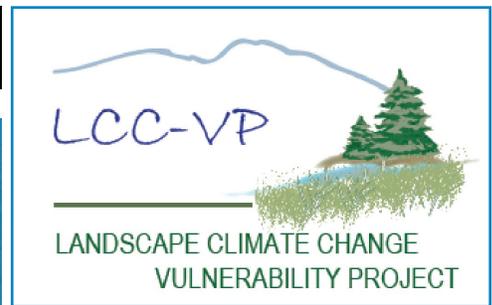


Greater Yellowstone Ecosystem

Tony Chang and Andrew J. Hansen



Introduction

Over the next century, public lands across the U.S. are expected to undergo climate change due to natural variability and human-induced greenhouse gas emissions. The Greater Yellowstone Ecosystem (GYE), the region including Yellowstone and Grand Teton national parks, is a large, wildland system with varied mountains and high plains (Figure 1). 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 the climate here is warming and drying. This resource brief summarizes the nature of climate change across the GYE over the past century and identifies projected trends for the coming century, including potential ecological consequences.

Climate Change over the Past Century

We draw on a data set called PRISM (Daly 2002) to characterize past climate for the GYE. PRISM uses data from meteorological stations as input and interpolates between these stations based on topography and other factors. 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. The GYE is subject to multiple-year periods

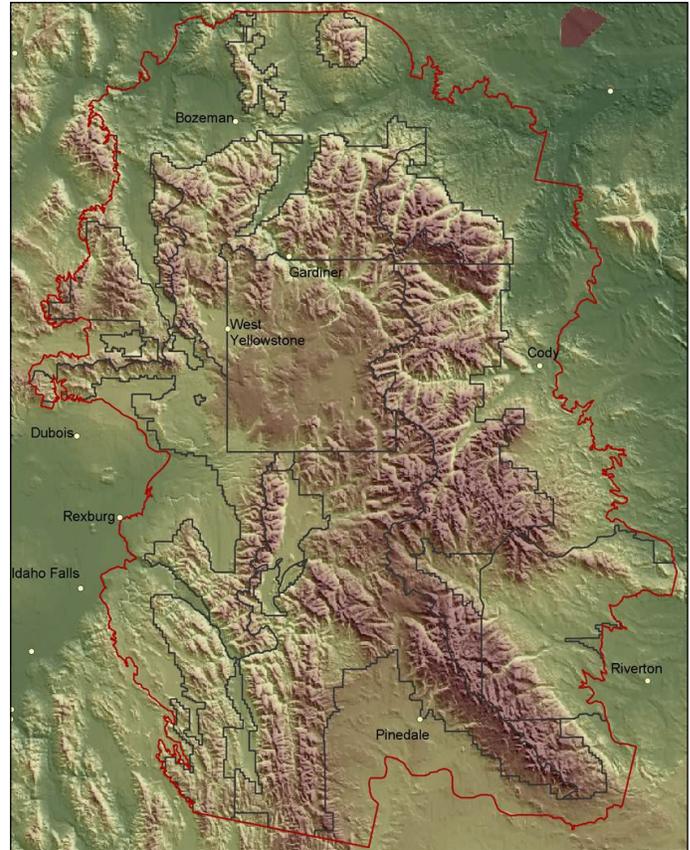


Figure 1. Map of the Greater Yellowstone Ecosystem depicting elevation (color gradient), federal lands (black lines), the boundary of the GYE (red line), and cities.

Fast Facts

- Temperature has increased about 1°F in the past century, primarily due to rises (1.5°F) in minimum temperatures in spring and summer and reduced winter extreme cold.
- Precipitation has increased slightly in the last three decades, but not enough to offset temperatures, thus aridity has increased.
- Snow pack has declined over the past 50 years and is now at about 20% of the 800-year average.
- Stream discharge has been declining since 1950, and stream temperatures warming.
- Changes in climate have favored insect outbreaks resulting in high levels of conifer forest die-off.
- Temperature is projected to rise 3.0-7.0°C in the coming century, and the GYE is projected to be largely snow free on April 1 by 2075 under the highest emission scenario.
- The projected warming is associated with increased fire frequency and severity, a shift from forest- to shrub-dominated vegetation, and reduced cold-water fish growth rates.

