean annual minimum and maximum temperatures have been increasing at the same rate of 0.3°F/decade for the GYE (table 1).

At a sub-regional level, we considered the temperature and precipitation averages and rates of change from 1948-2010, for the following areas (figure 3):

1. Yellowstone\Grand Teton National Park (YELL\GRTE)
2. Absaroka\Beartooth\N. Absaroka Wilderness Area (NA\ABT WA)
3. Washakie\Teton Wilderness Area (WA\TE WA)
4. Bridger\Fitzpatrick\Popo Agie Wilderness Area (BR\FI\PO WA)

Analysis at the sub-regional level reveal high variability across the entire GYE, with a general tendency for warming in the high elevation northern ranges of the Absaroka\Beartooth and Northern Absaroka wildernesses (0.39°F/decade) compared to the southern Wind River Range wildernesses (0.28°F/decade). Yellowstone and Grand Teton national parks as a whole followed a similar trend of warming to the entire GYE of ~0.3°F/decade (figure 4, table 1).

It should be noted that considering smaller areas of interest within the GYE possess more challenges. When we consider small regions, there is a reduction of actu-

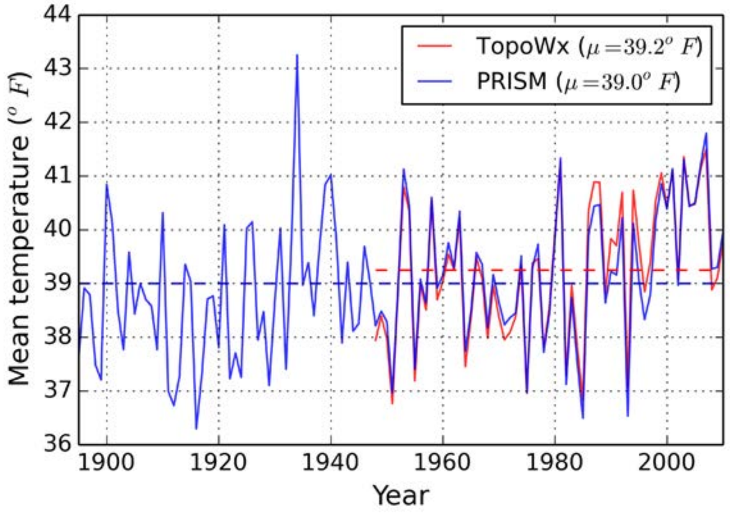

Figure 1. Mean annual temperatures averaged across the entire GYE for the past century. Dashed lines indicate the average since 1895-2010 (blue) and since 1948-2010 (red), using the PRISM and TopoWx gridded climate datasets respectively.

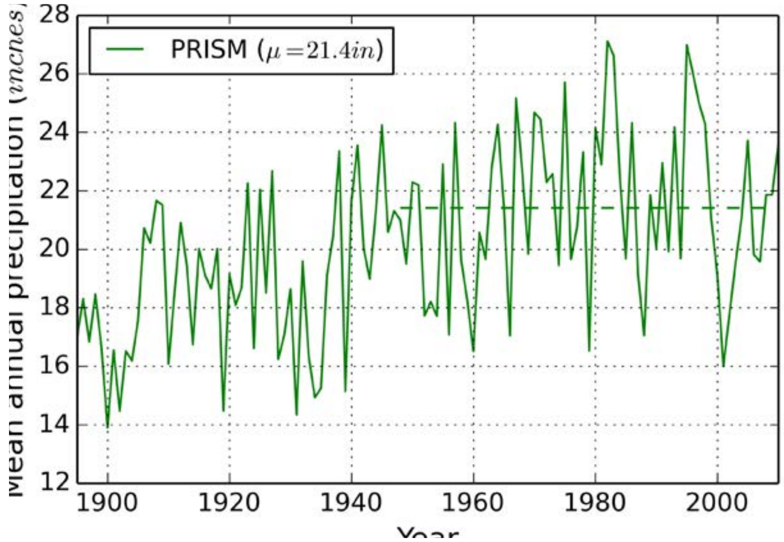

Figure 2. Mean annual precipitation averaged across the entire GYE for the past century. Dashed lines indicate the average since 1895-2010 using the PRISM gridded climate datasets. Dataset indicates a slight increase of precipitation over the past century at the rate of 0.4/in century.

