

Modeled Climate-Induced Glacier Change in Glacier National Park, 1850–2100

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The glaciers in the Blackfoot–Jackson Glacier Basin of Glacier National Park, Montana, decreased in area from 21.6 square kilometers (km²) in 1850 to 7.4 km² in 1979. Over this same period global temperatures increased by 0.45°C (± 0.15°C). We analyzed the climatic causes and ecological consequences of glacier retreat by creating spatially explicit models of the creation and ablation of glaciers and of the response of vegetation to climate change. We determined the melt rate and spatial distribution of glaciers under two possible future climate scenarios, one based on carbon dioxide–induced global warming and the other on a linear temperature extrapolation. Under the former scenario, all glaciers in the basin will disappear by the year 2030, despite predicted increases in precipitation; under the latter, melting is slower. Using a second model, we analyzed vegetation responses to variations in soil moisture and increasing temperature in a complex alpine landscape and predicted where plant communities are likely to be located as conditions change.

Keywords: glacier retreat, climate models, vegetation response

The mountains of Glacier National Park, Montana (figure 1), owe much of their striking beauty to glaciers. During the last ice age, massive valley glaciers up to 1000 meters thick sculpted the landscape into such rugged relief that local Native Americans, the Blackfeet, revered this area as the “backbone of the world.” Glaciated mountain features, such as hanging valleys and pyramidal mountaintops (figure 2), are so prominent that early visitors referred to Glacier National Park as the “little Switzerland of America.” During efforts to create a national park at the turn of the century, George Bird Grinnell, renowned ornithologist and conservationist, promoted these northern Rocky Mountains as the “crown of the continent” and referred often to the numerous glaciers contained therein.

Glaciers and climate

Since its establishment in 1910, Glacier Park has lost most of its glaciers. Over two-thirds of the estimated 150 glaciers existing in 1850 had disappeared by 1980 (Carrara and McGimsey 1981). Furthermore, over that same time period, the surviving glaciers were greatly reduced in area (figure 3). The local summer mean temperature increased 1.66°C between 1910 and 1980. These events reflect a worldwide pattern of glacial retreat and regional climatic change that, in aggregate, has been viewed as evidence of global warming.

The global retreat of mountain glaciers could have direct consequences for humanity. Fifty percent of the freshwater that humans consume yearly comes from mountains (Liniger et al. 1998). Disappearing glaciers have a significant impact on mountain hydrology (Fagre et al. 1997) and leave new terrain for plant colonization. In many parts of the world, distant mountain glaciers provide lowland rivers with the hydro-

logical base flow (i.e., the minimum flow when snowmelt’s contribution to flow is at its lowest) upon which agriculture depends in late summer. The reduction in the Zongo Glacier in the Bolivian Andes has created water-supply problems for downstream communities (Liniger et al. 1998). Globally, a 10- to 25-centimeter (cm) rise in sea level has been recorded during this century; Meier (1984) and others attribute part of this rise to the worldwide retreat of alpine glaciers. Thus, even those who live far from mountains have experienced the consequences of melting glaciers.

However, the most significant aspect of glacial retreat may be that it is tangible and intuitive evidence of broader environmental changes that are more difficult to measure. Glaciers are excellent barometers of climate change, because they respond directly to trends in temperature, precipitation, and cloud cover (which mediates solar radiation). These same climatic factors also drive ecosystem change. Unlike plants and animals, however, glaciers do not adapt behaviorally or physiologically in ways that mitigate the impacts of climatic

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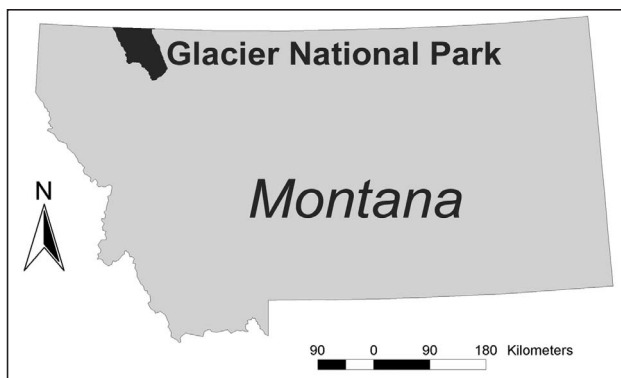


Figure 1. Location of Glacier National Park, Montana.

change. Although many abiotic aspects of ecosystems, such as stream hydrology, are greatly modified by plant community responses to changed conditions, glaciers are merely a physical reflection of the surrounding conditions. Moreover, they provide a signal that integrates climatic change over time, because they do not respond to year-to-year variability. Rather, they change their dimensions and mass slowly in response to decadal trends in climate. Thus, the global retreat of glaciers can be attributed to real climatic changes, not to temporary anomalies.

