NPS/GUY ADEMA

Glacier trends and response to climate in Denali National Park and Preserve

By Rob Burrows, Samuel Herreid, Guy Adema, Anthony Arendt, and Chris Larsen

Figure 1. Researcher Adam Bucki records data from test pits and an ablation stake at the index measurement site on Kahiltna Glacier.

GLACIERS ARE A SIGNIFICANT resource of mountain ranges in Alaska and a dominant feature on Mount McKinley. The glaciers of Denali National Park and Preserve, Alaska, are vast, covering 3,779 km² (1,459 mi²), approximately one-sixth of the park's area. Each year, these glaciers gain mass whenever snowfall accumulates at the surface, and they lose mass primarily through surface melting (ablation) during the summer. A glacier's mass balance is the difference between accumulation and ablation and describes the overall health of the glacier. Generally, the average summer season temperature (May to September) drives total ablation for any given year and total winter snowfall drives accumulation. When deviating mass balance trends persist for many years they can result in significant landscape changes that can alter park visitors' experience. These trends have a direct influence on a wide range of hydrologic, ecologic, and geologic systems. For example, glaciers provide a steady base flow of freshwater discharge upon which many ecosystems thrive, and when glacier meltwater and sediment discharge change because of a change in mass balance, these ecosystems are altered. Glaciers also advance and retreat in response to changes in mass balance, which can create new or destroy existing habitat and contribute to changes in the climate of alpine regions. Glacier behavior has a large influence on the braided river systems that are a common feature of the mountain landscapes of Alaska. On a global scale, long-term trends in glacier mass balance can make significant contributions to changes in sea level.

Each of the world's glaciers is a unique entity and has a different set of physical characteristics that dictate how it responds to changes in mass balance and hence climate. Corresponding to the wide variety of mountain shapes and sizes in the Alaska Range is a large array of shapes, sizes, and behaviors among glaciers (Molnia 2008). Important characteristics that determine glacier behavior include size, elevation range, aspect, slope, number and arrangement of tributaries, the area-altitude distribution (hypsometry), and the underlying and surrounding geology of the glacier's basin. Areas with readily erodable bedrock tend to have large areas of surface ice covered by rock debris, which can insulate the ice on the lower glacier, retarding melt rates, changing flow rates, and masking areal retreat. Many glaciers in the Alaska Range exhibit surge-type behavior, which

Abstract

Glaciers cover approximately one-sixth of Denali National Park and Preserve in Alaska. They are not only enjoyed by visitors for their scenic and recreational values but are also an important driver of Denali's diverse ecosystems by defining the hydrologic regime, generating landscape-scale braided river systems, and shaping the landforms of the Alaska Range. Scientists from the National Park Service and University of Alaska–Fairbanks have been researching glacier dynamics and monitoring glacier trends for more than 20 years using glacier outlining from satellite imagery, index mass balance measurements, longitudinal elevation profiles, repeat photography, analysis of regional gravity changes, and other localized research. Mass balance measurements on the Traleika and Kahiltna glaciers showed a cumulative net gain of mass from 1991 to 2003. Since 2003 the mass balance data and satellite-based gravimetric analysis show a net loss of ice mass. Airborne laser and lidar elevation profiles corroborate the mass balance measurements and also show localized changes because of glacier dynamics. Analysis of glacier extent reveals an 8% loss in area since 1950; however, whereas most glaciers lost area, a few surge-type glaciers gained area. Repeated photographs from historical images help refine trends seen in other methods and include dramatic examples of smaller glaciers decreasing in size and a surge-type glacier that has not changed as noticeably. Relations to climate trends are complicated and clearly demonstrate the importance of local influences on glacier behavior and trends. Losses of ice from smaller glaciers and dramatic changes of other glaciers in Alaska suggest that global climatic change may be overwhelming the dominant influence of large-scale climate oscillations on glacier change in Denali.

Key words

climate change, Denali, glacier, Kahiltna Glacier, mass balance, Traleika Glacier

is a periodic acceleration of all or part of the glacier to speeds of 10 to 100 times the normal quiescent speed. Surge-type glaciers may advance in a seemingly unpredictable way when other glaciers are retreating. With such a variety of glaciers it is imperative to have a thorough characterization of the glacier population and of which glaciers can represent the population as study glaciers.

The National Park Service has monitored the mass balance of two glaciers in Denali National Park since 1991. These field measurements give detailed information on mass variations at specific locations, but they have limited spatial coverage. Recently, satellite and airborne technologies have begun to provide information on glacier variations that span broader geographic regions. This article presents long-term field and recent remote sensing data sets that we combine in order to assess the following questions: What are the spatial patterns of ice loss and gain? What are the variability and trends of ice loss and gain through time? What glaciers are representative of and can serve as indexes of the changes taking place among the larger population of glaciers? Do all Denali glaciers exhibit a melting trend attributable to global or regional climate change?

Mass balance measurements

Direct field measurements are a vital component of long-term glacier monitoring programs. At the end of the winter accumulation season, glaciologists probe snow depths, dig pits, and measure snow density to determine the mass gained on the glacier over winter (winter balance). To track ablation these scientists install vertically oriented stakes in the snow and ice surface and revisit these locations to determine the change of the surface relative to the height of the stake (fig. 1). These changes are converted to water-equivalent values based on knowledge of the density of snow or ice that has accumulated or ablated at that place. Snow and ice ablated during the summer is termed summer balance. The units for water equivalent values are meters water equivalent (m w.e.). The sum of the winter and summer balances is the net balance, which is a measure of the annual gain or loss. Researchers then extrapolate the point observations to the entire glacier surface, based on measured or assumed gradients in the various mass balance terms, and calculate the mass balance of the entire glacier. Data from that glacier may be used to represent other unmeasured glaciers in a region. Glaciers chosen to represent broader regions in this way are known as "index glaciers," and are usually chosen based on their location, physical characteristics, and ease of access.

In Denali National Park, Larry Mayo (formerly of the U.S. Geological Survey), and Keith Echelmeyer (formerly of the University of Alaska–Fairbanks) chose the Kahiltna and Traleika glaciers as appropriate indexes because they capture a broad range of elevation and climate gradients spanning from the south to north side of the Alaska Range (Mayo 2001). These researchers established a single observation site on each glacier near the long-term equilibrium line altitude (ELA), the approximate line at which the average glacier mass balance is zero, and they determined mass balance gradients that are used to calculate the entire glacier mass balance from this location.

Index data collected since 1991 tell the story of variability and change in space and time (fig. 2, next page). The average 1991–2010 net balance at the Kahiltna Glacier site (shown in fig. 1) was 0.19 ± 0.27 m w.e., showing that it is just above the long-term ELA, while the average 1991–2010 net balance at the Traleika site was −0.62 ± 0.32, showing that it is below the long-term ELA (fig. 2A). The net balance

