ADAPTING TO THE REALITY OF CLIMATE CHANGE AT GLACIER NATIONAL PARK, MONTANA, USA

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ABSTRACT

The glaciers of Glacier National Park (GNP) are disappearing rapidly and likely will be gone by 2030. These alpine glaciers have been continuously present for approximately 7,000 years so their loss from GNP in another 25 years underscores the significance of current climate change. There are presently only 27 glaciers remaining of the 150 estimated to have existed when GNP was created in 1910. Mean annual temperature in GNP has increased 1.6^{0}C during the past century, three times the global mean increase. The temperature increase has affected other parts of the mountain ecosystem, too. Snowpacks hold less water equivalent and melt 2+ weeks earlier in the spring. Forest growth rates have increased, alpine treelines have expanded upward and become denser, and subalpine meadows have been invaded by high elevation tree species. These latter responses can be mostly attributed to longer growing seasons and warmer temperatures.

Ecosystem modeling of possible future changes in the GNP mountain environments suggest that increased tree growth rates and evapotranspiration will reduce soil moisture and streamflow. The drier forests, with more wood, will burn more frequently and with greater severity, leading to degradation in air quality and increased risk to people and infrastructure. Management of forest fires is an important issue in the arid western United States. In 2003, 13% of GNP's 4,082 km^2 was burned in three large fires and numerous smaller fires. Managers can accomplish some of their goals, such as preserving threatened wildlife populations, by altering their management of fires. In 2003, intense efforts were successfully made to divert the fires away from valuable grizzly bear (*Ursus arctos horribilis*) habitat that contained huckleberry plants (*Vaccinium spp*.) necessary to ensure bear survival through the winter.

INTRODUCTION

In 1990 the U.S. Congress passed the Global Change Research Act, directing federal agencies to examine how climate change potentially could affect natural resources of the nation. The National Park System was chosen to be a key player in the U.S. Global Change Research Program because national parks tend to be relatively pristine, making it easier to detect early or subtle changes attributable to climate change. The underlying dynamics of ecosystems also can be investigated more effectively with the nearly intact ecosystems found in national parks.

Glacier National Park (GNP) has had a global change research program for the past 15 years that seeks to understand the effects of past climatic variability on its mountain resources, document and understand the recent changes that are attributable to climatic warming, and project future changes that integrate available knowledge and information. In this paper, I describe some of the past and recent climate change-driven responses of GNP and surrounding areas. Evidence of past climatic change, and the response of mountain ecosystems, is key to making integrated projections for the future because these past changes are often analogs for future change.

In recent years there has been an emphasis on working directly with park managers to help adapt to the reality of climate change. Climatic forcing in mountain ecosystems occurs at multiple spatial and temporal scales, and some of these changes are distinctly nonlinear. Park managers and others in the Rocky Mountains must make decisions of increasing complexity and, often, within shorter time frames. They need information about dynamics, distributions, and future projections.

STUDY SITE

GNP is a 4,082 km^2 mountainous park located in the northwestern corner of the state of Montana along the border with Canada (Figure 1). Along with it's neighbor to the north, Waterton Lakes National Park (Canada), GNP was designated the Waterton-Glacier International Peace Park in 1932, a Biosphere Reserve in 1976, and a World Heritage Site in 1995. The Bob Marshall Wilderness Complex, extensive national, state, and provincial forest lands, and the Blackfeet Indian Reservation surround the national parks to form a relatively unaltered landscape when contrasted to other areas of western North America. This is a snow-dominated region with over 70% of the annual precipitation falling as snow at higher elevations, which remain snow-free for as little as six weeks in late summer. GNP is the headwaters for its region. Elevations range from 984 m in valley bottoms to 3190 m peaks comprised of sedimentary rock up to 1.3 billion years old. The mountain topography was extensively reshaped by glaciation. Expansive conifer forests cover approximately 75% of the area. This region contains relatively intact floral and faunal assemblages. Species distribution and abundance vary along elevational gradients (extending to alpine vegetation) and from west to east (including grassland). Climate is controlled by dominant air masses with areas west of the Continental Divide receiving a stronger maritime influence from the Pacific Ocean and areas east of the Divide having a distinctly more continental climate. Precipitation varies dramatically between high elevation sites located near the Divide and lower elevation sites along the plains near the eastern edges of the region. For example, precipitation varies from 350 cm/yr (west side, high elevation) to 40 cm/year (east side, low elevation). Other factors, including dessicating east side winds, can enhance smaller differences in precipitation regimes between the east and west sides. This contrast in precipitation and other climatic factors over relatively small distances has a profound impact on microclimate, vegetation distribution and disturbance regimes.

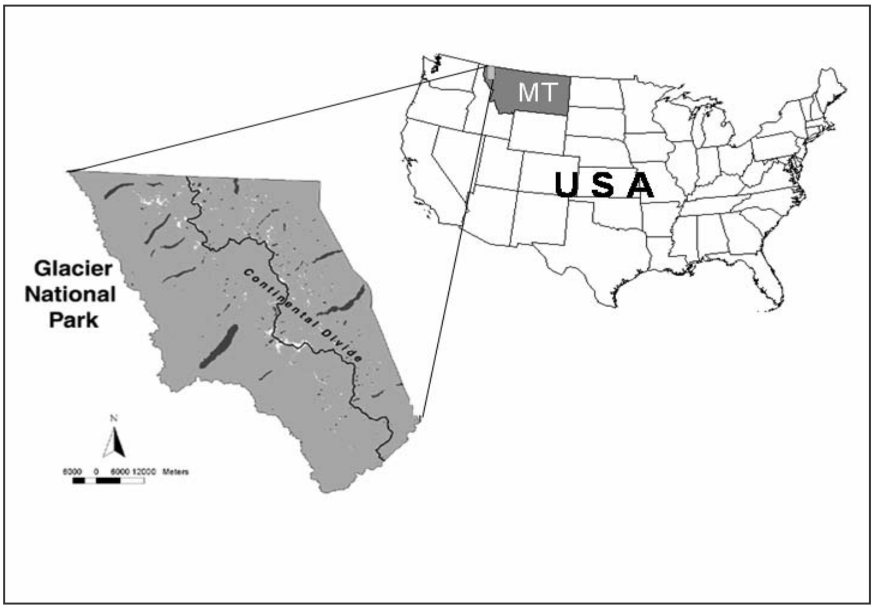

Figure 1: Location of Glacier National Park (GNP).