Glacial retreat is of particular significance in relatively unmodified natural systems such as Glacier National Park, because these protected areas function as early warning systems. In fact, national parks have been likened to the caged canaries that long ago were carried into coal mines. Signs of distress from the birds signaled the presence of dangerous levels of gases that could not easily be detected in any other way. Likewise, parks often provide the first tangible evidence of an ecosystem response attributable primarily to climate change.



Figure 2. Example of Glacier Park terrain after major glaciation. Mount Kipp is on the left, and Sue Lake is in the center of the photograph. Photograph: Lisa McKeon and Karen Holzer, US Geological Survey.

This response suggests the degree to which climate change is underlying transformations of other landscapes in which, because of the many additional anthropogenic forces at work, it is more difficult to determine the effects of changing climate.

The relatively rapid disappearance of the glaciers in Glacier National Park, as well as having national and global implications, potentially influences the natural resources the park was designed to protect. For instance, Lowe and Hauer (1999) determined that the distribution of stream insects, such as net-spinning caddisflies (*Trichoptera: Hydropsychidae*), was not greatly affected by gradients of food quantity and quality, current velocity, or substratum size but was highly responsive to water temperature. Because glacial meltwater is an important component of stream base flow in late summer, temperature-sensitive organisms must shift their distribution or perish as summer water temperatures rise in streams no longer fed by glaciers. Similar biological responses can be expected for bull trout and other aquatic biota.

Such ecological changes are of concern to park managers and the American public alike. In this article, we examine available records of glacier retreat and changing climate in Glacier National Park from 1850 to 1980. We use these data to develop spatially explicit models that incorporate the main drivers of glacial advance and retreat and vegetation response; we project the future status of this high-elevation ecosystem under two possible climate scenarios for the period 1980–2100. Our approach can be applied to other glaciated mountain ecosystems to examine the consequences of continued climatic changes.

Glacier National Park since the Little Ice Age. Gibson and Dyson reported in 1939 that nearly all the ice masses in Glacier National Park had been undergoing rapid recession since the turn of the century. In contrast, glaciers had been nourished sufficiently before 1850 (judging from moraine heights, some of which reached nearly 61 meters [m]) to maintain their size over a considerable length of time. During this “Little Ice Age,” which lasted from 1550 to approximately 1850 in North America, mountain glaciers grew and new glaciers formed (Grove 1988). Matthes (1940) indicated that many of the glaciers in the western United States that formed during the Little Ice Age began retreating about 1850 to 1855.

On the basis of tree-ring analysis in the forest fronting the Agassiz and Jackson Glaciers, Carrara and McGimsey (1981) estimated that within Glacier National Park the maximum glacial advances during the Little Ice Age occurred just before 1860. Retreat rates derived from their tree-



Figure 3. Historic and recent photos of Grinnell Glacier. Taken from the same point, the photographs clearly demonstrate the retreat of Grinnell Glacier over 88 years. Photographs: 1910, Fred Kiser, courtesy of Glacier National Park archives; and 1998, Karen Holzer, US Geological Survey.

ring data showed that before 1910 glaciers retreated at a modest rate (< 7 m per year). That rate increased dramatically between 1917 and 1926, reaching more than 40 m per year. Above the tree line, Carrara and McGimsey used terminal moraines, naturalists' notes, photographs, and park records to deduce that the glaciers retreated rapidly (> 100 m per year) between 1926 and 1932 and continued to retreat at more than 90 m per year until 1942. This period of accelerated retreat corresponds to a period of above-average summer temperatures in the climatic record of the region (figure 4). After the mid-1940s the rate slowed, but ablation continued. Carrara and McGimsey estimated that 21.6 square kilometers (km^2) of ice existed in the Mount Jackson–Gunsight Basin area in 1850. By 1979 it had been reduced to 7.4 km^2 . Of the original 27 glaciers in the basin only 10 remained. Most of those that had disappeared were either small or oriented due east. Blackfoot Glacier, originally 7.6 km^2 , divided into seven glaciers measuring approximately 3.0 km^2 in total area; the largest of these are Jackson and Blackfoot.

The pattern of glacial retreat in Glacier National Park corresponds to findings worldwide (Lawrence 1951, Finsterwalder 1962, Heusser and Marcus 1962, Meier and Post 1962, Hoinkes 1968, Burbank 1982, Haeberli et al. 1989, Nesje and Kvamme 1991). Between 1815 and 1976, reports to the International Glacier Commission from various regions of the world indicated that all monitored glaciers had diminished significantly or had completely disappeared, with isolated exceptions such as the rapid advance at Vernagtferner, Austria (Haeberli et al. 1989). Retreat of most mountain glaciers either slowed or stopped in response to the temporary decrease in global temperature from 1950 to 1975. Consequently, between 1977 and 1986, reports indicated new glacial advances. Carrara and McGimsey (1988) likewise show both Jackson and Blackfoot Glaciers in Glacier National Park advancing slightly between 1966 and 1979. Since 1979, however, measurements

of glacial extent in the park indicate renewed retreat, with some glaciers having virtually disappeared (figure 5). On the basis of areal measurement of selected glaciers within the park in September 1993, Key and colleagues (1998) estimated there had been a 73% reduction in glacial coverage since 1850 for the entire park. Only 27 km^2 remained of the 99 km^2 that existed at the time of maximum glacial advance. Out of 84 watersheds, 18 have only 1% of glacial cover remaining, 8 have 2%, and 4 have 3%.

Global climate since the Little Ice Age. A global instrument record for temperature exists for most of the period from 1850 to the present; the record for precipitation is shorter. The Intergovernmental Panel on Climate Change (IPCC) was commissioned by the World Meteorological Organization to examine these records as part of its assessment of rates and causes of climate change. More than 2500 scientists have been involved in these assessments and hundreds of studies have been summarized and released. In 1990, IPCC reported that the global mean temperature had increased 0.45°C ($\pm 0.15^\circ\text{C}$) since the late 19th century. Even after accounting for the uneven distribution of records around the world, incorporating estimates of ocean temperature change, and eliminating urban meteorological stations that reflect the effects of local land-use change on temperature, the pattern of global temperature increase remains the same. The 1990s were clearly the warmest decade in the record: Nine of the hottest years of the climate record dating back to the last century all occurred in the 1990s, with 1998 having the highest mean temperature. Year 2002 is the second hottest on record, followed by 2001.

Recent efforts have focused on extending the instrument record for temperature backward in time by using proxy measures of global temperature and precipitation such as tree-ring widths, borehole temperatures, layers of ice in glaciers, and growth patterns of coral. These reconstructions, such

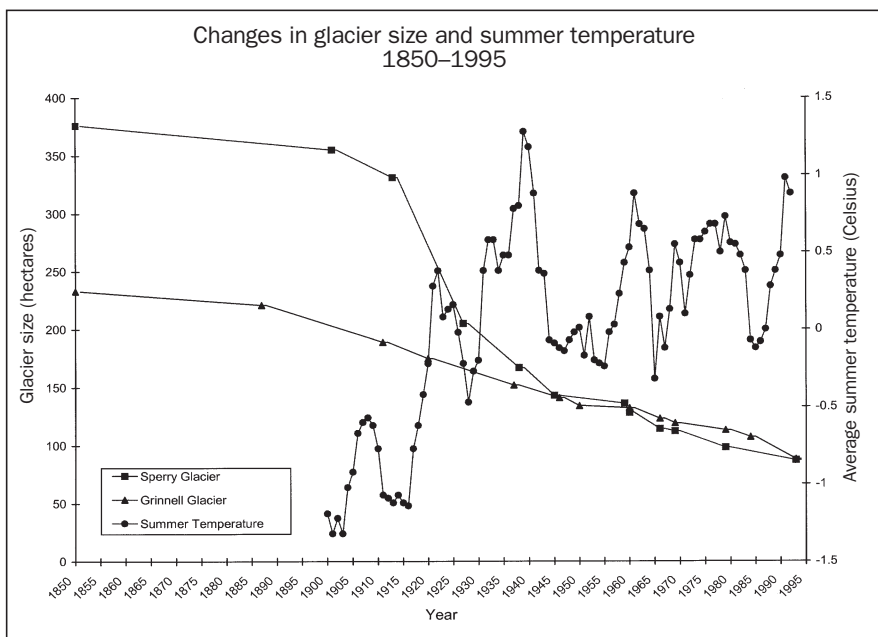


Figure 4. Changes in glacier size and summer temperature, 1850–1995. Summer mean temperatures are variable but have shown an upward trend during the past century. Sperry and Grinnell Glaciers have exhibited a steady decline in area and reflect the trend for nearly all glaciers in Glacier National Park. Provisional data (1996) courtesy of US Geological Survey, Northern Rocky Mountain Science Center.

as those summarized by Crowley (2000), indicate that the global mean temperature is higher now than it has been for 1000 years. Moreover, the temperature increases of the past two decades are unprecedented in rate and magnitude, placing them outside the bounds of natural variation during this 1000-year period.

In alpine regions the warming is even more pronounced (0.6°C to 1.0°C; Schwitter and Raymond 1993, Oerlemans 1994). Alpine glacier growth and shrinkage patterns over time led Wigley and Kelly (1990) to estimate that warming in alpine areas in the 20th century may be greater than in any century since AD 1000 and perhaps as great as the most pronounced century-long warming periods of the last 10,000 years.

In the vicinity of Glacier National Park, instrument records of temperature from the nearby town of Kalispell, at the foot of the mountains, date back to 1880. Shorter records of various lengths exist for locations within the park and on its border. Analysis of a local three-station (Kalispell airport, West Glacier, and Babb) weighted average temperature record, referred to as the KWGB, indicates an overall mean temperature increase in summer of 1.66°C between 1910 and 1980. This increase is greater than that in most alpine regions. Increases since 1980 have been modest, however, and have occurred primarily in the winter mean temperature rather than in the summer mean, underscoring the regional variation in rates of warming among mountain areas. Nonetheless, like most regions of the globe, this mountain environment has

experienced substantial overall warming since 1850.

The relation between climate and glacier behavior. To understand the major causes of specific patterns of glacier retreat in the spatially complex terrain of Glacier National Park, we combined geographic information system (GIS) tools with more traditional approaches to modeling glacier behavior. Oerlemans (1989a) reviewed a complete hierarchy of models relating glacier accumulation, ablation (melting), and advance and retreat to meteorological conditions. Some of the most recent work measures glaciers' responses to climate in terms of either mass balance (whether the glacier's volume is growing or shrinking) or "equilibrium line altitude" (the line across a glacier above which ice is accumulating and below which it is melting). However, because these measurements have been made systematically only in the last 30 years, most modelers have attempted to correlate climate with glacial extent or with the position of a glacier's front edge, often called its terminus or snout. The positions of glacier termini have been recorded over longer periods, either by people or by moraines, the deposits of earth and stones left behind during a glacier's retreat. Because it is mass balance (see box 1) that is affected by climatic change, understanding how mass balance is controlled by climatic factors such as temperature, radiation, and precipitation is an essential first step to modeling the spatial patterns of glacial growth or retreat.

The relation between glacial behavior and meteorological control is not completely understood. Early work by Hoinkes (1954) concluded that the decrease in glacial extent in the Alps during the past century was only to a small degree the result of the increase in summer temperature. However, summer temperature is indicative of overall summer weather conditions, with high temperatures usually associated with clearer skies and therefore increased sunshine duration and intensity. It appeared that solar radiation, coupled with lower albedo resulting from lower wintertime snowfall, accounted for most glacial melting. Although many scientists have studied the relation between glacial melting and solar radiation recently (e.g., Greuell and Oerlemans 1989), they typically calculate effects on the total volume of a glacier's ice. They do not account specifically for the spatial pattern of retreat.

Furthermore, early records of climatic data rarely contained detailed measurements of insolation factors, so most of the initial models describing changes in mass balance and glacier termini were based on temperature and precipitation forcing. They fall into two groups that differ in whether they attribute glacier mass balance and terminus fluctuation to



Figure 5. Boulder Glacier: 1932 (left), 1988 (right). These two views of Boulder Glacier demonstrate the dramatic reduction in ice in Glacier National Park and its ecological consequences. Vegetation has moved in where the ice cave used to be. Photographs: 1932, George Grant, courtesy of Glacier National Park archives; 1988, Jerry DeSanto, National Park Service.

summer temperature–induced melting or to winter (or annual) precipitation–derived snow accumulation. Posamentier (1977) analyzed the effects of both types of forcing. He found that together they explained about 70% of observed terminus variation since 1900. Hoinkes (1968) showed a correlation between the percentage of Alpine glaciers that advanced and both summer precipitation and temperature deviations from the mean. Martin (1974), using multiple regression to evaluate 16 years of measured mass balances in the Alps, found that deviations from the mean of both annual precipitation and May–August temperatures explained between 73% and 90% of the variation in mass balance. Tangborn’s model (1980) for estimating climate–mass balance relations for the Thunder Creek Basin glaciers in the North Cascades of Washington State suggests that the relation is highly sensitive. It appears from his studies of volume changes (from 1884 to 1974) that a decrease in summer air temperature of just over 0.50°C or an increase in winter accumulation of slightly more than 10% (350 mm) from the 1920–1974 average would cause these glaciers to grow continuously.

Analyzing two glaciers in Greenland, Brathwaite and Olesen (1989) found a relation between glacial ablation and the cumulative daily total of degrees above zero. This measure, called a positive temperature sum, is more reflective of total summer weather conditions than mean temperature alone. The correlation between seasonal ice ablation and positive temperature sum was high ($R = 0.98$), which means the factor can explain almost 96% of the variation in glacial melt rate. Brathwaite and Olesen (1989) also found that ablation can be estimated, although less accurately, from summer mean temperature. In this case R was equal to 0.72 and 0.87 for the two glaciers, indicating that between 52% and 76% of the variation in daily melting is explained by mean temperature alone. This result is helpful for analyzing the implications of climate change predictions, because most climatic models predict temperature rather than cumulative degree-days. Because the degree to which various drivers influenced glacier behavior

seemed to vary by region, we examined the glacier–climate relationship for Glacier National Park.

Methods: Analyzing climate and glacier retreat in Glacier National Park

We did not have long-term data on either mass balance or equilibrium line altitude for glaciers in Glacier National Park; hence our work utilizes a well-compiled record of glacial extent to explore the effect of climate on glacier response. We selected the Blackfoot–Jackson Glacier Basin as the site of this study, because it contains the largest concentration of glaciers and a relatively complete record of glacial history (figure 6). The area lies just east of the Continental Divide at an elevation between 1420 and 3064 m. At least five peaks measuring over 2700 m encircle the basin—Gunsight, Jackson, Blackfoot, Logan, and Citadel. Their flanks cradle, on both sides of the Continental Divide, five of the 37 named glaciers remaining

Box 1. Glacier mass balance

What is glacier mass balance? Climatic fluctuations cause variations in the amount of snow that falls and ice that accumulates on a glacier and in the amount of snow and ice lost by melting. These two processes are called accumulation and ablation, respectively. If the accumulation of snow and ice during the winter season exceeds the following summer’s ablation, glaciers increase in volume and are said to have positive mass balances. The opposite conditions create a negative mass balance. Therefore, typically, cold summers and winters with heavy snowfall contribute to a positive ice budget. If a series of positive ice budgets occurs, the volume of ice moving downslope increases and eventually the glacial front advances.

in the park (Sperry, Harrison, Pumpelly, Jackson, and Blackfoot), plus remnants.

Carrara and McGimsey (1988) mapped terminal moraine positions of all glaciers in a 65 km² area on and around Mount Jackson, including the Blackfoot and Jackson Glaciers, for various years between 1850 and 1979, using tree-ring analysis, terminal glacial moraine dating, historical field notes, and aerial photographs. We digitized these glacial extents using the GIS package Arc/Info(r) (ESRI 1992) and, because dated moraines are not evenly spaced, interpolated terminal positions for the beginning of each decade. We then related these estimated glacial extents to data on candidate climate drivers, much of which is decade centered.

We obtained temperature trend data for the Glacier National Park area from Finklin (1986), who summarized historic climate data through 1985. For the year starting each decade (i.e., 1930, 1940, 1950, etc.) we took 11-year means of departures from the calculated 1931–1980 annual and seasonal means. (The 11-year periods were centered on the decade-starting years; thus the 1960 mean represents the average temperature from 1955 to 1965.) These data are based on the KWGB record, which combines average temperature data from three weather stations, Kalispell airport, West Glacier, and Babb, located to the east of the Continental Divide. (The Babb readings are weighted by a factor of 2 to balance the two stations to the west.) Precipitation values for the years starting each decade were also taken from Finklin (1986). They were likewise expressed as the 11-year means of the percentage of the observed or estimated 50-year average annual and seasonal precipitation near or west of the Continental Divide and were centered as was done for the temperature data. The Montana State Library Natural Resource Information System supplemented these data with more recent data, as well



Figure 6. Location of the study area for the development of the glacial retreat model.

as stream discharge measurements from the US Geological Survey (USGS) record for St. Mary River near Babb, Montana.

Modeling glacier area and distribution. We wrote a FORTRAN simulation model entitled GLACPRED (GLACier PREDiction) that predicted post-1979 glacial advance or retreat. GLACPRED predictions are based on an empirical analysis of rates of melting (i.e., changes in glacial area per decade) between 1850 and 1979 and of the spatial distribution of melting. GLACPRED estimates both the glaciated area and the melt pattern for each decade from 1990 to 2100. This integration of simulation modeling with GIS analytical tools is best characterized as geographic or spatial modeling (Hall et al. 2000). The linking of geographical information systems and process modeling, an extension of the concepts given in the book by Hall and Day (1977), is used by increasing numbers of researchers in a wide variety of fields (Goodchild et al. 1992).

Forcing functions. To parameterize the model, it was necessary first to determine the important climatic forcing functions. Using digitized maps of historic glacial termini positions for the Blackfoot–Jackson Glacier Basin, we calculated glacial area extent for each decade. To determine the most significant climatic factors driving the glacier retreat, we used multiple linear regression to analyze glacier area at each decade against a variety of candidate drivers over the period of the local climatic record (1900–1980). The strongest predictors of glacier area were departure from the 1931–1980 mean July–August KWGB temperature and percentage of the 50-year mean annual precipitation; together these produced a correlation with glacier area of $R = 0.96$, indicating that they explain 92% of the change in glacier area over time. Therefore, the model's melt function is parameterized using predicted mean July–August temperature and mean annual precipitation.

Spatial patterns to glacial retreat. It was also important to address the landscape context of the glaciers, not just the volume or extent, to predict the spatial pattern of melting. It is assumed that over a sufficiently long period of time the terminus response of a glacier will reflect in a glacier's overall mass balance the integrated changes induced by climate forcing (Huybrechts et al. 1989). But topography (the structure and position of the land underlying the glaciers) and the flow characteristics of the ice mass also influence the response time of glacial termini (Heusser and Marcus 1962, Hoinkes and Rudolph 1962, Oerlemans 1989b, Huybrechts et al. 1989). Oerlemans (1994) derived an overall effective response time of 25 years (i.e., the response of glacier termini to mass balance perturbations). This estimate corrected for the geometries of 48 glaciers studied worldwide.

