



Glacier Monitoring in the Central Alaska Network

Protocol Narrative, Version 1.0



A guest scientist in the Geoscientist-in-Parks program uses a steam drill to prepare for ablation stake measurements on Kennicott Glacier, Wrangell-St. Elias National Park and Preserve, Alaska.

NPS

Glacier monitoring in the Central Alaska Network: Protocol narrative, version 1.0

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Contents

	Page
Figures.....	v
Tables.....	vi
Abstract.....	vii
Acknowledgments.....	viii
Revision Log History.....	viii
1. Introduction.....	1
1.1 Background.....	1
1.2 Rationale for Monitoring Glaciers.....	5
1.3 History of CAKN Glacier Monitoring	13
1.4 Monitoring Objectives.....	18
Mass Balance.....	23
Long-Term Change	24
2. Study Design, Methods, and Operational Requirements	26
2.1 Mass Balance.....	26
2.1.1 Sampling Design	26
2.1.2 Field Methods.....	29
2.1.3 Operational Requirements.....	37
2.2 Long-Term Change	38
2.2.1 Sampling Design	38
2.2.2 Field Methods.....	38
2.2.3 Operational Requirements.....	38
3. Data Management	40
3.1 Overview	40
3.2 NPS Standards	42
3.3 Data Collection.....	43
3.4 Data Entry/Import.....	44
3.5 Quality Control.....	44
3.6 Product Archival and Documentation	45

Contents (continued)

	Page
Deliverable GM-MB Photos.....	47
Deliverable GM-MB gps_logger.....	47
Deliverable GM-MB Positions.....	47
Deliverable GM-MB Notes	47
Deliverable GM-MB met_logger	47
Deliverable GM-MB Weather.....	48
Deliverable GM-MB legacy_stakes	48
Deliverable GM-MB Stakes	48
Deliverable GM-MB Database.....	48
Deliverable GM-MB Outlines.....	49
Deliverable GM-MB Elevations.....	49
Deliverable GM-LTC Elevations	49
Deliverable GM-LTC Velocities.....	50
Deliverable GM-LTC Outlines.....	50
3.7 Closeout.....	50
3.8 Dataset Certification and Publication.....	51
3.9 Analysis and Reporting	52
4. Protocol Revision and Archiving.....	53
Literature Cited	54

Figures

	Page
Figure 1. Glacier distribution in the National Park Service Central Alaska Network (CAKN):	2
Figure 2. The terminus of Hubbard Glacier.	3
Figure 3. Mean 1981-2010 annual temperatures in CAKN.	4
Figure 4. Mean 1981-2010 annual precipitation in CAKN.	5
Figure 5. Aerial (left) and lidar-based bare-ground hillshade (right) images of the same area just north of Anchorage, Alaska.	7
Figure 6. Temperature anomalies predicted for three different emissions scenarios.	10
Figure 7. Precipitation anomalies predicted for three different emissions scenarios.	11
Figure 8. Current (2025) monitoring sites on Kahiltna Glacier.	19
Figure 9. Current (2025) monitoring sites on Kennicott Glacier.	20
Figure 10. Glaciers of Denali National Park and Preserve.	21
Figure 11. Glaciers of Wrangell-St. Elias National Park and Preserve.	22
Figure 12. A typical glacier stake, in this case showing over 6 m exposed above the snow surface.	30
Figure 13. Measuring densities of multiple strata in a snowpit.	31
Figure 14. CAKN glacier monitoring weather stations at Kah 14,200, July 2021.	33
Figure 15. New Sultana weather station being installed in June 2024 on the south ridge of Mt. Foraker.	34
Figure 16. Examining stratigraphy on a retrieved core section.	36
Figure 17. Standardized CAKN Project Reference architecture in the IRMA DataStore.	40
Figure 18. Line of Sight.	41
Figure 19. Long-term monitoring project data management life cycle.	42
Figure 20. Data deliverables are defined in the monitoring protocol and archived in IRMA dataset references after each re-measurement cycle.	51

Tables

	Page
Table 1. Revision History Log	viii
Table 2. Glacier characteristics in WRST and DENA.	6
Table 3. History of repeat protocol-driven measurements on CAKN glaciers.	16
Table 4. Overview of objectives and activities for the CAKN glacier monitoring program.	18
Table 5. Standard Operating Procedures incorporated as part of the CAKN glacier monitoring protocol.	26
Table 6. Glaciological mass balance measurement sites on Kahiltna and Kennicott Glaciers.	27
Table 7. CAKN glacier monitoring data deliverables.	46

Abstract

Two of the three national parks that comprise the National Park Service Inventory & Monitoring Program's Central Alaska Network (CAKN) are covered by large quantities of glacier ice. Wrangell-St. Elias National Park and Preserve has 3,121 glaciers, and Denali National Park and Preserve has 881. These glaciers cover significant portions of the parks and exert substantial influence over the surrounding landscapes with impacts on weather, vegetation, animal migration, river flow, aquatic life, and even downstream marine ecosystems. They also provide a significant attraction—and hazard—for visitors. These glaciers are changing rapidly, primarily due to the influence of warming air temperatures. The impacts of glaciers on park resources and visitors are not only significant but also quickly evolving, with important consequences for park management. For all these reasons, the Central Alaska Network has identified glaciers as one of the vital signs that should undergo long-term monitoring. This document describes the protocol for conducting that monitoring program.

Glacier monitoring in the CAKN parks began in 1991 with measurements of mass balance (snow accumulation and melt) and surface elevation at one site on Denali's Kahiltna Glacier. The monitoring has evolved since that time to include mass balance measurements on a second large glacier (Kennicott Glacier) in Wrangell-St. Elias. Those two glaciers are highly visited, compared to most other glaciers in the parks, and are relatively accessible for monitoring purposes. The objectives of these measurements are to document seasonal and interannual changes in the primary climatic forces that control glacier change: snow accumulation and melt. Combined with periodic remeasurements of the glacier boundaries and surface elevations, the protocol records mass balances of these two glaciers with both glaciological and geodetic methods, allowing analysis of total mass balance with accompanying understanding of the climatic forces behind it.

The glacier monitoring protocol also calls for the use of increasingly available remote sensing techniques to document changes in glacier areas, surface elevations, and surface velocities for a broad collection of park glaciers. Outside the scope of the CAKN protocol, boundaries of all park glaciers have been digitized twice over the last decade, and this protocol calls for continuation of that decadal inventory using whatever remote sensing data and techniques are most applicable at each decadal time step. A subset of the largest park glaciers is also slated for measurement of surface elevations every 4–6 years, continuing the measurements made by Operation IceBridge since the mid-1990s.

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Revision Log History

All edits and amendments made to this document since its inception should be recorded in Table 1. Users of this protocol should promptly notify the project managers of recommended edits or changes. The project managers will review and incorporate suggested changes as necessary, record these changes in the revision history log, and modify the date and version number on the title page of this document to reflect these changes.

Table 1. Revision History Log. ^A

Previous Version #	Revision Date	Author	Changes Made	Reason for Change	New Version #
None	–	–	–	–	–
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^A This is the first version of this protocol, so there is no information about previous versions yet.

1. Introduction

1.1 Background

The Central Alaska Network (CAKN) is part of the National Park Service (NPS) Inventory and Monitoring (I&M) Program. The Inventory and Monitoring Program is the result of the 1998 National Parks Omnibus Management Act. This act directs NPS to “establish baseline [resource] information and to provide information on the long-term trends in the condition of National Park System resources.”

To accomplish this task, the NPS has grouped parks into 32 networks based upon broad ecological similarities. CAKN (Figure 1), one of four networks in Alaska, is composed of three conservation units: Wrangell-St. Elias National Park and Preserve (WRST), Denali National Park and Preserve (DENA), and Yukon-Charley Rivers National Preserve (YUCH).

The lands encompassed by CAKN are vast: the three park units within this network contain over 21.7 million acres (88,000 km²) and span an area that is around 485 miles (780 km) from east to west and around 410 miles (660 km) from north to south. Based on area, NPS land within this single network represents one-fourth of all the land in the National Park System. Elevations range from sea level to nearly 20,320 feet (6,200 m) and encompass several physiographic and climatic regions, including 12 of Alaska’s 32 ecoregions (Nowacki et al. 2002). Biomes range from boreal to maritime with a substantial transition zone. Most of WRST and DENA and all of YUCH have a continental climate (relatively low precipitation, long extremely cold winters, and short hot summers), while the south side of the Alaska Range in DENA and the coastal areas of WRST have a maritime climate (cool wet summers, relatively mild winters with extensive snowfall).

Each network has developed and prioritized a suite of “vital signs” for long-term monitoring (MacCluskie and Oakley 2005). The primary goals of vital signs monitoring are to:

1. Determine status and trends in selected indicators of the condition of park ecosystems to allow managers to make better- informed decisions and to work more effectively with other agencies and individuals for the benefit of park resources.
2. Provide early warning of abnormal conditions and impairment of selected resources to help develop effective mitigation measures and reduce costs of management.
3. Provide data to better understand the dynamic nature and condition of park ecosystems and to provide reference points for comparisons with other altered environments.
4. Provide data to meet certain legal and congressional mandates related to natural resource protection and visitor enjoyment.
5. Provide a means of measuring progress toward performance goals.

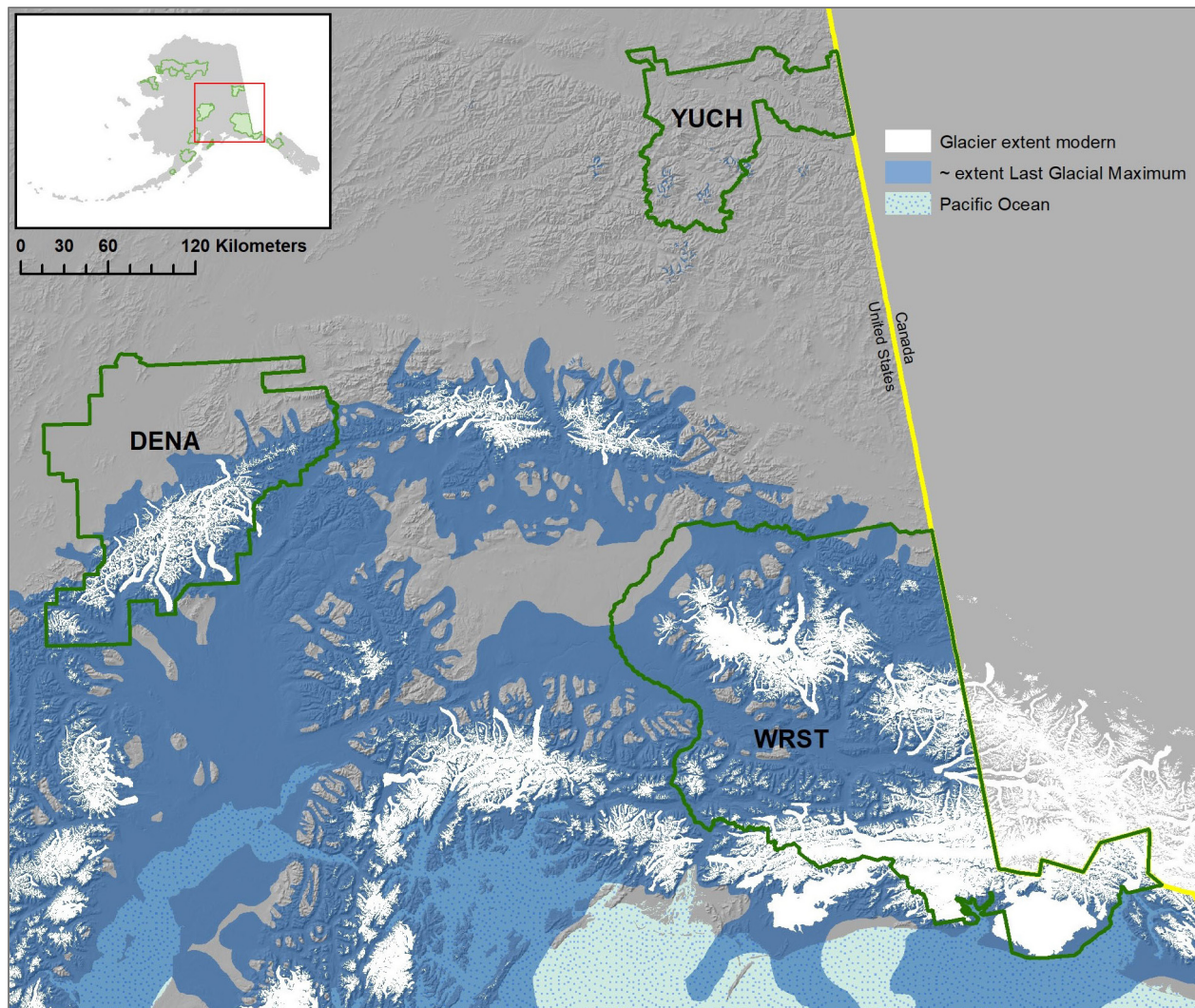


Figure 1. Glacier distribution in the National Park Service Central Alaska Network (CAKN): Wrangell-St. Elias National Park and Preserve (WRST), Denali National Park and Preserve (DENA), and Yukon-Charley Rivers National Preserve (YUCH). There are no modern glaciers in YUCH. Modern glacier cover (based on the Randolph Glacier Inventory 6.0; Pfeffer et al. 2016) is shown in white. Transparent blue shading shows approximate extent of glaciers at the Last Glacial Maximum (LGM) around 22,000 years ago (Kaufman et al. 2011). Pacific Ocean is shown stippled. Note there is no terrain or LGM glacier extent shown for Canada. NPS

Because CAKN parks are pristine and unstudied relative to most national park units, vital signs in the CAKN monitoring program focus on measures of general physical/ecological structure and function. While many long-term ecological monitoring programs have focused on local-scale anthropogenic causes of change, direct local-scale human effects tend to be more limited in our systems. Both physical and ecological systems are, however, changing in response to anthropogenic climatic change, and vital signs monitoring in CAKN is designed to detect these changes. Scientists are already observing changes in high-latitude ecosystems due to climate warming; moreover, Arctic and subarctic environments may be especially vulnerable to even slight shifts in temperature regimes. The relatively untouched nature of these vast parklands thus provides the CAKN with important

baselines against which to measure and evaluate the direction and magnitude of changes brought about by human influences on regional and global scales.

Glaciers have been identified as one of the vital signs of environmental condition that will be monitored over the long term in CAKN (MacCluskie 2005). Glaciers are one factor among a group of physical drivers of habitat conditions that also includes climate, hydrology, seasonal snow cover, permafrost, fire, flooding, landslides and avalanches, and disturbances related to tectonics (earthquakes and volcanoes). Many of the topics that appear in this list are linked by their role in the water cycle. Temperature is critical in the hydrological cycle because of the thermal thresholds that determine melting/freezing and evaporation/condensation, and this is especially true of glaciers, which, by definition, form in areas where solid precipitation (snow) accumulates faster than subsequent melt can remove it, causing the excess snow (which is gradually transformed to glacier ice) to flow downhill into a warmer microclimate where melt exceeds accumulation. Where these processes combine to create and maintain glaciers (Figure 1), glaciers are one of most important landscape-scale determinants of ecosystem structure and function (Figure 2).



Figure 2. The terminus of Hubbard Glacier. The largest temperate tidewater glacier in the world, it originates in Canada, crosses the international border to enter Wrangell-St. Elias National Park and Preserve, and terminates in the Pacific Ocean's Disenchantment Bay. The glacier is clearly a driver of landscape processes, but at 1,506 square miles (3,900 km²) it is perhaps appropriate to recognize that from some perspectives it *is* the landscape. NPS

Glaciers, defined here as bodies of ice, formed from perennial snow, that flow through internal deformation and basal sliding and cover an area greater than 0.1 km², are abundant in the CAKN parks but they are not uniformly distributed (Figure 1). The conditions that favor glaciation include some combination of heavy snowfall and cold temperatures, and these conditions are in the most general sense met in the mountains of CAKN. The coastal ranges of southern WRST are the most heavily glaciated, despite relatively warm temperatures in such close proximity to the coast (Figure 3). This is due to very high precipitation/snowfall (Figure 4). The more interior glaciers of WRST and of DENA form in high mountains that are both colder and drier than the coastal mountains (Figures 2 and 3). But cold temperatures alone are not sufficient to build or maintain glaciers, which are absent from the cold, dry hills of YUCH and were rare there even during the last ice age around 22,000 years ago (typically referred to by glaciologists as the Last Glacial Maximum; Figure 1). In contrast, the most recent complete count of glaciers in the Alaska parks found 881 glaciers in DENA

covering 1,442 square miles (3,734.5 km²), and 3,121 glaciers in WRST covering 11,232 square miles (29,041 km²; Loso et al. 2014). These figures, and indeed some of the glaciers themselves (Figure 2) dwarf the approximate 260 square miles (675 km²) combined coverage of all glaciers in the contiguous 48 United States (Pfeffer et al. 2016) and speak directly to the landscape importance of glaciers in these Alaska parks. That importance is addressed in greater detail in the next section.

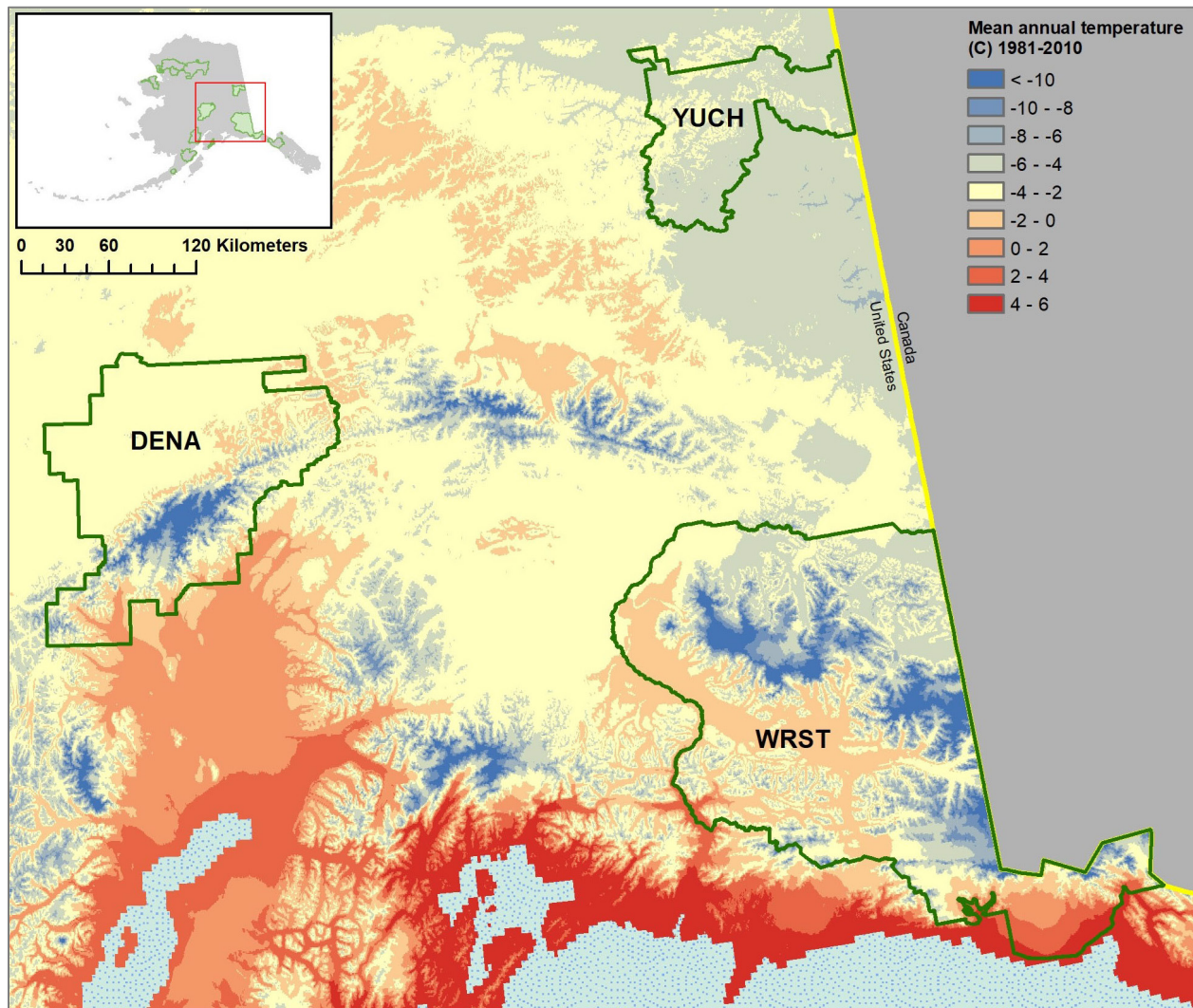


Figure 3. Mean 1981-2010 annual temperatures in CAKN. Reference Figure 1 for corresponding modern glacier extents (data from PRISM Climate Group 2018). NPS

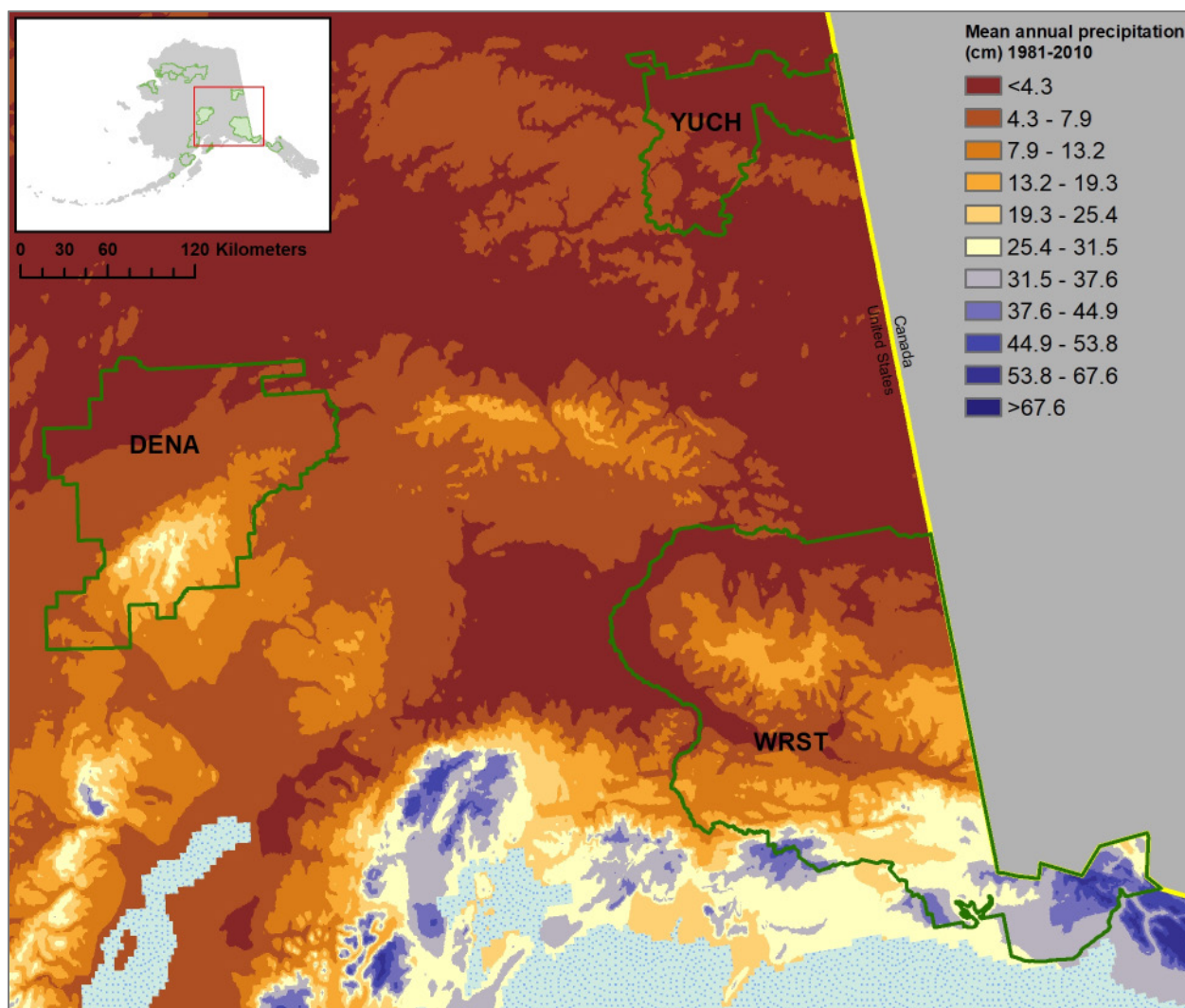


Figure 4. Mean 1981-2010 annual precipitation in CAKN. Reference Figure 1 for corresponding modern glacier extents (data from PRISM Climate Group 2018). NPS

1.2 Rationale for Monitoring Glaciers

Glaciers are more than attractive ornaments in the two glacierized parks of CAKN: Wrangell-St. Elias National Park and Preserve (WRST) and Denali National Park and Preserve (DENA). They comprise a substantial portion of these landscapes (18.9% for WRST, 15.0% for DENA; Table 2), and their presence exerts substantial control over physical and ecological processes on much of the adjacent, non-glacierized landscape.

Examples of physical processes and landscape characteristics impacted by glaciers include isostatic depression; physical erosion of bedrock; chemical weathering of bedrock and sediments; transport and deposition of unconsolidated glacier sediments; glaciofluvial discharge; hydrograph seasonality; fluvial and lacustrine water temperature and quality; lake formation and drainage; nearshore oceanographic conditions; katabatic winds and other microclimatic effects; and terrestrial basin topography with associated impacts on slope stability. Examples of ecological processes and

landscape characteristics impacted by glaciers include soil development (and destruction, in the presently rare case of advancing glaciers); primary plant succession; fluvial and lacustrine habitat conditions for aquatic invertebrates, anadromous fish, and other aquatic organisms; nutrient transport in rivers and into downstream lakes and oceans; supraglacial habitat for microorganisms and insects; travel corridors for wildlife and birds; and provision of iceberg-rich habitat for harbor seals and other marine organisms. Notable publications that dive into some of these phenomena with reference to the hundreds of pertinent studies include Ballantyne 2018, Fastie 1995, Gurnell and Clark 1987, Lydersen et al. 2014, Milner et al. 2017, O’Neel et al. 2015, and Pitman et al. 2021.

Table 2. Glacier characteristics in WRST and DENA. Modern values from Loso et al. (2014). Last Glacial Maximum values are approximate and taken from Kaufman et al. (2011). Glacier area for complete glaciers includes the entirety of each glacier that is at least partly within the park boundary. All other values reflect only the portions of glaciers within the park boundary.

Park		Modern				Last Glacial Maximum	
Park	Park Area (km ²)	Glacier (#)	Glacier Area Complete Glaciers (km ²)	Glacier Area Inside Park Boundary (km ²)	Glacier Cover Inside Park Boundary (%)	Glacier Area Inside Park Boundary (km ²)	Glacier Cover Inside Park Boundary (%)
WRST	53,321	3121	29,041	18,534	34.8%	50,055	93.9%
DENA	24,585	881	3,734	3,682	15.0%	12,524	50.9%

It is also notable that much of the presently non-glacierized portions of these park units was under ice during the Last Glacial Maximum, approximately 22,000 years ago (Kaufman et al. 2011). Table 1 shows that over half of DENA, and well over 90% of WRST were believed to be ice-covered at the peak of this last ice age. The extensive ice sheet that covered most of southern Alaska (Figure 1) took thousands of years to retreat back to something approximating modern glacier extent, and during that time exerted substantial controls over plant colonization (Ager and Brubaker 1985), proglacial lake development and drainage (Ferrians 1989), fish and animal colonization patterns (Wiedmer et al. 2010, Zink and Gardner 2017) and even human settlement and migration (Smith 2019), to name just a few examples. Even today, many thousands of years later, the signature of past glaciations is prominent in the deglaciated portions of southern Alaska. Where lidar-derived digital surface models are available, the ground topography masked by dense vegetation often provides surprisingly stark evidence of the effects of glaciers. The example in Figure 5, while not taken from an NPS unit, shows how apparently gentle topography adjacent to Alaska’s biggest city bears a lasting imprint of its deep glacial past. The same is true in many of Alaska’s national parks: vegetation, streams, soils, and human infrastructure are in many cases strongly influenced by these remnant landforms, even far from modern glaciers. Conversely, the evidence of these past glacier fluctuations provides valuable evidence about Earth’s past climates.

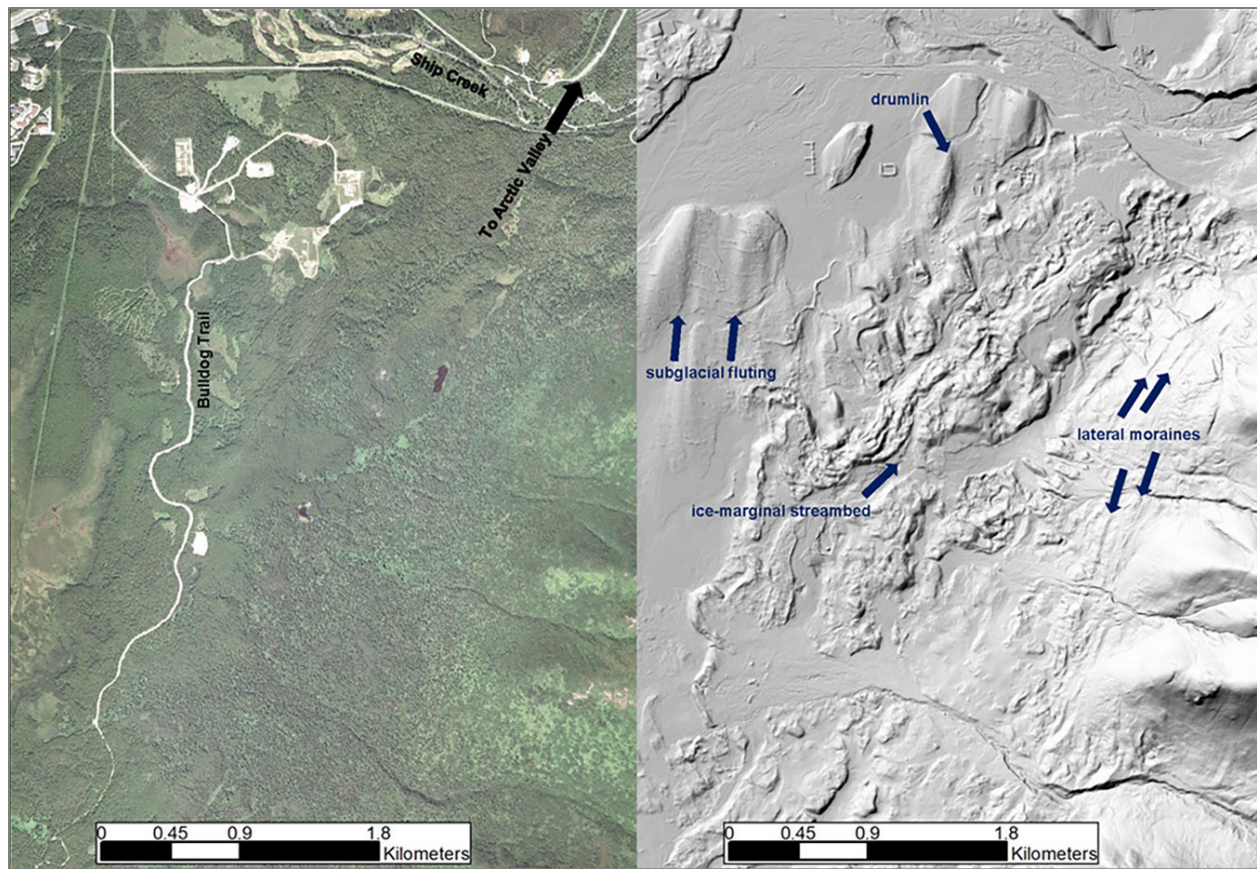


Figure 5. Aerial (left) and lidar-based bare-ground hillshade (right) images of the same area just north of Anchorage, Alaska. Vegetation obvious in the aerial photo hides, but importantly is growing in response to, the glacial landforms evident in a bare-ground image. Annotations on the left provide landscape orientation, and on the right point out abandoned glacial features more than 14,000 years old. NPS

Because they are extensive, and were formerly even more so, glaciers and their effects are important to understand. This is even more true because glaciers are presently changing so rapidly. Measures of modern glacier change are abundant and well-constrained. Globally, a recent study estimates that glaciers (not including global ice sheets) lost 267 gigatons per year of ice (averaged over the period 2000–2019, to melt and calving). This corresponds to 0.75 mm/yr of sea level rise, and is more than the ice loss, in the same period, of the Greenland and Antarctic ice sheets (Hugonnet et al. 2021). Equally important, this global study finds an acceleration of mass loss ($62 \pm 8 \text{ Gt yr}^{-1}$ per decade) during the same time period. The Hugonnet study echoes other recent global studies in finding that Alaska’s contribution to global mass loss is high, and disproportionately so, even given its extensive glacier cover. Hugonnet et al. (2021) conclude that Alaska contributes 25% of the total sea level rise attributable to global glacier loss, Gardner et al. (2013) concluded that Alaska contributes 19% of the global total, and yet Alaska’s total glacier cover is only 17% of the total (again, non-icesheet) global glacier cover. Details and methodologies among these and other studies (e.g., Zemp et al. 2019) vary, but the clear message from all of them is that Alaska is pulling its own weight—and then some—with respect to glacier mass loss and consequent sea level rise.

Studies within Alaska confirm, at a more granular level, the pace, ubiquity, and acceleration of glacier shrinkage in recent decades. The Glacier Status and Trends project (Loso et al. 2014) completed a statewide inventory of Alaska's glaciers at two epochs: the 1950s (when most topographic mapping was done) and the 2000s (latest available high-resolution satellite imagery at the time of the study). In aggregate, the 7,561 glaciers within Alaska national parks in the 2000s shrank by 8% (3,725 km² less ice-covered area) over that approximately 50-year period. WRST glaciers, specifically, shrank by 5% in that time, and DENA glaciers lost 8%. More recently, Roberts-Pierel et al. (2022) used automated techniques to outline biennial Alaska glacier boundaries during a more recent period, from 1985 to 2020, that partially overlaps with the latter ~third of the period measured by Loso et al. (2014). Statewide, Roberts-Pierel found net glacier area loss of 13%, with regional losses of 15.5% in the northeast gulf (including coastal WRST) and 8.4% in the interior (including DENA and northern WRST). Roberts-Pierel's inventory, completed using different techniques, confirms the ubiquitous glacier loss found by Loso et al. (2014) and suggests, at least in the coastal areas, an acceleration of loss.

Loso et al. (2014) also analyzed surface-elevation changes (a proxy for volume/mass loss) for a subset of Alaska glaciers. In total, 17 glaciers were monitored in WRST and 9 in DENA over multi-year epochs spanning from 1994 to 2012. [Note that some of these results, inadvertently omitted from Loso et al. 2014 by a typesetting error, were republished in Loso 2020.] Of the glaciers/epochs measured in WRST, most had negative mass balances (a negative area-averaged thinning rate over the entire glacier, indicating thinning) of up to 1.65 m/yr, but some were very close to neutral (± 0.10 m/yr). Some conspicuous exceptions with very high (up to 5.87 m/yr) or low mass balances (down to -8.56 m/yr) were all part of the massive, surging Bering Glacier complex which cyclically gains and loses mass in response to its surge cycles (Burgess et al. 2012). In WRST, the median mass balance (across all glaciers and epochs observed) was -0.54 m/yr. Of the glaciers/epochs measured in DENA, all non-surging glacier had negative mass balances with values ranging from -0.40 to -1.60 m/yr. Here again, the exceptions were Muldrow and Traleika Glaciers, which are well-known surging glaciers (Harrison 1964). In DENA, the median observed mass balance was -0.76 m/yr.

Larsen et al. (2015) performed subsequent analysis of these and other elevation data to derive regional mass balance estimate for interior Alaska (roughly corresponding to glaciers in DENA and the northern half of WRST) and southcentral Alaska (southern WRST). In both areas, he found that land-terminating glaciers were the most consistent in their response to climatic forcing. The mass balance of lake and tidewater-terminating glaciers are subject to an additional mass balance forcing related to their subaqueous (or submarine) tongues. For the land terminating glaciers only, the derived median mass balances from 1994-2013 were -0.88 m/yr (interior) and -0.73 m/yr (southcentral). These values, based on precise airborne laser measurements, attest to a strong and widespread trend of net ice loss throughout the CAKN parks. Importantly, the Larsen study further concludes that surface mass balance (snow accumulation and melt) are the critical drivers of this mass loss. The more variable and unpredictable losses of ice at lake-terminating and tidewater glaciers are an important contributor, but "ultimately the dominance of surface mass balance will result in more widespread wastage of these glaciers under a warming climate" (Larsen et al. 2015).