Table 1. Summary of the regional and sub-regional mean climate conditions and median rates of change using the TopoWx dataset for temperature and PRISM dataset for precipitation 1948-2010.

| | GYE | YELL/GRTE | NA/ABT WA | WA/TE WA | BR/FI/PO WA |
|---|---|---|---|---|---|
| $T_{mean}$ average (°F) | 37.8 | 34.1 | 33.5 | 33.3 | 32 |
| $T_{max}$ average (°F) | 49.4 | 45.7 | 42.7 | 43.5 | 42.6 |
| $T_{min}$ average (°F) | 26.1 | 22.4 | 23.3 | 23.1 | 21.4 |
| $P_{pt}$ average (in) | 24.8 | 34.8 | 34.5 | 34.1 | 31.3 |
| | | | | | |
| $T_{mean}$ average (°F/decade) | | | | | |
| $P_{pt}$ average (in/decade) | | | | | |

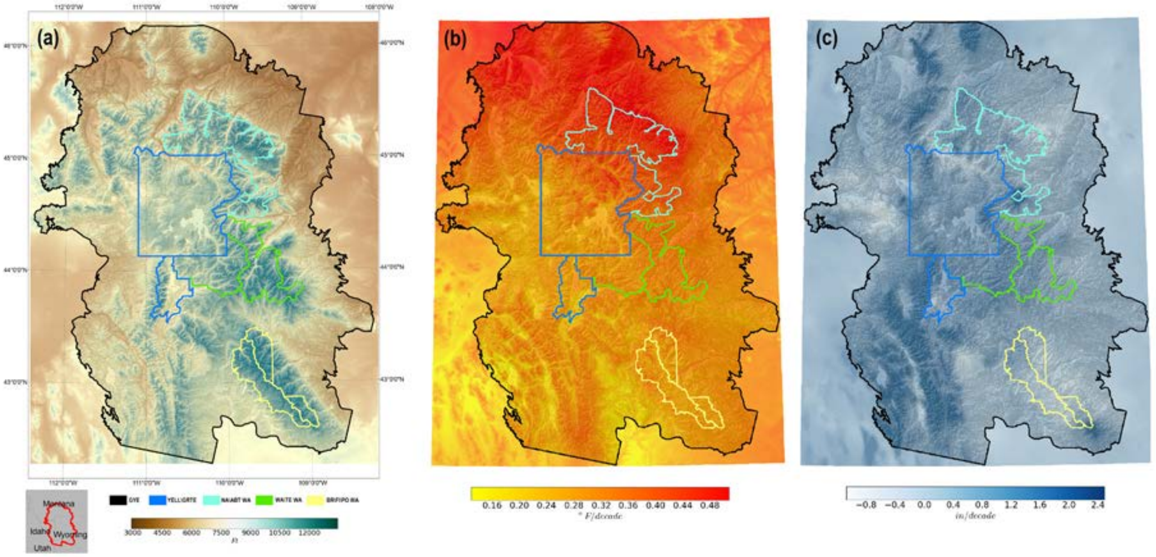

Figure 3. The Greater Yellowstone Ecosystem (58,186 square miles) and the surrounding wilderness and national park sub-regions for historic climate analysis. (a) illustrates the complex elevation gradient within the GYE region ranging from 1,713-13,800 ft. (b) TopoWx rate of change of mean annual temperatures between 1948-2010 within the GYE and sub-regions. (c) PRISM rate of change of mean annual precipitation between 1948-2010 within the GYE and sub-regions.

al stations from which the algorithms for TopoWx and PRISM can utilize to fill in the unknown areas, so there is increased uncertainty regarding sub-regional analyses, despite these datasets representing our best estimates of climate change. To overcome such uncertainty, local field observations from stream gauge and weather stations can verify some of the warming trends, and describe potential microsite conditions the ecological system may be responding to (Thoma et al., this issue).

One example of this is the observed temperature changes influencing stream flow and temperature over the past century. Stream discharge has declined during 1950-2010 in 89% of streams analyzed in the Central Rocky Mountains, including those in the GYE (Leppi et al. 2012). Reduced flows were most pronounced during the summer months, especially in the Yellowstone River. Stream temperatures have also changed across the range of the Yellowstone, observing a warming of 1.8°F over the past century (Al-Chokhachy et al. 2013). This stream warming during the 2000s exceeded that of the Great Dust Bowl of the 1930s and represents the greatest rate of change over the past century. Continued warming could have major implications to the management and preservation of the many aquatic resources we have today.

## The Projected Climate of the GYE

General circulation models (GCM), or global climate models, have been in development since the mid-1950s and are currently our best method of understanding and predicting the impacts of humans and natural variability on the Earth. Originally produced to computationally investigate weather patterns, rapid advances in computing allowed physics based modeling of atmospheric patterns on the entire Earth. As computer processing speeds increased, higher modeling resolution and increased levels of complexity were able to create models with the levels of sophistication that exist today. However, despite the differences of past and present GCM complexity, they all model the same underlying general principles of motion and laws of thermodynamics that have been understood for centuries.