As in Oerlemans's analysis, our data revealed a 10- to 25-year lag between significant climatic swings and glacial termini response. The cooling and heavy snow accumulation of the 1950s resulted in the advance of several glaciers in the basin during the 1970s. Thus the glacial response we are seeing now must be integrating the climate changes of several decades past. Because most of Glacier National Park's larger glaciers were valley glaciers in 1850 but are now cirque gla-

ciers (steep-walled, high-mountain, often amphitheater-shaped glaciers), we expected intermediate response times of 10 to 20 years.

We derived the spatial pattern of glacier retreat using GIS tools and three factors required for this analysis—the slope, aspect (solar orientation), and mean July–August temperature for each grid cell in the area. A comparison of the proportional differences of the three factors showed that elevation, which corresponds to temperature, was at least twice as powerful a predictor as either aspect or slope in explaining which cells had melted. A final “probability of melt” factor was assigned to each remaining glacial cell, giving two weights to elevation and one each to slope and aspect. This cell-by-cell approach provided spatially explicit responses over time of each glacier’s retreat in complex topography and provided a means by which we could project future dimensions of the glacier in its landscape context.

This approach determines glacial melt patterns as influenced by topography and then extrapolates that information by simulating future melting. We studied two possible climate scenarios. The first, the carbon dioxide–doubling scenario, is based on the US Environmental Protection Agency’s prediction of a doubling of atmospheric carbon dioxide by year 2030 (Smith and Tirpak 1989) with a concurrent global temperature response of 2.5°C by year 2050. This is IPCC’s “best estimate of climate sensitivity” for a doubling of carbon dioxide. For the period 1990–2100, we incorporate scientists’ prediction (Houghton et al. 1992) of a total temperature increase of 3.3°C and 5% to 10% increases in winter precipitation for middle- and high-latitude continents. The second, the linear temperature–extrapolation scenario, assumes a cyclical climate not linked to human-caused increases in atmospheric concentrations of carbon dioxide. Future temperatures for 1990–2100 are based on linear extrapolation of the global warming trend from 1850 to 1980, portraying the gradual emergence from the Little Ice Age. This leads to a temperature rise of 0.21°C by 2050 at an annual rate of 0.0035°C per year, which we extend to year 2100 based on the estimate (Houghton et al. 1992) of a global temperature increase of 0.45°C ($\pm 0.15^\circ\text{C}$) between 1850 and 1980. We hypothesized that (a) under a carbon dioxide–doubling scenario, glacier melting would be buffered by additional winter precipitation, and the loss of glacial mass would be slowed; and that (b) under a linear temperature–extrapolation scenario, in which there is no increase in precipitation, glaciers would melt at the rate of the 1980s and therefore would disappear by the middle of this century.

Simulating the future. We simulated glacial extent and distribution into the future (beginning with 1980) by subtracting the predicted total glaciated area for each decade from the previous decade’s glacial area to determine the total area of melting. The model then searched the matrix of previously glaciated cells for those frontal cells (i.e., those at the glacier’s edge) with the highest probability-of-melt factor, derived as described above. The model melts those cells and iteratively

continues the melting process until the total area predicted to melt has been reached. The model can be run for any number of future climate scenarios by simply changing the values for predicted summer mean temperature and annual precipitation.

Outcomes of scenarios

Contrary to our initial hypothesis that glacial loss under a carbon dioxide–doubling scenario would be buffered by additional winter precipitation (snowfall), glaciers in the Blackfoot–Jackson Glacier Basin melt rapidly in this scenario (approximately 1.50 km² per decade; table 1). Under the linear temperature–extrapolation scenario, in which we expected glaciers to melt at the 1980s rate and therefore disappear by the middle of this century, melting is slower (0.21 km² per decade; table 2). Despite the difference in the rate of melting under the two scenarios, the spatial melt patterns are similar.

For each climate scenario, we combined the results of GLACPRED and VEGPRED (a companion model written to analyze current vegetation distribution along gradients of summer mean temperature and soil moisture) and then extrapolated into the future. This allowed us to create an image of both vegetation and glacier distribution at each 10-year interval from 1850 to 2100. We draped each image on a three-dimensional terrain model of the Blackfoot–Jackson Glacier Basin using IDRISI geographic information system software (Eastman 1999; e.g., figure 7). Twenty-six images provide a time series computer visualization of a changing landscape (see www.nrmsc.usgs.gov/research/glacier_model.htm).

Glacier changes under a carbon dioxide–doubling scenario.

Under this climatic regime, in which temperatures increase dramatically as a result of radiative forcing caused by accumulating atmospheric trace gases, the glaciers in the Blackfoot–Jackson Glacier Basin disappear completely by the year 2030 (figure 7), despite increasing annual precipitation. The summer mean temperature in 2100 is predicted to reach 19.76°C.

Glacier changes under a linear temperature–extrapolation scenario.