About the Landscape Climate Change Vulnerability Project

This brief is one product of our Landscape Climate Change Vulnerability Project (LCCVP), which facilitates climate adaptation planning on federal lands through the use of National Aeronautics and Space Administration (NASA) data and products (see <http://www.montana.edu/lccvp/>). The LCCVP is assessing the vulnerability of terrestrial landscapes to climate and land use change in the Appalachian and Great Northern Landscape Conservation Cooperatives (LCCs), 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 brief is meant to inform resource managers of past change, describe projected climate change for the period 1900–2100, and discuss ecological changes that may result.

of warmer and dryer conditions versus cooler and dryer periods, as can be seen in Figure 2. These cycles have been associated with a natural ocean dynamic termed Pacific Decadal Oscillation (PDO), which has been in place for centuries. Human-induced climatic warming is thought to be occurring on top of the PDO cycles, possibly accounting for 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 1930s Dust Bowl Era; although mean annual maximum temperatures (T_{\max}) have not exceeded the historically recorded highs. This suggests that the major temperature changes that have occurred are primarily due to minimum temperature (T_{\min}) rises. One manifestation of change in minimum temperatures is less extreme winter cold periods. Very cold winter monthly temperatures ($<0^{\circ}\text{F}$) occurred about every six years prior to 1993, and have not occurred since then.

Changes in temperature vary seasonally. T_{\min} increased in all seasons, most rapidly in summer and spring, and less rapidly in the 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 (Figure 3). 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 is balanced by loss of moisture from evaporation and transpiration. The ratio of loss to potential evapotranspiration (PET) to

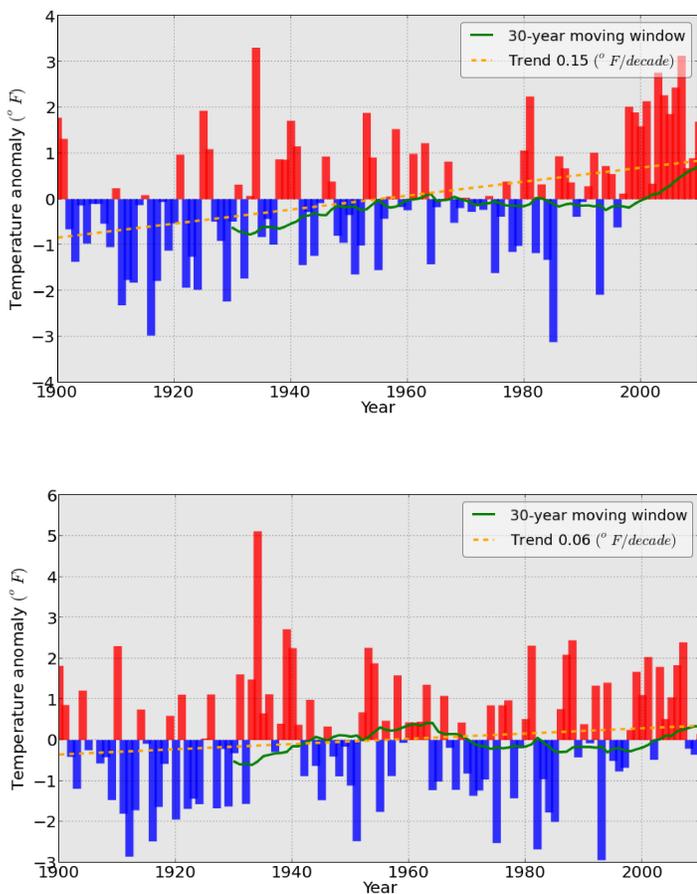


Figure 2. Temperature anomaly within GYE during 1900–2010 for minimum annual temperature (top) and maximum annual temperature (bottom). Red indicates temperatures above the 110-year average and blue below the average. The green line is a 30-year moving average.