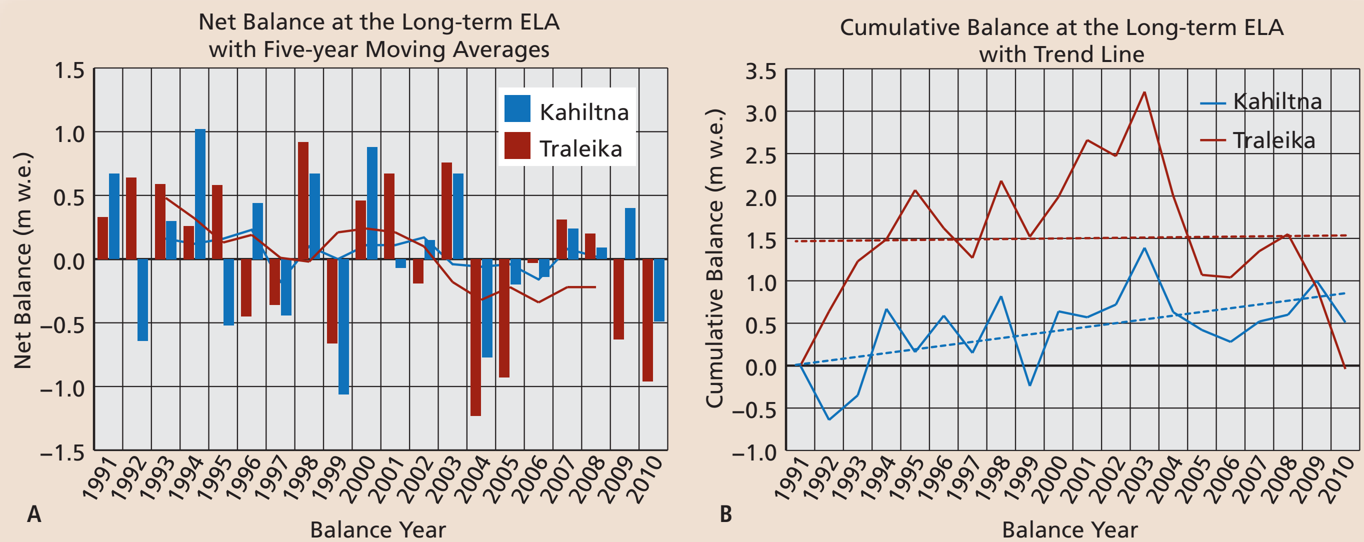

Figure 2. Net and cumulative mass balances on the Kahiltna and Traleika glaciers derived from index stake measurements show relative trends of two of Denali's largest glaciers. Graph A (left) shows the yearly net balance data adjusted to the long-term equilibrium line altitude, along with the five-year moving averages (solid lines). Graph B (right) shows the cumulative net balance and more correctly shows changes in balance that will drive advance or retreat. The trend lines show neutral to positive net balance, which is strongly tempered by the negative trend since 2004.

values are shown with their error estimates to show the relative uncertainty we have in estimating these values. We adjusted these values to the long-term ELAs using a predetermined balance gradient, yielding an approximation of the glacier-wide net balance (fig. 2A). A cumulative sum of the net balance through time shows that both glaciers generally gained mass from 1991 to 2003, but began to lose mass after 2004 (fig. 2B).

Data from each index site demonstrate the distinct precipitation gradient from the south to the north side of the Alaska Range, with significantly less winter snowfall on the north side. Traleika winter balances (average of 0.67 ± 0.19 m w.e.) are 40% lower than those of Kahiltna (average 1.08 ± 0.12 m w.e.).

Measurements from the Gravity Recovery and Climate Experiment (GRACE) offer estimates of regional ice loss across Alaska that can be compared with our field observations. Implemented jointly by the National Aeronautics and Space Administration and the German Aerospace Center, GRACE examines time variations in Earth's gravitation field based on precise measurements of orbital variations of a tandem pair of satellites. Data suggest that glaciers in the portion of the Alaska Range that Denali National Park and Preserve occupies contributed about 5% to the total of ice lost from Gulf of Alaska glaciers from 2003 to 2009 (updated estimates from Luthke et al. 2008). A correlation analysis with the regional GRACE data from 2003 to 2009 shows that the Traleika balances correlate better with the GRACE data, indicating Traleika is more representative of regional conditions than Kahiltna. Further index monitoring and GRACE data, along with current and future research, will help elucidate the relationship of these data to temporal and spatial patterns of other glaciers and climate in the Alaska Range.

Repeat laser altimetry profiling

Using airborne laser and lidar, we have measured elevation profiles along the centerline of a large number of glaciers in the Alaska Range at multiple times between 1995 and 2010. These profiles reveal the range and distribution of glacier change and highlight different glacier responses occurring in various geographic settings. In Denali National Park and Preserve the data set includes repeated profiles on a total of 13 glaciers, with the most extensive data on Muldrow and Kahiltna glaciers. In the most recent measurement interval, 2007–2010, Kahiltna laser profiles indicate little change in surface elevation and hence volume, which is in close agreement with the relatively steady mass balance measured at the index site for that period (fig. 2B). Some minor elevation increases (~10 m) were detected on a small portion of lower reaches of the Kahiltna, likely related to localized ice flow dynamics. On

SAM HERREID, BASED ON UNIVERSITY OF ALASKA–FAIRBANKS DATA

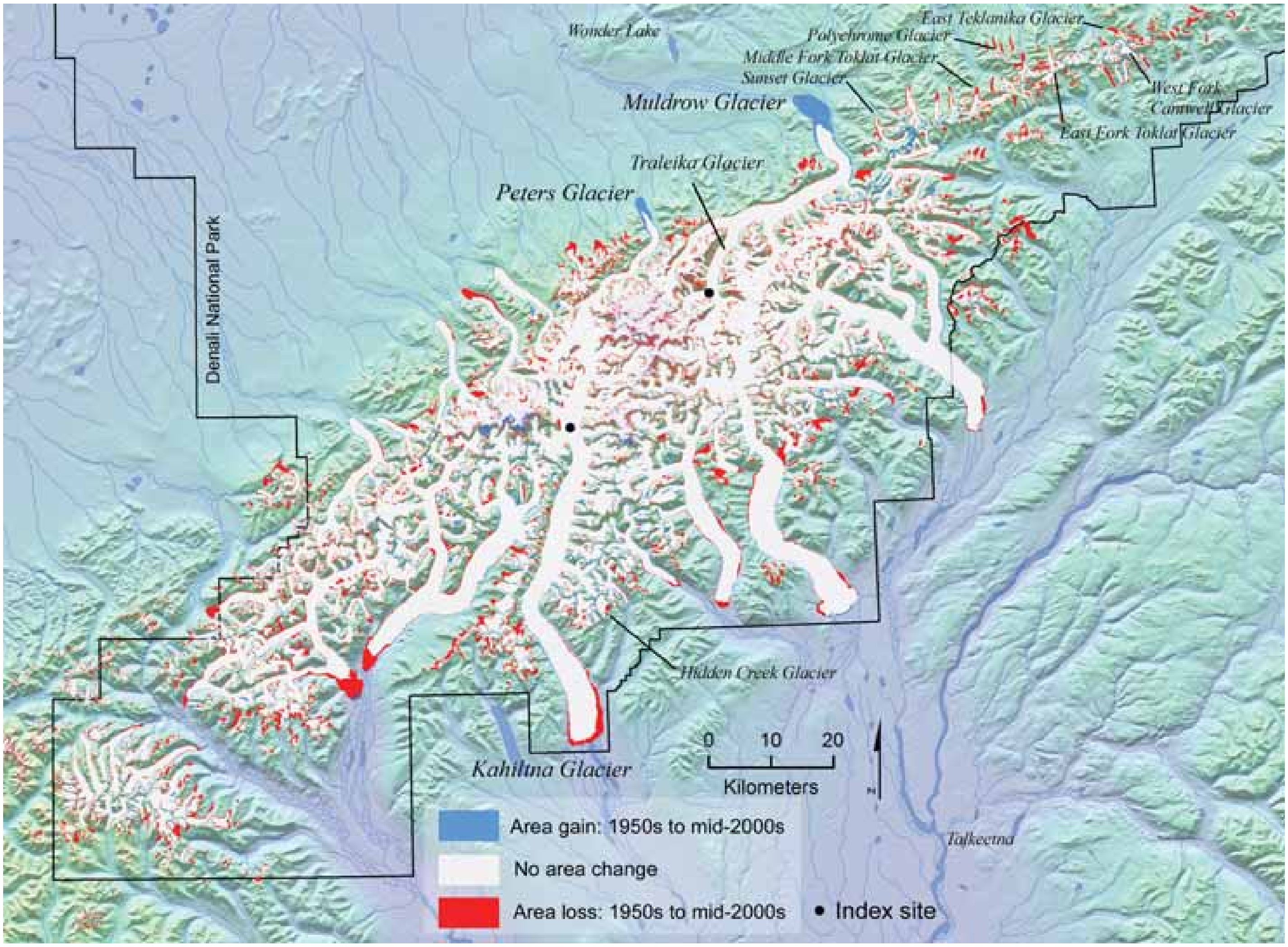

Figure 3. Change in glacier surface area from the 1950s to the present has been about –347 km² (–134 mi²) or –8%. Glacier surface area was mapped by the U.S. Geological Survey using aerial photographs taken in about 1952. These data were provided in digital form by Berthier (2010) with the addition of minor edits. Glacier surface area was again mapped using satellite imagery from 2003 to 2010. Area loss during this approximately 55-year period is indicated in red, gain is in blue, and areas of no spatial change are in white.

Muldrow Glacier, extensive debris cover leads to complex patterns of elevation change when laser profiles are compared with one another. Additional glacier change analysis is possible on Muldrow to better understand how this surge-type glacier redistributes its mass over time. Three data sets are available: the U.S. Geological Survey quadrangle topographic maps from about 1952, a high-precision topographic map produced by Bradford Washburn in the 1970s, and a lidar map of the glacier produced in 2006. This analysis shows overall loss of volume on the lower glacier from about 1952 to 2006, but the 1970s to 2006 comparison shows thickening of much of the area "drained" by a 1956–1957 surge.

Changes in glacier extent

We have compiled a new inventory of glaciers in Denali that will improve our understanding of landscape evolution, glacier response to climate, and contribution of these glaciers to rising sea level. We have manually digitized glacier extents from optical band satellite imagery acquired from 2003 to 2010 and compared them with extents mapped by the U.S. Geological Survey derived from aerial photography collected in approximately 1952. The total area in 1952, 4,126 km² (1,593 mi²), decreased to 3,779 km² (1,489 mi²) in 2003–2010, resulting in a total area change of –347 km² (–134 mi²) or –8%. Uncertainties in these estimates have not been investigated for this region, but we assume an error of ±10%, found in a previous study (Nolan et al. 2005). Most glaciers in the park lost area (fig. 3) during the 55-year period, consistent with observations of volume loss and increases in mean summer temperatures observed in other studies (Hartmann and Wendler 2005; Arendt et al. 2009). However, the extent to which climate changes are expressed as fluctuations in glacier area is complicated by the unique dynamics, geometry, and surface cover of each glacier. For example, many glaciers have a significant amount of debris covering their lower reaches and terminus areas, which can significantly alter terminus response. In addition nearly all the large glaciers on the north side of the mountain system are surge type, periodically transporting large amounts of accumulated mass from an upper reservoir area to the lower terminus area. In the 55-year period documented here, the Muldrow, Peters, and two unnamed glaciers to the east of Muldrow Glacier experienced surge events that caused significant terminus advance (shown in blue in fig. 3). Other glaciers have surged over this time but not with enough volume to cause a significant increase in area.

Glacier dynamics will always be strongly influenced by local features such as terrain, elevation, and local weather patterns, but larger-scale climatic patterns and trends will dominate long-term glacier change.

Repeat photography

Repeat or comparative photography (fig. 4) is a powerful method for documenting and communicating glacier change, allowing us to relate the trends we are seeing with index, altimetry, and extent data. We see substantial change in the small and medium-sized glaciers at lower elevations. A dramatic example is the East Teklanika Glacier, a small valley glacier that has retreated a great deal in the last century. Other striking examples include Polychrome, West Fork Cantwell, Sunset, and Hidden Creek glaciers. In the case of Muldrow Glacier, an aerial photo pair shows the terminus only a couple of years after the surge and then after 47 years of melting and downwasting (see fig. 4). From farther up on Muldrow Glacier, a photo pair shows notable loss of glaciers mantling the mountainside above it, but not thinning of the trunk glacier itself.

Comparison to climate trends

Climate in much of Alaska is strongly driven by seasonal to decadal variations in sea surface temperature of the Pacific Ocean. A multidecadal oscillation driven by these variations is known as the Pacific Decadal Oscillation (PDO), which is an index that tracks anomalies in Pacific Ocean sea surface temperatures (Mantua et al. 1997). The PDO oscillates between positive and negative phases on a 20- to 30-year cycle. In Alaska the positive phase of the PDO generally corresponds with higher air temperatures (particularly winter temperatures) and increased cloudiness and precipitation, whereas the negative phase tends toward cooler and drier climate averages (Hartmann and Wendler 2005).

A look at regional climate data illustrates the effect of PDO phase shifts on long-term trends. Between 1951 and 2001 there was a 1.7°C (3.1°F) increase in the mean annual air temperature in interior Alaska, with the greatest increases occurring in winter and spring (Hartmann and Wendler 2005). The increasing trend is largely explained by the shift from a negative phase of the PDO (1945 to 1976) to a positive phase (1976 to 2005). Thus climate trends related to PDO phase shifts (and other large-scale climate oscillations) must be considered carefully when calculating climate averages, establishing climate-glacier relationships, and interpreting global climate change and warming trends in Alaska. We note that the data on which these trends are based are from relatively low-lying areas and are not necessarily representative of the mountains that the glaciers occupy.

The glacier and climate link may show us trends in mountainous regions of Alaska. Arendt et al. (2009) found that 76% of 46 glaciers measured with repeat laser altimetry across Alaska showed increased rates of ice loss since the mid-1990s, with loss driven by increased summer temperatures. Likewise, the benchmark glaciers (Gulkana and Wolverine) monitored by the USGS show increased rates of ice loss since the late 1980s (Van Beusekom et al. 2010). Before 1989, mass balance values of Wolverine Glacier (and South Cascade Glacier in Washington State) correlated well with the PDO index; however, a dramatic increase in the rate of loss (driven by increases in summer temperatures) since 1989 appears to be less tied to the PDO and other large-scale climate oscillations and is likely forced by global-scale climatic changes (Rasmussen and Conway 2004).

The mass balance data on Kahiltna and Traleika glaciers do not show dramatic losses since 1991 as many other glaciers in Alaska do. We note that unlike the Wolverine and Gulkana glaciers, these glaciers have very high-altitude accumulation areas (on the upper reaches of Mount McKinley) and thus are very cold and less prone to changes from rising temperature trends. Comparing the periods before and

BRADFORD WASHBURN

S. R. CAPPS

NPS/GUY ADEMA

NPS/RON D. KARPILO

Figure 4. Modern photos of glaciers compared with images taken from early scientists and explorers help researchers interpret long-term rates of change. From top to bottom, left to right in pairs: Muldrow Glacier terminus 1959 (soon after the 1956–1957 surge) and again in 2006, Teklanika Glacier 1919 and again in 2004.

after the 1976 PDO-induced climate shift, there was an approximately 20% increase in autumn and winter precipitation that would have offset some of the effects of the increased air temperatures. We also note that average annual temperature for Alaska's interior region from 1976 to 2001, although shifted above the 1951 to 1976 values, reveals a slight decreasing trend (Hartmann and Wendler 2005). This, together with the snowfall increases, could explain the mass balance observations on Kahiltna and Traleika, which indicate cumulative mass gains during a portion of that period (fig. 2B).

The loss of glacier mass in the smaller, lower-altitude glaciers in the eastern portion of the park (as seen in the repeat photography) is in part due to the shift from the cold period known as the Little Ice Age (16th to 19th centuries) to the warmer 20th century. Continued loss of glacial mass from about 1952 to present may be driven by the temperature increase associated with the 1976 shift in PDO. Analysis of terminus retreat on two of Denali's eastside glaciers shows West Fork Cantwell Glacier has been retreating at a constant rate from about 1950 to present and Middle Fork Toklat Glacier has been retreating at an increased rate from 1992 to 2002. Unfortunately, more recent volume loss data for these smaller glaciers and others in the vicinity are not available to indicate if the rate of ice mass loss has increased since the mid-1990s as on many other glaciers in Alaska. Further research and monitoring may elucidate these rates.

Summary and conclusion

Monitoring glacier behavior and trends using a variety of techniques provides insight into the complexity of glacier change and increases our ability to distinguish local effects from regional and global trends. Formal glacier monitoring in Denali began in 1991 and has tracked mass balance trends on two large valley glaciers, with trends neutral to positive from 1991 to 2003 and negative since 2003. Parkwide analysis of glacier extent change since the 1950s indicates a consistent trend of glacial retreat, except for glaciers that have surged. Longitudinal surface elevation profiling and repeat photography reveal relative stability in larger glaciers, but dramatic long-term mass loss on small, relatively low-elevation, valley glaciers characteristic of the eastern portion of Denali National Park and Preserve. These patterns of ice loss are somewhat unique to the western interior Alaska Range and on the larger glaciers appear to contrast with increasing rates of ice loss from USGS benchmark glaciers and large glaciers that border the Gulf of Alaska.

Continued glacier monitoring, along with enhanced climate monitoring, will allow for correlations between climate and glaciers to be refined. Glacier dynamics will always be strongly influenced by local features such as terrain, elevation, and local weather patterns, but larger-scale climatic patterns and trends will dominate long-term glacier change. Projected climate change scenarios up to the year 2080 for Denali indicate a possible increase in summer temperature of 3°C (5.4°F) and a 25% increase in winter precipitation, along with a 6°C (10.8°F) increase in average winter temperature (SNAP 2009). This scenario uses the "intermediate" CO_2 emissions scenario (A1B) from the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart 2000). Glacier mass balance modeling will be required to determine whether the projected temperature increases would be offset by the increased amount of precipitation. In addition the National Park Service is evaluating the likely impacts on visitation and recreation, along with changes to hydrologic and geomorphic conditions and dependent habitats.

Acknowledgments

Glacier monitoring work in Denali has been the result of a long-term collaboration between park staff and staff from the Geophysical Institute at the University of Alaska–Fairbanks. The NPS Inventory and Monitoring Program and the Central Alaska Network have been primary supporters of routine monitoring work. Numerous fieldworkers have contributed data to the long-term record, including Keith Echelmeyer, Phil Brease, Larry Mayo, Adam Bucki, Jamie Roush, Pam Sousanes, Chad Hults, Ron Karpilo, Denny Capps, and others.

References

Arendt, A., J. Walsh, and W. Harrison. 2009. Changes of glaciers and climate in northwestern North America during the late 20th century. Journal of Climate 22(15):4117–4134.

Berthier, E., E. Schiefer, G. Clarke, B. Menounos, and F. Remy. 2010. Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. NatureGeoscience 3(2):92–95.

Hartmann, B., and G. Wendler. 2005. The significance of the 1976 Pacific Climate Shift in the climatology of Alaska. Journal of Climate 18:4829–4839.

Luthke, S. B., A. Arendt, D. Rowlands, J. McCarthy, and C. Larsen. 2008. Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions. Journal of Glaciology 54(188):767–777.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific decadal climate oscillation with impacts on salmon. Bulletin of the American Meteorological Society 78:1069–1079.

Mayo, L. R. 2001. Manual for monitoring glacier responses to climate at Denali National Park, Alaska, using the index site method. Denali National Park contractor's report. Glacier Gnome Consulting, Anchorage, Alaska, USA.

Molnia, B. F. 2008. Glaciers of Alaska. (With sections on: Columbia and Hubbard tidewater glaciers, by R. M. Krimmel; The 1986 and 2002 temporary closures of Russell Fiord by the Hubbard Glacier, by B. F. Molnia, D. C. Trabant, R. S. March, and R. M. Krimmel; and Geospatial inventory and analysis of glaciers: A case study for the eastern Alaska Range, by W. F. Manley.) *In* R. S. Williams, Jr., and J. G. Ferrigno, editors. Satellite image atlas of glaciers of the world. USGS Professional Paper 1386-K. U.S. Government Printing Office, Washington, D.C., USA.

Nakicenovic, N., and R. Swart, editors. 2000. Emissions scenarios. Cambridge University Press, Cambridge, UK. Available at http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/index.htm.

Nolan, M., A. Arendt, B. Rabus, and L. Hinzman. 2005. Volume change of McCall Glacier, Arctic Alaska, from 1956 to 2003. Annals of Glaciology 42:409–416.

Rasmussen, L., and H. Conway. 2004. Climate and glacier variability in western North America. Journal of Climate 17:1804–1815.

SNAP (Scenarios Network for Alaska Planning). 2009. Projected climate change scenarios for Denali National Park and Preserve. Available from http:// www.snap.uaf.edu/files/docs/Climate_Change_Sums/Denali_ClimSum.pdf.

Van Beusekom, A. E., S. R. O'Neel, R. S. March, L. C. Sass, and L. H. Cox. 2010. Re-analysis of Alaskan benchmark glacier mass-balance data using the index method. Scientific Investigations Report 2010-5247. U.S. Geological Survey, Reston, Virginia, USA.

About the authors

Rob Burrows *(rob_burrows@nps.gov) is a physical scientist.* ***Sam Herreid*** *(sjherreid@alaska.edu) is a student researcher.* ***Guy Adema*** *(guy_adema@nps.gov) is a Natural Resource Team leader.* ***Anthony Arendt*** *(arendta@gi.alaska.edu) is an assistant research professor.* ***Chris Larsen*** *(chris.larsen@gi.alaska.edu) is assistant research professor. Burrows and Adema are with Denali National Park and Preserve, Alaska; Herreid, Arendt, and Larsen are with the Geophysical Institute, University of Alaska–Fairbanks.*

PS