This scenario envisages no increase in mean annual precipitation and a summer mean temperature of 16.94°C in 2100, which is 2.82°C cooler than under the carbon dioxide–doubling scenario. Summer mean temperatures increase by 0.47°C from 1980 to 2100, compared to the 3.30°C increase in the carbon dioxide–doubling scenario.

The surface area of the glaciers in the Blackfoot–Jackson Glacier Basin decreases in the linear temperature–extrapolation scenario from 6.2 km² in 1980 to 3.71 km² by the year 2100. Visual analysis of three-dimensional terrain models (figure 7) reveals that the remaining glaciers generally break into many smaller pieces, which remain for the longest time at the highest elevations. Clearly, solar orientation is not the overriding driver of glacial melt, since even today one of the largest remaining glaciers (Harrison) faces

Table 1. Projected mean summer temperature, precipitation, glacier melt, and glacier area remaining in Glacier National Park, based on a carbon dioxide–doubling scenario.

Year	Mean temperature, July to August (°C)	Percentage of 50-year (1931–1980) mean annual precipitation	Glacier area predicted to melt (km ²)	Remaining glacier area predicted (km ²)
1990	16.61	102.75	1.16	5.05
2000	16.78	103.00	1.15	3.89
2010	17.01	103.31	1.45	2.44
2020	17.30	103.69	1.82	0.62
2030	17.66	104.15	2.29	0.00

south–southeast. Overlay analysis in IDRISI (Eastman 1999) indicates that all the glacier cells remaining in the study lie at elevations above 2461 meters. At the rate of melting predicted in the linear temperature–extrapolation scenario, the glaciers could be expected to last until the year 2277.

Vegetation changes. Although the disappearance of Glacier Park's namesake glaciers is dramatic and has numerous ecological consequences, the vegetation response is also significant. We analyzed the distribution of five taxons according to where they are located along two environmental gradients—summer mean temperature and soil moisture—that explain their presence or absence in 1980. The model redistributes these five vegetation taxons into the future as conditions change in response to changing climate. Rules of succession are applied, as is the time sequence of soil development and establishment of vegetation on deglaciated terrain observed and recorded by Cooper (1923, 1931, 1939, 1942), Lawrence (1958), Crocker and Major (1955), and Ugolini (1968) in Glacier Bay, Alaska. The model predicts that vegetation will move up the mountain and increase in area from 30.70 km² in 1980 to 44.72 km² in the linear temperature–extrapolation scenario and to 50.77 km² in the carbon dioxide–doubling scenario. The pattern is more varied than we hypothesized, however. Rather than predicting clear bands of vegetation progressing altitudinally, the model predicts considerable spatial variation in the distributions. This reflects, in particular, the

variation in soil moisture resulting from the different solar exposure of various facets of the terrain. Conditions change so much that the model can no longer utilize the two-dimensional gradient analysis that is based on conditions in 1980; for example, new taxons that did not exist in 1980, such as grassland, are predicted to appear. From this point forward the model relies on the more generalized, temperature-dependent distributional scheme of Habeck (1987). This results in a pattern much closer to that originally hypothesized, that is, distinct bands moving up the mountain.

In the carbon dioxide–doubling scenario, forests reach their maximum extent around 2020–2050 and decline for 40 years thereafter. The altitudinal rate of forest advance is approximately 20 m per decade. In the linear temperature–extrapolation scenario, there is a general increase in the area of all vegetation types. Coniferous dense (closed canopy) mesic forests become established throughout much of the glacier basin by the year 2100. Actual rates of vegetation expansion could be slower because of constraints on plant dispersal and *in situ* competition (Matthews 1992).

Implications of glacier retreat

The area that is now Glacier National Park has changed dramatically over the past 150 years as glaciers have receded in response to warmer summer temperatures. Vegetation also has changed a great deal (summarized by Elias 1996), although records are far less complete than for the glaciers. As illustrated

Table 2. Projected mean summer temperature, precipitation, glacier melt, and glacier area remaining in Glacier National Park, based on a linear temperature–extrapolation scenario.

Year	Mean temperature, July to August (°C)	Percentage of 50-year (1931–1980) mean annual precipitation (held constant)	Glacier area predicted to melt (km ²)	Remaining glacier area predicted (km ²)
1990	16.56	100.00	0.20	6.01
2000	16.59	100.00	0.21	5.80
2010	16.63	100.00	0.21	5.59
2020	16.66	100.00	0.21	5.38
2030	16.69	100.00	0.21	5.17
2040	16.73	100.00	0.21	4.96
2050	16.77	100.00	0.21	4.75
2060	16.80	100.00	0.21	4.54
2070	16.83	100.00	0.21	4.33
2080	16.87	100.00	0.21	4.12
2090	16.91	100.00	0.21	3.92
2100	16.94	100.00	0.21	3.71

by the simulations, future loss of glaciers will have important implications at multiple scales and for multiple stakeholders.