The climate is warming. Glaciers respond with great sensitivity to climate. And the results summarized above, along with countless other research efforts (e.g., Marzeion et al. 2014), confirm that glacier loss is indeed occurring in response to the warming climate. It is not the central aim of this narrative to predict future glacier loss, but it seems valuable to briefly consider the prospects for future change. Borrowing from work done by Loso et al. (2014) but with a specific focus on the CAKN area, we use Scenarios Network for Alaska and Arctic Planning (SNAP) outputs (SNAP 2013) to visualize potential future changes in temperature and precipitation over a half-century timescale. We compared predicted average air temperature and precipitation—on the basis of three different forcing scenarios—from the period 2060–2069 to the period 2010–2019 (nominally “2065” and “2015” in the figures). The three scenarios examined were the A1B, A2, and B1 scenarios (IPCC SRES 2000), summarized here:

- A1B: A more integrated world with rapid economic growth, global population of 9 billion by 2050 and then declining, and a quick spread of efficient technologies.
- A2: A more divided world with self-reliant nations, continuously increasing population, and regionally oriented economic development (highest greenhouse gas emissions).
- B1: An ecologically friendly world with rapid economic growth, rapid population growth to 9 billion by 2050 but then declining, reductions in material usage and an emphasis on environmental stability (lowest greenhouse gas emissions).

Predicted annual and summer temperature changes are shown in Figure 6. Warming is predicted for all parks at all time intervals under all three scenarios. Annual average warming is greater than summer only warming (because the most warming is expected in winter), but if we focus on summer—when glaciers are most sensitive to temperature—we see a very consistent prediction of 1 to 2° warming for all parks under scenarios A1B and A2, and a slightly more modest prediction of 0 to 1° C warming under B1. Comparable maps of precipitation trends are shown in Figure 7. The dominant statewide prediction is an increase of total precipitation by <25 cm, with slightly greater summer wetting in DENA’s Alaska Range. Over the winter months of DJF, when glaciers receive much of their annual accumulation, this trend is uniform under all scenarios except for more significant increases in precipitation in the coastal mountains under scenarios A2 and A1B.

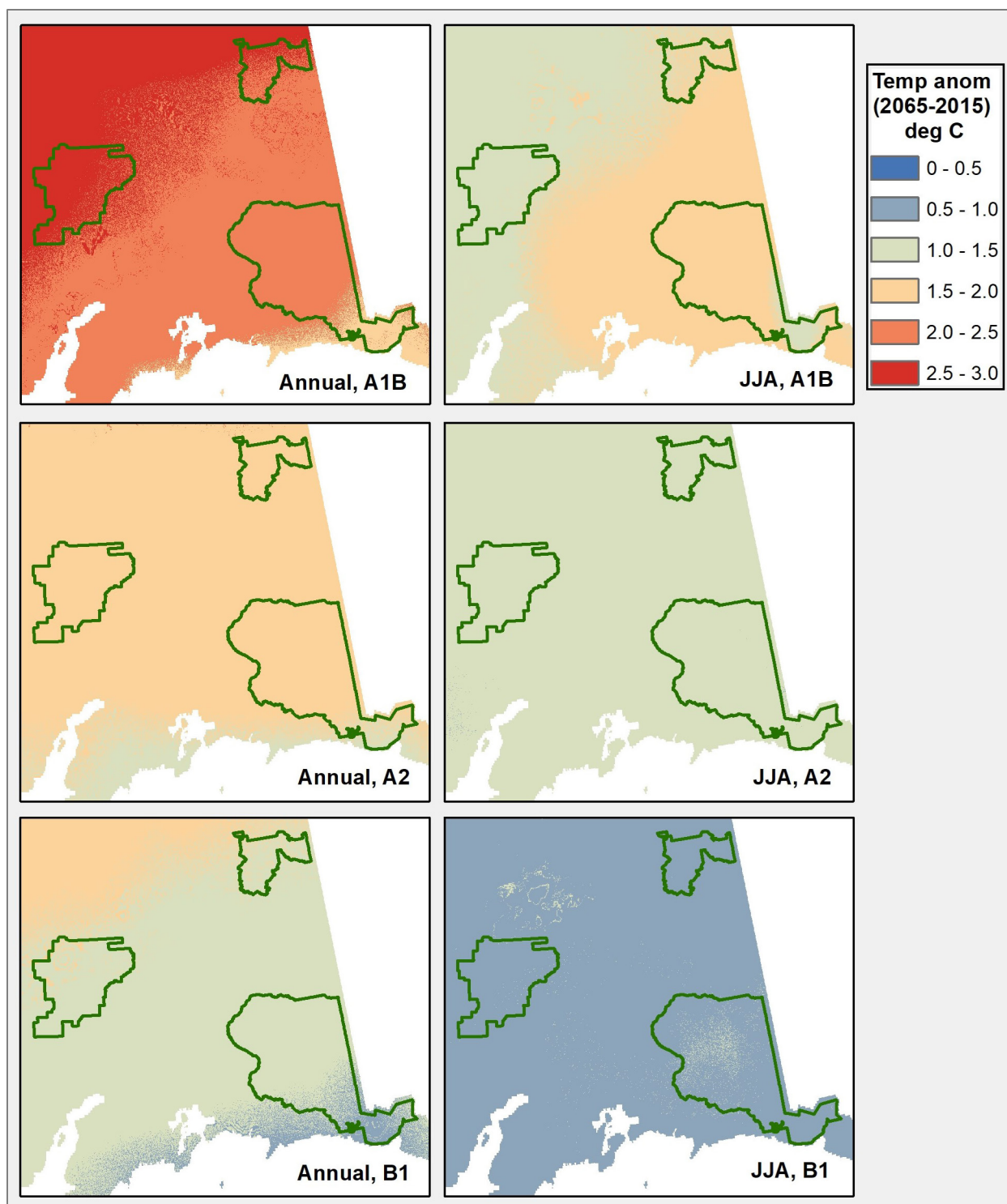


Figure 6. Temperature anomalies predicted for three different emissions scenarios. Anomalies compare predicted average temperatures from 2060–2069 to 2010–2019. Annual averages at left, summer months only on right ('JJA'). NPS

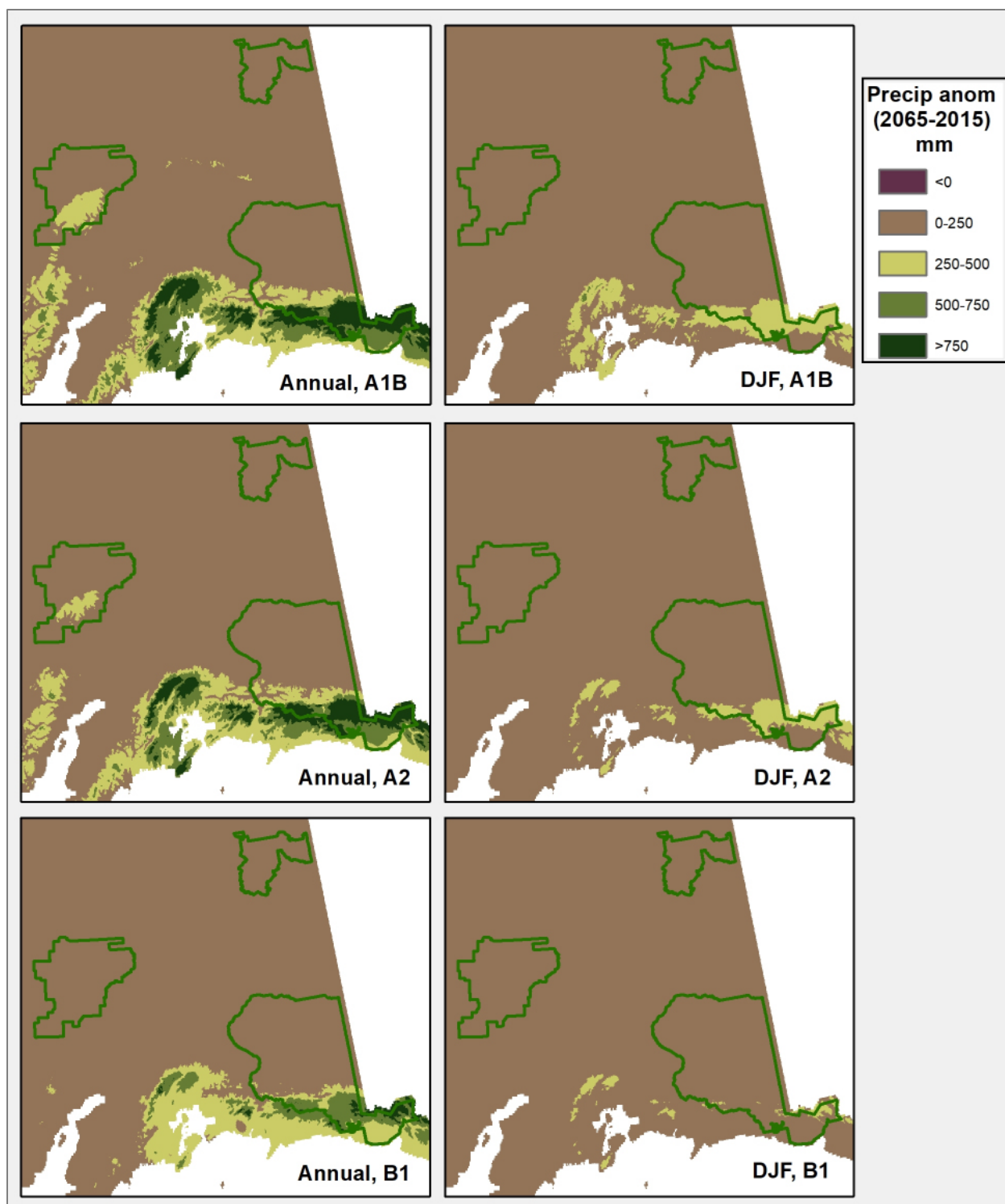


Figure 7. Precipitation anomalies predicted for three different emissions scenarios. Anomalies compare predicted average total precipitation from 2060–2069 to 2010–2019. Annual totals at left, winter months only on right ('DJF'). NPS

In summary, the generalized trend of warmer summers that prevailed over the last 50 years in most Alaska parks is expected to continue in the next 50. This prediction is based on the averaged results of five global climate models and remains true over a range of emissions scenarios. Even the most conservative scenario suggests that the trend will in fact accelerate, with greater than 1° C of warming and consistently wetter winters in all parks. Translating these trends to a quantitative prediction of glacier change is outside the scope of this project, and at minimum would require consideration of greater spatial and temporal detail, of the change in frequency of rain vs. snow at different seasons, of individual glacier dynamics, and of each glacier's particular seasonal sensitivity characteristic (SSC; Oerlemans and Reichert 2000). The SSC, a measure of the glacier's mass balance sensitivity to changes in precipitation and temperature throughout the year, would be particularly important since the trend toward wetter winters will, to varying degrees, tend to counteract the tendency toward more summer melt. In general, however, the SSC is much greater for temperature than for precipitation (Leclercq and Oerlemans 2013), suggesting that the predicted intensification of recent climatic trends will on most glaciers lead to a comparable intensification of recent glacier trends: negative mass balances, diminished ice cover, and reduced ice volume. This is confirmed by a recent numerical model of global glacier change (Rounce et al. 2021) which shows that glaciers in Alaska will be the largest regional contributor to sea level rise between 2015 and 2100, losing in most portions of the state over half their mass by 2100 under even the most modest global warming projection considered.

Glaciers are extensive and changing rapidly, but the management imperative for monitoring that change derives not from an untenable desire to manage the root cause of glacier loss (global climate change), but rather from the need to understand, plan for, and share with stakeholders the consequences of that loss. Understanding the changes requires documentation of past and current glacier loss, forecasting of future glacier loss, and strategic consideration of the diverse impacts of that loss. The most direct impact is the diminishment of the glaciers themselves and has been documented in papers such as Loso et al. (2014) and Roberts-Pierel et al. (2022). One recently published example of the less direct impacts of glacier change involves the potential of glacier retreat near Dry Bay, Alaska, to reroute the future course of the Alsek River (Loso et al. 2021). This change might necessitate legislative or regulatory changes to adapt to significant impacts on commercial and subsistence fisheries, recreational rafters, and other stakeholders. Another, broader-scale example assesses the role of glacier retreat (both ongoing and future) in changing the habitat quantity and quality available for Pacific salmon (Pitman et al. 2021). This would have widespread impacts on commercial, recreational, and subsistence fisheries, interlinked aquatic and terrestrial ecosystems, and associated fisheries management. These examples, along with many others, exemplify the importance of documenting and understanding the consequences of glacier change despite our inability to directly manage their climatic underpinnings.

Armed with knowledge of past and projected future glacier changes, managers have numerous opportunities to incorporate this knowledge into park planning and operations. Detailed knowledge of glacier behavior and subsequent changes (especially in glacial rivers) can facilitate efficient and safe siting and maintenance of infrastructure in heavily glacierized portions of WRST and DENA. Roads, trails, airstrips, buildings, and bridges are all vulnerable, if poorly designed, to glacier change.

Vulnerability may arise from physical hazards as well as loss of functionality. A well-known example includes the location of the U.S. Forest Service Begich, Boggs Visitor Center at Portage Lake, south of Anchorage. That multi-million-dollar facility was built in 1986 with the express purpose of providing a view of the nearby Portage Glacier. However, by 1994, the glacier had retreated out of view of the Visitor Center as predicted earlier by glaciologists (O’Neel et al. 2015), leading to a substantial drop in visitation (Krossen 2002). In similar and in less spectacular ways, park management and planners have an opportunity, when given good information, to avoid such mistakes. Knowledge of glacier changes can also help parks manage hazards to visitors. Glacier shrinkage is often associated with geohazards that include heightened risk of landslides (Kim et al. 2022), glacier collapses (Jacquemart et al. 2020), tsunamis (Higman et al. 2018), and flooding (Curran et al. 2017). Glacier monitoring will rarely be able to predict the timing of such events with sufficient accuracy to warrant dramatic management changes such as closure of discrete areas to visitation, but knowledge of the locations and natures of emerging (or diminishing) hazards associated with glacier change can at least allow managers and staff to appropriately warn visitors of potential hazards and to suggest reasonable mitigations.

Glacier monitoring also provides value to NPS management by allowing the parks to share pertinent information with stakeholders. Visitors are the most obvious category at most parks, and they will be interested in research about glacier change to help them understand and mitigate hazards (as described above), to help them understand and interpret the landscapes they are seeing, and to help them understand the causes of glacier change. This latter item is important. Glacier changes are among the most tangible and comprehensible evidence of climate change that can be viewed by the public, but the changes are occurring largely (though not exclusively) in very remote areas. When interpretive staff are able to point out and explain these changes to the public—whether inside the parks or through other media—the NPS advances its mission of protecting park resources by educating the democratic citizenry about the relationships among public policies, personal choices, and climatic changes (e.g., Chambers et al. 2020). Local residents, including (in Alaska especially) subsistence users, are another important category of stakeholder that benefit from knowledge of glacier change.

Finally, to return to an idea from the start of this description of the rationale for monitoring glaciers, glaciers are indeed an “attractive ornament” on the landscape. As described above, they are much more than that, too. But it does not trivialize the work of glacier monitoring to acknowledge that glaciers are beautiful and inspiring; that they are symbolic of the exceptional wildness of many Alaska parks; or that seeing them is typically one of the primary goals of park visitors. It is an unfortunate scientific fact that they are being diminished by mass loss that continues to accelerate, and that many Alaska glaciers will be entirely gone by the end of the century (Rounce et al. 2021 and unpublished data). Glacier monitoring is one way that we can pay attention to the majesty and the plight of these magnificent features.

1.3 History of CAKN Glacier Monitoring

The glacier monitoring protocol documented in this report is an evolution of NPS work that began in 1991. Because any form of long-term monitoring is premised, in part, on the value of repeat

measurements over a long period of time, the work being conducted by NPS in 2025 (and beyond) must be evaluated in the context of what has been done before. Decisions about the “best” strategy for glacier monitoring must balance new ideas, new technologies, and new opportunities against the value of continuing measurements that were initiated at some time in the past. For this reason, it is valuable to briefly recall the origins, motivations, and efforts of that previous work. This history focuses on work conducted as part of the CAKN glacier monitoring *protocol* (including the protocol executed under the preceding LTEM program), and it is not meant to be a comprehensive history of the glacier monitoring *program*, which we define here as including the many other short-term and ad hoc studies conducted by NPS scientists and by academic and government collaborators over the years.

Glacier monitoring in CAKN has its origins in a 1991 NPS-sponsored glacier research workshop in Eagle River. The report from that workshop (Sturm et al. 1991) made recommendations about glacier monitoring that guided the first monitoring-oriented measurements in DENA. In that same year, DENA submitted a proposal to the national Inventory and Monitoring Program to become a prototype Long-Term Ecological Monitoring (LTEM) site, within which multiple ecosystems components—ultimately including glaciers—would be monitored. Importantly, the LTEM work was explicitly focused only on Denali National Park and Preserve. The glacier work begun in 1991 and subsequently incorporated into the LTEM program therefore excluded any glaciers in WRST.

Early work in DENA was guided initially by Brease (1991), which called for (1) measurement of surface elevations on the Muldrow Glacier, (2) Index Site measurements (mass balance, elevation, and velocity at a single site near the glacier’s Equilibrium Line Altitude, or ELA) on Traleika and Kahiltna Glaciers, and (3) additional work including weather stations, elevation surveys, photo documentation, water flow monitoring, and data compilation from multiple glaciers throughout DENA. Fieldwork continued in ensuing years with protocol refinement from Brease (1995), Mayo (2001), Adema (2006), and Burrows (2011). Each of these documents called for continuation of the work on Muldrow, Kahiltna, and Traleika Glaciers. Between 1997 and 2015 the protocols also included varied measurements on East Fork Toklat Glacier.

With creation of the Central Alaska Network Vital Signs Monitoring Plan (MacCluskie and Oakley 2005), glacier monitoring objectives were broadened to include glaciers from WRST. The two primary objectives from that plan were to (1) Monitor mass balance of selected glaciers in DENA and WRST, and (2) Monitor long-term changes in the location and extent of glaciers in DENA and WRST using aerial photography, satellite imagery, landscape profiling, and field surveys. In belated response to these objectives, and in recognition of the dominantly glacial character of WRST (which contains the world’s largest non-polar icefields and has more than twice the glacier cover of the other Alaska national parks combined), the CAKN Glacier Monitoring Program began regular monitoring efforts in WRST—on Kennicott Glacier—in 2016. In order to maintain program sustainability, however, that addition required abandonment of some other components of the program. East Fork Toklat Glacier was dropped because mass balance monitoring had not been done since 2010, and the survey work done there through 2015 was replicable using remote sensing techniques. Mass balance work on Traleika Glacier was dropped because Traleika is well known as a surging glacier (along

with Muldrow Glacier), a fascinating behavior that nonetheless complicates any meaningful interpretation of traditional mass balance measurements.