DOCUMENTING RESPONSES TO CLIMATE CHANGE

Changes in small alpine glaciers, especially mass balance and area covered, reflect changes in recent climate. In the western United States, virtually all the small alpine glaciers are shrinking and many will be gone in a few decades if current warming trends continue. These vanishing glaciers are indicative of pervasive changes throughout mountain ecosystems that are not as readily apparent nor as easily measured as are glaciers. Mountain ecosystem dynamics, and "services" to humans, will be affected in concert with changes to glaciers. One change glaciers readily reflect is a change to hydrologic regime and perhaps the most important mountain ecosystem service is the provision of water to a growing population in the American West.

The history and potential future of glaciers in Glacier National Park (GNP) clearly suggest that major mountain ecosystem changes are a reality. Glaciers were present within current park boundaries as early as 7,000 years ago but may have survived an early Holocene warm period (Carrara 1989), making them much older. These modest glaciers varied in size, tracking climatic changes, but did not grow to their Holocene maxima until the end of the Little Ice Age (LIA) around A.D. 1850. Climate reconstructions representative of the GNP region extend back multiple centuries and show numerous long-duration drought and pluvial events that influenced the mass balance of glaciers (Pederson et al. 2004). Of particular note was an 80-year period (~1770-1840) of cool, wet summers and above-average winter snowfall that led to a rapid growth of glaciers just prior to the end of the LIA. Thus, in the context of the entire Holocene, the size of glaciers at the end of the LIA was an anomaly of sorts. In fact, the large extent of ice coverage removed most of the evidence of earlier glacier positions by overriding terminal and lateral moraines.

The late Holocene history of glacial extent for GNP was derived largely from morainal evidence. Records show that around A.D. 1850 there were an estimated 150 glaciers and large perennial snow/ice fields (Carrara 1989). Tree-ring based climate records and historic photographs indicate the initiation of frontal recession and ice mass thinning between A.D. 1860 and 1880. The alignment of decadal-scale climate anomalies over the early 20th century produced a period of glacial recession somewhat analogous to conditions experienced over the past few decades. The coupling of hot, dry summers with substantial decreases in winter snowpack (~30% of normal) produced dramatic recession rates as high as 100 m/yr from A.D. 1917-1941 (Pederson et al. 2004). These multidecadal episodes have substantially impacted the mass balance of glaciers while superimposed on the long-term trend of a 1.6^{0}C increase in annual temperature since A.D. 1900. Based on 1966 aerial photographs, the first comprehensive map of the regions glaciers was published by the U.S. Geological Survey in 1968. Only 37 glaciers were named out of a total of 84 perennial snow-and-ice bodies (Key et al. 2002). It's likely that some of the remaining 47 snow-and-ice bodies may have qualified as glaciers. GNP documents list "about 50" glaciers during this period. Key et al. (2002) estimated that 99 km^2 of ice covered GNP in 1850 but that only 26 km^2 remained by 1968.

Aerial photographs were acquired in late September 1998 of all GNP glaciers. The glacier area measurements from these photographs were the first for all glaciers since 1966. The overall glacier coverage for GNP was reduced to 17 km^2. Using glacier criteria of 0.1 km^2 minimum area, and/or visual evidence of crevasses in the ice surface indicative of downslope movement, only 27 glaciers existed of the original 150. Other former glaciers appeared to have shrunk to the point of being miniscule and stagnant ice masses. Between 1993 and 1998, glaciers ranging in size from 0.15 – 1.72 km^2 became 8-50% smaller. The relative rate of shrinkage was greatest for the smaller glaciers. Red Eagle glacier, for example, was reduced to half its size between 1993-1998 and no longer meets the 0.1 km^2 criterion for being considered a glacier. A glacier margin survey was completed for Grinnell Glacier in 2001 and showed a loss of 0.17 km^2, or 19%, from 1993-2001. The margin survey of Grinnell was repeated in 2004 and a further loss of 0.4 km^2, or 5.6%, occurred in 3 three years. Many watersheds no longer contain any glaciers (Key et al. 2002) and the area covered by glaciers in any of the remaining watersheds does not exceed 3%. Furthermore, glaciers have thinned by hundreds of meters, and like Grinnell Glacier (Figure 2) , may have less than 10% of the ice volume that existed at the end of the Little Ice Age. The area within park boundaries covered by ice and permanent snow was reduced 82% from 99 km^2 to 17 km^2 by 1998.