For the park ecosystem, the disappearance of glaciers is a highly visible reflection of ecosystem-wide change. For

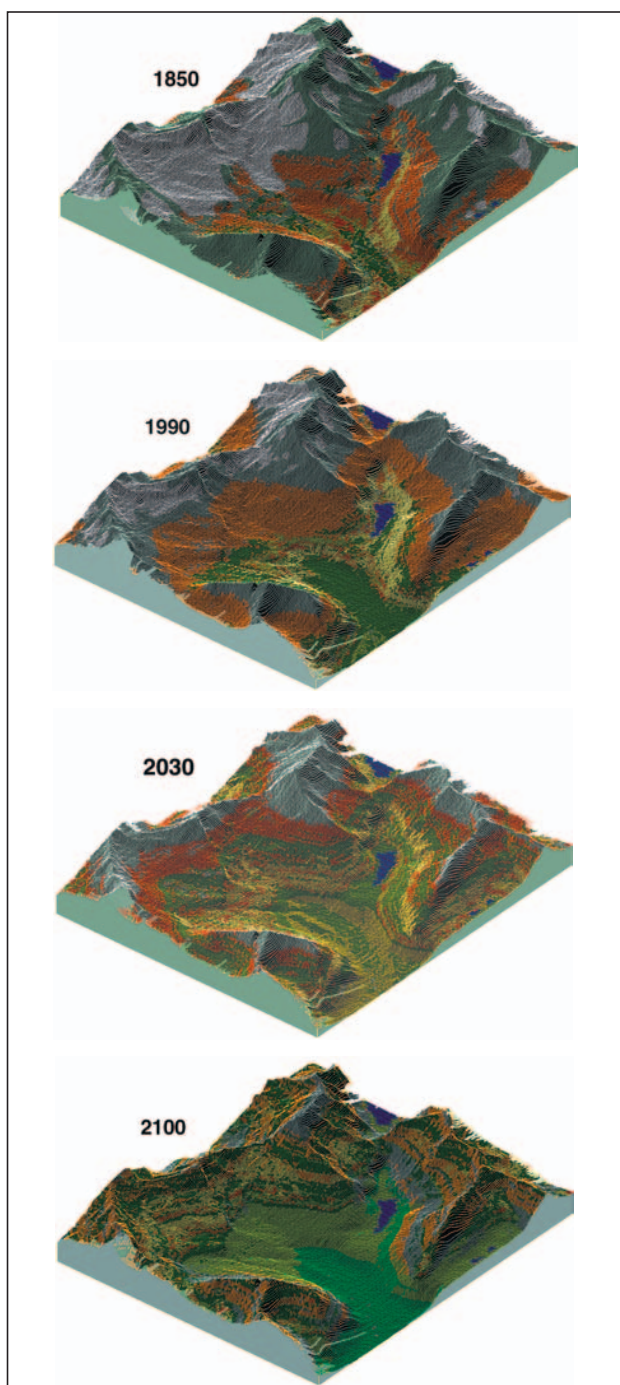


Figure 7. Responses of glaciers and vegetation using the carbon dioxide–doubling scenario at different points in time for the Blackfoot–Jackson Basin in Glacier National Park from 1850 to 2100. Orange represents dry herbaceous cover; yellow, mesic herbaceous cover; red, deciduous trees or shrubs; yellow-green, coniferous open dry cover; forest green, coniferous dense mesic cover; bright green, grassland; white, glacier; gray, rock; blue, water.

instance, the reduced snowpacks that lead to glacier recession also allow high-elevation trees to become established above the current treeline and in subalpine meadows (Peterson 1998). These tree invasions will reduce the diversity of herbaceous plants in open areas. Disappearance of glaciers will change cold air drainages, reduce moisture in glaciated basins during late summer, and increase stream temperatures, thus affecting temperature-sensitive aquatic invertebrates (Fagre et al. 1997). Glacial retreat provides new areas for plant colonization and alters sediment transport in streams. Glacial retreat also reflects other climate-related ecosystem changes, such as changing soil moisture, altered fire frequency, forest growth, and distribution changes in vegetation.

For the park visitor, the disappearance of one of the park's charismatic features presents a great irony and aesthetic loss, because the park was established to protect a landscape that has now changed. Park naturalists report, on the basis of the questions they field, that the general public is very interested in glaciers. Visitors experience a tangible lesson about climate-induced ecosystem change along with the loss of visual beauty.

For the whole world, the shrinkage of the glaciers in Glacier National Park—indeed, the shrinkage of glaciers worldwide—provides powerful evidence of global environmental change and an important means of tracking that change. The simulation model GLACPREP can be used to examine glacial behavior elsewhere and provide glimpses of the possible fate of other glacier-containing mountain areas. The results from both the GLACPREP and VEGPREP models, especially the animated three-dimensional visualization, will help influence and shape the values and policies of people far removed from the mountains and assist them in making appropriate responses to climate change.

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