In summary, since 2016, the CAKN glacier monitoring protocol has focused on multi-stake mass balance measurements on Kahiltna Glacier and Kennicott Glacier. The description, sporadic implementation, and occasional abandonment of other additional work have continued to varying degrees throughout the history of the program, but a broad view of the glacier monitoring protocol as actually implemented between 1991 and 2025 indicates that the scope of sustained, repetitive, protocol-driven measurements remained focused on mass balance of the glaciers described above (Table 3). While the methods and objectives of the glacier monitoring program have evolved over its 30-plus year history, the core work and significant evolutionary steps can be summarized as follows:

- Ongoing mass balance work on Kahiltna Glacier is the longest single data stream.
- Mass balance work on Traleika Glacier was abandoned in 2016 to allow for the inclusion of Kennicott Glacier in WRST. East Fork Toklat Glacier was only briefly included in the protocol effort.
- Mass balance measurements have trended toward larger numbers of sites per glacier, and GPS measurements have eclipsed optical survey methods.
- Ground-based surveys of elevations, terminus positions, and velocities on glaciers like Muldrow and East Fork Toklat have largely been abandoned in favor of remote sensing.
- Additional work has continued, but with a more explicit acknowledgement that short-term and opportunistic glacier research is a part of the glacier monitoring *program* and should not be considered part of the core *protocol*.

In recent years, emphasis has been placed on experimenting with new field techniques at both Kahiltna and Kennicott Glaciers. At Kahiltna, that experimentation has involved the novel use of on-glacier weather stations and of snow corers to extend the breadth of the measurements. At Kennicott, that experimentation mostly involved the selection and refinement of measurement sites, since it had not been previously monitored. In both parks, and indeed statewide, remote sensing has become an important source of other glacier information. Now, an updated protocol (this report) is being developed to document the establishment of this evolution.

Table 3. History of repeat protocol-driven measurements on CAKN glaciers.

Year	DENA Kahiltna	DENA Traleika	DENA E Fk Toklat	DENA Muldrow	WRST Kennicott
1991 ^A	Index spring fall ^C	Index spring fall ^C	–	None ^F	–
1992 ^A	Index spring fall ^C	Index spring fall ^C	–	Surveys ^E	–
1993 ^A	Index spring fall ^C	Index spring fall ^C	–	Surveys ^E	–
1994 ^A	Index spring fall ^C	Index spring fall ^C	–	Surveys ^E	–
1995 ^A	Index spring fall ^C	Index spring fall ^C	–	None ^F	–
1996 ^A	Index spring fall ^C	Index spring fall ^C	–	None ^F	–
1997 ^A	Index spring fall ^C	Index spring fall ^C	10 sites fall ^D	None ^F	–
1998 ^A	Index spring fall ^C	Index spring fall ^C	10 sites spring fall ^D	None ^F	–
1999 ^A	Index spring fall ^C	Index spring fall ^C	10 sites spring fall ^D	None ^F	–
2000 ^A	None ^F	None ^F	None ^F	None ^F	–
2001 ^A	Index spring fall ^C	Index spring fall ^C	10 sites spring fall ^D	Surveys ^E	–
2002 ^A	Index spring fall ^C	Index spring fall ^C	10 sites spring fall ^D	Surveys ^E	–
2003 ^A	Index spring fall ^C	Index spring ^C	10 sites spring fall ^D	None ^F	–
2004 ^A	Index spring fall ^C	Index spring fall ^C	10 sites fall ^D	None ^F	–
2005 ^A	Index spring fall ^C	Index spring fall ^C	None ^F	Surveys ^E	–
2006 ^B	Index spring fall ^C	Index spring fall ^C	None ^F	Surveys ^E	–
2007 ^B	Index fall ^C	Index spring fall ^C	None ^F	None ^F	–
2008 ^B	Index fall ^C	Index spring fall ^C	None ^F	None ^F	–

^A 1991-2005 data from Adema (2006).

^B 2006-2010 data from Burrows (2011).

^C 'Index' indicates mass balance, elevation, and velocity measurements at a single elevation near the glacier ELA.

^D 'x sites' indicates mass balance, elevation, and velocity measurements at x elevations.

^E 'Surveys' indicates some combination of terminus mapping, surface elevation mapping, and velocity measurements using ground-based GPS or, in early years, optical survey techniques.

^F 'None' indicates the work was scheduled or planned, but not completed. Dashed cells, in contrast, indicate that the work was not a part of the glacier protocol at that time.

Table 3 (continued). History of repeat protocol-driven measurements on CAKN glaciers.

Year	DENA Kahiltna	DENA Traleika	DENA E Fk Toklat	DENA Muldrow	WRST Kennicott
2009 ^B	Index spring fall ^C	Index spring fall ^C	None ^F	None ^F	–
2010 ^B	Index spring fall ^C	Index spring fall ^C	some stakes (?) fall	None ^F	–
2011	Index spring fall ^C	Index spring fall ^C	Surveys ^E	None ^F	–
2012	Index spring fall ^C	Index spring fall ^C	Surveys ^E	None ^F	–
2013	Index spring fall ^C	2 sites spring ^D	Surveys ^E	None ^F	–
2014	Index spring 2 sites fall ^{C, D}	2 sites spring ^D	Surveys ^E	None ^F	–
2015	3 sites spring fall ^D	2 sites spring fall ^D	Surveys ^E	None ^F	–
2016	3 sites spring fall ^D	–	–	–	3 sites spring fall ^D
2017	3 sites spring fall ^D	–	–	–	3 sites spring fall ^D
2018	5 sites spring fall ^D	–	–	–	5 sites spring fall ^D
2019	5 sites spring fall ^D	–	–	–	5 sites spring fall ^D
2020	5 sites spring fall ^D	–	–	–	5 sites spring fall ^D
2021	5 sites spring fall ^D	–	–	–	5 sites spring fall ^D
2022	5 sites spring fall ^D	–	–	–	5 sites spring fall ^D
2023	5 sites spring fall ^D	–	–	–	5 sites spring fall ^D
2024	6 sites spring fall ^D	–	–	–	6 sites spring fall ^D

^A 1991-2005 data from Adema (2006).

^B 2006-2010 data from Burrows (2011).

^C 'Index' indicates mass balance, elevation, and velocity measurements at a single elevation near the glacier ELA.

^D 'x sites' indicates mass balance, elevation, and velocity measurements at x elevations.

^E 'Surveys' indicates some combination of terminus mapping, surface elevation mapping, and velocity measurements using ground-based GPS or, in early years, optical survey techniques.

^F 'None' indicates the work was scheduled or planned, but not completed. Dashed cells, in contrast, indicate that the work was not a part of the glacier protocol at that time.

1.4 Monitoring Objectives

Broadly speaking, the goals of the CAKN Glacier Monitoring Program stem from the 2005 CAKN Vital Signs Monitoring Plan referenced above (MacCluskie and Oakley 2005):

- Monitor mass balance of selected glaciers in DENA and WRST, and
- Monitor long-term changes in the location and extent of glaciers in DENA and WRST using aerial photography, satellite imagery, landscape profiling, and field surveys.

At a more granular level, concrete contemporary objectives of the CAKN glacier monitoring protocol are shown in Table 4 and combine the existing annual mass balance measurements on two large glaciers (Kahiltna and Kennicott) with periodic remotely sensed measurements—on many glaciers—of long-term change in glacier surface elevation, velocity, and area.

Table 4. Overview of objectives and activities for the CAKN glacier monitoring program. Prospective sites are mapped in subsequent figures. Details in text and in associated standard operating procedures.

Glacier(s)	Objective	Unit	# sites WRST	# sites DENA	Frequency
Kahiltna	Glaciological mass balance	meters weq	–	6	annual
	Climate	air temp, precip, etc.	–	2	daily
	Surface elevation	meters asl	–	1	every 2–3 yr
	Boundary and area	polygon, km ²	–	1	every 2–3 yr
Kennicott	Glaciological mass balance	meters weq	6	–	annual
	Climate	air temp, precip, etc.	1	–	daily
	Surface elevation	meters asl	1	–	every 2–3 yr
	Boundary and area	polygon, km ²	1	–	every 2–3 yr
Many	Surface elevation	meters asl	30	12	every 4–6 yr
	Surface velocity	meters per day	30	12	every 4–6 yr
All	Boundary and area	polygon, km ²	3121	881	every 10 yr

General activities associated with each of the aforementioned objectives are summarized in Table 3 and mapped in Figures 8–11. Details of the sampling design, study methods, and operational requirements are provided in Chapter 2. Chapter 3 describes the data collection, management, archiving, and reporting practices associated with the protocol. Finally, Chapter 4 summarizes the procedure for updating this protocol. Below, we briefly provide a rationale for the particular objectives included in the CAKN glacier monitoring protocol and listed in Table 4.

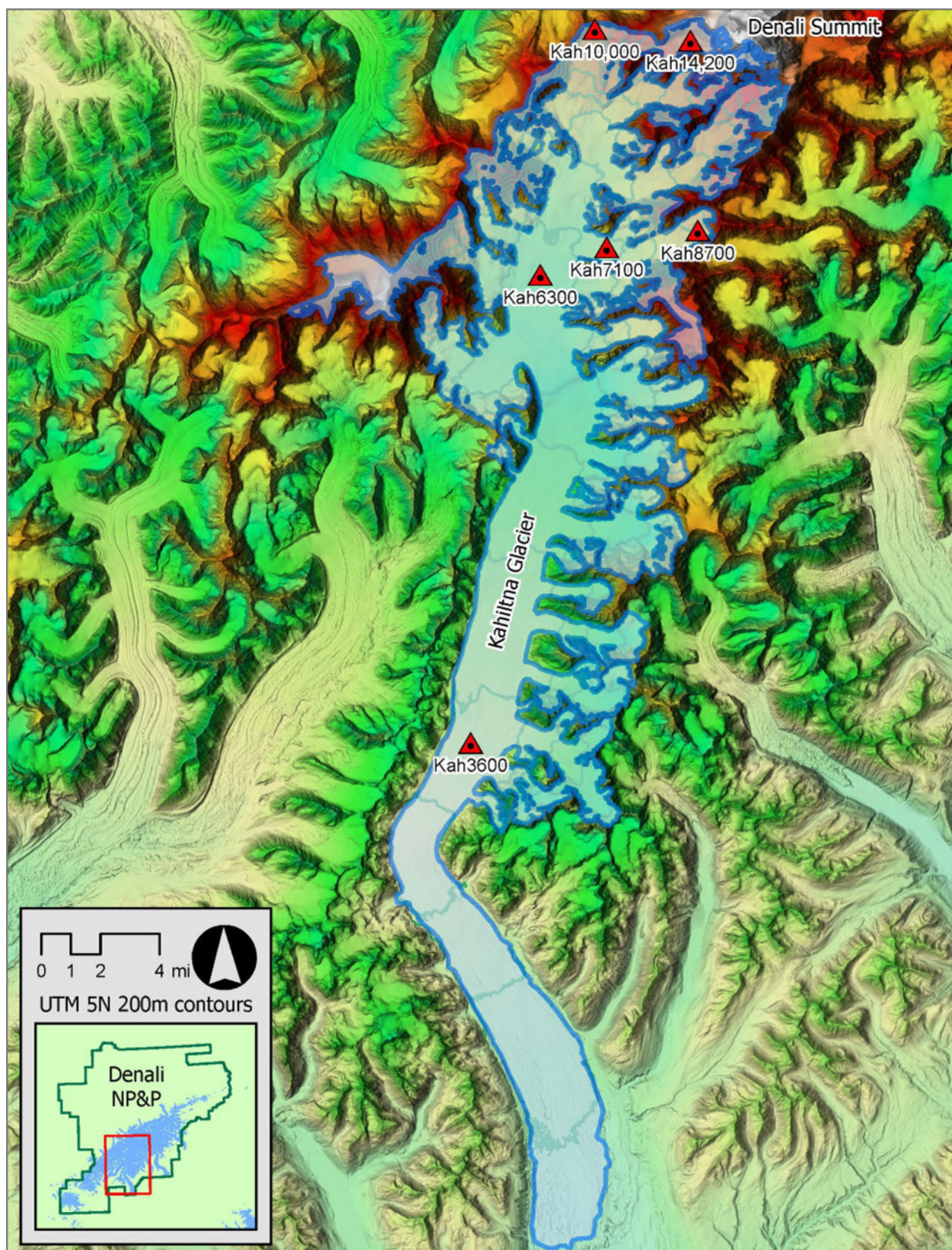


Figure 8. Current (2025) monitoring sites on Kahiltna Glacier. Lowest of the 200-meter contours is at 400 m asl. Equilibrium Line Altitude is generally just below Kah6300. NPS

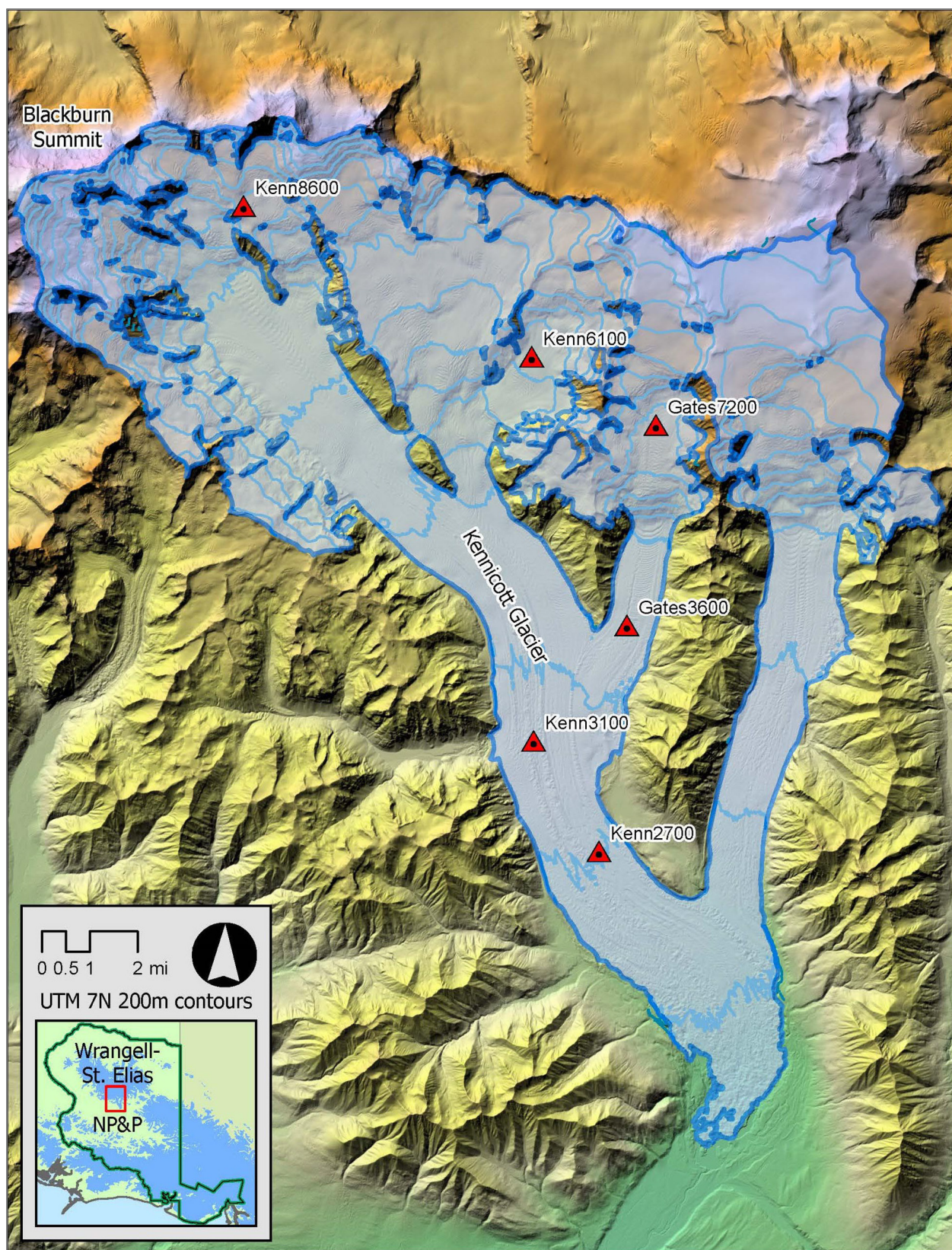


Figure 9. Current (2025) monitoring sites on Kennicott Glacier. Lowest of the 200-meter contours is at 600 m. Equilibrium Line Altitude is generally just below Kenn6100. NPS

