National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Glacier Monitoring in Denali and Wrangell-St. Elias National Park and Preserve, 2016-2021

Inventory and Monitoring Program, Central Alaska Network

ON THE COVER

Denali South District Ranger Tucker Chenoweth installing a high-altitude weather station and accumulation/ablation sensor at the Genet Basin camp (~14,200') on Denali's Kahiltna Glacier, May 2018 (NPS/MICHAEL LOSO)

Glacier Monitoring in Denali and Wrangell-St. Elias National Park and Preserve, 2016-2021

Inventory and Monitoring Program, Central Alaska Network

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Abstract

This report summarizes glacier monitoring activities that occurred during the years 2016-2021 in the glacierized Central Alaska Network parks: Denali National Park & Preserve and Wrangell-St. Elias National Park & Preserve. Work completed in both parks is described with an emphasis on activities, logistics, and accomplishments. Preliminary results from the monitoring work are described briefly but are not the focus of this paper. Final results will be presented separately, with appropriate error analysis and interpretation, in peer-reviewed technical report(s) and/or scholarly publications.

Glacier monitoring has occurred in Central Alaska Network since 1991, and is based upon monitoring protocols initiated by Larry Mayo at that time (Mayo, 2001) and updated in 2011 by Rob Burrows (Burrows, 2011). Work during that period and until 2015 was focused on the Kahiltna and Traleika Glaciers in Denali. The principal investigator and program structure of the glacier monitoring program both changed in 2016. In 2016, Michael Loso took over as glaciers PI and adjusted the program objectives to include a major glacier in Wrangell-St. Elias (Kennicott Glacier) and to discontinue monitoring of the Traleika Glacier. Monitoring efforts on Kahiltna and Kennicott Glacier comprise the bulk of the glacier monitoring activity described here, but this report also describes ancillary work and accomplishments.

Introduction

This report summarizes glacier monitoring activities that occurred during the years 2016-2021 in the glacierized Central Alaska Network parks: Denali National Park & Preserve and Wrangell-St. Elias National Park & Preserve. Work completed in both parks is described with an emphasis on fieldwork, logistics, and accomplishments. Preliminary results from the monitoring work are described briefly but are not the focus of this paper. Final results will be presented separately, with appropriate error analysis and interpretation, in peer-reviewed technical report(s) and/or scholarly publications.

Glaciers Vital Sign: Monitoring Objectives

Glaciers and glacier systems are dominant and dynamic physical features of two of the three parks (Denali, Wrangell-St. Elias) in the Central Alaska Network and are a driver of landform and ecosystem change in them. Glaciers are inextricably tied to climate and the hydrological cycle. Because glacier systems are regulated primarily by climate fluctuations, they provide a reliable record of long-term climate change that has already occurred. Upper elevation climate is nearly impossible to measure directly and can be well represented by glacier dynamics. Glaciers provide significant hydrologic base flow to major rivers in Central Alaska national parks.

Mass balance (snow accumulation and snow/ice melt) is the primary variable monitored on an annual basis in Denali and Wrangell-St. Elias. In Denali, mass balance has been measured twice annually (spring and fall) on Traleika and Kahiltna glaciers since 1991. Measurements on Kahiltna are ongoing, while measurements on Traleika were discontinued in 2016. In Wrangell-St. Elias, mass balance is measured twice annually on Kennicott Glacier, and is ongoing. Glacier mapping is completed for the parks using aerial and/or satellite imagery every decade or so. In addition, repeated measurements of surface elevation are taken on a subset of glaciers by collaborators through the NASA-funded Operation Icebridge. These data are analyzed roughly once per decade.

Structure of This Report

The bulk of the report is focused on describing the protocol-based glacier monitoring sites and the activities conducted therein, organized by glacier and then by year. There is a short description of how we manage the collected data. Following that, I present some very brief preliminary results from these monitoring sites. Finally, the report concludes with a brief overview of other glacier monitoring activities conducted by the PI and colleagues during the 2016-2021 period.

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Kahiltna Glacier Monitoring Sites and Activities

Overview

Historically, the Kahiltna Glacier work began with direct measurements at an index site located roughly where the K17 stake (**Figure 1**) is now located. Additional lower altitude stakes were sporadically measured over the years between 1991 and 2015, but beginning in 2016 we have routinely measured accumulation and ablation at K17, K53, and (when possible) KahiltnaPass. We added BaseCamp and 14Camp as measurement sites in 2018, specifically by adding year-round telemetered weather stations. Efforts were made several times to install and maintain a weather station at Kahiltna Pass, but accumulation rates there (even in summer) have been determined to be too high to successfully obtain weather data there.

As of 2021, the full suite of ongoing measurements at Kahiltna Glacier (Figure 1) includes (with nominal elevations shown in parentheses):

- K53 (1113 m): Ablation stake and snowpit-based accumulation measurements
- K17 (1933 m): Ablation stake and snowpit/snowcore-based accumulation measurements
- BaseCamp (2163 m): Year-round weather station with hourly measurements of snow accumulation and ablation, augmented by a neighboring ablation stake
- KahiltnaPass (3055 m): Net accumulation measurements, via snowpit/snowcore in spring and fall, with no stakes or weather stations
- 14Camp (4346 m): Year-round weather station with hourly measurements of snow accumulation and ablation

Glacier monitoring work at Kahiltna Glacier has evolved to emphasize high altitude measurements that are uniquely possible because of the support of the Talkeetna rangers and their exclusive use rescue helicopter. On any glacier, measurements of mass balance are most difficult in the accumulation zone, but that is particularly true on large high-altitude glaciers like the Kahiltna. The operations of the Talkeetna (“South District”) rangers, in support of climbing activities on Denali, provide infrastructure, safety and travel expertise, aviation capacity, and an independent need for real-time weather data that has led to a productive collaboration.

The logistics of all work on Kahiltna Glacier are based in Talkeetna. The South District Ranger (presently Tucker Chenoweth) functions as a primary point of contact for the work conducted. The support of the Talkeetna rangers includes aviation (the A-Star B3e and an exclusive NPS fuel cache), equipment storage (in the rescue cache behind the ranger residence), temporary use of a staging area in the loading bay of the ranger station, personnel support for fieldwork, and other items. In compensation for that support, the Glacier Monitoring Program provides direct funding for the aviation component, plus in-kind contributions that include (most importantly) maintenance and operation of the telemetered real-time weather stations and (seasonally) training and educational programs for ranger staff and the public. But importantly, all the support provided by the rangers is secondary to their primary mission of ensuring safety and SAR preparedness for the public, especially during the climbing season. Clear communications between the Glacier Monitoring PI

(Loso) and the South District Ranger are therefore critical for the smooth functioning of the program, and the Glaciers PI must approach all activities on the Kahiltna with clear prior statements of goals and expectations, but also with a frank and humble understanding of the always present possibility that the South District support could be withdrawn at any time for more pressing needs. A good "plan B" is always smart, and the most critical components of that backup planning would include consideration of alternate dates (weather plays in here too), planning for backup support personnel if the ranger staff are unavailable, and planning for backup aviation if the A-Star is unavailable.

Aviation costs for the Kahiltna Glacier portion of the Glacier Monitoring Program are managed jointly by the Program and by the South District Rangers. This is because both the tool (the helicopter) and one of the primary program objectives (real-time measurement of weather conditions) are shared between the Program and the rangers. Most glacier monitoring work is based from the exclusive use A-Star, and that helicopter is frequently utilized by the rangers for on-mountain activities ranging from camp maintenance to search and rescue, so it is commonly the case that a given day of glacier monitoring work will share use of the helicopter with other ranger-focused activities. That makes it difficult to bill the Glacier Monitoring Program's use of the helicopter in the standard hourly-plus-availability payment format. But equally importantly, the Program's weather stations were developed jointly with the rangers and contribute substantially and directly to their own safety and operations. Because of these shared costs and objectives, the Glacier Monitoring Program PI works jointly with the South District Ranger each spring to determine a flat rate cost that will be borne by the Monitoring Program for all needed aviation. Depending on the amount of flying done each year, that cost provides a substantial but variable cost-savings to the Monitoring Program and simplifies planning and logistics for the rangers. The flat rate has varied from year but typically runs to about $8000 per season (including both spring and fall work). On rare occasions the A-Star is unavailable (in the last six years, this occurred only once—in the fall of 2021) and the Program is forced to use a vendor. The fall 2021 visit costed about $4800 for a day's work with a Robinson R66.

With all those contingencies in mind, a typical season of work on the Kahiltna would consist of two visits, one in spring and one in fall. A spring visit will occur in mid-late May or at the latest early June, and will consist of a minimum of one day flying but often more, depending especially on the need for weather station maintenance. The mission will utilize the A-Star and will start with preparation of gear at least a day prior to the flight, so that gear and personnel are ready for a briefing at the ranger station the morning of the trip. One day is typically enough for stake and snowpit/snow core measurements, but if significant work is needed on one or both weather stations, more days are added as needed, and may occur in the context of multiple flights (while sleeping in Talkeetna) or in the context of a ranger patrol (while camping on the mountain), depending on details. In the fall, the work is typically completed in a single day in late August or early September. The exclusive use contract for the A-Star end typically ends sometime in late summer, with quite a bit of variability, so we typically aim to track that end date and schedule the work to utilize that helicopter when possible, but a vendor helicopter may be needed if the work occurs after the contract ends. If a vendor is used, an R66 or A-Star B-2 are the minimum aircraft for the higher altitude work on the Kahiltna—an R44 is not adequate. Note that the 14Camp weather station maintenance is often excluded from this regular seasonal schedule because of the complication of work at such high altitudes. The program is

working towards a goal of having the Talkeetna rangers trained and prepared to do all weather station work at that site (since ranger teams regularly travel up there in an acclimatized fashion), but sporadic trips to 14Camp by unacclimatized glacier monitoring staff are only sometimes accomplished—when a combination of factors (weather, team strength, logistics, etc.) are in place to support the safety of that objective. In any case, all these components vary each year, and I therefore summarize below the activities that specifically occurred each year since 2016.

2016

We visited Kahiltna Glacier twice in 2016. The first visit occurred May 12-13, and included Michael Loso, Tucker Chenoweth, and Ken Hill. The second visit occurred August 16 and included Michael Loso and Tucker Chenoweth. All aviation was completed with the Denali A-star B3e 0AE with Andy Hermansky as pilot.

We were able to make standard measurements at all sites except BaseCamp and 14Camp in both spring and fall. A small temporary Campbell Scientific weather station was installed at Kahiltna Pass and removed in the fall. An Onset weather station with time lapse cameras was installed at K53 and left for the coming winter.

2017

We visited Kahiltna Glacier twice in 2017. The first visit occurred May 11-12, and included Michael Loso, Becca Stenerson, Tucker Chenoweth, and Nate Smith. The second visit occurred August 8 and included Michael Loso and Tucker Chenoweth. All aviation was completed with the Denali A-star B3e 0AE with Andy Hermansky as pilot.

We were able to make standard measurements at all sites except BaseCamp and 14Camp in both spring and fall. A small temporary Campbell Scientific weather station was installed at Kahiltna Pass and removed in the fall. The Onset station at K53 was maintained.

2018

We visited Kahiltna Glacier twice in 2018. The first visit occurred May 25-June 5, and included Michael Loso, John Sykes, Tucker Chenoweth, Jake Behren, and Korinne Kreiger. The second visit occurred August 28 and included Michael Loso and Chris Erickson. All aviation was completed with the Denali A-star B3e 0AE with Andy Hermansky as pilot.

We were able to make standard measurements at all sites including new stations at BaseCamp and 14Camp in both spring and fall, except that we did not visit 14Camp in the fall. New, ostensibly permanent, Campbell Scientific weather stations were installed at BaseCamp, KahiltnaPass, and 14Camp. The Onset station at K53 was maintained. The spring installation work was done in the context of an extended patrol that lasted 12 days.

2019

We visited Kahiltna Glacier twice in 2019. The first visit occurred May 17-22, and included Michael Loso, Lia Lajoie, and Tucker Chenoweth. The second visit occurred August 7-8, and included Michael Loso, Emily Baker, Tucker Chenoweth, and Becca Stenerson. All aviation was completed with the Denali A-star B3e 0AE with Andy Hermansky as pilot.

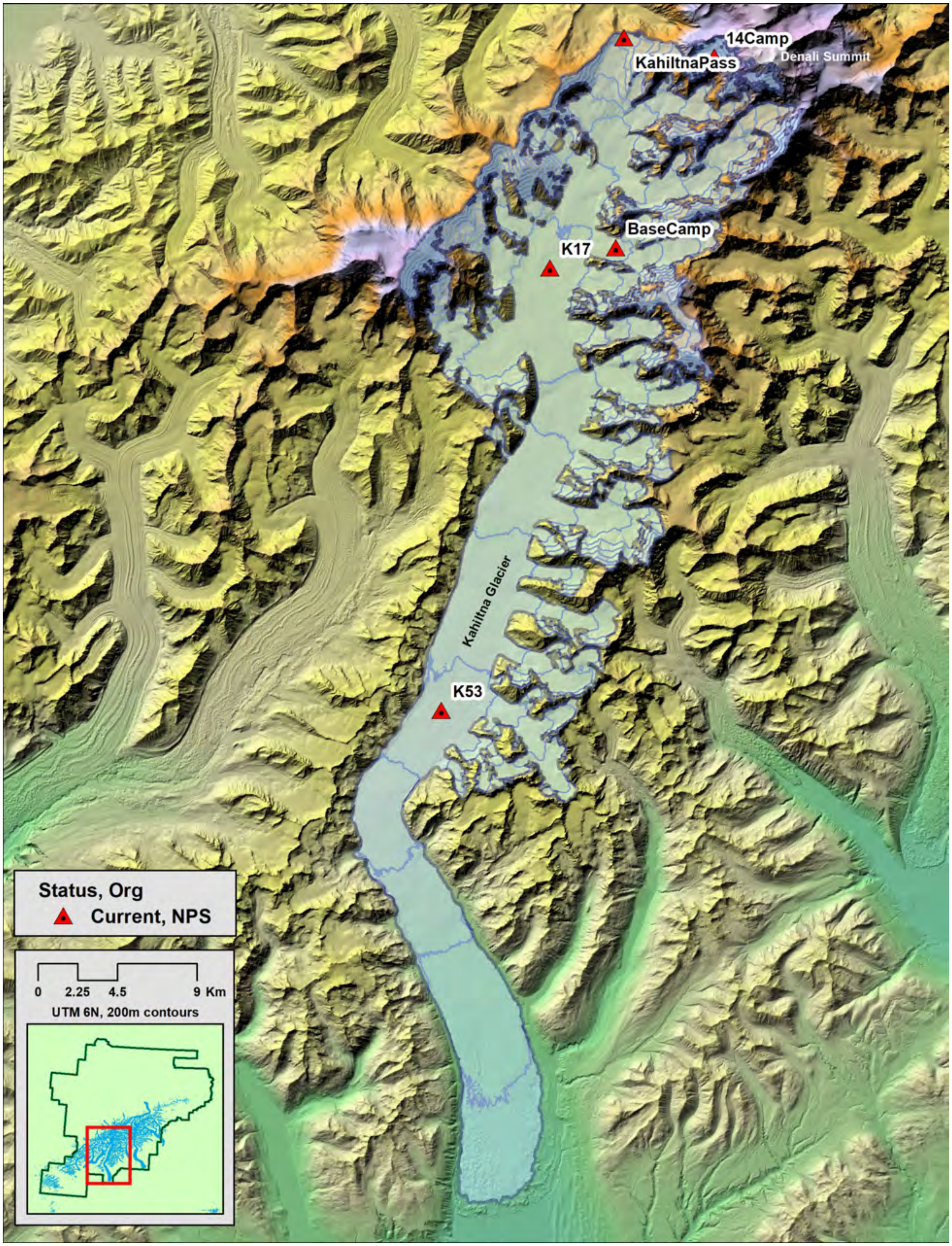

Figure 1. Stake monitoring sites on Kahiltna Glacier. The glacier is outlined in semi-transparent gray using the RGI 6.0 boundary.

We were able to make standard measurements at all sites in both spring and fall. The Campbell Scientific weather stations at BaseCamp and 14Camp were maintained. The weather station at Kahiltna Pass had been buried by winter snow, but we located it in the spring using a metal detector, dug it up, and removed it permanently. The spring work was done from a temporary camp at BaseCamp. The Onset station at K53 was permanently removed in the fall. We also did detailed surveys of optical survey sites surrounding K17 (from the Mayo days) during the fall visit.

2020

We visited Kahiltna Glacier twice in 2020. The first visit occurred July 14-15 (delayed by covid mitigations) and included Michael Loso and Tucker Chenoweth. The second visit occurred August 28 and included Michael Loso and Galen Dossin. All aviation was completed with the Denali A-star B3e 0AE with Andy Hermansky as pilot.

We were able to make standard measurements at all sites in both spring (which was really mid-summer, because of covid) and fall, except that in the spring our team was unable to visit KahiltnaPass or 14Camp. We maintained the Campbell Scientific weather stations at BaseCamp, and fortunately the 14Camp weather station was rebuilt onsite by a ranger patrol. After the 2-day BaseCamp weather station maintenance in mid-July, Loso and Chenoweth saved on the cost of a helicopter ride back to Talkeetna by traversing out of the range via skis, hiking, and a raft.

2021

We visited Kahiltna Glacier three times in 2021. The first visit occurred April 27 and included Michael Loso, Travis Baldwin, and Galen Dossin. The second visit occurred May 24, and included Michael Loso, Anna Thompson, and Galen Dossin. The third visit occurred August 28 and included Michael Loso and Anna Thompson. All spring aviation was completed with the Denali A-star B3e 0AE with Andy Hermansky as pilot. The fall mission was completed with a Vertical Solutions (vendor) R66 with Jon Elsass as pilot.

We were able to make standard measurements at all sites in both spring and fall, except that in the fall our team was unable to visit KahiltnaPass or 14Camp. We maintained the Campbell Scientific weather station at BaseCamp during the early spring visit (April 27), and fortunately data from the 14Camp weather station was downloaded by a ranger patrol.

Kennicott Glacier Monitoring Sites and Activities

Overview

Kennicott Glacier work began in 2016, over a decade after the Kahiltna Glacier monitoring work, in recognition of the importance of including a comparable mass balance program in the country’s most heavily glacierized NPS unit. Initial measurement sites evolved slightly over the ensuing years in response to logistical and safety constraints that emerged in the early years. We are now routinely measuring accumulation and ablation at five sites on Kennicott Glacier (including the Gates Glacier tributary), as listed below. Early efforts to install an ablation stake and weather station at higher

altitudes (above the highest currently maintained stake at Gates7200) were abandoned for safety reasons.

As of 2021, the full suite of ongoing measurements at Kennicott Glacier (Figure 2) includes (with nominal elevations shown in parentheses):

- Kenn2700 (806 m): Ablation stake and snowpit-based accumulation measurements
- Kenn3100 (932 m): Ablation stake and snowpit-based accumulation measurements
- Gates3600 (1083 m): Ablation stake and snowpit-based accumulation measurements
- Kenn6100 (1833 m): Ablation stake and snowpit/snowcore-based accumulation measurements
- Gates7200 (2173 m): Ablation stake and snowpit/snowcore-based accumulation measurements

In contrast with the Kahiltna Glacier, glacier monitoring at Kennicott Glacier is focused more on lower elevation phenomena. We do have two sites in the accumulation zone (Gates7200 and Kenn6100), but we lack any good measurements at the higher elevations of this large glacier (max glacier elevation is >4800 m, at the summit of Mt. Blackburn). We retain a goal of better constraining surface mass balance processes at those high elevations, but at present we have not developed any safe and consistent way to make measurements above 2173 m. Kennicott Glacier provides an excellent opportunity, however, to better understand the mass balance processes typical of a large Alaskan glacier's ablation zone: melt on both clean ice and on debris-covered ice, and also interaction (calving, sublacustrine melt) with a growing proglacial lake. Our work on Kennicott Glacier also benefits from a high degree of interest from outside collaborators, and our stake network is presently augmented by additional data from stakes and temporary weather stations installed by collaborators at University of Alaska Fairbanks and the Chinese Academy of Science. I do not focus on those measurements in this document, but they will be utilized in our subsequent analyses. Finally, the Glacier Monitoring program does not maintain a permanent year-round weather station on Kennicott Glacier, but we do benefit from a long-term Automated Weather Station (AWS) maintained on the Goat Hair Ridge nunatak by the NPS/CAKN Climate Monitoring Program.

The logistics of all work on Kennicott Glacier are based in the McCarthy/Kennicott area. The PI (Loso) maintains an office in the Kennecott Mines NHL and most equipment is stored there. Most aviation is based out of the primary DOT-maintained McCarthy airstrip. On occasion, usually at the preference of pilots, we will instead utilize the Rowcon-maintained Fireweed airstrip on the west side of the Kennicott River. Avgas and JetA are available at both sites. No helicopter vendors operate out of the McCarthy/Kennicott area, so the program typically relies on either the exclusive use WAFM Firepro helicopter or a vendor, either of which would have to ferry to the McCarthy airstrip from other locations. Over the years the program has transitioned towards less reliance on the Firepro helicopter, largely because timing (to take advantage of weather windows) is so critical, and scheduling the Firepro ship is difficult with the possibility that it can be diverted to missions in other parks with short notice. Support personnel for glacier monitoring work are usually drawn opportunistically from (in descending order of priority) the Glacier Monitoring PI's Scientist-in-the-Parks intern, Kennecott-based VRP/ranger staff, and other WRST staff.

Aviation costs for the Kennicott Glacier portion of the Glacier Monitoring Program are managed directly by the Program PI. Uncommonly, the PI will take opportunistic advantage of options to share helicopter time with other users (VRP, maintenance, non-NPS users), with the advantage of being able to share ferry and/or availability costs, but it is more typical that the entire cost of the helicopter mission is borne by the Program, including ferry time, availability, fuel, hourly flight time, and (rarely) per diem for multi-day visits. Importantly, these costs can vary significantly based on many factors, and the cost of the fall visit is borne by the Program very close to the end of the fiscal year, so careful planning is required to ensure that the overall Program remains within budget. Costs per mission (spring or fall) have varied through the years between $3500 and $7300, but overall aviation costs on a per-year basis (spring plus fall) have averaged out to about $9400/yr since 2016.

A typical season of work on the Kennicott Glacier consists of two visits, one in spring and one in fall. Both spring and fall visits can each typically be conducted in a single day of work, and the PI endeavors to keep the scope of work simple enough to maintain that schedule since the jump to a 2-day mission would require a substantial step increase in aviation costs. Because there are no weather stations to maintain, and because Kennicott Glacier is so much closer to the airstrip than Kahiltna Glacier, the logistics of fieldwork on Kennicott Glacier are in general much simpler. The helicopter, if not already in the Kennicott Valley (sometimes the Firepro ship is already present for other work), will ferry to the McCarthy airstrip early in the morning, where Loso and assistant(s) will meet it with all gear prepped and weighed. All the sites are close to each other and to the McCarthy airstrip, so the flying consists of very short hops and the helicopter/pilot wait on site while work is conducted. The most time-consuming portion of the work is often steam-drilling of 6-10 m deep holes ablation stakes on the lower glacier, and good planning is required to ensure that enough time is available at the end of the day to complete these holes. If the crew ran out of time, it would be critical to prioritize helicopter time to complete work at the upper sites, which are strictly accessible only by helicopter. The two lowest sites could, with difficulty, be accessed later on foot if needed. Below, I summarize the activities that specifically occurred each year since 2016.

2016

We visited Kennicott Glacier twice in 2016. The first visit occurred May 26-27, and included Michael Loso, WRST ranger Kirin Riddell, and Firepro Heli Manager Jessica Sherwood. Spring aviation was completed with the EAFM Exclusive Use A-star B2 N570 with pilot Ruston Boucher. Some of the flying on May 27 involved VRP work in upper McCarthy Creek. The second visit occurred August 20 and included only Michael Loso. Fall aviation was completed with the Vertical Solutions (vendor) R66 N808VS with pilot Leigh Coates.

We were able to visit Gates3600, Gates7200, and the later-abandoned site “Gates High” at 2875 m during both spring and fall trips. Standard measurements were made at all sites, except that during our fall visit to Gates High we found that the stake (emplaced in spring) had been carried by fast ice flow into a serac field where we could not see or access it, and meanwhile the site had been threatened by a very recent serac-fall event from cliffs above, suggesting that the site was unsafe for further work.

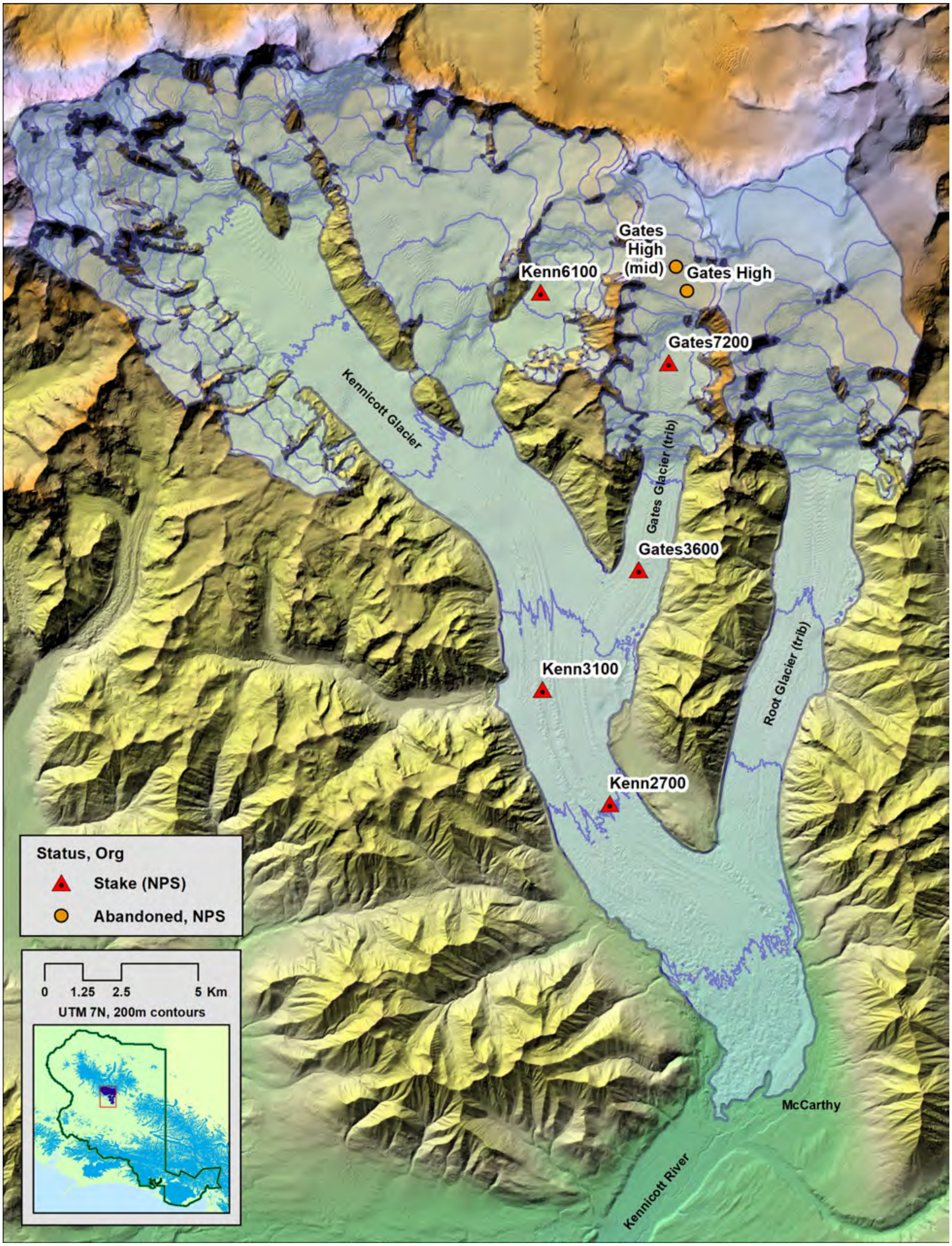

Figure 2. Stake monitoring sites on Kennicott Glacier. The glacier is outlined in semi-transparent gray using the RGI 6.0 boundary.

2017

We visited Kennicott Glacier twice in 2017. The first visit occurred May 26, and included Michael Loso, WRST ranger Kirin Riddell, and Firepro Heli Manager Tim Baron. Spring aviation was completed with the EAFM Exclusive Use A-star BA NS954 with pilot Ruston Boucher. The second visit occurred September 30 and included Michael Loso and Denali ranger Joey McBrayer. The fall aviation was initially scheduled to utilize the Vertical Solutions R66, but that helo became unavailable, so we completed with the Denali A-star B3e 0AE, which had luckily had its contract extended by over a month. Andy Hermansky was the pilot.

We were able to visit and complete standard measurements at both Gates3600 and Gates 7200. We made a final visit to the later-abandoned site “Gates High” at 2875 m during the fall trip, with the only purpose of probing to try and assess snow depth.

2018

We visited Kennicott Glacier twice in 2018. The first visit occurred May 17, and included Michael Loso, GIP Guest Scientist John Sykes, and Firepro Heli Manager Chris Havener. Spring aviation was completed with the EAFM Exclusive Use A-star BA NS954 with pilot Ruston Boucher. The second visit occurred August 29 and included only Michael Loso. Fall aviation was completed with the Vertical Solutions (vendor) R66 N808VS with pilot Travis Yenter.

We were able to visit Kenn2300, Kenn3100, Gates3600, Kenn6100, and Gates7200 during both trips, except that we were unable to land (due to poor visibility) at Kenn6100 and Gates7200 during out spring trip. Kenn2300, Kenn3100, and Kenn6100 were new sites; Kenn2300 was later abandoned. Standard measurements were made at all visited sites.

2019

We visited Kennicott Glacier twice in 2019. The first visit occurred June 7 and included Michael Loso and GIP Guest Scientist Lia Lajoie. Spring aviation was completed with the Vertical Solutions (vendor) R66 N808VS with pilot Leigh Coates. The second visit occurred August 22 and included Michael Loso and WRST ranger Kirin Riddell. Fall aviation was completed with the Vertical Solutions (vendor) R66 N808VS with pilot Kelton Porter.

We were able to visit Kenn2300, Kenn2700, Kenn3100, Gates3600, Kenn6100, and Gates7200 during both trips, except that we visited Kenn2300 only in the spring, removing the stake and subsequently abandoning that site. Kenn2700 was a new site in spring 2019. With the addition of that stake, the stake network stabilized in 2019 and has been consistent since that time. Standard measurements were made at all visited sites.

2020

We visited Kennicott Glacier twice in 2020. The first visit occurred June 26 (delayed by covid mitigations) and included Michael Loso and Denali ranger Joe Reichert. Spring aviation was completed with the Denali A-star B3e 0AE, which we ferried from Talkeetna with pilot Andy Hermansky because this was the only acceptable covid-compatible flight option at that point in the newly emerging pandemic. The second visit occurred September 13 and included Michael Loso and

WRST trail crew leader Charlie Hebbers. Fall aviation was completed with the Vertical Solutions (vendor) R66 N808VS with pilot Turner Pahl. For the fall visit we met the pilot (who had ferried from Valdez) in Chitina, instead of our usual operating base of McCarthy.

We were able to visit, and conduct standard measurements at, all sites including Kenn2700, Kenn3100, Gates3600, Kenn6100, and Gates7200 during both trips. During the fall trip we also made brief overflights of three stakes emplaced and maintained by our collaborators at UAF.

2021

We visited Kennicott Glacier twice in 2021. The first visit occurred June 11, and included Michael Loso, SIP intern Anna Thompson, and WRST ranger Spencer Williamson. Spring aviation was completed with the Vertical Solutions (vendor) A-Star B2 N351VS with pilot Thomas Bue. We shared the helicopter ferry and availability costs with VRP. The second visit occurred September 8 and included Michael Loso and SIP intern Anna Thompson. Fall aviation was completed with the Vertical Solutions (vendor) R66 N808VS with pilot Al Carbono.

We were able to visit, and conduct standard measurements at, all sites including Kenn2700, Kenn3100, Gates3600, Kenn6100, and Gates7200 during both trips. In addition, in the spring we placed temporary temperature sensors on sliding sleeves over the stakes at Gates 3600 and Kenn6100, removing them in the fall.

Data Management

Data from the glacier monitoring work described above are managed and archived in accordance with National Inventory and Monitoring Program standards. Here I present an overview of the workflow associated with that process; details and SOPs can be found elsewhere. The flow of data can be best visualized as consisting of three components: field data, working archives, and the glaciers database. I describe each in order.

Field Data

Field data consist typically of five products. Each is expected to be archived digitally in at least two locations within 2 days of completion of fieldwork.

1. Field notebooks kept by the PI and by other project participants are a primary repository of detailed measurements and other information, some of which provide redundancy for other digital products. These notebooks are scanned and saved as pdfs.
2. GPS data, typically collected within Trimble GeoXH mapping grade receivers, are collected using a data dictionary (latest is 'GlacierMapping2021_06_07.ddf') that provides for recording of ancillary measurements, as well as GPS position. These data are downloaded to a workstation, post-processed using Pathfinder Office, and archived as both raw and corrected files.

3. Stake and snowpit/snowcore measurements, as recorded in products 1 and 2 above, are entered into a structured excel spreadsheet that standardizes terminology, units, nomenclature, etc.
4. Downloaded weather station data (from stations directly managed by the Glacier Monitoring Program—this does not apply to stations managed by collaborators) are archived directly as .csv or .xlsx files.
5. All field photos are organized and stored in a labelled subdirectory.

Working Archives

Field data described above, plus all other program files (including historic files, reports, administrative content, and data from ancillary projects) are maintained in well-organized directories on the PI's workstation. These directories are mirrored (and thus backed up) regularly to a network drive (the 'G' drive) at the Alaska Regional Office in Anchorage. That drive is mapped as \\INPAKROVMIM\cakn\Monitoring. That is the authoritative repository for all the "other" program files.

The data files specifically produced under the monitoring protocol (essentially, the archived field data) are further uploaded once per year, in the fall, to the IRMA Project #2216228 ("Glacier Monitoring in the Central Alaska Network of National Parks"). These annual data (Table 1) are uploaded as a single .zip file and contain the updated and complete data from ALL years, except that field photos are not included—to minimize the total size of the archive. The most recently uploaded archive is always the most authoritative and updated record for the entire archive and supersedes earlier data uploads. Those older uploads are maintained on IRMA for archival purposes. The data files uploaded to IRMA are internally viewable.

Table 1. IRMA data records associated with the CAKN Glacier Monitoring Program, 2016-2021.

Data Year(s)	IRMA Code	Title	Upload Date
Pre-2017	2248211	CAKN Glacier Protocol Datasets 2017	December 29, 2017
2017	2248211	CAKN Glacier Protocol Datasets 2017	December 2017
2018	2258495	CAKN Glacier Protocol Datasets 2018	December 19, 2018
2019	2274312	CAKN Glacier Protocol Datasets 2019	June 1, 2020
2020	2278743	CAKN Glacier Protocol Datasets 2020	September 20, 2020
2021	2287576	CAKN Glacier Protocol Datasets 2021	October 5, 2021

Glaciers Database

In 2021, the Glacier Monitoring Program completed the creation of a new SQL Server database for the CAKN glaciers data. This involved substantial guidance and contributions by Data Manager Scott Miller, to whom I'm very grateful. The CAKN_Glaciers database, which is housed at <inpyugamsvm01\nuna_dev> and accessed through the Microsoft SQL Server Management Studio, is oriented around two distinct time periods. The first is all pre-2016 glacier monitoring data,

primarily from Denali. These data, collected by a variety of investigators using multiple techniques, were recently QC'd and homogenized under a Focused Condition Assessment project, described elsewhere in this report, and are now entered into the database as <dbo.Stakes_pre2016>. Data from 2016 forward are stored in two separate tables. Stake measurements are stored in <dbo.Stakes> and snow measurements are stored in <dbo.Snow>. These tables will be updated each year as new data are collected. Weather station measurements are not yet entered into the database but a new table for those measurements will be added in 2022.

Preliminary Results

Here we present a subset of results from the quality-controlled, certified datasets collected between 2016 and 2021. Complete results and detailed analyses are not included here. These data are presented with an important caveat, described below. The significance of this caveat is that time-series of accumulation and melt presented here should not be interpreted as indicative of inter-annual changes.

These results describe *measured* changes (ablation and/or accumulation) at the various sampling sites, which are functions not only of actual mass balance patterns but also of sampling dates. Seasonal totals for accumulation (in winter) and ablation (in summer) are the most important fundamental objective for this program, but measurement dates in spring and fall never coincide exactly with the start or end, respectively, of the accumulation and ablation seasons. Measurements must therefore be augmented by modeled changes that occur between the measurement dates and the actual mass maxima/minima dates. That is the primary reason that we rely on weather station data to augment our stake measurements—so that we may model these unmeasured changes with a reasonable degree of accuracy. That modeling has been undertaken for a subset of these data (results were presented at the 2021 American Geophysical Union annual meeting), and a snapshot of that modeling is shown later in this report. The complete results await further analysis and inclusion in a more complete research paper. The following results are therefore considered to be high-quality and reliable, but not amenable for interpretation of climatic trends.

Summer Balances

Ablation (and rarely, at high elevation, accumulation) is measured over the course of the summer melt season through measurement and re-measurement of aluminum stakes inserted into holes on the glacier surface. As the snow/ice melts, more of the pole is exposed, yielding a cumulative measurement of melt. Combined with measurements or estimates of the densities of melted strata (900 kg/m^3 for ice, variable between 50-600 kg/m^3 for snow), we have an estimate of ablation in units of meters snow water equivalent (m SWE).

Summer balances at each site on Kahiltna and Kennicott Glacier are broadly consistent from year to year (Figure 3). Note that dashed lines connecting the points are not meant to reflect accumulation trends in between measurement dates, but rather are presented only to visually connect the measurements from each site. The subtle year-to-year variability of ablation at these sites is

important because it reflects the direct role of climate (specifically temperature) on melt. As mentioned above, however, I caution that these measurements have not yet been extended to include the entire melt season, and thus the variability in these plots is due at least as much to variability in the timing of measurements as it is to the variability in summer temperatures. As an example. Note the generally high (less negative, as in less melt) values of ablation at sites measured in fall 2021. This is primarily because we made our "spring" measurements late that year—due to covid delays—thus resulting in measurement of a shortened melt season.

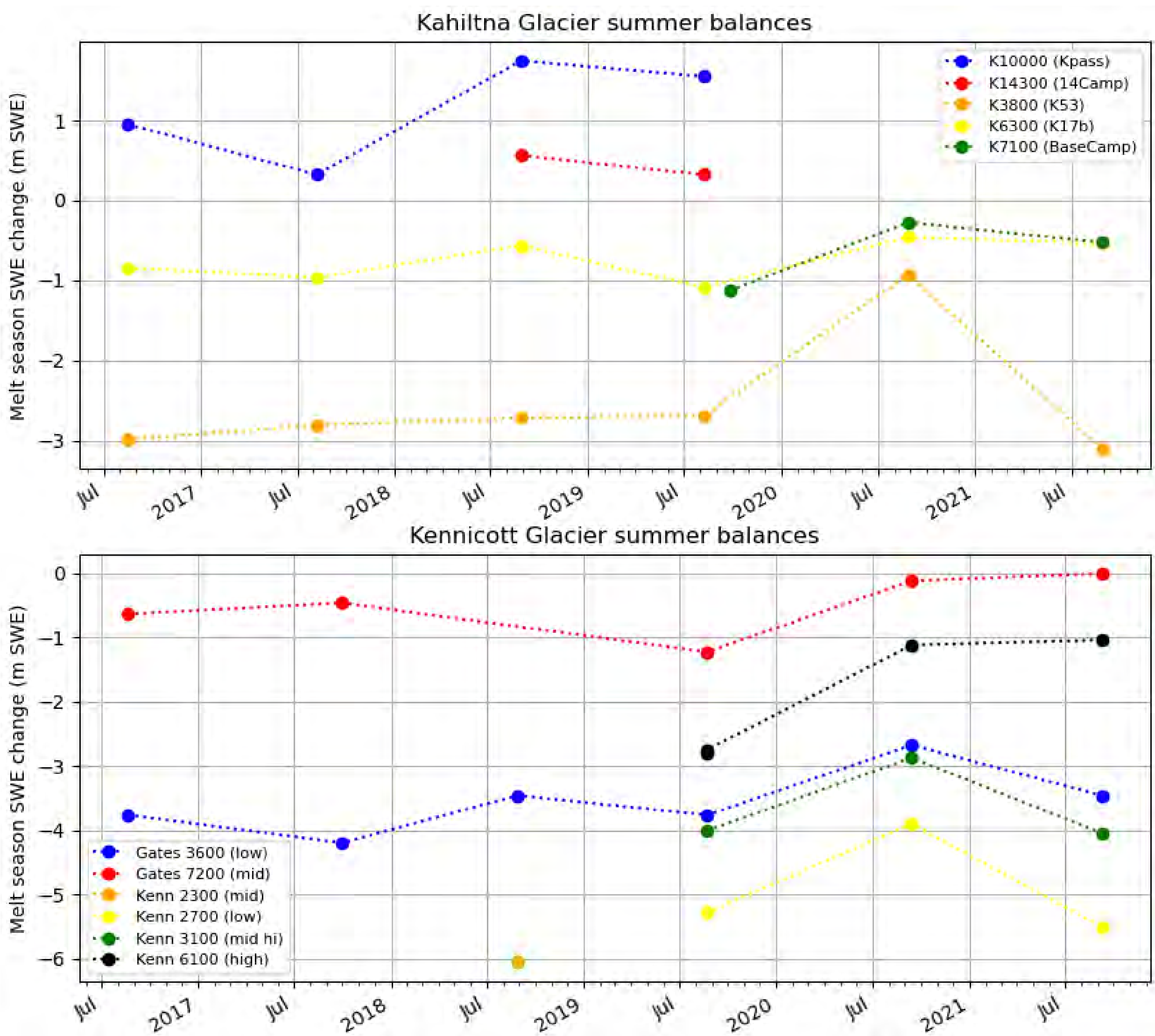

Figure 3. Measurements of ablation, in units of meters snow water equivalent (m SWE), at multiple sites on Kahiltna (above) and Kennicott (below) glaciers. Note that ablation is for the measured time interval only--see text for details.

A few other notes about the results shown here:

- Where measured summer balances are positive (K10000 and K14300 on Kahiltna Glacier), these reflect net summer accumulation at those sites. This does not imply that ablation did not occur—only that accumulation during the measurement period exceeded ablation.
- Missing values for K14300 after 2019 will be filled in from analysis of weather station data at that site—but this analysis has not yet occurred.
- Missing values at K10000 reflect a change in measurement approach at that site. The very high summer accumulation at that site has presented challenges to a variety of measurement techniques, and the current approach is now to core that site in spring and fall, but omit weather stations and/or stakes. This complicates, but does not prevent, calculation of summer and winter balances at that site—further analysis is required to derive those values.

Winter Balances

Snow accumulation over the winter season is measured each spring through a combination of snowpits, snow cores, probes, and stake measurements. Where the snowpack is reasonably shallow (<~1.5 m), a snowpit is sufficient to measure snow depth and the density of distinct stratigraphic layers. Where the snow is deeper, a shallow snowpit is augmented by measurements of deeper layers in core sections collected with a Kovacs corer. Measurements of the ablation stake are used to corroborate these measurements but are rarely used as the primary indicator of snow accumulation because an unknown amount of surface melt may have occurred after the prior fall's measurement. And in cases where the surface underlying the new snow is rough (most common in the ablation zone), we will augment the snowpit/core measurements with 10 probed measurements of snow depth in the surrounding area, using the average probe depth to adjust the single value found in the pit/core. Snow thickness and density are used to derive a final estimate of accumulation in units of meters snow water equivalent (m SWE).

Winter accumulation measurements at each site on Kahiltna and Kennicott Glacier reveal consistent trends (Figure 4). Note that dashed lines connecting the points are not meant to reflect accumulation trends in between measurement dates, but rather are presented only to visually connect the measurements from each site. As with the ablation measurements, we caution that these trends—as presented here—have not been corrected for length of measurement period and thus are biased by variability in sampling date. On Kennicott Glacier, where there are more low-elevation measurement sites, it is also worth noting that many of these sites have already lost their shallow snowpack before we typically arrive in the spring. These "zero accumulation" measurements are common, but do not reflect a complete absence of winter snowpack at these areas.

Weather and Melt Modeling

The Glacier Monitoring Program maintains two year-round weather stations on Kahiltna Glacier. These telemetered stations provide real-time access to a variety of weather products, but for the purpose of glacier monitoring they are most valuable for their direct measurements of air temperature and snow thickness, which reflects the combination of accumulation, melt, compaction, and wind. Snapshots of these data are provided in Figure 5 and Figure 6. The continuous records (actually quasi-continuous because of power failures at K7100) provide more insight into snow accumulation

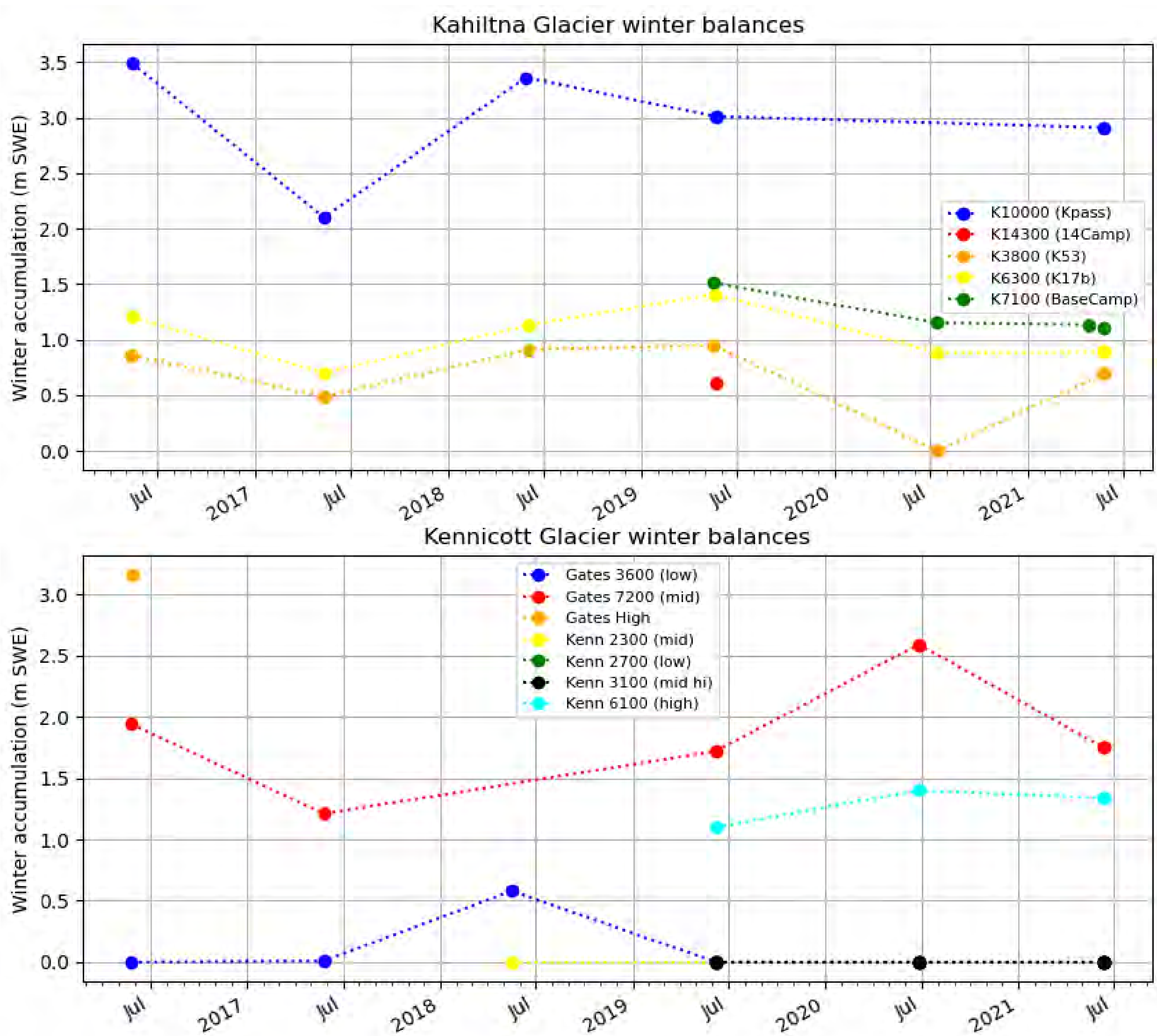

Figure 4. Measurements of snow accumulation, in units of meters snow water equivalent (m SWE), at multiple sites on Kahiltna (above) and Kennicott (below) glaciers. Note that accumulation is for the measured time interval only--see text for details.

and ablation than comparable biennial measurements at stakes. One example is the evidence for most accumulation occurring in summer at K14300. This is a common pattern in the Himalayas, but not on Alaskan glaciers, and is probably unique to very cold portions of the highest glaciers in the state.

Another example is the comparative observation that K7100, though roughly 7000 feet lower than K14300, and subject to much more ablation, has accumulated nearly as much snowpack since spring 2018. We now know that the highest accumulations on the mountain occur at K10000 (Kahiltna Pass), but initial efforts to maintain a weather station at that site have been abandoned in the face of logistical challenges.

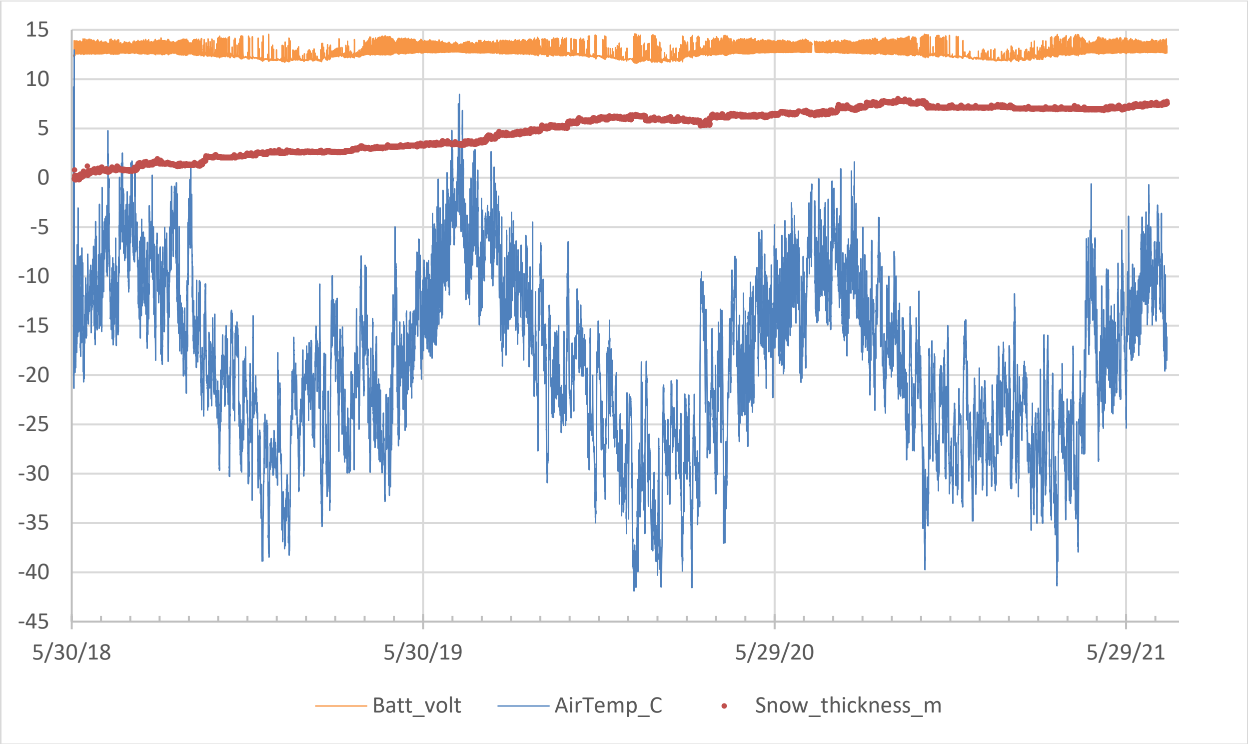

Figure 5. Air temperature, snow thickness, and battery voltage at the Genet Basin (K14300) site on Kahiltna Glacier. Snow thickness is measured from an arbitrary baseline.

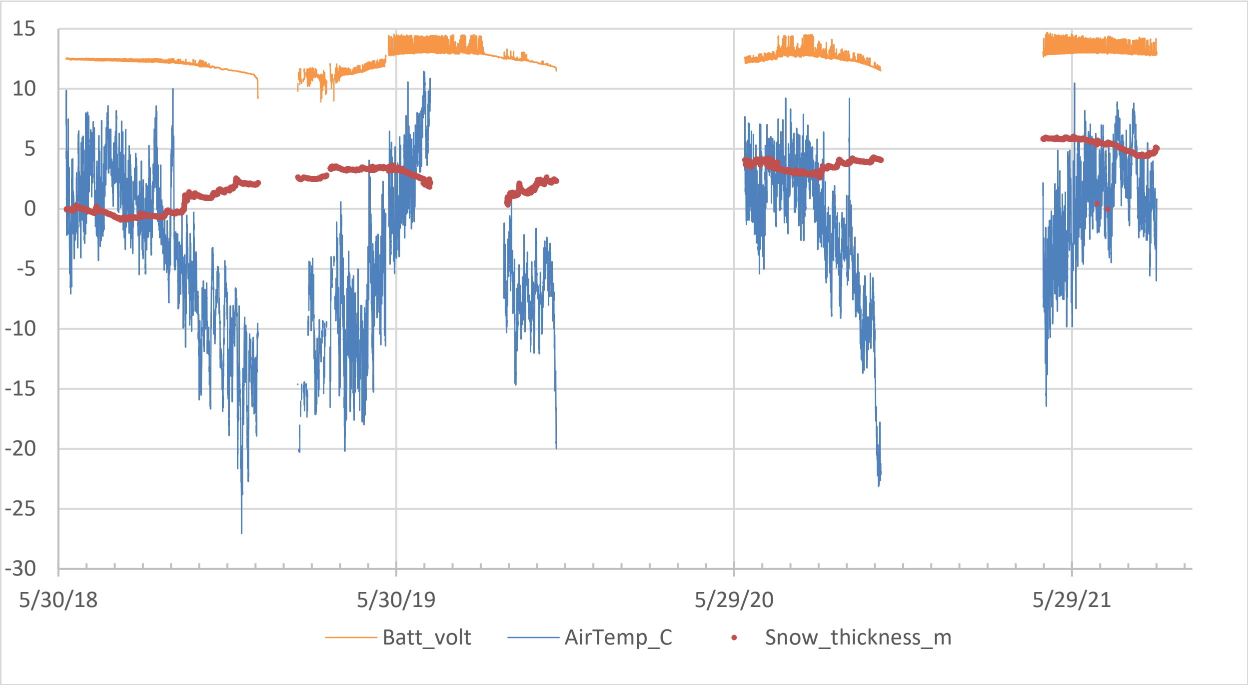

Figure 6. Air temperature, snow thickness, and battery voltage at the Base Camp (K7100) site on Kahiltna Glacier. Snow thickness is measured from an arbitrary baseline. Gaps reflect loss of power during periods in winter when the station is in the prolonged shade of Mt. Hunter, but cumulative snow thickness is adjusted appropriately for changes that occur during outages.

At Kennicott Glacier, we do not maintain a Glacier Monitoring-specific weather station, but stations maintained by others allow us to do the melt modeling necessary for mass balance calculations. As mentioned above, a preliminary analysis of this sort was presented at the American Geophysical Union meeting in December 2021 (Loso and others, 2021), and three figures highlighting that work are included here.

An array of weather station measurements in the Kennicott Glacier area were first compared with the most stable long-term weather station on the Goat Hair Ridge nunatak. That analysis was used to derive a numerical model that predicts hourly on-glacier air temperatures at all glacier elevations since 2016 (**Error! Reference source not found.**). Those temperatures were then used to calculate positive degree days (PDD: cumulative sum of daily average temperatures above zero degC at a given site) for each stake location. Comparison of the modeled PDD with the measured melt during a summer measurement period at any given stake (Figure 8). These data allow us to calibrate a *degree day factor* that predicts melt, at any given location, based on the modeled temperature.

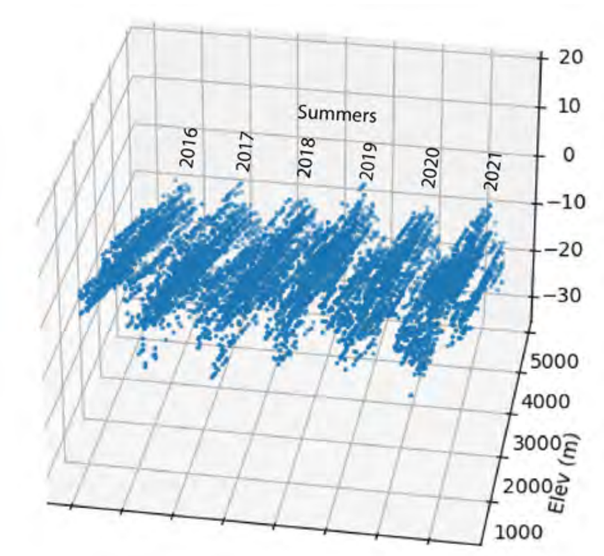

Figure 7. Modeled air temperatures at the glacier surface at all elevations since 2016.

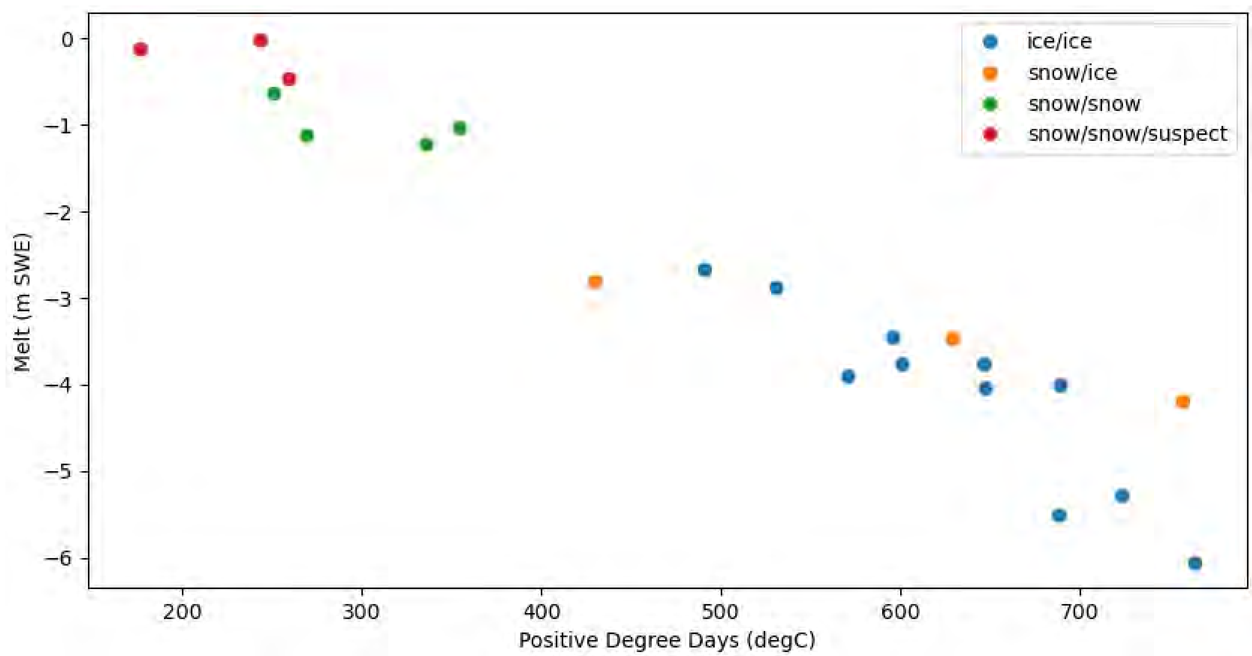

Figure 8. Melt (ablation) measurements at stakes on Kennicott Glacier compared with modeled temperatures (in positive degree days) at each site. Grouped by surface type (snow, ice, or both).

The calculations described above can be used to extend the measured ablation at a given stake to the portions of the summer melt season, in spring and/or fall, that were not covered by field measurements. Those calculations are not shown here, but Figure 9 summarizes the next step: calculation of total hourly melt at all locations on the glacier for the entire measurement period. That figure also shows results of a separate calculation, not discussed here, for melt on debris-covered ice. Many details are omitted in this presentation, and there are some components of this analysis that require further refinement, but the purpose of showing these summary figures is to orient the reader to how our stake measurements and weather data can be combined to assess glacier-wide mass balance at both Kahiltna and Kennicott glaciers as this project moves forward.

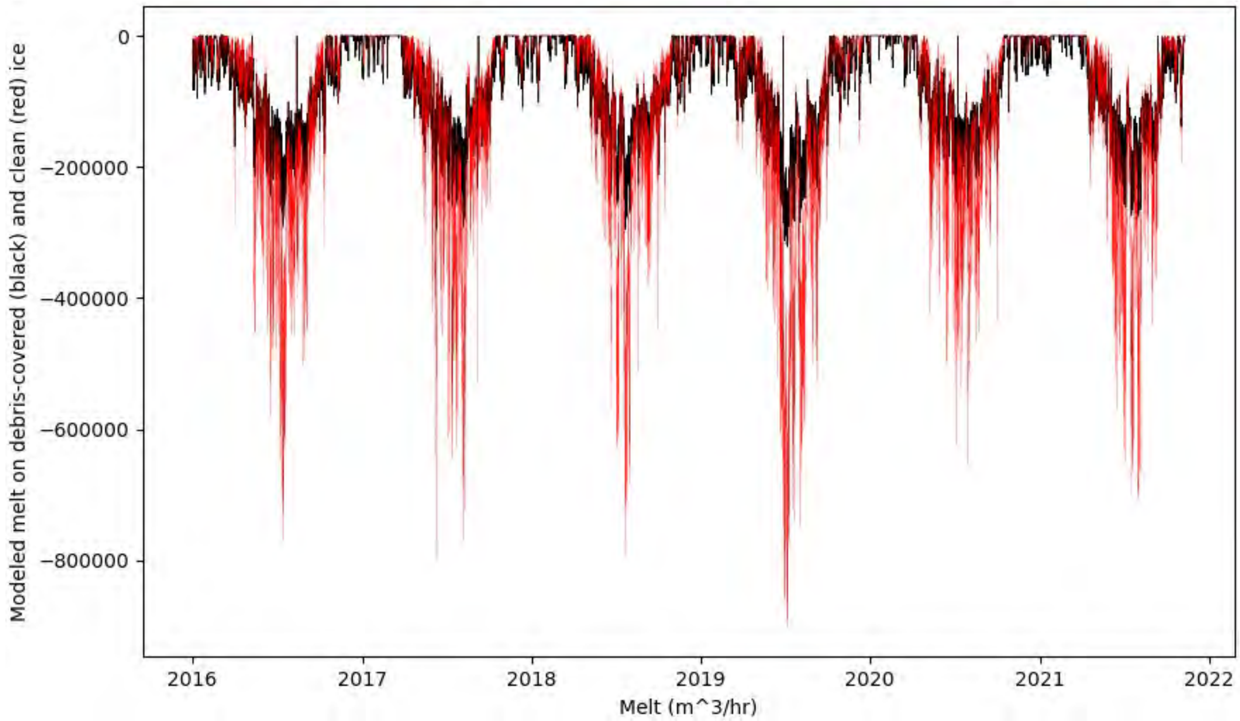

Figure 9. Estimated glacier-wide melt, in cubic meters per hour, from 2016 to 2021 on Kennicott Glacier. Black line shows melt on debris-covered ice; red lines are for clean ice.

Other Glacier Monitoring Activities

Overview

Glacier monitoring in the Central Alaska Network is focused on the mass balance measurements described in the bulk of this report. These measurements are guided by protocols and maintained with long-term intentions. But these measurements describe only two glaciers, and the Central Alaska Network is home to over 4000 individual glaciers. This substantial glacier cover, and the impacts it has upon the ecosystems around it, provides an opportunity—and at times a requirement—that the monitoring program pay attention to phenomena outside the strict bounds of the protocol-based work. Here I describe very briefly some of the other projects that have, with substantial assistance from numerous collaborators inside and outside NPS, been undertaken in the last several years.

Icy Bay Landslide/tsunami

Glaciers, and specifically glacier retreat, are contributing to new kinds and frequencies of geohazards in the parks. In one example, retreat of Tyndall Glacier, near Mt. St. Elias in WRST, destabilized a hillside that failed catastrophically on 17 October 2015. The landslide was very large, and most of it ran out into the water of Taan Fjord, creating a local tsunami with a wave runup of up to 193 m, stripping much of the vegetation and soil from the shoreline of Icy Bay. The CAKN Glacier

Monitoring Program collaborated with numerous outside investigators to respond to this event, in part with funding from the Oceans Alaska Science and Learning Center, and completed a multi-faceted research project that produced several peer-reviewed publications (Bloom, 2017; Gualtieri and Ekström, 2018; Dufresne and others, 2018; Williams, 2018; Haeussler and others, 2018; Higman and others, 2018; Franco and others, 2021). In addition to that work, NPS funded and produced a widely distributed outreach video about the event, the research, and the findings.

Flat Creek Glacier Collapse

Another type of geohazard resulting from climate-induced glacier change is the catastrophic glacier collapse. Flat Creek Glacier, a small informally named glacier in northeast WRST, underwent a series of catastrophic glacier collapses in 2013, 2015, and 2016. Like the Icy Bay landslide, these events were (fortunately) not witnessed firsthand by any visitors, but after their initial detection in 2015 we convened a group of researchers, led by University of Colorado PhD candidate Mylene Jacquemart, to study the origin and consequences of these events. With funding assistance from academic funders and from the NPS GRD, fieldwork and remote sensing analyses culminated in several publications that significantly enhanced the regional and global understanding of these apparently new, and dangerous, forms of glacier retreat (Jacquemart, 2018; