Over the next century, public lands across the US are expected to undergo climate change associated with natural variability and human-induced greenhouse gas emissions. The Greater Yellowstone Ecosystem (GYE), centered on Yellowstone and Grand Teton National Parks, is a large, wildland system with varied mountain and high plains landforms. Climate is known to be naturally variable in the GYE, both across the landscape and among years. Despite this natural variability, resource managers have a sense that climate here is warming and drying. The objective of this resource brief is to summarize the nature of climate change across GYE over the past century and projected for the coming century and potential ecological consequences.

This resource brief is one product of our Landscape Climate Change Vulnerability Project (LCCVP), which is aimed at helping to facilitate climate adaptation planning on federal lands through the use of NASA data and products (see http://www.montana.edu/lccvp/). The LCCVP is assessing the vulnerability of terrestrial landscapes in two USDI Landscape Conservation Cooperatives (Appalachian and Great Northern) to climate and land use change, with an emphasis on lands managed by the National Park Service. Our approach uses data from the past and future projections of climate and land use change to explore possible ecosystem and species level responses to those changes and the implications for management of high priority park resources. The climate change information in this resource brief is meant to both inform resource managers of past and projected climate change for the period 1900-2100 and serve as input to our models to forecast ecological response.

We draw on 800-m PRISM data (Daly 2002) to characterize past climate for a bounding box centered in the GYE. This approach uses data from meteorological stations as input and interpolates between these stations based on topography and other factors. The Intergovernmental Panel on Climate Change (IPCC) released in 2013 the most recent projections of future climate under scenarios of greenhouse gas emissions (CMIP5) (IPCC WGI ARG 2013). Some 17 global climate models were used to project climate under four so-called 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/atmosphere. We report here results for RCP 4.5 which assumes stabilization in atmospheric CO$_2$ concentration at 560 ppm by 2100, 6.0 which models a rise of CO$_2$ concentration to 740 ppm by 2100, and RCP 8.5 which assumes increases in atmospheric CO$_2$ concentration to 1370 ppm by 2100. Actual measured rates of greenhouse gas emissions since 2000 have been consistent with the RCP 8.5 scenario (Rogelj et al 2012, Diffenbaugh and Field 2013). Thatcher et al. (2013) downscaled these GCM outputs to an 800-m grain size and we present the average projections (termed “ensemble average” or ea) of the GCMs. We additionally report projections of ecosystem processes under future climate and land use which were derived from the NASA Terrestrial Observation and Prediction System (Nemani et al. 2009). These predictions were done within the GYE Protected Area Centered Ecosystem (PACE) (Hansen et al. 2011), which is somewhat smaller in area than the traditional GYE boundary.
How has Climate Changed over the Past Century?

Mean annual temperature has increased 1.1 °F / 100 years since 1900. Mean annual minimum temperatures, which indicate nighttime conditions, have increased more rapidly (1.5 °F / 100 years) than mean annual maximum temperatures (0.7 °F / 100 years), which indicate daytime conditions (Fig. 1). The GYE is subject to multiple-year periods of warm and dryer conditions versus cooler dryer periods, as can be seen in Figure 1. These cycles have been associated with a natural ocean dynamic termed Pacific Decadal Oscillation, which has been in place for centuries. Human induced climatic warming is thought to be occurring on top of the PDO cycles, thus the increasing temperature trend since 1900. Rates of increase have been particularly pronounced since 1980. In fact, the rise in minimum temperatures in the last decade exceeds those of the 1930’s Dust Bowl Era. Mean annual maximum temperatures have not exceed the historically recorded highs. This suggests that the major temperature changes that have occurred are primarily due to minimum temperature rises. Changes in temperature vary seasonally. $T_{min}$ increased in all seasons, most rapidly in Summer and Spring, and less rapidly in Fall. $T_{max}$ increased most rapidly in winter and spring but experienced little change in fall.

Precipitation has increased slightly since 1900 with a 9.3 mm / century increase (Fig. 2). Drier than average years predominated prior to about 1940 and wetter than average years since then. However these changes in precipitation are very small relative to the long-term average of about 800 mm / year.

The effect of precipitation on water availability in an ecosystem is balanced by loss of moisture to the atmosphere from evaporation and transpiration. The ratio of loss to potential evapotranspiration (PET) to the input from precipitation is a measure of aridity of the system. A plot of the aridity index for GYA reveals that aridity declined during 1900 to about 1977 and then began to increase (Fig. 3). This suggests that in the last twenty five years, increases in precipitation have not be adequate to offset increases in PET that resulted from increases in temperature. Thus, the ecosystem has been becoming slightly more arid during this time since 1977.

The significant increase in minimum temperatures in the recent decades has also had an observable impact on snowpack. A reconstruction of April 1 snow water equivalent (SWE) for the period
1200-2000 (Pederson et al. 2011) found that current SWE across GYA is ~20% lower than the long term average and 1900-2000 is the longest period of below average snowpack in the past 800 years (Fig. 4). During the past century, snowpack was particularly low during the 1930s and 1990s.

These average trends in climate across the GYE mask the substantially spatial variation in rates of climate change. Spatial analysis suggests that high elevations may have experienced the greatest temperature warming, while lower elevations are receiving no change or a slight reduction in precipitation (Fig. 5).