Today, climate models simulate not only the atmosphere but also surface and deep ocean dynamics. When ocean and atmosphere models are linked together, we refer to the GCM as 'coupled,' which result in a more realistic simulation of our planet's climate. Determination of 'realism' for GCMs tend to be quantified in their ability to accurately predict the movement and evolution of disturbances, such as frontal systems and tropical cyclones. Common recognizable metrics include the ability to detect the El Nino Southern Oscillations and Pacific Decadal Oscillation. As more institutions began climate system modeling, questions regarding the impact of increased carbon emissions on temperature became prevalent. To address these questions, climate modelers generate scenarios of future potential atmospheric/ocean chemical compositions and investigate the impacts they have on the Earth's climate.

In 2013, the IPCC released the most recent projections of future climate under scenarios of greenhouse gas emissions (IPCC 2013). Some 46 global climate models were used to project climate under four representative concentration pathways (RCPs). RCPs are designed to characterize feasible alternative futures of the climate considering physical, demographic, economic, and social changes to the environment and atmosphere. Here we report results from two models for an analysis of the GYE: RCP 4.5, which assumes stabilization in atmospheric CO2 concentration at 560 ppm by 2100; and RCP 8.5, which assumes increases in atmospheric CO2 concentration to 1370 ppm by 2100. Actual measured rates of greenhouse gas emissions since 2000 have been consistent with the RCP 8.5 scenario (Diffenbaugh and Field 2013, Rogelj et al. 2012). Thrasher et al. (2013) downscaled these GCM outputs to an 800-m pixel size so regional level analysis could be possible. For this GYE summary, we referenced the Rupp et al. (2013) analysis of GCMs that best represents the Pacific Northwest region.

Within the GYE, mean annual temperature is projected to rise under each of the climate scenarios. By 2100, temperature is projected to increase 2-8°F above the average for the reference period of 1900-2010 (figure 5a). Mean annual precipitation is projected to vary between -2.0 to +8.9 inches by 2100 (figure 5b). While temperature is projected to rise at similar rates across seasons, precipitation increases most rapidly in spring and decreases slightly in summer. Changes in aridity are projected to increase moderately under RCP 4.5 and more substantially under RCP 8.5. This suggests the current climate changing pattern we have experienced for the last 30 years will likely continue and become more severe.

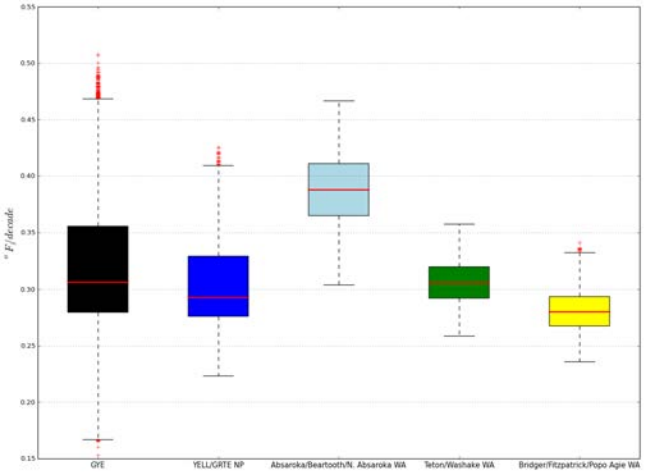

Figure 4. Box and whisker plots of warming trends across the GYE and 4 sub-regions. Northern range wilderness areas depict the greatest level of warming over 1948-2010 compared to the southern wilderness areas of the Wind River range.