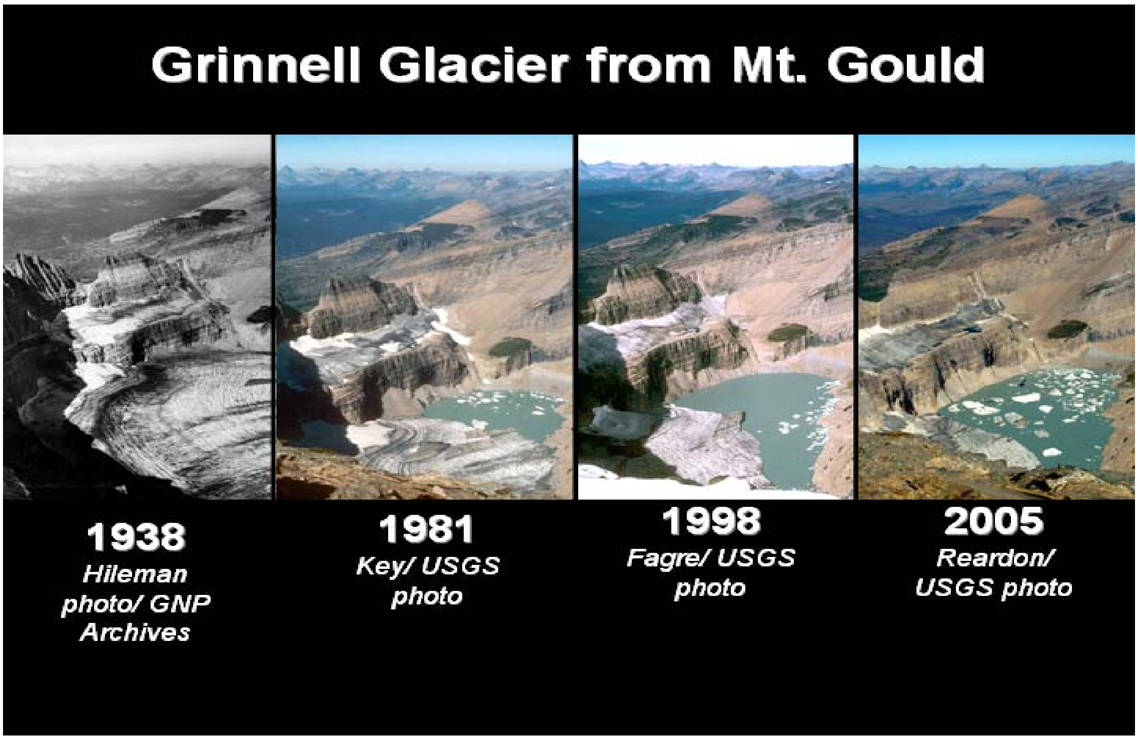

Fig. 2. Grinnell glacier melts into Upper Grinnell Lake and is estimated to be 10% of its volume from its maxima in 1850.

The loss of glaciers continues. Sperry glacier, a glacier more representative of climatic change because it lacks a proglacial lake such as the one fronting Grinnell glacier, was chosen as an index glacier for annual surveys and other measurements. Sperry glacier shrank from 0.89 km^2 in 2003 to 0.86 km^2 in 2005 based on precision GPS surveys of the margins at the end of the ablation season. This represents a 3.6% loss in 2 years. Sperry glacier will be monitored annually for mass balance, movement and ice depth. A climate station and automated camera have been installed and GPS surveys of its margins will continue annually.

Instrumental weather data from the nearby town of Kalispell, in the Flathead Valley approximately 60 km from GNP, indicate a trend of increasing temperature for the period of record (1899 – present) with substantial increases in minimum temperatures (all seasons) rather than only maximum temperatures. Hall and Fagre (2003) interpolated a temperature record for GNP from surrounding locales that reflected a 1.6^0C increase in mean annual summer temperature from 1900-1980. This is nearly three times the global average of 0.6^0C (USGCRP 2000) for the same period. A regional temperature analysis indicates that spring and summer minimum temperatures similarly have increased more than other temperatures (Watson et al. in press). Finally, the temperature trend for GNP and the immediate area mirrors that for Western Montana (Pederson, unpubl. Data)(Figure 3). This analysis was based on corrected climatic data from the Historic Climate Network of the National Climatic Data Center. Warmer spring temperatures mean that the glaciers are not as cold and that ablation is more readily initiated by the onset of summer. Despite the fluctuations in temperature within the overall increasing trend over the past century, glaciers continued to shrink even during the cooler periods.

As glaciers disappear from mountains because of climatic change, snowpacks obviously will be affected as well. Numerous studies document lower moisture content in late spring snowpacks and earlier melting of these snowpacks by as much as three weeks (cf Mote et al. 2005, Stewart et al. 2005) during the past 50 years throughout the western United States. The GNP is no exception (Figure 4).

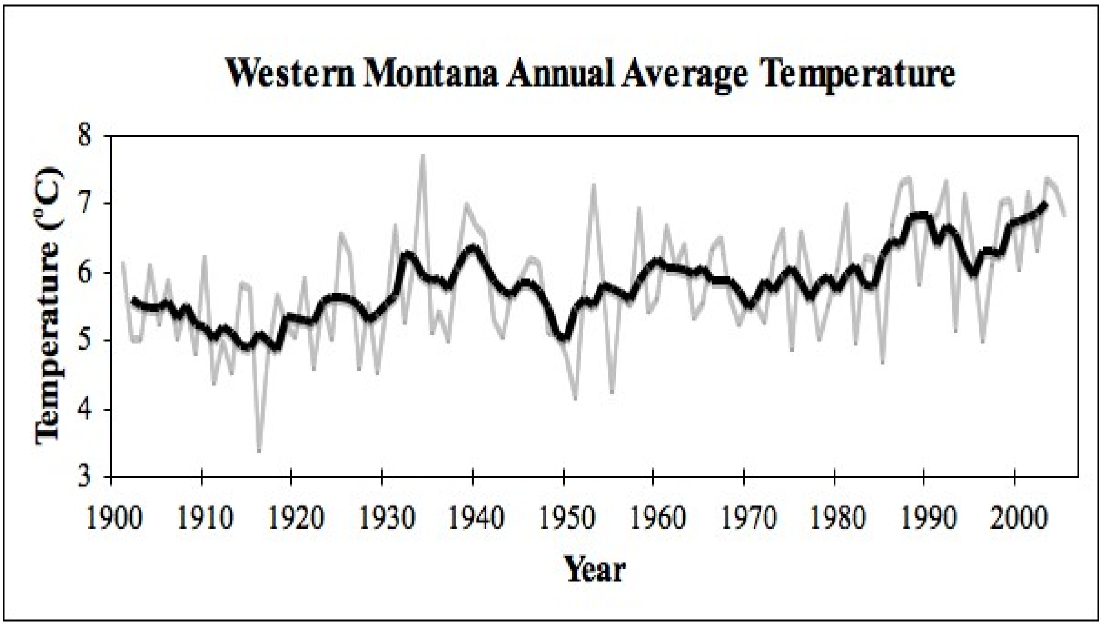

Fig. 3. Annual mean temperature trend for Western Montana. Dark line is a 5-year running average. Western Montana is currently 1^{0}C warmer than 100 years ago.