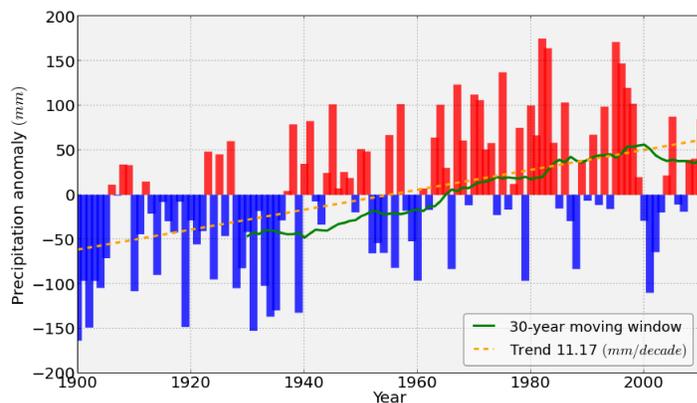


Figure 3. Precipitation anomaly within GYE during 1900–2010.

the input from precipitation is a measure of aridity of the system. A plot of the aridity index for the GYE reveals that aridity declined during the period between 1900 and 1977 and then began to increase (Figure 4). 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, and has resulted in the ecosystem becoming slightly more arid 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 the GYE is ~20% lower than

the long-term average; and the century between 1900 and 2000 is the longest period of below-average snowpack in the past 800 years (Figure 5). During the past century, snowpack was particularly low during the 1930s and 1990s.

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

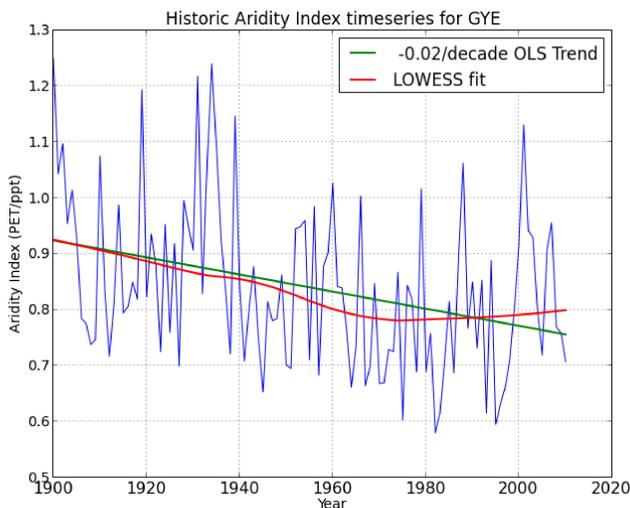


Figure 4. Aridity index (PET/PPT) for the GYE for the period 1900-2010. The green line shows the long-term trend, and the red line is a LOWESS smoother, which indicates an inflection point at the year 1977.

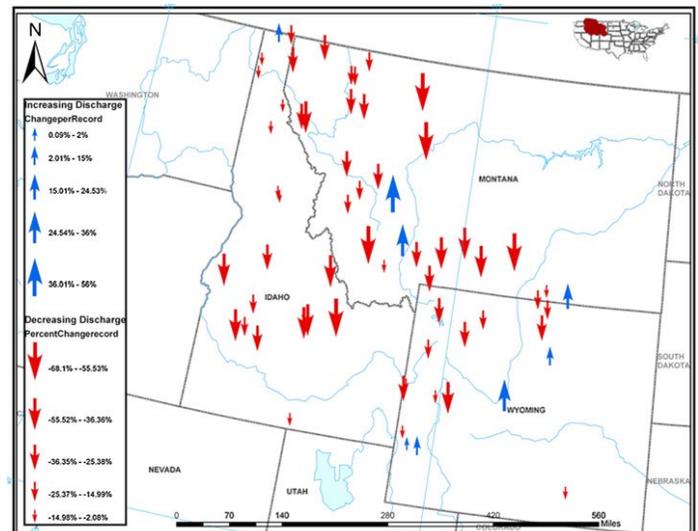


Figure 6. Amount and type of normalized stream discharge change across the Central Rockies. The downward-pointing red arrows signify a decreasing slope and the upward-pointing blue arrows signify an increasing slope. The larger the arrow, the larger the discharge change at each gauging station (from Leppi et al. 2012).