Changes in temperature over the past century have also influenced stream flow and temperature. 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) (Figure 6). Reduced flows were most pronounced during the summer months as illustrated by data from the Yellowstone River (Figure 7). Stream temperature across the range of the Yellowstone cutthroat trout, which includes the GYE, have warmed by 1 °C over the past century (Al-Chokhachy et al. 2013). Stream warming during the decade of the 2000s exceeded that of the Great Dustbowl of the 1930s and represents the the greatest rate of change over the past century.

What have been the Ecological Consequences of Past Climate Change?

To summarize, the major changes in climate across the GYA since 1900 are a substantially increase in temperature, especially annual minimum temperatures in spring and summer. An important consequence of this warming has been a reduction in spring snowpack, with April 1 SWE during the 1990s the lowest in 800 years. This reduced snowpack has resulted in lower soil moisture in uplands, warmer stream temperatures, and reduced stream runoff, especially in summer.

One consequence of warming during the winter and spring months has been an outbreak of forest pests and forest dieoff. 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 et al. 2010, Logan and Powell 2009). This reduction in mortality of overwintering broods 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 exceeds the frequencies, impacts, and ranges documented during the last 125 years (Raffa et al. 2008, Macfarlane et al. 2013). Aerial assessment of whitebark pine species population within the GYE have indicated a 79% mortality rate. These dramatic changes may be the first indicators of how sensitive the vegetation communities in Greater Yellowstone are to shifts in climate patterns.

How is Climate Projected to Change in the Next Century?

Within the GYE PACE, mean annual temperature is projected to rise under each of the climate scenarios. By 2100, temperature is projected to increase from 2.7 °C (RCP 4.5) to 5.7 °C (RCP 8.5) above the average for the reference period of 1980-2005 (Fig. 8a). Mean
annual precipitation is projected to increase by 55 to 125 mm by 2100 (Fig. 8b). While temperature is projected to rise at similar rates across seasons, increases in precipitation are most rapidly in spring and decrease slightly in summer (Fig. 9). The projected warming results in projected snow pack on April declining by 80-110 mm by 2100 (Fig. 10a). The reduction in snow pack is most pronounced in spring and summer, with GYE projected to be largely snow free by 2075 under RCP 8.5.

What are the Projected Impacts on Ecosystems?

These projected changes in climate are expected to influence ecosystem processes such as soil moisture, runoff in streams and rivers, and primary productivity. Average annual soil water projections show considerable interannual variability but have shallow positive trend, increasing about 10 mm by 2100 with increases mostly in spring and a slight decline in summer (Fig. 10b). Mean annual runoff increases more rapidly, with pronounced increases in spring and decreases in summer. The projected pattern for gross primary productivity similarly increases annually and in spring and decreases in summer (Fig. 10c). Stream temperatures are projected to increase by 0.8 to 1.8 °C by 2050-2069 (Al-Chokhachy et al. 2013). Yellowstone cutthroat trout growth rates are projected to increase at high-elevation sites in the future, but decline by 23% between June and August at low-elevation sites. 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 the potential effects of projected climate change on vegetation is to determine the climate conditions within which a vegetation type currently occurs and map the locations that are projected to be within this range of climate conditions in the future. While dispersal limitations and other factors may prevent vegetation from establishing in areas with newly suitable climates, this methods is a meaningful way to interpret climate from the vegetation perspective. Rehfeldt et al.
(2012) projected suitable climactic conditions for biome types across North America. Plotting their results within the GYE, we found that land area with suitable climate was projected to decrease for the subalpine conifer forest and alpine tundra biome types and increase largely for Great Basin Montane Scrub biome type (Fig. 11). This suggests that climate conditions which currently support conifer forests may be replaced with climate conditions that are suitable for the desert scrub vegetation types now found in central Wyoming. If vegetation changed in parallel with these climates, these results suggest that snow pack, runoff, and primary productivity would be substantially reduced.

In summary, this climate brief indicates that climate is and will continue to change substantially during the 200 years from 1900-2100 (Fig. 12). This period began at the close of the Little Ice age, one of the coldest periods since deglaciation and is projected to end with temperatures has high as at any time in the warm periods of the Holocene. This rapid change in temperature has resulted in substantial reductions in snowpack and stream runoff and increases in stream temperature, fire frequency, and mortality of

![Figure 10. Greater Yellowstone PACE regional water balance summaries for (a) the seasonal April 1 snow water equivalent, (b) soil water, and (c) stream runoff projected by the TOPS model for the ensemble average of global climate models for the coming century under three IPCC representative concentration pathways.](image)

![Figure 11. Projected change in the area with climate suitable for biome types within the GYE.](image)
whitebark pine trees. Projections for the coming century suggest that these trends will continue and intensify and that thresholds may be reached where the GYE moves to a new state with little summer snow, very low stream flows, frequent and severe fire, and a switch from forest-dominated vegetation to desert scrub vegetation. Such changes will sorely tax resource managers. Strategies for adaptation and mitigation in natural resource management should be considered given the magnitude of potential future ecosystem impacts.

Literature Cited


Chang et al. 2013. In prep.


Thatcher et al. 2013. EOS.