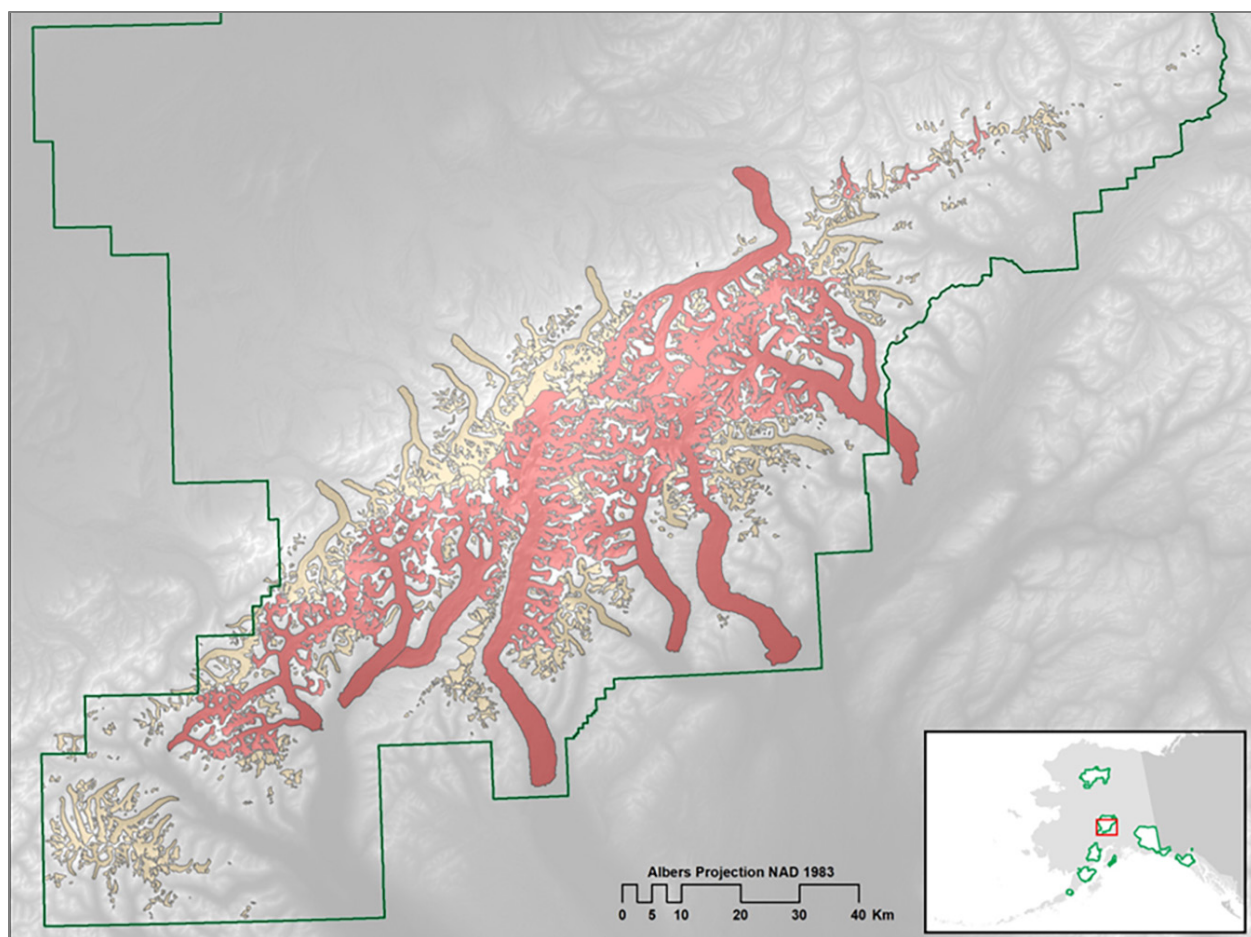


Figure 10. Glaciers of Denali National Park and Preserve. Glaciers previously surveyed by Operation IceBridge are shown in red. NPS

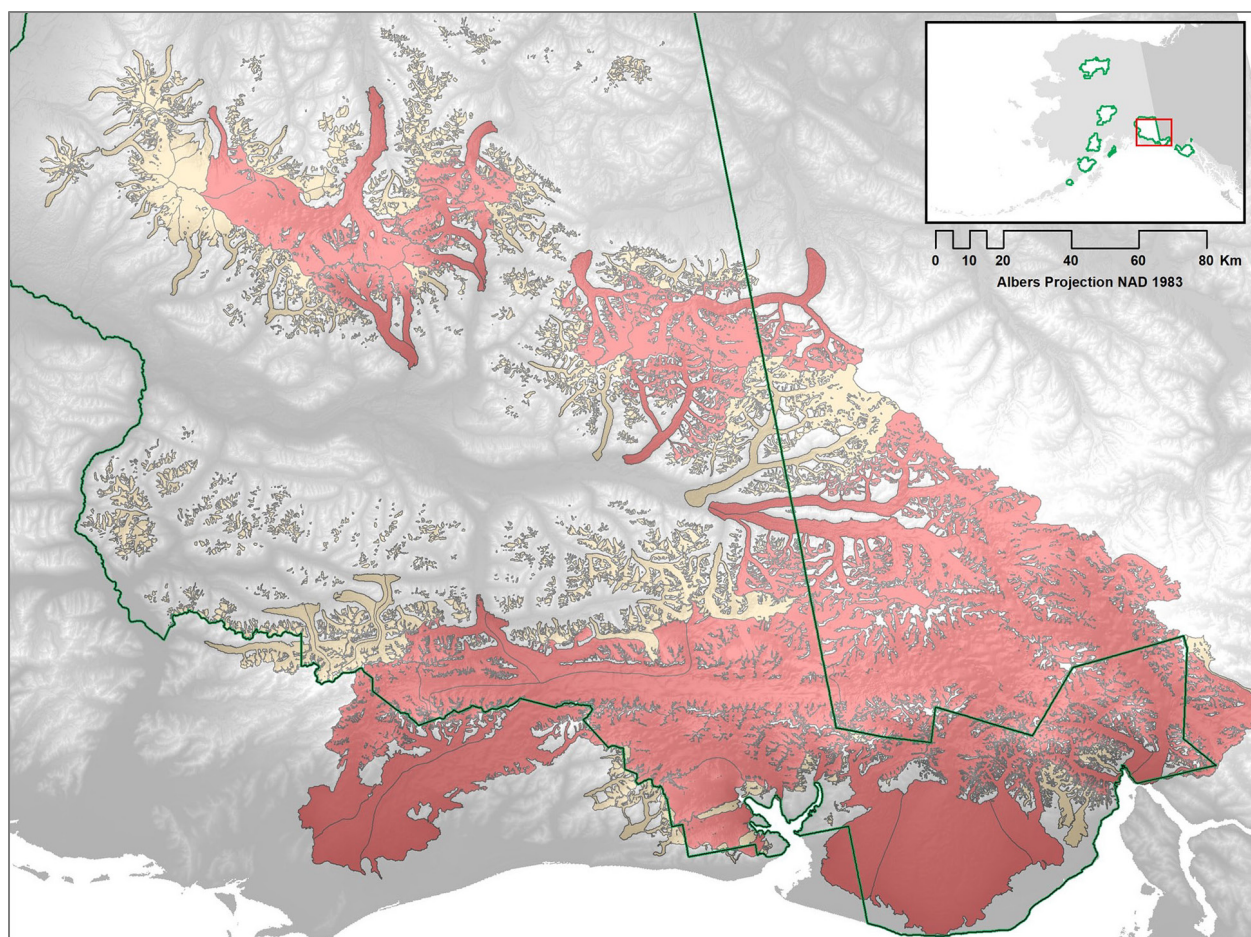


Figure 11. Glaciers of Wrangell-St. Elias National Park and Preserve. Glaciers previously surveyed by Operation IceBridge are shown in red. NPS

Mass Balance

The primary purpose of monitoring mass balance, climate, surface elevation, and boundaries of Kahiltna (Figure 8) and Kennicott (Figure 9) Glaciers is to link the evolution of large, publicly conspicuous glaciers to ongoing climatic changes. This work maintains continuity with measurements that have, since 1991, formed the core of the glacier monitoring program. Neither glacier is meant to be statistically representative of the broader population of park glaciers; the long-term change component of this protocol is aimed at capturing population-scale trends. Rather, these glaciers were chosen because they are visible to the public, because they are important to park management, and because they represent a distinctive component of the Alaska glacier population (large valley glaciers) that is otherwise absent from most existing Alaska mass balance monitoring programs¹.

Kahiltna Glacier was initially chosen for mass balance monitoring in 1991 because it is a large, non-surging glacier that is thus presumed responsive to climatic influences on the south side of the Alaska Range (Brease 1991). It also has high visitation and public awareness due to the presence of the highly trafficked West Buttress climbing route, and also because of high levels of flightseeing and glacier landing tourism. The monitoring program benefits from relatively high levels of aviation and support infrastructure maintained on the glacier during the climbing season (April-July) by the DENA South District Rangers. When the decision was made to add a large WRST glacier to the mass balance program in 2016, Kennicott Glacier was chosen because it is comparable to Kahiltna in overall size and character, because it is also non-surging and thus representative of climate in the central Wrangell Mountains, and because it is also highly visited. Kennicott Glacier lies adjacent to the Kennecott National Historic Landmark and the private community of McCarthy and it thus receives more attention from tourists and residents than any other glacier in WRST. It is also, because of its proximity to the town and to the McCarthy airstrip, relatively easy and affordable to access by foot (in the lower ablation zone) and by helicopter (throughout).

We characterize mass balance through a combination of glaciological (field based) and geodetic (remote sensing based) methods. By visiting sites (a site may involve aluminum stakes driven into the glacier surface, weather stations, or simply GPS coordinates where we conduct periodic coring missions) at multiple elevations on each glacier in spring and fall of every year, the program can record seasonal patterns of snow accumulation and ablation (melt), the two key climatic drivers of glacier change. These “glaciological mass balance” methods (Cogley et al. 2011, Østrem and Brugman 1993) allow an estimate of mass balance at each site. Climate measurements at automated weather stations are necessary to link the measured mass balance parameters to climatic forcing and also for inferring the amount of accumulation and/or ablation that we fail to directly measure due to

¹ Currently or recently monitored glaciers in Alaska include McCall (6 km², Nolan et al. 2005), Eklutna (29 km², Sass et al. 2017), Wolverine (15 km², O’Neel et al. 2019), Gulkana (16 km², O’Neel et al. 2019), Lemon Creek (10 km², McNeil et al. 2020). The only other large Alaska glacier with ongoing mass balance monitoring is Taku Glacier, in the climatically distinct mountains of Southeast Alaska (725 km², McNeil et al. 2020).

the variable timing of our field visits. These climatic measurements must be sufficiently accurate and frequent—daily if not hourly—to support the estimation of daily patterns of accumulation and melt.

Measurements of changes in the surface elevation and the glacier boundaries at Kahiltna and Kennicott can be made less frequently (every 2-3 years) but are a critical supplement to the seasonal mass balance measurements because we are not monitoring enough stakes, on either glacier, to reconstruct a reliable glacier-wide mass balance from the stake measurements alone. Young et al. (2018), for example, noted the inadequacy of the original single measurement site (the index site) on Kahiltna Glacier and recommended adding more measurement sites, particularly at higher elevations. This motivates the present multi-stake program, but even six sites per glacier are not enough to accurately determine the glacier-wide balance without periodic calibration (Fountain and Vecchia 1999). We do this calibration of the glaciological mass balance results using “geodetic mass balance” methods (Cogley et al. 2011), wherein we estimate changes in glacier mass based upon measurements of changes in glacier surface elevation, estimates of the density of lost material (e.g. Huss 2013), and estimates of glacier area change (Florentine et al. 2023). The combination of the glaciological and geodetic methods of measuring mass balance on the two glaciers allows us to infer the overall extent of glacier change (mass change and changes in extent), but also to tie those changes directly to the climatic forcing. This is especially important because land-terminating glaciers lose mass due to reduced solid precipitation, enhanced melt-season temperatures, or a combination of both, and seasonal measurements allow us to partition their relative importance.

Long-Term Change

Some remote sensing work has been used to detect long-term change throughout the history of the program, notably including the first Glacier Status and Trends project (Loso et al. 2014) and the ongoing Glacier Status and Trends 2.0 project (Roberts-Pierel et al. 2022, plus presently unpublished data). These statewide efforts were supported by project funding external to the Central Alaska Network. Because the outcomes of those project-funded efforts have proven highly valuable to the Glacier Monitoring Program, we now explicitly include them in the protocol to ensure continuity of funding support for such work in the future. Periodic measurements of this type (surface elevations, velocities, and outlines for a large number of glaciers) provide population-level estimates of long-term change in surface elevation, surface velocity, and area throughout the CAKN parks.

We monitor surface elevation and velocities on a subset of the largest glaciers in the two parks. These measurements are meant to provide a geographically broad estimate of the rates of mass loss on most of the very large glaciers in the two parks. The glaciers selected for these measurements (red polygons in Figures 10 and 11) will likely evolve over time, but for now correspond to the subset of glaciers already measured several times by NASA’s Operation IceBridge, which has been conducting airborne laser-based surface elevation measurements since the 1990s. Papers reliant on those data include Johnson et al. (2013) and Loso et al. (2014). Because Operation IceBridge has recently concluded, for the foreseeable future a likely substitute measurement platform will be NASA’s ICESat-2 satellite mission (Magruder et al. 2021). The glaciers selected are large, and so while relatively few in number (Table 4) they cover a substantial portion of the total glacier-covered area in both parks. Importantly, these glaciers include a wide variety of glacier types, including both surging

and non-surging glaciers; land-, lake-, and tidewater-terminating glaciers; and coastal to interior climate types. Satellite-based velocity measurements from the NASA ITS-LIVE website (Gardner et al. 2019), or another comparable source as technologies evolve, will be downloaded and archived to document spatial and temporal patterns in glacier surface speeds. Collectively, these measurements of surface elevation and velocity will provide a good estimate of overall glacier change in the two parks, help to estimate their contributions to sea level rise, help to identify surging glaciers (and the timing of their actual surges), and highlight areas where unexpected changes are occurring.

When measuring glacier boundaries and areas, we extend the inventory to include all glaciers from both parks (both red and tan polygons in Figures 10 and 11). Elevations and velocities of small glaciers are difficult to resolve with satellite-based measurements, but glacier outlines can be accurately delineated from an increasing number of high-resolution and short repeat-interval satellite platforms. Outlines are the most basic measure of glacier change and allow us to catalog trends in the number and areal coverage of all glacier ice in both parks. Annual changes in glacier perimeter are relatively small in comparison with the confidence intervals associated with glacier outlining, so we prescribe a long (approximately decadal) repeat interval for this effort. This also accommodates the traditionally high workload and cost associated with digitizing boundaries of such a large number of glaciers (Table 2).

2. Study Design, Methods, and Operational Requirements

As summarized above, we break the protocol into two broad categories: *mass balance* measurements on two glaciers and measurements of *long-term change* on many glaciers. We organize this next section around these two components.

In addition to this summary narrative, the CAKN glacier monitoring protocol includes a short report summarizing pertinent Data Quality Standards and the Standard Operating Procedures (SOP). Each SOP is published as a concise document that describes methodology for every step of protocol implementation (Table 5). Because measurement techniques, field logistics including aviation, and especially the technology associated with data collection and analysis all change quickly, the SOPs are designed and written to be easily editable. Unlike this Protocol Narrative and the accompanying Data Quality Standards, which should be revised and republished only occasionally and in such cases with a full peer-review, the SOPs can be easily modified by the PI as needed. Changes and additions are simply recorded sequentially in a Revision History Log at the start of each SOP, and then the revised version posted at the IRMA Project Reference. The following descriptions of study design, methods, and operational requirements are therefore concise and general, with details found in the corresponding SOPs.

Table 5. Standard Operating Procedures incorporated as part of the CAKN glacier monitoring protocol. Each is published as a separate document.

SOP#	Title	Brief contents
1	Preparation for fieldwork	Planning; aviation; equipment; safety and communications.
2	Stake measurements	Finding, measuring, shortening/extending stakes; GPS measurements.
3	Snow measurements	Measuring and describing snow properties using snowpits, snow cores, probing, and other techniques.
4	Weather stations	Station design, equipment, and tools; telemetry, programming, and data; installation and maintenance.
5	Demobilization and data entry	Data downloading and documentation; GPS processing; data entry; quality control.
6	Glacier surface elevations	Operation IceBridge data; upcoming alternatives.
7	Glacier velocities	ITS_LIVE data; data acquisition.
8	Glacier outlines and areas	Descriptions of the Glacier Status and Trends 1.0 and 2.0 datasets.
9	Data archiving	Data archival strategy; database maintenance; data backup.

2.1 Mass Balance

2.1.1 Sampling Design

The CAKN Glacier Monitoring Protocol calls for periodic measurements of mass balance on Kahiltna and Kennicott Glaciers. As explained earlier, we specifically include two separate components of mass balance: glaciological mass balance and geodetic mass balance. Glaciological

mass balance is the field-based measurement of snow accumulation and density, snow, firn, and ice ablation, and related characteristics at multiple sites per glacier. Geodetic mass balance is the typically less frequent measurement of whole-glacier changes in outline and surface elevation and, hence, ice volume.

The specific sites chosen on each glacier for glaciological (field-based) mass balance measurements will likely vary in the future for logistical, financial, scientific, or other reasons, but they are presently well-established after years of experimentation and modification. The present sites are shown in Figures 8 and 9 and described in Table 6. Site names are derived from the glacier name and the elevation of the site in feet (rounded and approximate). Note that some measurements on Kennicott Glacier are technically on the named tributary Gates Glacier. Listed site coordinates are nominal, in the specific sense that the actual locations of our measurements will on any given day be determined (1) by the precise location where the site was previously emplaced (which might acceptably differ slightly from the nominal coordinates), and (2) by the flow of the glacier (which carries our stakes and weather stations downhill at a slow quasi-continuous rate). Stakes are typically reset to approximately their nominal positions once per year. Because the sites are generally located in areas with low slope and our measurements are aimed at characterizing mass balance at a particular elevation, these small differences from the nominal location are not important.

Table 6. Glaciological mass balance measurement sites on Kahiltna and Kennicott Glaciers.

Glacier / Park	Site	Latitude	Longitude	Elevation (m)	Technique
Kahiltna / DENA	Kah 3600	62.729686	-151.328319	1,113	Stake
	Kah 6300	62.957354	-151.240666	1,933	Stake
	Kah 7100	62.969863	-151.168610	2,163	Met Station / Stake
	Kah 8700	62.976766	-151.070360	2,660	Stake
	Kah 10,000	63.076553	-151.174675	3,055	Coring
	Kah 14,200	63.069646	-151.072172	4,346	Met Station
Kennicott / WRST	Kenn 2700	61.529943	-143.011558	806	Stake
	Kenn 3100	61.562757	-143.055767	932	Stake
	Gates 3600	61.597968	-143.000001	1,083	Stake
	Kenn 6100	61.678210	-143.066222	1,833	Stake
	Gates 7200	61.659135	-142.985095	2,173	Stake
	Kenn 8600	61.721844	-143.251456	2,620	Coring

Glaciological Mass Balance

The measurements are scheduled to be completed twice yearly with field visits once in spring and once in fall. The actual selected dates would in theory best be chosen to correspond with the mass maximum in the spring (when the maximum snowpack has been accumulated prior to widespread melt, typically around mid-April but varying with elevation) and with the mass minimum in the fall (when maximum melt has occurred prior to widespread snowfall; typically, late September). In

practice the actual dates are more commonly dictated by logistics, safety, and scheduling considerations, and commonly occur in late May and early September. Field visits are scheduled well in advance to allow sufficient time for planning, aviation procurement, gear preparation, and weather contingencies. Discrepancies among balance measurements and actual mass maxima/minima are estimated using data from local weather stations.

The detailed activities and measurements made during each visit vary among sites, and between seasons, but the general goal is to determine the point surface mass balance for each site. These terms are chosen purposefully with distinct meanings as described in Cogley et al. (2011): *point* refers to the measurement at a particular site, and *surface mass balance* describes the sum of surface accumulation and surface ablation for a given time period (typically the time since the last measurement). In detail, the goal is to characterize the snow depth and column-averaged density of the portion of the snowpack represented by new seasonal snow, the depth and column-averaged density of all ice and snow lost to ablation, and the precise location of the measurement point. Data are normalized by density to a commonly used reference frame: Snow Water Equivalent (SWE), equivalent to the thickness in meters of a given snow, firn, or ice column once melted. Methods are summarized below and described in more detail in the accompanying Standard Operating Procedures (SOPs; Table 5).