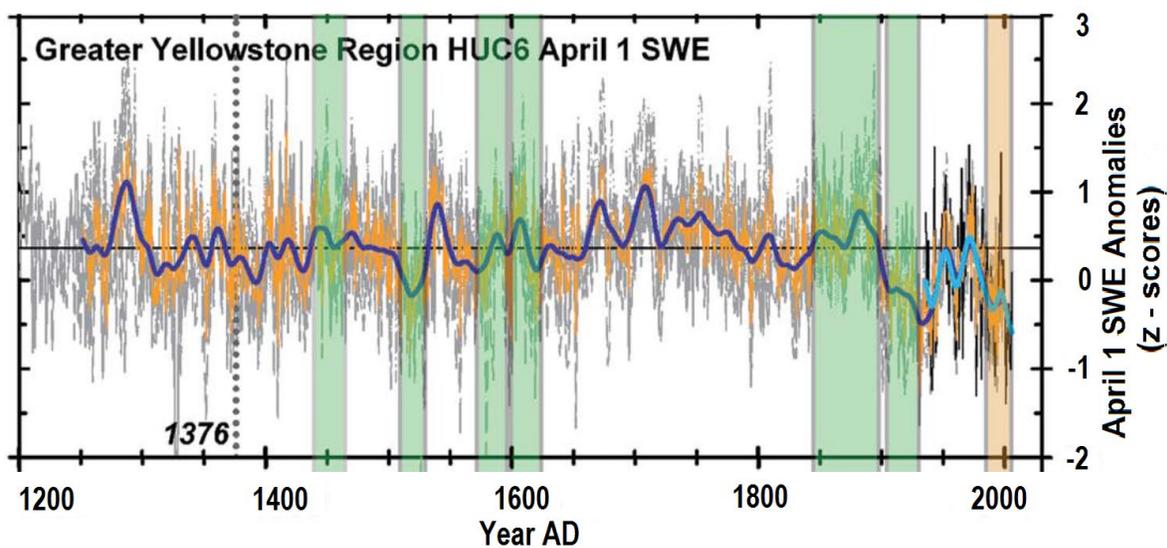


Figure 5. April 1 snowwater equivalent (SWE) anomaly for the Greater Yellowstone Ecosystem. The base period for estimating the anomaly was 1400-1950. The dark blue line indicates the 20-year regional SWE average. The light blue line indicates the 20-year spline of observed records. Shaded intervals indicate decadal-scale SWE anomalies (from Pederson et al. 2011).

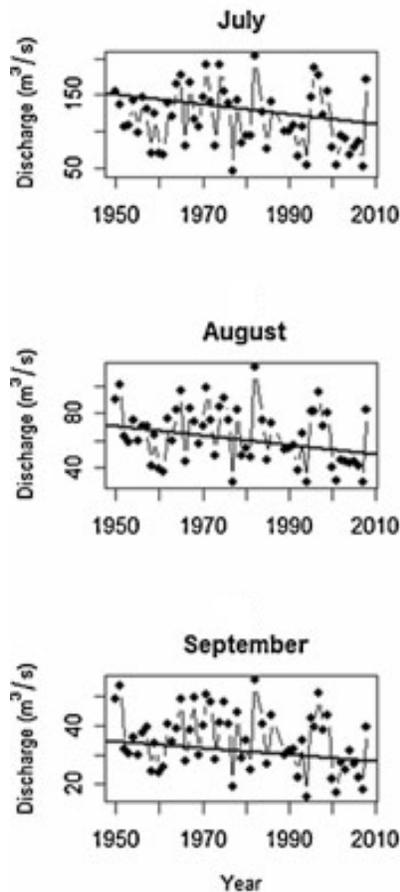


Figure 7. Discharge in the Yellowstone River during the months of July, August, and September for the years 1950–2010 (from Leppi et al. 2012).

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 greatest rate of change over the past century.

Ecological Consequences of Past Climate Change

The major changes in climate across the GYE since 1900 are a substantial 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 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 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 populations within the GYE has indicated a 79% mortality rate of mature trees. These dramatic changes may be the first indicators of how sensitive the vegetation communities in the GYE are to shifts in climate patterns.

Projected Climate Change in the Next Century

In 2013, the Intergovernmental Panel on Climate Change (IPCC) released 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 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 for RCP 4.5, which assumes stabilization in atmospheric CO₂ concentration at 560 ppm by 2100; RCP 6.0, which models a rise of CO₂ concentration to 740 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 (Rogelj et al. 2012, Diffenbaugh and Field 2013). Thrasher et al. (2013) downscaled these general circulation model (GCM) outputs to an 800-m grain size and we present the average projections (termed “ensemble average” or ea) of the GCMs. Additionally, we 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.

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 3.0°C (RCP 4.5) to 7.0°C (RCP 8.5) above the average for the reference period of 1980–2005 (Figure 8A). Mean annual precipitation is projected to increase by 55 to 125 mm by 2100 (Figure 8B). While temperature is projected to rise at similar rates across seasons, precipitation increases most rapidly in spring and decrease slightly in summer (Figure 9). Aridity index is projected to increase moderately under RCP 4.5 and more substantially under RCP 8.5.

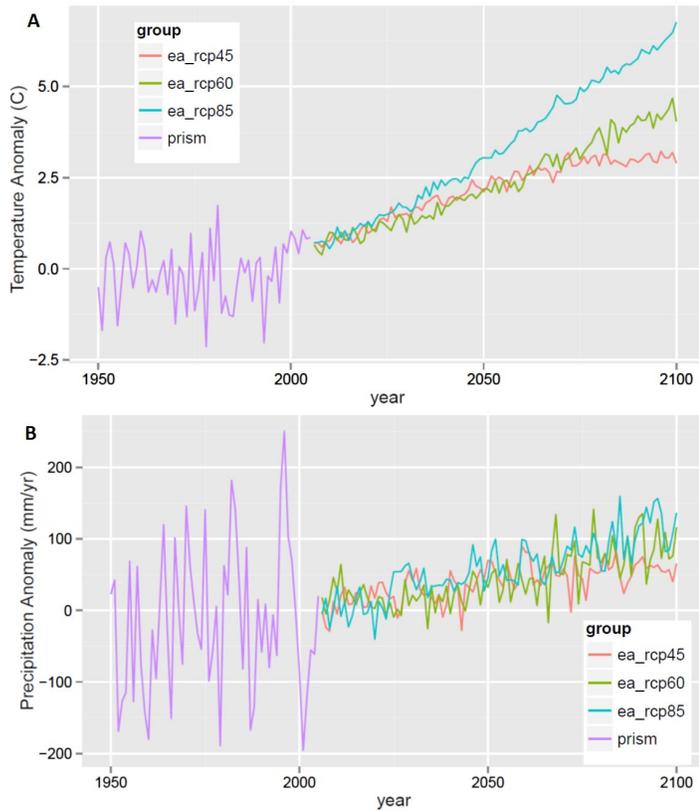


Figure 8. Mean temperature and precipitation anomaly for historic measured data (A) and projected by the ensemble average of global climate models for the coming century under three IPCC scenarios (B). Reference period is 1980-2005.

Projected Impacts on Ecosystems

The projected changes in climate are expected to influence ecosystem processes, such as soil moisture, runoff in streams and rivers, and primary productivity. The projected warming results in April 1 snow pack declining by 80-110 mm by 2100 (Figure 10A). The reduction in snow pack 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 10 mm by 2100 with increases mostly in spring and a slight decline in summer (Figure 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 in spring and decreases in summer (Figure 10C).

Stream temperatures are projected to increase between 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

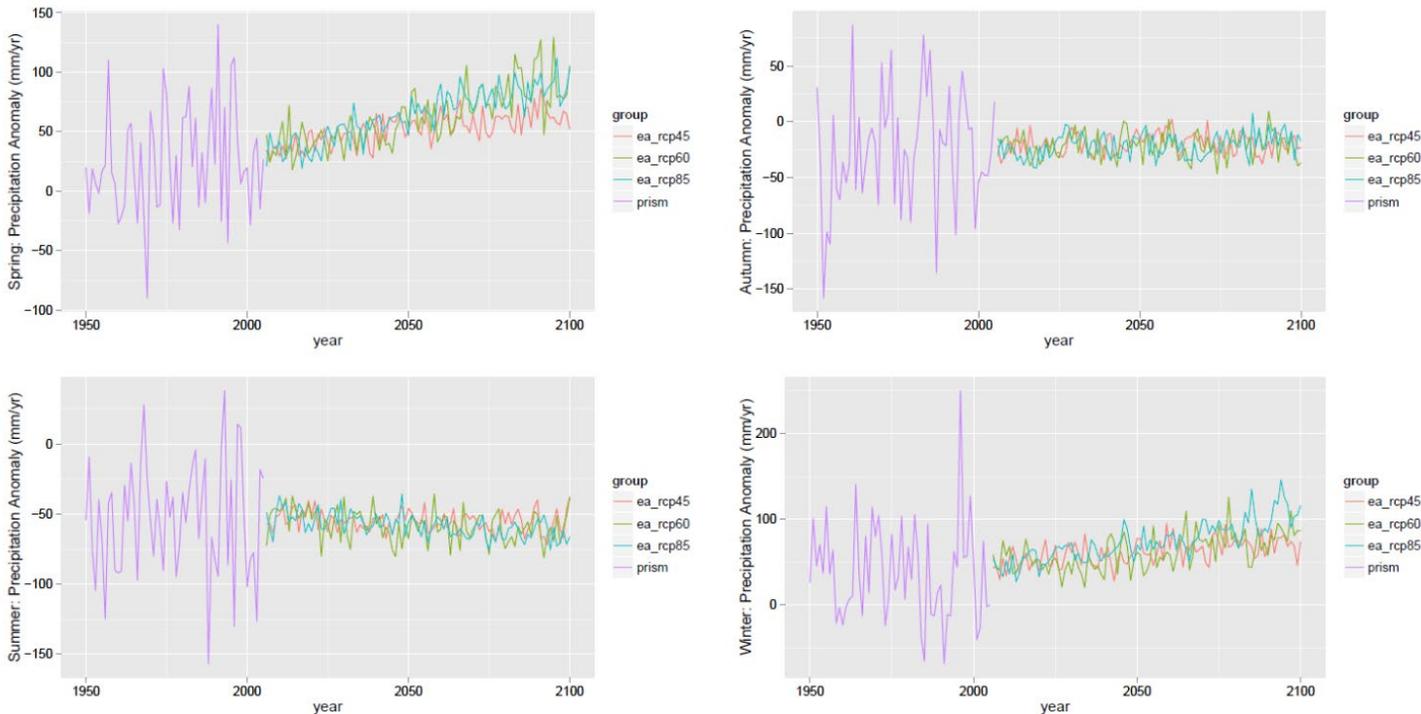


Figure 9. Seasonal precipitation anomaly for historic measured data and projected by the ensemble average of global climate models for the coming century under three IPCC scenarios. Reference period is 1980-2005.

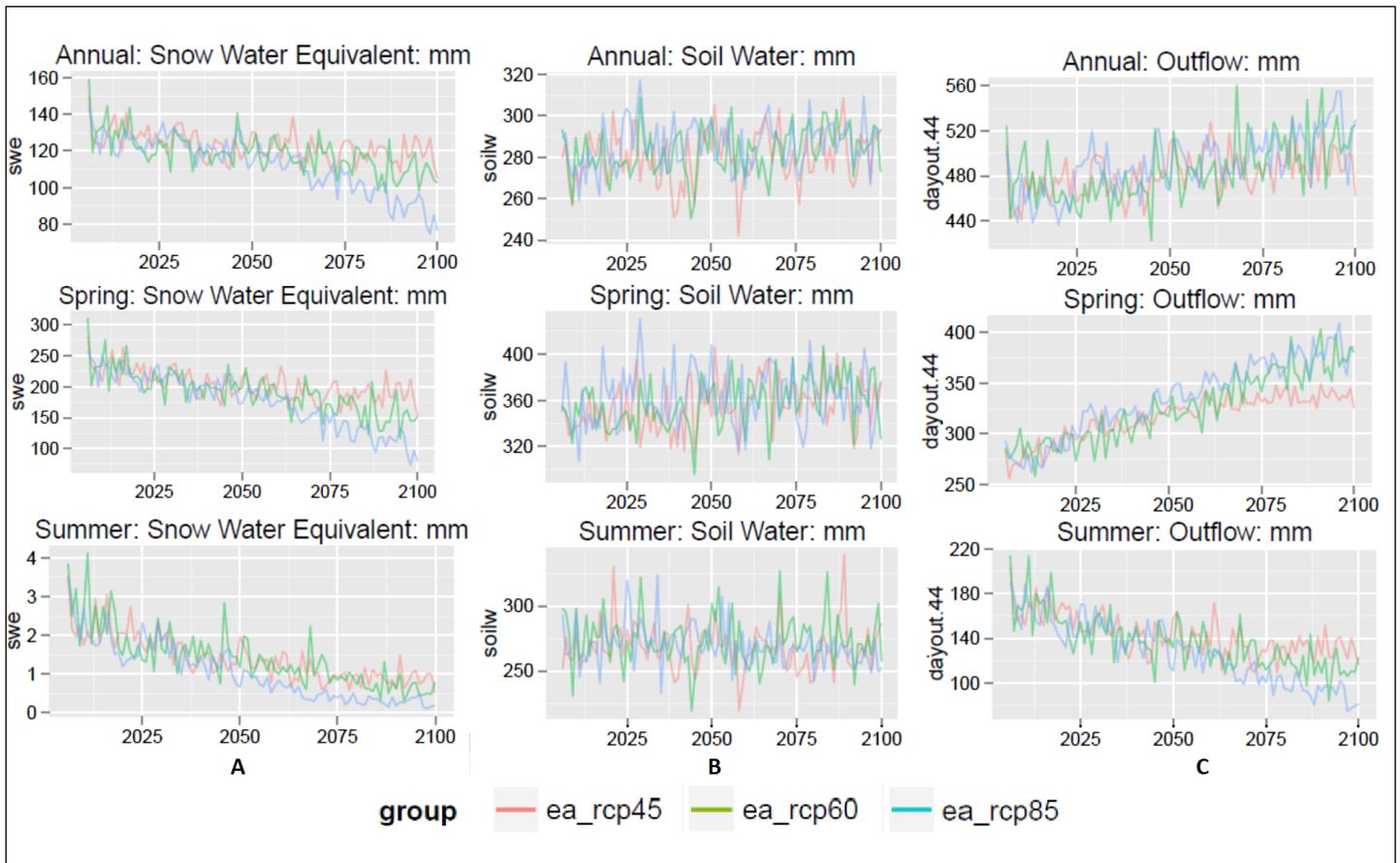
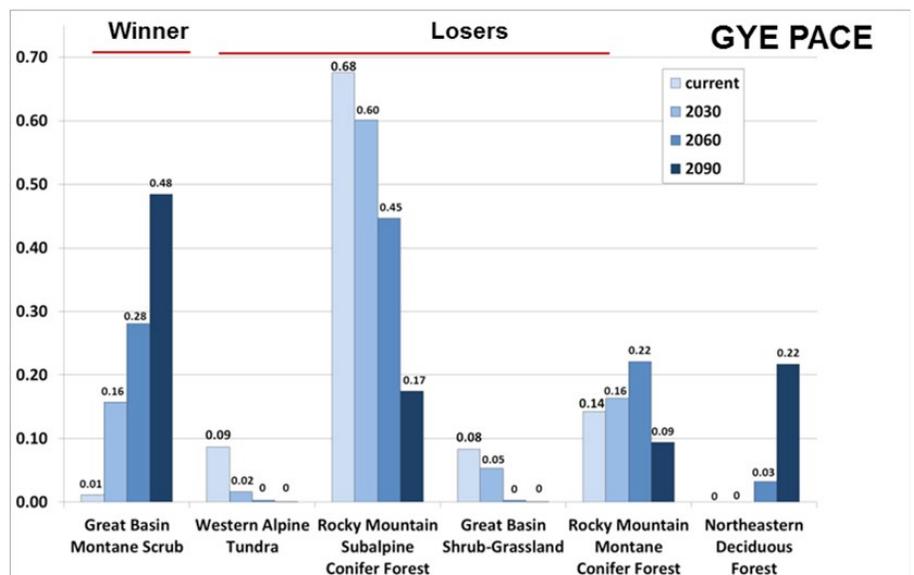


Figure 10. Greater Yellowstone PACE regional water balance summaries for (A) the seasonal April 1 snow water equivalent, (B) soil water, and (C) stream runoff projected by the TOPS model for the ensemble average of global climate models for the coming century under three IPCC representative concentration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

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 method is a meaningful way to interpret climate from the vegetation perspective. Rehfeldt et al. (2012) projected suitable climatic 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 (Figure 11), and to a lesser degree the northeastern deciduous forest now in the Lake states. This suggests that

climate conditions that 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.

Figure 11. Projected change in the area with climate suitable for biome types within the GYE. The left axis is the proportion of the GYE with climate suitable for each biome type. Data derived from Rehfeldt et al. 2012, using simulated shifts in climate niches of biome types across North America under an average of the climate predictions of seven global climate models.



Conclusion

In summary, these results indicate that climate is and will continue to change substantially during the 200 years from 1900-2100 (Table 1). 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 as 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 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

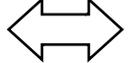
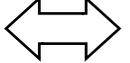
to desert scrub vegetation. Such changes will challenge resource managers. Strategies for adaptation and mitigation in natural resource management should be considered given the magnitude of potential future ecosystem impacts.

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Table 1. Summary of trends in past and projected future climate and ecosystem processes for the period 1900-2100.

Climate Variable	Trend	Change since 1900	Projections for 2100	Notes	Sources
Temperature (average annual)		1.1°C/100 years	+3.0-7.0°C	Similar rates in all seasons	Chang et al. in prep Melton et al. in prep
Precipitation (average annual)		9.3 mm/100 years	+55-125 mm	Increases in spring and decreases in summer	Chang et al. in prep Melton et al. in prep
Aridity Index (PET/PPT)		-14%	+7-18%	Decreases 1900-1977 and increases 1977-2010	Chang et al. in prep Melton et al. in prep
April 1 Snow Water Equivalent		~20% lower than 800-year average	-80-125 mm	Decline is most rapid in spring and summer	Pederson et al. 2011 Melton et al. in prep
Runoff			 +40 mm	Decreased during 1950-2010; Future increases in spring and decreases in summer	Leppi et al. 2012 Melton et al. in prep
Stream Temperature		+1.0°C	+0.8-1.8°C by 2050-2069	Warming in past and future	Al-Chokhachy et al. 2013
Gross Primary Productivity				Future increases in spring and decreases in summer	Melton et al. in prep
Fire Severity		Increased since 1980s	Projected to increase	Increasing in past and future	Westerling et al. 2011

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For More Information, Contact:

Andrew Hansen
 Ecology Department
 Montana State University
 Bozeman, MT 59717
hansen@montana.edu