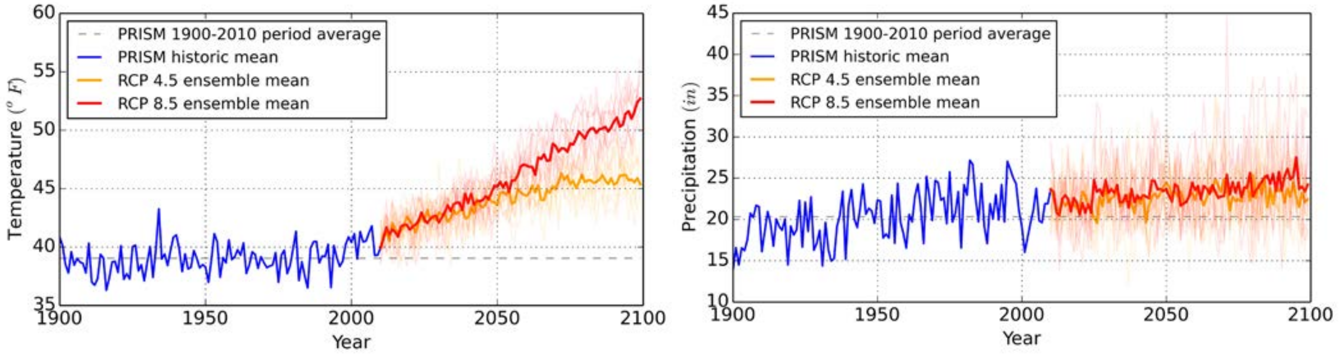

Figure 5a & 5b. Projections of CMIP5 GCM ensembles from 2010-2099 (a) mean annual temperatures and (b) mean annual precipitation anomaly from long-term average.

## Current & Projected Impacts on Ecosystems

A consequence of warming during the winter and spring months and seasonally high summer aridity has been an outbreak of forest pests causing forest die-off. Mild winter temperatures in alpine regions have been found to directly relate to the survivorship of overwintering broods of mountain pine beetle, the major disturbance agent acting on whitebark pine species (Logan and Powell 2001, Logan et al. 2010). Arid summers (high temperatures, low precipitation) likely provide a compounding effect of increasing pine beetle development rates and increasing resource stress on whitebark pine. This reduction in mortality of overwintering broods, increased development rates, and reduced tree defense can result in an expansion of the dispersal and colonization effectiveness of insect pests.

Since 1999, an eruption of mountain pine beetle events has been observed that exceed the frequencies, impacts, and ranges documented during the last 125 years (Macfarlane et al. 2013, Raffa et al. 2008). Aerial assessment of whitebark pine species populations within the GYE has indicated a 79% mortality rate of mature trees. These dramatic changes may be the first indicators of how GYE vegetation communities are to shift due to changed climate patterns.

Projected changes in climate are expected to continue to influence ecosystem processes, such as soil moisture, runoff in streams and rivers, and terrestrial net primary productivity through shifts in vegetative communities. The projected warming results in April 1 snowpack declining 3.2-4.3 inches by 2100. The reduction in snowpack is most pronounced in spring and summer, with the GYE projected to be largely snow free on April 1, by 2075 under RCP 8.5. Average annual soil water projections show considerable inter-annual variability, but have a shallow positive trend, increasing about 0.4 inches by 2100 with increases mostly in spring and a slight decline in summer. Mean annual runoff increases more rapidly, with pronounced increases in spring and decreases in summer. The projected pattern for gross primary productivity also increases annually in spring and decreases in summer.

Stream temperatures are projected to increase between 1.4-3.2°F by 2050 to 2069 (Al-Chokhachy et al. 2013). Yellowstone cutthroat trout are projected to decline by 26% in response to this temperature increase due to its positive influence on non-native species (Wegner et al 2011). In uplands, warming temperatures are projected to result in severe wildfires becoming more common within the GYE (Westerling et al. 2011), which could result in major changes in vegetation type and seral stage.

One way to gauge potential effects of projected climate change on vegetation is to determine the climate conditions within which a vegetation type currently occurs and map locations projected to be within this range of climate conditions in the future. While dispersal limitations, competition from other species, disturbances, etc., may prevent vegetation from establishing in areas with newly suitable climates, this method is a meaningful way to interpret climate from a vegetation perspective. Piekielek et al. (in preparation) projected suitable climatic conditions to decrease for the subalpine conifer forest and alpine tundra biome types and increase largely for Great Basin montane scrub biome type and slightly increase for montane conifers such as Douglas-fir (see Hansen et al., this issue). If vegetation changed in parallel with these climates, these results suggest snowpack, runoff, and net primary productivity would be substantially reduced.

## A New Status Quo

These results indicate climate has and will continue to change substantially. Our summary of projected climate suggests the future will experience temperatures higher than any time in the warm periods of the Holocene. This rapid temperature change can result in substantial reductions in snowpack and stream runoff and increases in stream temperature, fire frequency, and mortality of currently dominant tree species. One possible future is for the system to move into a new state with little summer snow, very low stream flows, frequent and severe fire, and switch from forest-dominated vegetation to desert scrub vegetation. Such changes will challenge resource managers in the effort to ensure the health and integrity of this complex natural system while still providing the recreational experiences the public has come to expect. Strategies for adaptation and mitigation in natural resource management should be considered given the magnitude of potential future ecosystem impacts.

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