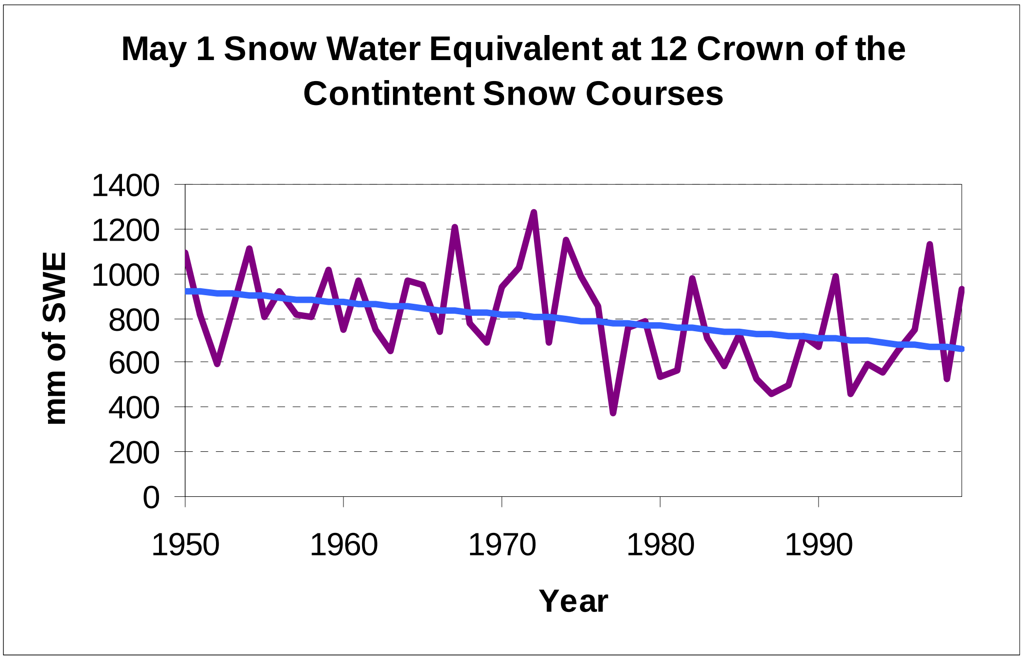

Fig. 4. Snow Water Equivalent (SWE) as measured on the first of May at snow courses in and surrounding GNP (the Crown of the Continent Area). Snow course measurements are made with a standardized sampling tube to obtain depth and density of snow.

However, annual mean precipitation for nearby Kalispell has actually increased during the last century (0.09 cm/year, p=0.03)(Selkowitz et al. 2002). Because there has been a 10% increase to total annual precipitation in GNP during the past century, increases in temperature are the primary driver of smaller snowpacks.

Alpine treelines have advanced upward in elevation (Butler and DeChano 2001), have increased in biomass as spaces between patches have filled in (Klasner and Fagre 2002), and many trees have changed from the prostrate, krummholz form to begin growing as upright trees (Klasner and Fagre 2002). Many subalpine meadows have been invaded by high-elevation tree species (Figure 5).

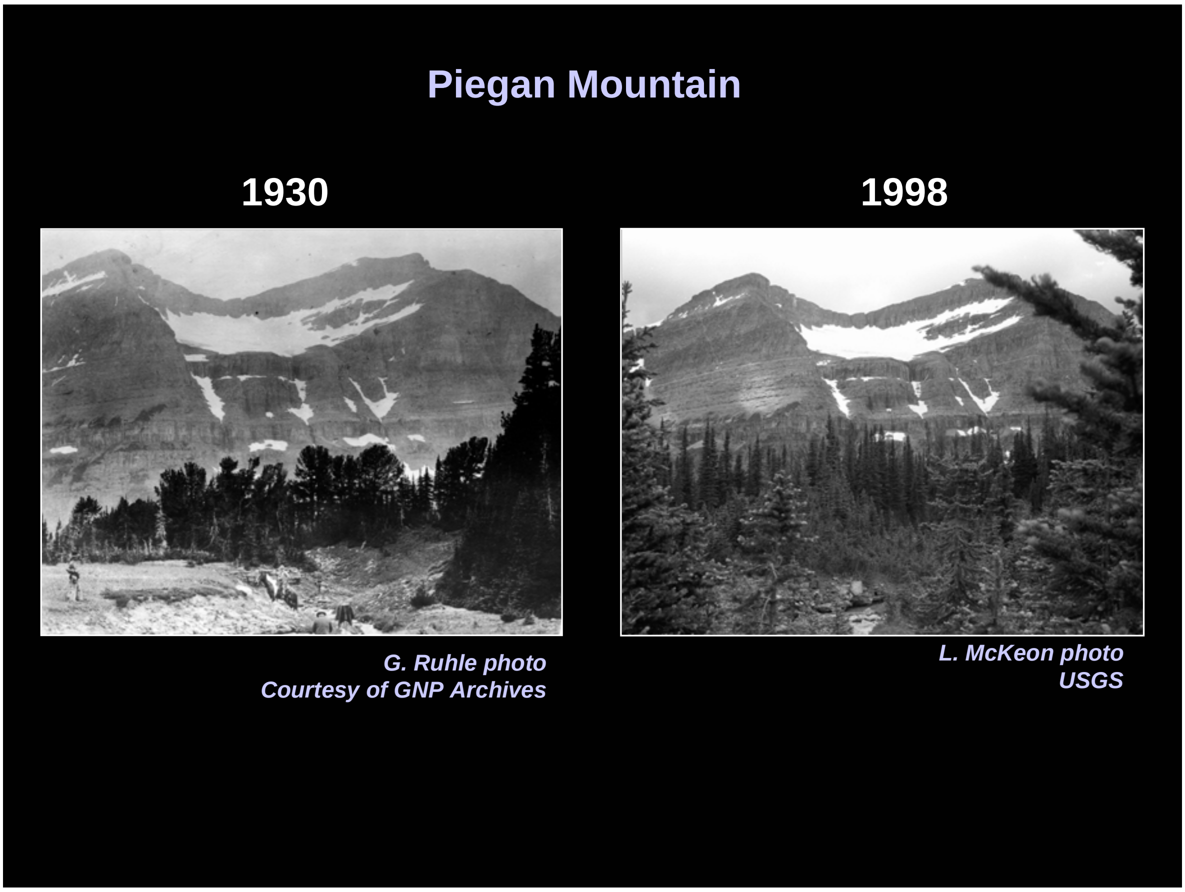

Figure 5. Paired repeat photographs of Piegan Mountain in Glacier National Park, Montana, showing the invasion of a subalpine meadow by the surrounding forest in 68 years.

Because the timing and magnitude of seasonal snowpacks are the proximate drivers for tree seedling establishment and growth at upper elevation sites (Peterson 1998), the long-term decreases in snowpack size and duration are likely the major cause for tree invasions of alpine tundra and subalpine meadows in GNP. However, alpine tree establishment and growth have occurred in episodic fashion rather than incrementally, suggesting that snowpack variation may have similar periodicity. These changes must be interpreted carefully, however, because of the influence of multidecadal climate phenomena such as the Pacific Decadal Oscillation (PDO). The PDO is an an ENSO-like interdecadal pattern of Pacific Ocean sea surface temperature variability that has 20-30 year phases (Mantua et al.1997, Zhang et al. 1997). Selkowitz et al. (2002) documented the dominant effect of the PDO on snow accumulation in the GNP region (Figure 6). The large fluctuations in mean snow accumulation during the multidecadal PDO phases have affected tree seedling establishment patterns in alpine tundra (Alftine et al. 2003), glacier mass balance fluctuations and fire frequency (Pederson et al. 2006), and undoubtedly drives many other ecosystem processes. Studying the responses of GNP to this pattern of climatic variability will provide insights into future responses to long-term climate change.

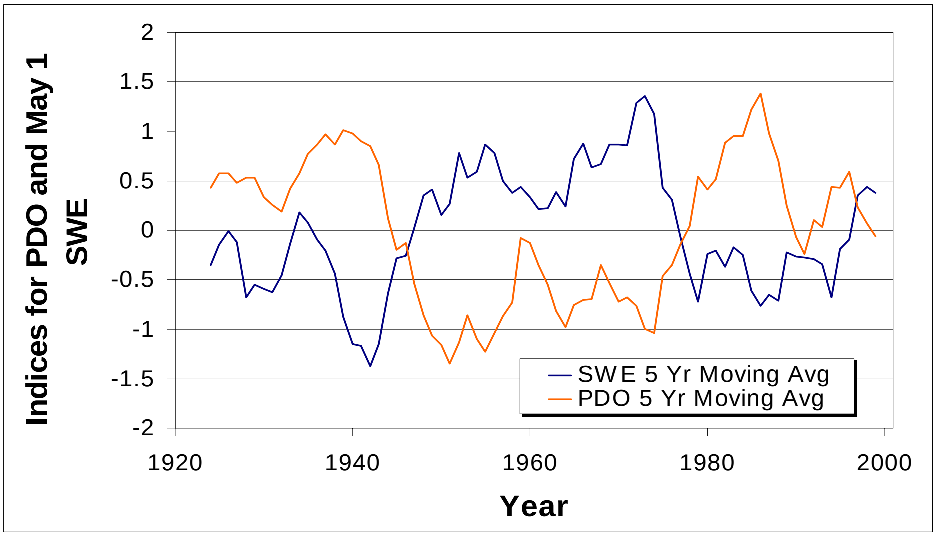

Figure 6: Indices of the Pacific Decadal Oscillation (PDO) and Snow Water Equivalent (SWE) measured on standardized snow courses in and around Glacier National Park, Montana.

UNDERSTANDING ECOSYSTEM PROCESSES

One ecologically significant consequence of losing glaciers in GNP is through changes in hydrology. Glaciers act as a "bank" of water (stored as ice) that is released during dry periods of the year or during extended drought. This keeps a continual flow in streams that otherwise might dry up and is critical for maintaining riparian and aquatic biota. Once glaciers are gone in a watershed, many streams will become ephemeral, overall water supply will diminish, and the aquatic communities will experience a more unpredictable environment. Of equal importance to the loss of streamflow in late summer is the effect of glacier disappearance on increased water temperature that affects the distribution and behavior of aquatic organisms. Without the cold water supplied by glacial melt, summer water temperatures increase. Many stream insects are temperature sensitive and cannot complete their life cycle outside narrow temperature ranges (Pepin and Hauer 2002). These insects will migrate to upper stream elevations as glacier meltwater is reduced. Some insects may become locally extinct if regional water temperatures exceed their tolerance after the glaciers are gone (Figure 7).

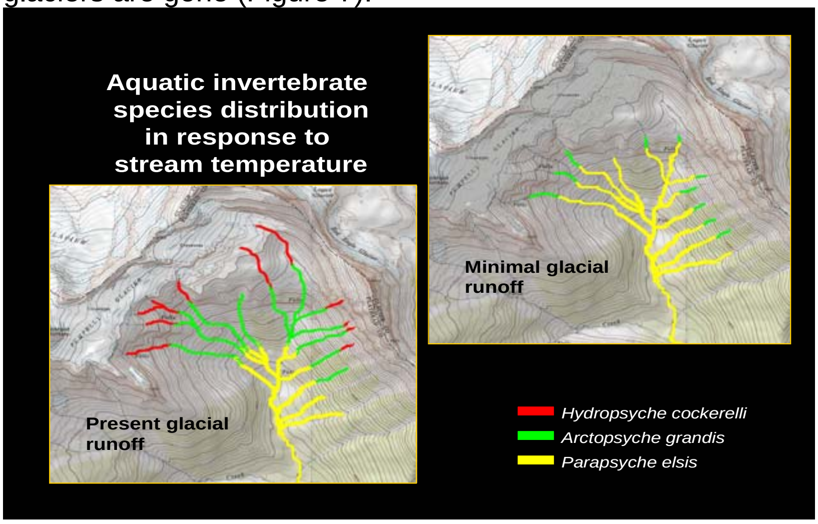

Figure 7: Simulation of changes in invertebrate distribution after all glaciers disappear within a watershed. Stream temperatures are projected to increase in late summer without a supply of glacial meltwater.

MODELING FUTURE RESPONSES TO CLIMATE CHANGE

The climatic causes of glacier retreat were analyzed, the melt rate (change in glacier area/decade) determined, and the topographic influences on the spatial pattern of melt were examined. Analysis of glacial area extent per decade from 1850-1979 versus a variety of climatic drivers reveals that annual precipitation and summer mean temperature together explain 92% of the loss over time (Hall and Fagre 2003). Analysis of the spatial distribution of these glaciers as a function of three topographic variables --elevation, slope and solar aspect shows elevation (or temperature) to be twice as important as slope or aspect in determining the pattern of glacier shrinkage. Using this information to parameterize the simulation model GLACPRED (Hall and Fagre 2003), the potential future glacier behavior was predicted: all glaciers in the basin will disappear by the year 2030 if current trends continue. Even if no further climatic forcing occurs, the glaciers are predicted to be all but gone by 2100.

The response of mountain ecosystem components to future climate change was assessed with several well-established modeling approaches (Fagre et al. 2005). The first step was to compare ecosystem model outputs with observations of the current ecosystem. Carbon budget estimates for the watersheds indicated close agreement with observed values for soil CO_2 effluxes and productivity for both low and high elevation forest that cover 75% of the watersheds. At Glacier National Park, only 4 of 84 watersheds have as much as 3% of their area covered by glacial ice and 18 have only 1%. Nonetheless, in watersheds with remnant glaciers, higher observed values, compared to modeled values, during late summer underscored both the contributions of glacial meltwater to streamflow and the need to include this source in future models of mountain hydrology in the region. Even small glaciers matter. Additionally, modeled daily estimates of stream temperatures throughout the watershed closely matched daily measurements from 7 monitored streams when glacier outputs were included (Fagre et al. 1997). White et al. (1998) concluded that reasonable estimates of ecosystem processes were generated for these watersheds by the models. Some ecosystem process estimates such as net primary productivity were much less sensitive to scale than hydrologic discharge.

Ecosystem modeling of possible future changes in the GNP mountain environments suggests that increased tree growth rates and evapotranspiration will reduce soil moisture and streamflow under warming conditions. Even when the mean values for annual temperature and precipitation are held constant but the variability increases, there are significant changes to GNP. In this latter scenario, after 120 years, long-term conifer net primary productivity in Glacier Park decreased 4% on the western side of the continental divide and 13% on the eastern side (White et al. 1998). Broadleaved shrubs and alpine vegetation increased 2-7% on the west side but grass net primary productivity at the forest-grassland ecotone decreased on the east side. In fact, the lower treeline (the forest-grassland ecotone) rises under this scenario, permanently reducing the amount of forest cover in the St. Mary watershed. This eventually reduces the fuel load for large fires but probably increases the frequency of fires.

Under most future climate scenarios used in our modeling efforts, more productive forest landscapes will generate more frequent and severe fires than the same landscapes experienced historically even with increases in annual precipitation (Keane et al. 1997). There is an increased risk to people and infrastructure and smoke emissions from fires nearly double in the future. This jeopardizes the pristine air quality that the GNP area currently enjoys and poses a management challenge for park managers who need to restore historic fire frequencies. Because fire frequency has been altered by humans throughout the northern Rocky Mountains for the past century, fuel loads have built up to levels that could lead to fire intensities higher than might have been experienced in the past.

To examine the implications of the GNP modeling results for larger regions, the BIOME-BGC model was used to more closely examine spatial variability in climate, vegetation production, water budgets, and carbon stocks in the Northern Rocky Mountains and Pacific Northwest (Washington, Idaho and Montana)(Fagre et al. 2005, Kang et al. 2004). The BIOME-BGC model worked well explaining how current climatic variability drives ecosystem attributes, so climate change scenarios were applied that decreased current summer precipitation and increased annual temperature (the IPCC A2 scenario). This resulted in reduced water supplies (outflows) from mountain areas and across the region (Figure 8). However, the greatest effects were at mid-elevation sites where most of the forests grow and where the increasing human population tends to build new homes. Under this scenario, the amount and predictability of the regional water supply will be of even greater concern than today. The low-lying areas, already relatively dry, show no major changes but the highest elevations increased outflow, suggesting that these areas will be even more important for providing needed water to people in the future.

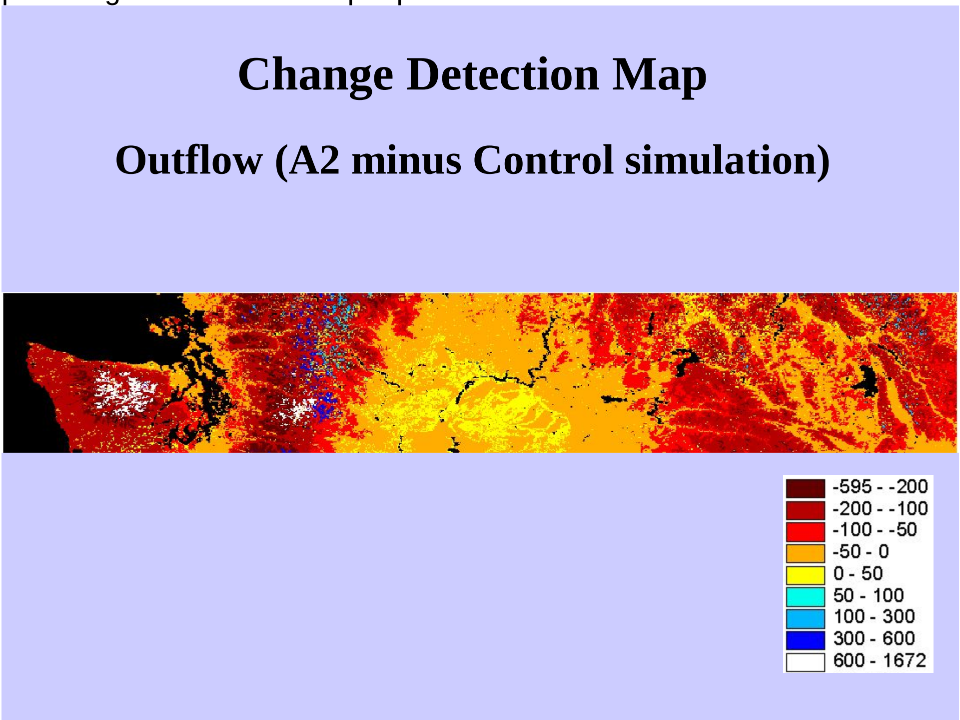

Figure 8. Modeled water supplies using the IPCC A2 climate change scenario for the Pacific Northwest Region of the U.S. including the states of Washington (Left), Idaho (Center), and Montana (Right). The red areas that show the greatest reductions in outflow are the mountains. (After Kang et al. 2004).

ADAPTING TO CLIMATE CHANGE

The awareness of climate change impacts to GNP documented by research led to several changes. GNP management incorporated climate change into their General Management Plan and Resource Management Plan as an issue of concern. As a result of the publicity regarding the disappearing glaciers, GNP established wayside exhibits at strategic locations where glaciers are visible along the Going-to-the-Sun Road. These exhibits address climate change issues for the park visitor as they look at the glaciers. The park interpretation staff has undergone training to explain climate change and describe its effects on GNP's resources to visitors. Specific "talking points" have been formulated so that the message is consistent and scientifically valid. Displays and posters on climate change effects to GNP are in visitor centers and a building that is dedicated to environmental education.
GNP has also participated in a national program of the National Park Service called the Climate Friendly Parks Initiative. Under this program, the park has conducted a greenhouse gas inventory and has taken steps to reduce its emissions. This includes the use of propane-powered buses for transporting tourists within the park, the establishment of an employee commuter service on a low-emission bus, and the purchase of numerous bicycles for employees to use within the park. The large construction and maintenance equipment now uses biodiesel fuel and ongoing insulation upgrades to GNP buildings are continuing.

Snow avalanches, rockfall hazards,and debris flows are a constant issue facing management as they attempt to maintain roads and other infrastructure to support visitor use of the park. These avalanche considerations apply especially to the alpine section of the Going-to-the-Sun road that crosses nearly fifty avalanche paths midslope and sustains considerable damage each winter from frequent avalanches. In addition, more frequent landslides and rockfall seem to be occurring as the annual precipitation becomes more dominated by rain rather than snowfall. Possible melting of permafrost could be contributing to the magnitude of damaging slides and park managers need to ensure that the engineering during the $180 million, 10-year reconstruction of the Going-to-the-Sun can withstand these consequences of future climatic change. Finally, the Going-to-the-Sun Road is vital to the regional economy because tourists are not attracted to GNP until the road is opened each spring. Shifts in snowpack peak accumulation to later in the spring, and changes in avalanche frequency or magnitude, could have large economic consequences if the opening of the Highway is frequently delayed. Park managers have already addressed this to a degree with the purchase of better snow removal machinery, changes in policy, and the establishment of a professional avalanche forecasting program (Reardon and Lundy 2004).

Large magnitude snow avalanches also shape ecosystem pattern and process by carving linear swaths out of the forest from ridge top to valley bottom. These avalanche paths create vegetation diversity, are utilized by many wildlife species, and act as fuel breaks to large forest fires. Therefore, snow avalanche frequency for the past 100 years in GNP was examined to help management better understand its role and to indicate whether avalanches will become more disruptive in the future. Historic records and tree-rings were analyzed (Reardon et al. 2004, Reardon et al. in review) and indicate that avalanche frequency reflects climatic variability due to the Pacific Decadal Oscillation (PDO). This multidecadal shift between wet and dry phases mimics some expected climate conditions of the future if climate change continues. Avalanches are expected to track those climatic shifts.

Changes to the mountain environment due to climatic change will affect tourism also. Not only do tourists stay away from GNP during large fires (that may burn several months) due to smoke and visibility issues, large parts of the park are closed to any access. Hazards exist for a year or more due to burned upright trees that can topple over and such areas are either closed by park management or unappealing for people to walk through. Thus, projected increases in fires may suppress tourism.

Management of forest fires is an important issue in the arid western United States. In 2003, 13% of GNP's 4,082 km^2 was burned in three large fires and numerous smaller fires (Figure 9). Because forest fires are projected to become more frequent and intense under continued climate change, managers can accomplish some of their goals, such as preserving threatened wildlife populations, by altering their management of fires. In 2003, intense efforts were successfully made to divert the fires away from valuable grizzly bear (*Ursus arctos horribilis*) habitat that contained huckleberry plants (*Vaccinium spp*.) necessary to ensure bear survival through the winter. The fires were also directed away from riparian areas so that trees could continue shading streams and prevent water from increasing in temperature. Cold water is critical for mountain aquatic species such as the threatened bull trout (*Salvelinus confluentus*) that has been the object of much scientific study to maintain its population in this region. Fire also has been used under controlled conditions to artificially maintain some open meadow habitats by burning the invading trees and shrubs. Finally, decisions about allowing some naturally started fires to burn and others to be controlled are being made with a complex set of considerations that include the volume of smoke emissions and consequent effects on human health as well as climate change.

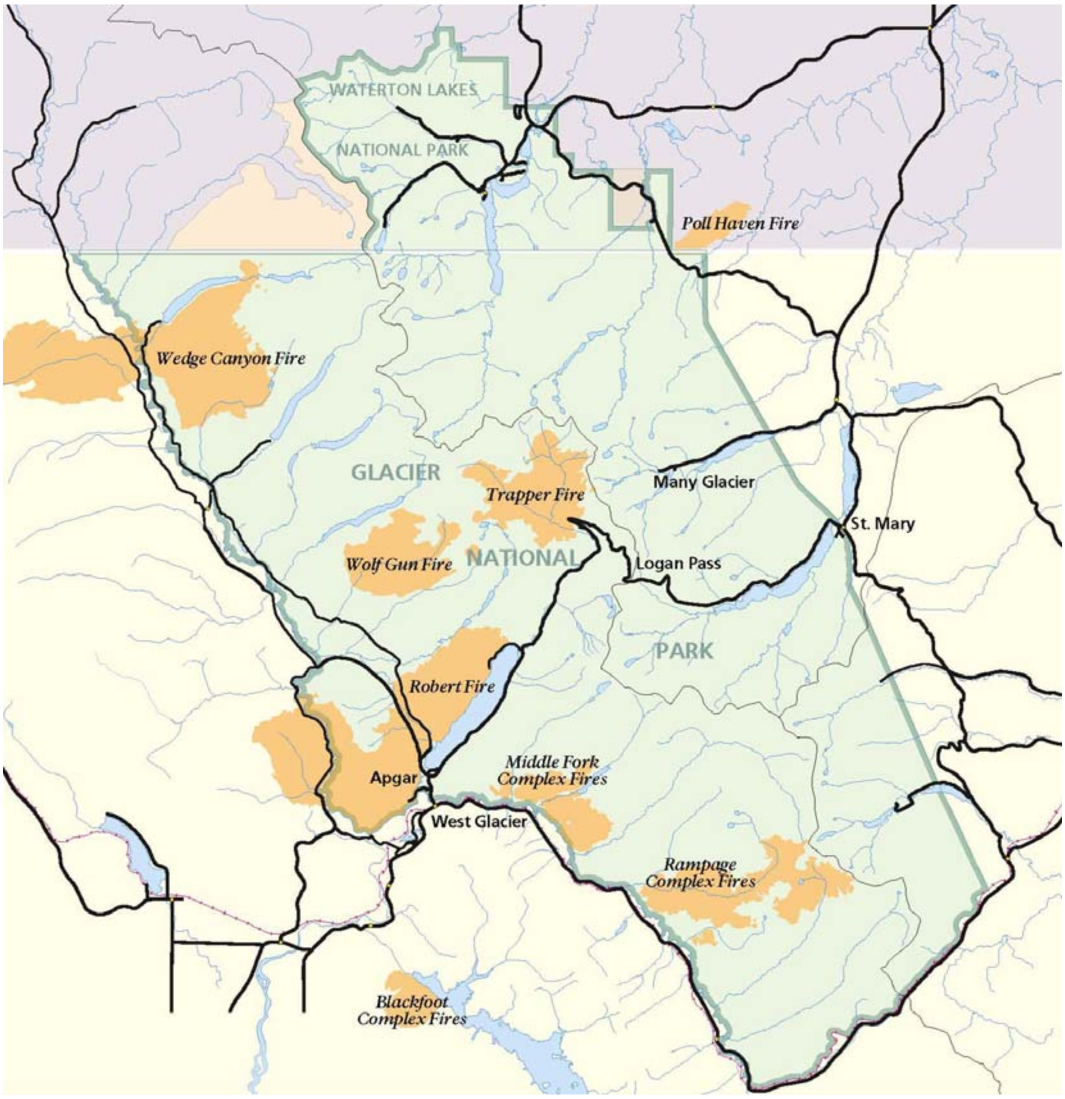

Figure 9: Fires that burned around and in Glacier National Park during summer 2003.

CONCLUSIONS

Research at GNP for the past 15 years has clearly identified many of the changes that have already occurred to the park's natural resources that are due to a changing and variable climate. Extensive studies and modeling have been used to project future responses of GNP to ongoing climate change and provide GNP managers with information and options for managing this change. Adapting to the reality of climate change has already begun and a continuing partnership between management and research will provide additional opportunities for the future.

ACKNOWLEDGMENTS
Research described in this paper has been supported by grants from the U.S. Geological Survey and National Park Service. Special thanks to GNP staff and USGS scientists Karen Holzer, Lisa McKeon, Greg Pederson and Blasé Reardon. Numerous collaborators over the past 15 years are acknowledged for their contributions.

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