Geodetic Mass Balance

For geodetic mass balance, we separately seek to measure the changes in surface elevation and boundary of each glacier every 2–3 years. Together, these measurements allow us to determine the overall change in size, and presumably mass (based upon an assumption about the density of lost material) of the glacier between epochs. This geodetic mass balance augments the glaciological mass balance measurements and allows us to infer mass balance trends in parts of the glacier away from our glaciological mass balance measurement sites. Geodetic methods are based exclusively on remote sensing.

Glacier boundaries can be easily measured from satellite imagery and require only the procurement of a suitable image for digitizing the boundary. A suitable image would ideally have relatively high spatial resolution (<10 m), minimal cloud cover, and complete spatial coverage of the glacier. It would also ideally be collected late in the melt season when the boundary between the glacier margin and the surrounding land is most clear because seasonal snow has mostly melted away from the unglaciated terrain. In practice, complete coverage of the lower glacier (below the ELA) is usually sufficient since marginal changes are negligible above that point.

Surface elevations are not as easily measured and must be opportunistically gathered from any of a number of available sources. The ideal measurement would occur contemporaneously with the capture of a satellite image used for boundary delineation, and like that image would have high spatial resolution, complete glacier coverage, and good accuracy. Here, more than in any other component of the program, the protocol must remain flexible to take advantage of the range of new technologies becoming available for glacier topography measurements. Potential sources for such data include:

- Structure-from-Motion photography collected by NPS or by collaborators from an aircraft
- Lidar collected by collaborators from an aircraft
- Lidar collected by satellite-based sensors
- Photogrammetric analysis of paired optical satellite images
- Interferometric Synthetic Aperture Radar (IFSAR) collected by collaborators from satellites or aircraft
- Supplemental direct measurements of surface elevation by differential GPS.

None of these sources is perfect in its various characteristics, but the goal is to create, by a combination of measurement and—if necessary—extrapolation to unmeasured areas, a glacier-wide map of changes in surface elevation from one measurement epoch to another.

2.1.2 Field Methods

The technique for making field-based (glaciological) mass balance measurements will vary among sites and seasons, but in most cases involves remeasurement of a stake (hollow aluminum tubing several meters long) drilled vertically into the glacier surface, a combination of snow coring, snowpits, and snow probing to determine snowpack properties, and use of a mapping-grade or better GPS unit. These measurements must be supplemented by climatic measurements from one or more nearby automated weather stations that monitor hourly snowpack thickness, air temperature, and other parameters. On Kahiltua Glacier, our program presently maintains two such sites. On Kennicott Glacier, we rely on stations installed and monitored by other programs. Below, we summarize these methods. Detailed field techniques, along with other aspects of the protocol (preparation, demobilization, data entry, archiving data, etc.) are presented elsewhere in the Standard Operation Procedures (SOPs; Table 5).

Stakes

At sites where we maintain and measure glacier stakes (Table 6), our first visit in the spring is concerned primarily with measuring the thickness and column-averaged density of the winter snowpack. After landing adjacent to an existing glacier stake (Figure 12), we first excavate a snowpit deep enough to reach the prior summer surface (which may be ice, in the ablation zone, or new firn in the accumulation zone). If there is no snow, this step is omitted. If the seasonal snow is more than approximately 1.5 m deep, we stop the snowpit at about that depth and sample the remaining snowpack by coring as described below. After excavating and cleaning the snowpit, we divide the snow into roughly homogeneous strata (on the basis of the hand test hardness scale; American Avalanche Association 2022) and then measure strata thicknesses and densities (Figure 13). Where water ice lenses are present, their location and thickness are measured, and ancillary data including snow temperatures and other observations are recorded. These latter measurements are useful for interpreting snowpack stratigraphy.

The length of the exposed portion of the existing glacier stake is measured and recorded at this time and should (by comparison with the fall measurement) provide a rough check on the snowpack

thickness established in the snowpit (and by coring, if applicable). At sites located on rough terrain in the glacier ablation zone, snow depth as measured in the pit will be augmented by multiple snow depth probes to establish an average snow depth for the immediate area. A mapping grade or better GPS unit is used to measure the precise location of the existing glacier stake (measuring at the snow/ice surface). We usually will remove the older ice-transported existing stake and move upstream to the nominal stake location to place and measure a new replacement stake (using a Heucke ice drill or similar).

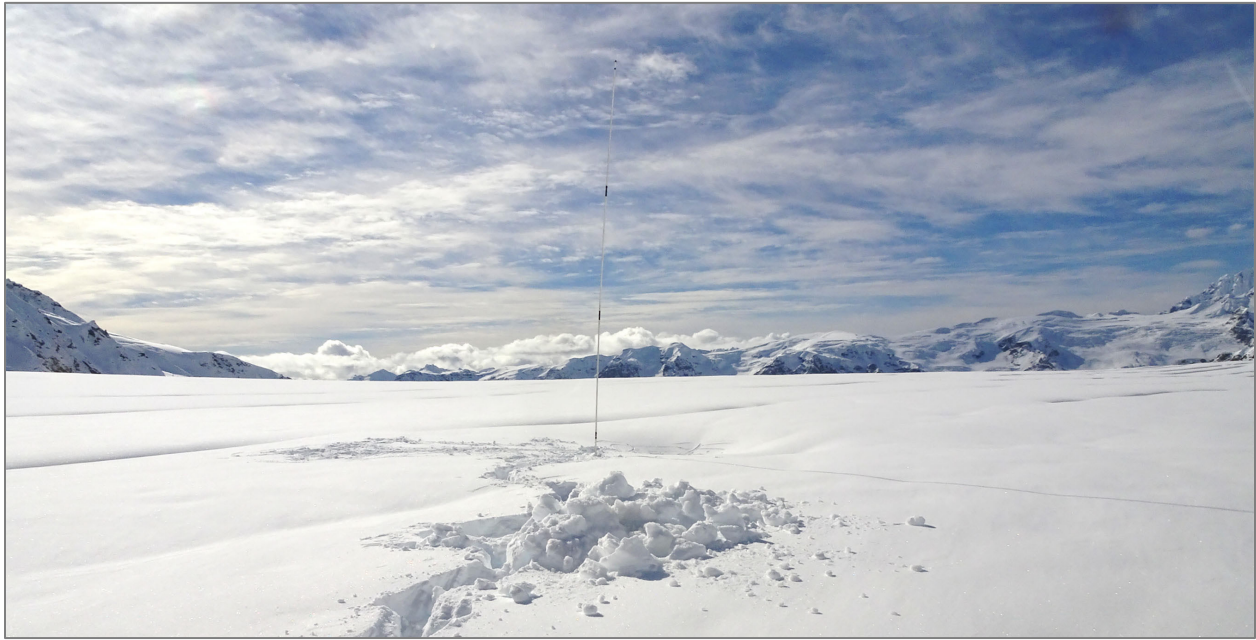


Figure 12. A typical glacier stake, in this case showing over 6 m exposed above the snow surface. NPS

Similar methods are employed in the fall, but our focus then is on measuring cumulative melt season ablation. Measurements of exposed stake length and GPS coordinates are the primary tool, but we also measure the thickness and density of any new (late summer or early fall) that may have fallen already on the old summer surface. If portions of the older stake remain at the downstream site, they are removed. The length of the newer stake, which will be left in for the winter, is typically adjusted at this time to ensure sufficient exposure to remain visible after the winter snowpack accumulates.

These methods are presented in more detail in SOPs 2 and 3 (Table 5).



Figure 13. Measuring densities of multiple strata in a snowpit. NPS

Met Stations

We maintain weather stations at two sites on Kahiltna Glacier that automate the collection of climate information in addition to the collection of other weather data. These stations are a collective effort of the CAKN glacier monitoring program and the DENA South District (mountaineering) rangers and are telemetered so they can provide real-time weather information for climbers and rescuers. The stations measure air temperature, relative humidity, snow depth, incoming and reflected solar

radiation, wind speed and direction, and battery voltage. Air temperature and snow depth are the primary variables for glacier monitoring, although the others are also useful and interesting. The telemetered data are only a subset of the full data stream, and data tables downloaded directly from the dataloggers at least once per year constitute the primary results from this portion of the protocol.

Locations of stations have varied over time for logistical and scientific purposes. One is located at Kah 14,200² (Figure 14), and because it flows slowly downhill with the glacier ice it must be periodically moved back upstream. Because it is also in the glacier's accumulation zone, it would in any case need to be reset occasionally so as not to become completely buried. Recent experience suggests that the Kah14,200 station can go 3 years between resets, but this will depend on weather and other factors and must be evaluated by the rangers and CAKN glacier monitoring PI. The aspiration of the program is to own sufficient weather station equipment to allow for 2 complete stations so that a complete set of tested, maintained, and calibrated equipment can be ready for construction of the new station each time a reset occurs.

The second Kahiltna Glacier weather station is being relocated at the time of this writing. After several years maintaining a second on-glacier weather station at Kah 7100, we have concluded that the location is too challenging (because of glacier flow, high amplitude mass balance, and shading) to successfully maintain a year-round station there. As a consequence, we have installed a new station nearby (~4.0 miles/6.5 km away, similar elevation) on a bedrock ridge on the south ridge of Mt. Foraker³ (Figure 15). Though this station will not provide granular details about on-glacier climate, it has the advantage of being more durable, better powered (because of its solar exposure), and importantly, it will require less frequent maintenance and hence be more affordable. The station was installed June 28, 2024, and the data can be viewed online at <<https://waterdata.usgs.gov/monitoring-location/625632151172901>>. In order to determine a stable statistical relationship between the data at the new and old sites, we have left the existing Kah 7100 station standing and intend to remove it in summer 2025.

² 63.069600022° N, 151.072402562° E, 14,258' asl (4,346 m)

³ 62.9424306° N, 151.2914694° E, 7825' asl (2,385 m)



Figure 14. CAKN glacier monitoring weather stations at Kah 14,200, July 2021. NPS



Figure 15. New Sultana weather station being installed in June 2024 on the south ridge of Mt. Foraker. This station will become the permanent replacement for the "Base Camp" weather station at Kah7100. NPS

Measures of climate forcing are critical for all glacier mass balance projects. They are important, of course, for understanding the climate signal that the glacier changes are responding to. But they are also important for the purpose of filling gaps in our glaciological mass balance record. Snow accumulation and melt commonly occur in the (ideally) short intervals between (1) mass maximum and our spring measurement, and (2) our fall measurement and the mass minimum. Weather records allow us to model the magnitudes of those ‘missed’ measurements, and therefore infer full-season records from our direct measurements. The two weather stations described above serve this purpose for Kahiltna Glacier. And at Kennicott Glacier, where there are no on-glacier weather stations maintained by the CAKN glacier monitoring program, such a record is needed at all times. For this purpose, we rely upon the [Gates Glacier RAWS](#) weather station installed and maintained by the CAKN Climate Vital Sign. Details about accessing these data, and about the CAKN glacier monitoring program-maintained weather station equipment, programming, installation, and maintenance methods are presented in more detail in SOP 4 (Table 4).

Coring

Coring is the only method of establishing snow depth and stratigraphy at sites with very high snow accumulation rates: Kahiltna Pass (Kah 10,000 in DENA) and at Kenn 8600 (in WRST). Our experience is that stakes tend to become buried and lost when left at such sites. Probing is not used in

these locations because probes (1) do not reliably indicate position of the prior summer surface, especially where ice lenses are present, and (2) do not provide estimates of snowpack density. We also use cores to measure snow depth and stratigraphy at other sites where the seasonal snowpack is typically more than about 2 m deep, even where there is a glacier stake. Coring is performed at the bottom of a ~1.5 m deep snowpit, allowing us to work on a firmer platform than is typically available at the surface and also to keep the core barrel shaded from the sun. Snowpit stratigraphy is described as in subsection Stakes above. From that point on, a Kovacs Mark III, FELICS, or other type of corer is used to drill and sequentially extract cores of variable lengths typically between 0.30 and 0.70 m. From each of these drives, we measure the density of one subsample and then describe the snow stratigraphy qualitatively (Figure 16), paying close attention for signs of the transition from the base of the seasonal snowpack (in which we are interested) to the top of the prior summer's snowpack (new firn). Those signs include dust layers, melt/refreeze layers, and most commonly, a transition (moving down-core) from large, poorly bonded, faceted (but healing) snow crystals to the firm, rounded, smaller crystals of the prior summer. Once reaching clear evidence of that transition (usually by coring past it), the total seasonal snow depth is noted and the pit is refilled. Whether a stake is present or not, a GPS coordinate is collected near the coring location to establish a glacier surface elevation before departure. These methods are presented in more detail in SOP 3 (Table 5).

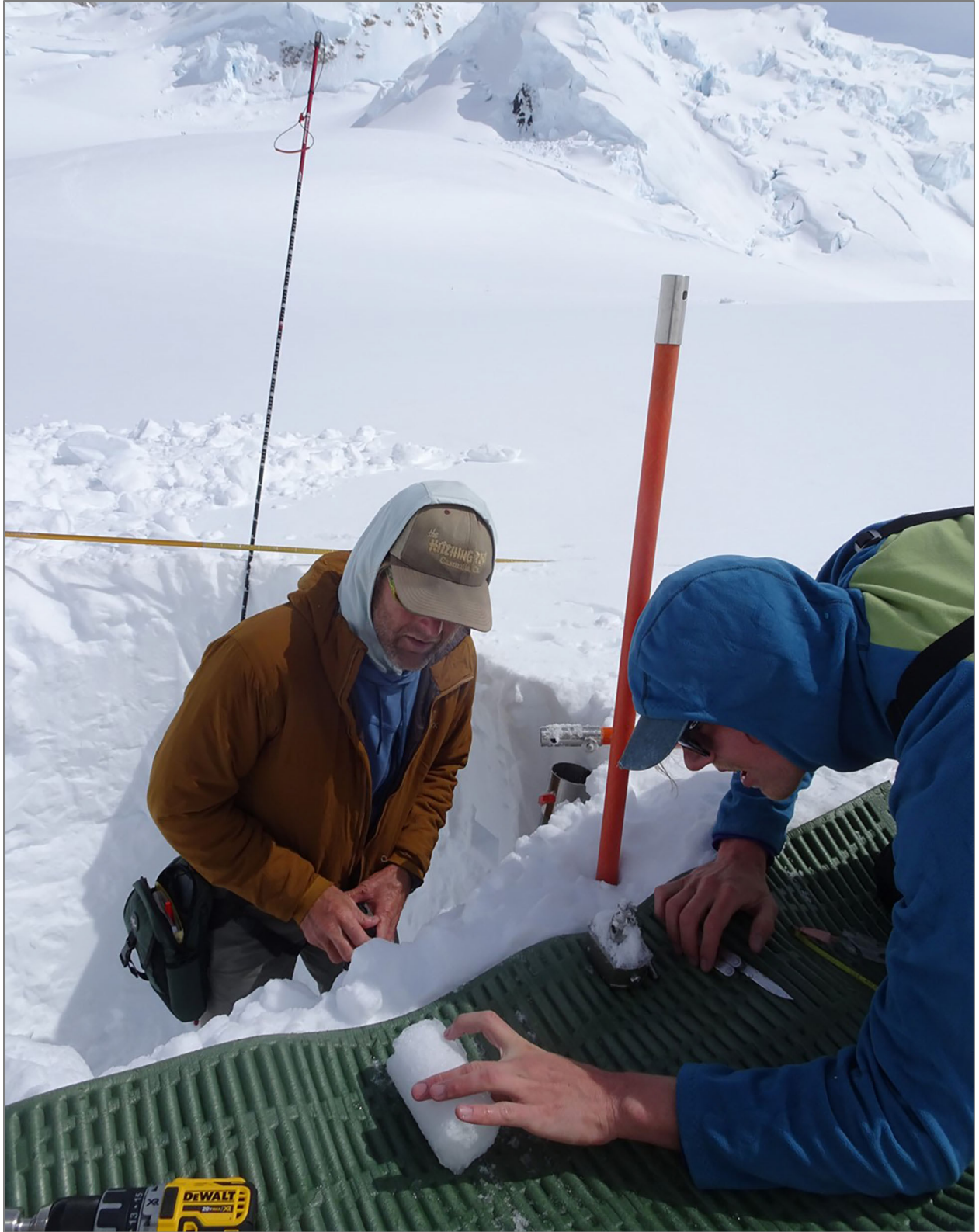


Figure 16. Examining stratigraphy on a retrieved core section. NPS

2.1.3 Operational Requirements

The mass balance programs on Kahiltna and Kennicott Glaciers both require biannual visits to all of the monitoring sites on each glacier, and that work is dependent upon helicopter access. The lowest sites at Kennicott Glacier are at least theoretically approachable by foot/ski, but access to Kahiltna Glacier and to the upper sites on Kennicott Glacier is not safe, practical, or reasonable without helicopter support. Except when the weather stations on Kahiltna need to be reset, the work at each glacier can usually be completed in a single long day of flying. The current CAKN glacier monitoring budget can just barely cover the cost of those four days (spring and fall at Kahiltna, spring and fall at Kennicott) of helicopter use, and we rely on collaboration with other projects (especially including the DENA South District Mountaineering Program) to share costs and maintain sustainability. The aviation component of the program also requires substantial training and experience on the part of the PI (at a minimum, helicopter manager). The important point is that there is little capacity to increase the scope of the field-based mass balance program. This highlights the importance of remote sensing techniques, which, as described above, are an integral and likely growing source of data for the broader program.

Working in the accumulation zone of glaciers also requires specialized safety training. The typical fieldwork does not require extensive glacier travel or mountaineering, but the skills associated with those pursuits (crevasse rescue, rope management, skiing, terrain management and judgment, etc.) *are* required as a means of mitigating any potential hazards. Fieldwork participants must carry and know how to use appropriate safety and survival equipment, and it is worth noting that the program is not presently able to outfit participants with all the necessary gear (especially clothing and ski equipment) needed for the work. The program is working toward a goal of having all necessary gear available, but in the meantime, some specialized personal gear is required.

Specialized research equipment is also required. A complete list is available in the SOPs, but the important larger tools and equipment are a steam drill, a snow corer, weather station structures and sensors (for Kahiltna Glacier only), a mapping grade or better GPS unit, and an industrial-quality snow probe. The PI has found that it makes the fieldwork logistics much easier if a large proportion of the equipment is duplicated and thus stored/available at the appropriate logistical base for each project, as dictated by the logistical and travel needs of the field crew. Regardless of the duty station of the PI, seasonal access to these logistical bases also requires travel, typically on the order of 2-3 days unless the PI resides at the field site in question.

Finally, it is important to clearly articulate the important fact that none of this fieldwork can be done by a solo researcher. The lack of a dedicated, base-funded technician/assistant places a significant strain on the PI and the program and in the past has required—for every mission—an ad hoc solicitation of assistance from a variety of potential sources: the Scientist-in-Parks (SIP) program, DENA and WRST rangers, other NPS staff, and Volunteers-in-Park (VIPs). In recent years, a funded collaboration with the USGS Benchmark Glaciers Program has helped address this need. This is presently mitigating the challenge of finding skilled help, but regardless the fieldwork always requires a minimum of two participants who have sufficient training in aviation, glacier travel,

scientific research techniques, and wilderness safety to be able to effectively contribute to the mission.

2.2 Long-Term Change

2.2.1 Sampling Design

In contrast with the mass balance program, our aim with this portion of the protocol is to collect basic information at a broad level about as many glaciers as possible within DENA and CAKN. In the recent past, this work has been accomplished outside the scope of the CAKN glacier monitoring protocol as part of a broader and separately funded set of projects that conducted multiple, independently funded glacier inventories for all the Alaska park units. In the first Glacier Status and Trends project (GST 1.0; Loso et al. 2014; Loso 2020), outlines of all glaciers were collected for two epochs: the 1950s and the 2000s. Surface elevations were also documented for the subset of glaciers measured by Operation IceBridge (shown for DENA and WRST in Figures 10 and 11). GST 2.0 is underway as of this writing and is digitizing glacier outlines for all glaciers in the state from 1985 to 2020 (Roberts-Pierel et al. 2022) as well as updating the Operation IceBridge measurements (unpublished results). The intention of this part of the CAKN glacier monitoring protocol is to commit CAKN to supporting ongoing decadal repetition of this inventory.

The remote sensing inventory is likely to evolve with changing technologies, but at present is aimed toward repeating the glacier outlines (for all glaciers), the surface elevation measurements (for Operation IceBridge glaciers, at minimum, adding others if possible). Additionally, it calls for adding in a new measurement: the documentation of spatially varying surface flow velocities for the glaciers measured by Operation IceBridge. Outlines are scheduled to be completed every 10 years and surface elevations/velocities every 4–6 years, but in practice that schedule is expected to vary slightly in response to funding, staffing, and other capacity-related factors. Because this schedule of data collection has been manageable in the past and is likely to become easier as remote sensing technologies improve, this schedule of data collection is considered both modest and sustainable and may easily be enhanced by some combination of greater frequency, enhanced coverage (e.g., to include elevation and velocity on the non-IceBridge glaciers), and/or additional measurement parameters.

2.2.2 Field Methods

No field methods are associated with this part of the protocol. It is accomplished solely by remote sensing. Data sources and analytical techniques, which are both expected to adapt rapidly over time, are contained in Standard Operating Procedures 6, 7, and 8 (Table 5).

2.2.3 Operational Requirements

The remote sensing objectives of this protocol require substantial office work dedicated to procuring, analyzing, and reporting on the remote sensing data. Most of the satellite data potentially useful for this portion of the protocol is publicly available for free, including for example that from ICESat-2 (National Snow and Ice Data Center 2022), ArcticDEM (Porter et al. 2018), ITS_LIVE (Gardner et al. 2022). Airborne data collection, including, for example, lidar and SfM, has traditionally not been freely available, however, and the choice to use either or both of those technologies might require

procurement of additional money above and beyond the CAKN glacier monitoring program base budget. In any case, the 10–year repeat interval of this portion of the protocol, combined with the rapid evolution of remote sensing technology, virtually guarantees that the data selected for this analysis will be different at each decadal interval and cannot be predicted confidently at this time.

Analysis of these data sets is in most cases non-trivial and can consume a substantial portion of investigator time. Open-source software and data-sharing portals like the NSIDC (National Snow and Ice Data Center 2022) promise greater efficiency in these tasks, but at present, even an automated glacier delineation technique like the one used by Roberts-Pierel et al. (2022) still requires more than a year of dedicated effort by a Ph.D. student; that is faster than the manual digitizing effort previously required for GST 1.0 (Loso et al. 2014), but still beyond the capacity of a single PI with other responsibilities. For this reason, and because there tends to be some economy of scale in remote sensing (where the effort to conduct a spatial analysis of one park’s glaciers is not substantially less than the effort to do the same analysis on many parks’ glaciers), previous inventories of this sort have been statewide efforts conducted largely through agreements with academic collaborators. That may continue to be necessary and CAKN should plan its budget to contribute to such an agreement on the proposed timeline (Table 4). Should CAKN aim to conduct the remote sensing work in-house, they should anticipate requiring substantial programming and analytical skills of the PI and ideally a technical assistant. In comparison with the analysis task, reporting is expected to be straightforward and well within the scope of the glacier monitoring PI.

3. Data Management

3.1 Overview

All data from the CAKN glacier monitoring protocol are ultimately destined for archival storage in NPS' Integrated Resource Management Applications (IRMA) DataStore. IRMA DataStore is the single authoritative source for all CAKN products (not just data) and is distinct from the working directory described earlier on which day-to-day work is carried out. A single master IRMA project reference (<https://irma.nps.gov/DataStore/Reference/Profile/2216228>) includes authoritative copies of the project protocol (including this document, SOPs, and other related documents), project reports and resource briefs, and project data (Figure 17). It is the joint responsibility of the PI and the data manager to keep the entire system of related IRMA DataStore references up-to-date. In this section, we focus on the collection, management, and archiving of project data and related metadata, collectively included in the Dataset Reference of Figure 17.

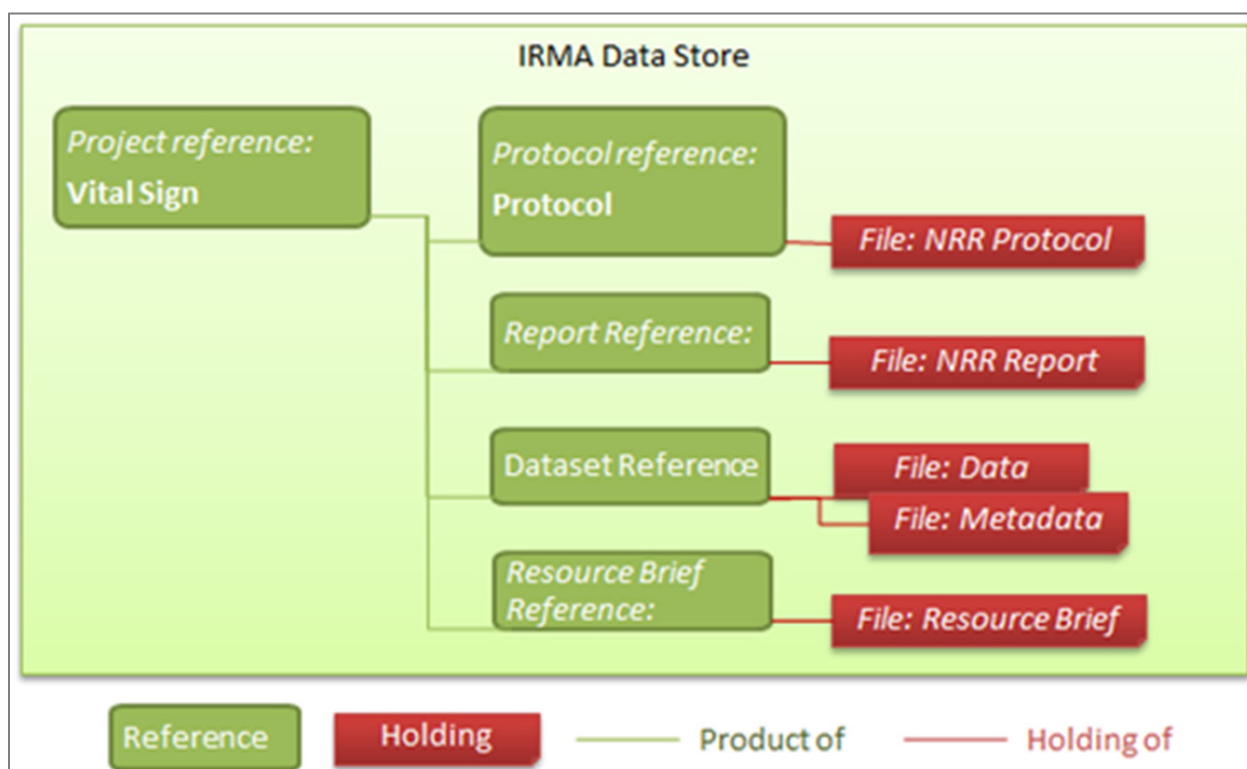


Figure 17. Standardized CAKN Project Reference architecture in the IRMA DataStore. NPS

Line of Sight is the informal name given to the I&M program's philosophy that every product should be inextricably linked in a traversable way to the standard operating procedure and protocol version that guided its collection (Figure 18). This custodial chain is maintained through each data deliverable's metadata, which will refer to the particular protocol narrative and SOP versions that guided collection and processing of that data. All current and former protocol narratives and SOPs will be stored on the IRMA DataStore (only the most current version will be public), and revision logs within all those documents will provide a further description of the history and timing of

methodological revisions. A data consumer will therefore be reliably able to access a data record and discover the standard operating procedure version that defined its collection and processing.



Figure 18. Line of Sight. Each informational component informs and is informed by other components. Discovery of one component leads to discovery of all other components in a formalized data management chain of custody. NPS

Data management for the glacier monitoring program will proceed through an ongoing life cycle as shown generically in Figure 19 (NPS 2008). Major stages of the life cycle include data collection, data entry and import, quality control, data product documentation and archival, seasonal closeout, and dataset certification (Wilder 2005). Data analysis and reporting are separate from the data management cycle but are a critical periodic component of this protocol and are included in the figure for completeness. The PI is responsible for the timely completion of all data collection and management tasks outlined in this protocol and summarized in Figure 19. The network data manager maintains the hardware and software platform in support of the vital sign's data stream, provides for data security, accessibility, and longevity, and gives technological support and guidance in all aspects of data management activities. The PI and data manager are jointly responsible for dataset certification and publication. After a summary of applicable NPS standards for data management, an overview of each component of the data management life cycle follows. As with the field methods, specific procedures are given in the Standard Operating Procedures (SOPs).

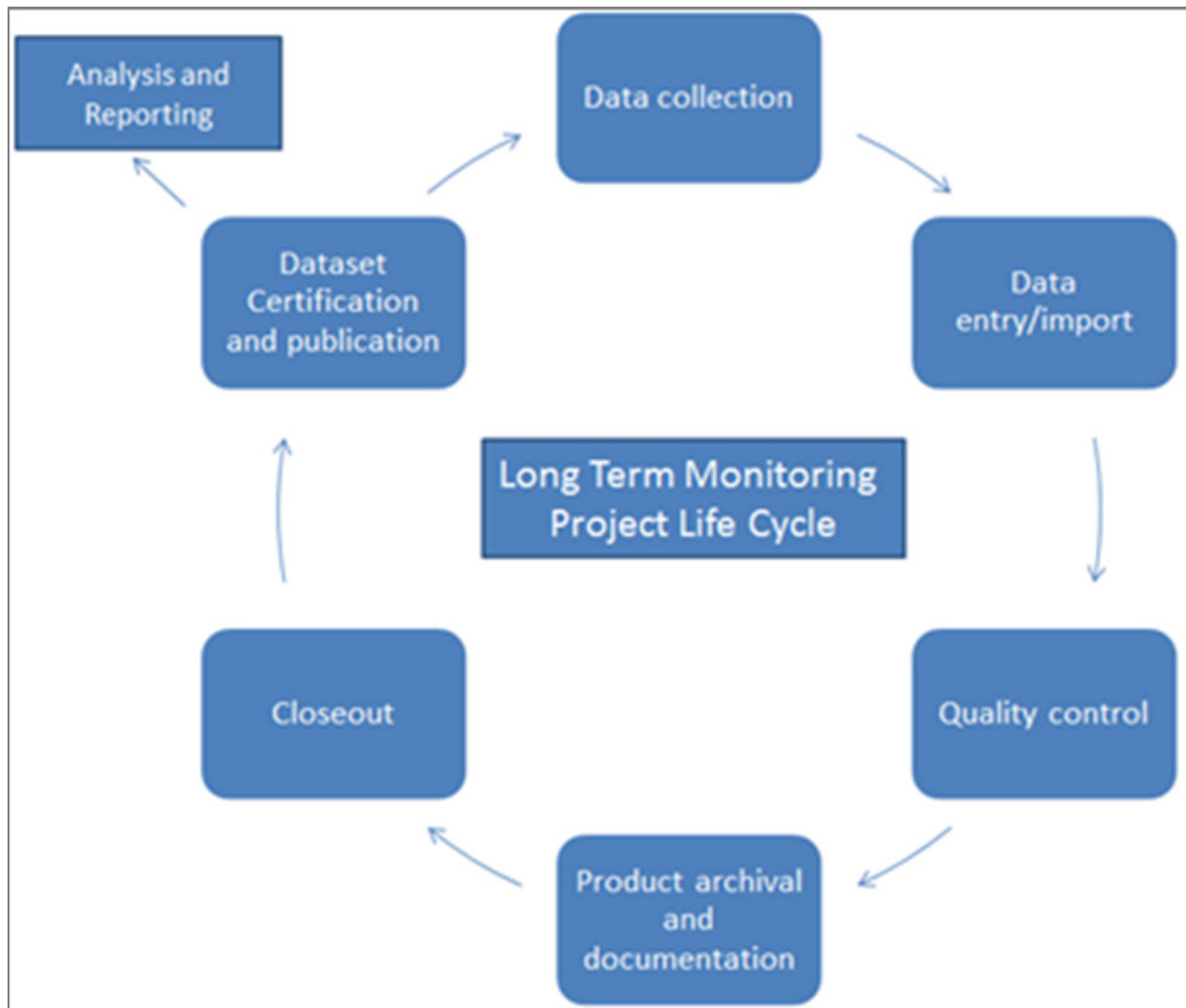


Figure 19. Long-term monitoring project data management life cycle. NPS

3.2 NPS Standards

The CAKN glacier monitoring protocol complies with all pertinent NPS standards for scientific data collection and dissemination. These are summarized here.

Director’s Order #11A, Section 5.8: Data Integrity Standards outlines the NPS policy for accuracy, completeness, and review of scientific data (NPS 2005b):

“All information owners will maintain all official NPS records and data in a manner which meets the highest data integrity standards, including timeliness, accuracy and completeness (also see DO #19). Each information owner will take whatever steps necessary to ensure that NPS systems have sufficient data quality reviews and audits from both an internal system perspective, as well as externally thorough control reviews.”

Director's Order #11B mandates a high level of information quality from the service's scientific programs (NPS 2005c):

"The National Park Service will ensure that information it releases will be developed from reliable data sources and will otherwise ensure information quality at each stage of information development. The NPS's methods for producing quality information will be made transparent, to the maximum extent practicable, through accurate documentation, use of appropriate internal and external review procedures, consultation with experts and users, and verification of the quality of the information disseminated to the public. The NPS will also keep users informed about corrections and revisions.

Information will be developed only from reliable data sources based on accepted practices and policies utilizing accepted methods for information collection and verification. It will be reproducible to the extent possible. Influential information will be produced with a high degree of transparency about data and methods."

Direction for managing physical and digital materials is in NPS Director's Order #11D (NPS 2012):

"The NPS has a strong business need for excellent records management, in that the Service's mission is to care for natural and cultural resources so that they are left "unimpaired" for future generations. This requirement for managing resources in perpetuity sets a high standard for record keeping. No resources can be managed well in the future without complete records of how they were managed in the past. Because the NPS manages some of America's most significant cultural and natural resources, the public also has a significant interest in our records. Section 1.9.2 of NPS Management Policies 2006 (NPS, 2006) states that the future of the Service depends on the availability, management, dissemination, and preservation of information, and directs the agency to implement professional quality programs to manage information resources."

The CAKN glacier monitoring protocol does not define the collection of sensitive data and requires no special handling procedures. The I&M Network will comply with all FOIA restrictions regarding the release of data as instructed in NPS Director's Order #66B (NPS 2005a).

3.3 Data Collection

Data collected in the CAKN glacier monitoring program fall into three primary categories. Handling of these data will be described in the next section.

- *Raw data* are gathered during the course of fieldwork, and include items such as field notes, photographs, GPS files, and datalogger files.
- *Partner data* are records collected by others but of direct usefulness for the program and include items such as records from other agencies' climate stations, satellite-derived spatial data, and varied data from research project collaborators.

- *Processed data* are various types of records that have received some degree of editing or processing subsequent to collection. These include items such as differentially corrected GPS positions, spreadsheets with mass balance calculations, QC'd weather records, and so forth.

3.4 Data Entry/Import

The first step in almost all data entry is importing data to the PI's computer hard drive. Field notes are scanned and imported. Electronic data are uploaded and checked for completeness. Public records are downloaded from websites, FTP servers, or email attachments. Edited data records are saved during the course of processing. In the course of filing these various data types, *Raw data* are identified as such in either their filenames or subdirectory names. *Partner data* are clearly labelled by their source and acquisition date. And *Processed data* will always have the date of the last revision embedded either within the file or in the filename.

Recognizing that mission-critical information should never reside solely on individual I&M staff computers, the program maintains a dedicated directory on an I&M network server that mirrors the working files on the PI's computer. All data (along with other administrative and program documents) are routinely—and always within <48 hours of importing new data—backed up to that server. The server is maintained by the Alaska Regional Office in Anchorage and constitutes the definitive working directory for all data collected by the program. This is distinct from the final *archival* repository. The following sections describe the process associated with handling and archiving those data subsequent to collection.

3.5 Quality Control

Ensuring data quality is a high priority for the CAKN glacier monitoring protocol. Quality control procedures focus on verifying data as well as identifying and correcting errors in final data products. Quality control safeguards include:

- Immediate (within 48 hours) checking of collected/downloaded data for completeness,
- Regular collection, scanning, and archiving of field notes to maintain a record of data collection abnormalities,
- Regular checking of data for extreme or impossible values,
- Regular calibration of sensors on manufacturer recommended schedules,
- Graphical and visual exploratory data analysis,
- Statistical error or outlier identification, and
- Ultimate dataset certification (as described in Section 3.8).

The CAKN glacier monitoring protocol plans for quality assurance by proactively deploying a system of administrative procedures including:

- Standard Operating Procedures (SOPs) designed to minimize the introduction of errors during data collection and processing,
- Regular PI (and field assistant, if applicable) training,

- Regular dataset archiving and backup to prevent data loss or corruption,
- Application-level data entry checks and business rule enforcement, and
- Periodic data quality audits and reports, including reporting on uncertainties associated with all measurements.

3.6 Product Archival and Documentation

All data scheduled for archival storage on the IRMA DataStore are referred to as deliverables (Table 7). These deliverables include *Raw* and *Processed* data that will be internally viewable only by NPS staff, and *Certified* data that are publicly viewable. Section 3.7 describes the closeout process in which the raw and processed data are periodically uploaded to IRMA; and Section 3.8 describes the comparable certification process for public data. Here, we describe the structure, contents, and delivery schedule for all the data deliverables. The deliverables are grouped by identifiers that describe their general contents. ‘GM’ is a general header for Glacier Monitoring data; ‘MB’ refers to Mass Balance-related work on Kennicott and Kahiltna Glaciers, and ‘LTC’ refers to remote sensing datasets for measuring long-term change in a broader suite of glaciers in both parks. Data are subdivided on the basis of data type (raw, processed, or certified). The schedule of delivery describes the frequency of anticipated uploading to IRMA and corresponds to the schedule in Table 3. Deliverables are described below.

Table 7. CAKN glacier monitoring data deliverables. Types 'raw' and 'processed' are uploaded to IRMA as internally viewable data records. 'Certified' records are intended to be publicly viewable.

Identifier	Deliverable	Type	Format	Schedule
GM-MB notes	Field notebooks and data sheets	raw	Scans, *.pdf	Annual
GM-MB photos	Field photographs	raw	Photos, typically *.jpg	Annual
GM-MB gps_logger	GPS datalogger files (raw)	raw	Evolving	Annual
GM-MB positions	Corrected, QC'd GPS records and exported shapefiles	processed	Evolving	Annual
GM-MB met_logger	Met station datalogger files	raw	Table, *.csv	Annual
GM-MB weather	Corrected, QC'd met station records	processed	Table, *.xlsx	Annual
GM-MB legacy_stakes	Mass balance records (pre-2016)	processed	Table, *.xlsx	Complete
GM-MB stakes	Mass balance records (2016-modern)	processed	Table, *.xlsx	Annual
GM-MB database	Certified mass balance records	certified	SQL database engine	Annual
GM-MB outlines	Glacier outlines for Kahiltna and Kennicott Glaciers	certified	Arc, *.shp or other	2–3 yr
GM-MB elevations	Surface elevations for Kahiltna and Kennicott Glaciers	certified	Raster, *.tif	2–3 yr
GM-LTC elevations	Surface elevations for a subset of DENA/WRST glaciers	certified	Raster, *.tif	4–6 yr
GM-LTC velocities	Surface velocities for a subset of DENA/WRST glaciers	certified	Raster, *.tif	4–6 yr
GM-LTC outlines	Glacier outlines for all DENA/WRST glaciers	certified	Arc, *.shp or other	10 yr

Deliverable GM-MB Photos

Photos are often taken during fieldwork for documentation of site conditions, to record observations of glacier phenomena, and for outreach purposes. Most will be saved as *.jpg files but other formats are possible, including video. Best practice involves collection of geotagged images, but further image description (by renaming with a descriptive caption) is encouraged. All useful images will be retained as internal data products. Pertinent SOPs include 2, 3, and 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Internally viewable. Responsibility: PI.

Deliverable GM-MB gps_logger

For some time, GPS measurements were made using a Trimble GeoXH mapping grade GPS unit with external Zephyr antenna. A glacier monitoring-specific data dictionary was used to electronically record some additional mass balance information. That workflow is evolving at the time of this writing due to significant changes in NPS geospatial data collection requirements, so storage formats and workflows will evolve. In any case, this deliverable should include raw data files and ancillary data records. Pertinent SOPs include 2, 3, and 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Internally viewable. Responsibility: PI.

Deliverable GM-MB Positions

Raw GPS data files are differentially corrected using appropriate post-processing software, and any ancillary data in the data dictionary (if applicable) can be updated or corrected with that same software. These updated positions and ancillary data were previously stored by Pathfinder Office as *.cor files and could be exported as shapefiles that retain the ancillary data as attributes. As geospatial formats and techniques evolve, the base requirement is that this deliverable include corrected GPS positions and exported GIS-suitable positions with related data. Pertinent SOPs include 2 and 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Internally viewable. Responsibility: PI.

Deliverable GM-MB Notes

Though much of the data collected within this protocol is digital, it is best practice to keep field notes while conducting any fieldwork. Notes may include some or all of the following: data, observations, equipment notes, start/stop times for sensors, weather information, and other items. Regardless of content, all field notes associated with CAKN glacier protocols will be scanned to *.pdf and uploaded as an internal data product. Pertinent SOPs include 2, 3, and 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Internally viewable. Responsibility: PI.

Deliverable GM-MB met_logger

Weather data from CAKN glacier monitoring program-maintained weather stations may be downloaded in a variety of formats from different types of dataloggers, but most will come as direct downloads from Campbell Scientific CR1000 or CR1000x dataloggers in *.dat format. These, or files in other formats, can all be transformed to *.csv files without any modification, and all weather station files will be uploaded under this deliverable as raw, unmodified files stored in *.csv format. Note that telemetered data files from these weather stations are a suitable substitute for downloaded files where circumstances prohibit direct downloading, but the downloadable tables are more complete and authoritative and should constitute the primary archivable data source whenever

possible. Measured variables of primary importance are temperature and snow depth, but all variables will be stored. Pertinent SOPs include 4 and 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Internally viewable. Responsibility: PI.

Deliverable GM-MB Weather

Weather station data frequently require a substantial amount of quality control to identify and flag periods of inoperation, periods of sensor malfunction, and so forth. Periodically downloaded files also need to be combined sequentially to create a complete, ever-lengthening record. Following these steps, a complete QC'd record of all measured variables (including no data) will be saved with pertinent notes in a *.xlsx format. This deliverable may also include downloaded, QC'd weather station data from other pertinent stations not maintained directly by the CAKN glacier monitoring program, including for example those in Table 6. Pertinent SOPs include 4 and 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Internally viewable. Responsibility: PI.

Deliverable GM-MB legacy_stakes

Over the history of the program at Kahiltna Glacier, beginning in 1991, mass balance data have been collected by a variety of investigators using variable techniques for measurement and archiving. In 2020, the program undertook an effort to consolidate, QC, and homogenize all those data. The result of that effort is stored in this deliverable. The primary dataset is a series of *.xlsx files that correspond to years of data collection; one workbook per year, one worksheet per site. The workbooks are extensively commented to explain the decisions and uncertainties associated with the data consolidation. This data deliverable is kept separate from the mass balance data recorded since 2016 using contemporary methods (and archived under GM-MB stakes), and therefore is considered complete. Pertinent SOPs include 2, 3, and 5 (Table 5). Schedule: This package of 1991-2015 mass balance results is complete, locked, and saved independently to the project database and DataStore. Internally viewable. Responsibility: PI.

Deliverable GM-MB Stakes

Since 2016, all data related to the glaciological mass balance program are recorded each year in a single Excel workbook. The default format for these workbooks includes a first sheet with comments, a second sheet detailing measurements pertinent to the stakes at each site, and a third sheet describing snow measurements (mostly, densities and thicknesses of individual measured strata). These workbooks constitute this deliverable, with a new workbook added each year. The workbooks serve both to consolidate other data sources from GPS units, snowpits, field notes, etc., and as a place for QC and commenting. Expert opinion of the PI is often required to interpret ambiguities in snow depths, stake measurements, etc., and these workbooks reflect and document those opinions. Pertinent SOPs include 2, 3, and 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Internally viewable. Responsibility: PI.

Deliverable GM-MB Database

All mass balance data from the internal deliverables GM-MB legacy_stakes and GM-MB stakes are ultimately stored in a SQL Server database designed and co-managed by the CAKN Data Manager

and the PI. The database serves as a definitive repository for all the mass balance data from 1991-present and is machine-readable for subsequent analysis. The database is designed to be certified and publicly viewable. The database is accessed by SQL Server Management Studio and the database engine is stored on a CAKN network server. Pertinent SOP is 5 (Table 5). Schedule: Uploaded annually at the conclusion of the field season. Certified and publicly viewable. Responsibility: PI and data manager (for database assistance and certification).

Deliverable GM-MB Outlines

Digitized outlines of both Kahiltna and Kennicott Glacier are expected to be generated at minimum every 2-3 years. Methods will vary but the ultimate product is an enclosed polygon, possibly with internal holes for nunataks, suitable for display and analysis in ArcGIS or other software. Shapefiles (*.shp) have been used in the past but may be replaced with other formats (*.geojson, *.gpkg). These and other spatial data described below will generally be saved in UTM projection, WGS1984 datum, ellipsoid heights (where pertinent). In any case, these items (projection, datum, etc.) will always be stored in accompanying metadata. Since outline change occurs most rapidly at the terminus, digitizing work may in many cases focus only the lower portion of the glacier, but if so, the updated boundaries should always be only those portions that were digitized. Pertinent SOP is 8 (Table 5). Schedule: Uploaded as often as annually when new outlines are digitized, but at minimum every 2 to 3 years. Certified and publicly viewable. Responsibility: PI and data manager (for certification).

Deliverable GM-MB Elevations

Glacier surface elevations of both Kahiltna and Kennicott Glacier are expected to be generated at minimum every 2-3 years. Methods will vary, and in some cases the data will be based upon point-clouds from lidar (rather than original DEMs), but in any case, the ultimate product will be a *.tif format raster file of the highest possible spatial resolution (but varying from epoch to epoch) documenting surface elevations of all or a subset of the glacier surface. The product will in many cases be only a partial subset (as it is with centerline swath lidar measurements under Operation IceBridge), but that is an acceptable product. Extrapolation to unmeasured areas is a likely operation during the analytical phase of the program, but that is not the focus of this document, and the extrapolated elevations should not be stored as part of the deliverable. QC will often be necessary, prior to uploading, to remove or correct artifacts. Pertinent SOP is 6 (Table 5). Schedule: Uploaded as often as annually when new data sets are acquired, but at minimum every 2-3 years. Certified and publicly viewable. Responsibility: PI and data manager (for certification).

Deliverable GM-LTC Elevations

Glacier surface elevations of as many park glaciers as possible are expected to be generated at minimum every 4-6 years. Methods will vary, and in some cases the data will be based upon point-clouds from lidar (rather than original DEMs), but in any case, the ultimate product will be a *.tif format raster file of the highest possible spatial resolution (but varying from epoch to epoch) documenting surface elevations of all or a subset of the glacier surfaces. As described above, partial subsets are acceptable. The subset of park glaciers scheduled for measurement under this deliverable is presently dictated by the former scope of recently ended Operation IceBridge measurements but will likely change as data sources evolve. An effort will be made to maintain the time series of

measurements on those IceBridge glacier, in particular. QC will often be necessary, prior to uploading, to remove or correct artifacts. Pertinent SOP is 6 (Table 5). Schedule: Uploaded when new data sets are acquired, at minimum every 4-6 years. Certified and publicly viewable. Responsibility: PI and data manager (for certification).

Deliverable GM-LTC Velocities

Glacier surface flow velocities of as many park glaciers as possible are expected to be generated at minimum every 4-6 years. Methods will vary, but this deliverable will likely depend in the near future on publicly available data from ITS_LIVE (Gardner et al. 2022), and thereafter will likely continue to be publicly available from unpredicted sources. The data can be visualized and stored in a variety of formats, but *.tif rasters with velocities as the pixel values are preferred. Pertinent SOP is 7 (Table 5). Schedule: Uploaded when new data sets are acquired, at minimum every 4-6 years. Certified and publicly viewable. Responsibility: PI and data manager (for certification).

Deliverable GM-LTC Outlines

Digitized outlines of all AK park glaciers >0.1 km² area are expected to be generated at minimum every 10 years. Methods will vary but the ultimate product is an enclosed polygon, possibly with internal holes for nunataks, suitable for display and analysis in ArcGIS or other software. Shapefiles (*.shp) have been used in the past but may be replaced with other formats (*.geojson, *.gpkg). These and accompanying spatial data/metadata will be stored as this deliverable. Pertinent SOP is 8 (Table 5). Schedule: Uploaded when new data sets are acquired, at minimum every 10 years. Certified and publicly viewable. Internally viewable. Responsibility: PI and data manager (for certification).

3.7 Closeout

Closeout is the part of the glacier monitoring data management life cycle through which seasonal data collection files (deliverables) are archived in the IRMA DataStore. Closeout happens after a re-measurement cycle when data files have been collected, processed, and quality controlled. The closeout schedule generally requires that all collected data types (whether internal or public and certified) be archived to IRMA within one year of collection, although the ambition is to complete closeout within at most a few months after the conclusion of each field season. Closeout is complete when the IRMA dataset's holdings match the deliverables schedule (Figure 20). After closeout, all permissions are removed from the seasonal IRMA dataset reference except for the project leader and data manager. The dataset reference will then be linked to the main glacier monitoring IRMA project reference so that it becomes discoverable within the NPS. The data manager, in conjunction with IT staff at FAC and with the Central Support Office in Fort Collins, Colorado, is responsible for backups, security, and longevity of monitoring data. Procedures for public, certified datasets follow a similar schedule and are described in the next section.

Protocol Narrative

Table 1 shows the field data deliverables that will be collected seasonally.

Table 1. Data deliverables schedule

Identifier	Deliverable
DS01	Field database file
DS02	Field data collection forms
DS03	Survey Photos
DS04	Tracklogs
DS05	Waypoints
DS06	NRDS Report

REFERENCE: 2173037

IRMA Portal Integrated Resource Management Applications

[Portal](#) > [Home](#) > [IRMA Applications](#) > [Data Store](#) > [Profile](#) >

Scientist, A. 2012. Title of remeasurement dataset. Dataset. National Park Service XXXX Inventory and Monitoring Program. Fairbanks, AK. Generic Dataset-2222131.

Reference Status as of 07/31/2015: Active
Visibility: Internal

Holdings
DS01 FieldDatabase.zip (.shp, 134kb)
DS02 Field data collection forms (pdf, 320kb)
DS03 SurveyPhotos-2011.zip (.jpg, Compressed archive, 300Mb)
DS04-05 Tracklogs-Waypoints.zip
DS06 NRDS Report (link)

Closeout is complete when the deliverables in the deliverables schedule are available in the IRMA Data Store

Figure 20. Data deliverables are defined in the monitoring protocol and archived in IRMA dataset references after each re-measurement cycle. Closeout is complete when the holdings in the dataset reference match the deliverables in the protocol's data deliverables schedule. NPS

3.8 Dataset Certification and Publication

Certification is the phase of the data management life cycle where the PI and the CAKN data manager both formally confirm that a particular data deliverable is ready for analysis and public viewing. Certification, which affirms the scientific and technical integrity of the program that underlies the data deliverable, is implicit in the process of publishing a publicly viewable *Certified Dataset* in the IRMA DataStore. These data therefore differ, by definition, from *Raw* and *Processed* data deliverables that are archived in the IRMA DataStore but are only internally viewable by NPS employees.

All certified datasets will be accompanied by metadata that summarize collection procedures, data quality, and other pertinent notes. The mandate for adequate metadata comes from Director's Order #11A (NPS 2005b):

"All NPS data systems will develop data dictionaries and conform to available NPS organization-wide dictionaries. Geographic Information and Metadata must meet all Federal standards, DOI standards and NPS standards."

Spatial metadata will be in [Federal Geographic Data Committee](#) (FGDC 1998) format. Tabular metadata will be developed in [Ecological Metadata Language](#) (Knowledge Network for Biocomplexity 2015a; Michener et al. 1997) using [Morpho](#) (Knowledge Network for Biocomplexity 2015b) or similar tool. Detailed certification procedures and metadata formats for each certified data deliverable are defined in the relevant SOPs, but in general the process of releasing a certified data deliverable on the IRMA DataStore indicates that the PI and Data Manager both confirm the following:

- The dataset is of sufficient quality that analyses may be performed on it and the results published.
- The protocol and pertinent standard operating procedures are current and up-to-date. The data deliverable is traceable, via the metadata, to the specific protocol and SOP versions that guided its collection (i.e., line of sight).
- Raw and intermediate data deliverables have been processed via documented quality control procedures, all closeout activities have been performed, and those products have been archived and documented appropriately within the DataStore.
- The dataset is published in a publicly accessible, machine-readable format appropriate for public consumption, and is accompanied by a complete metadata text file.
- The Vital Signs' IRMA DataStore cross-reference architecture is complete and up-to-date and reflects the inclusion of the new data.

3.9 Analysis and Reporting

Analysis and reporting of certified protocol data can take many forms, but the primary tool for reporting is the Science Report Series. These reports disseminate information, analysis, and results of scientific studies and related topics concerning resources and lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The PI will periodically release reports and resource briefs in the Science Report Series or other publication formats after new findings to reflect current understanding of the resource's trend and implications for park management. The cycle for these revisions can vary but should in most cases occur at least every 5 years. The most recent example, at the time of this writing, is Loso (2024) and can be viewed at DataStore—*Glacier Monitoring in Denali and Wrangell-St. Elias National Park and Preserve, 2022-2024*. All such reports are archived in the IRMA DataStore and then linked to the main Vital Sign Project reference as a product (Figure 17).

Other reporting consistent with the goals of the CAKN glacier monitoring program include journal articles, outreach videos, web and social media content, and book sections. All of these may, at times, be appropriate venues for dissemination of protocol data but they should, in every case, reference the authoritative data source (the project reference at the IRMA DataStore: DataStore - *Glacier Monitoring in the Central Alaska Network of National Parks*) in the same manner as internal publications.

4. Protocol Revision and Archiving

All edits and amendments made to the protocol narrative and/or SOPs should be recorded in the revision history log table (Table 1) at the beginning of this document (for revisions to the narrative) and at the beginning of each SOP for SOP revisions. Major changes to the protocol narrative are expected to go through regular peer review. More minor changes in the narrative or in the data quality standards and SOPs can be done without peer review, so long as they are reflected consistently in the revision history log. Users of this protocol should promptly notify the project manager/PI of recommended edits or changes. The project manager will review and incorporate suggested changes as necessary, record these changes in the revision history log(s), and modify the date and version number on the title page of this document to reflect these changes. This protocol and any future versions will be archived in the CAKN SQL Server databases, database backup files, and in the IRMA DataStore. The most up-to-date protocol document will be available on the public network website.

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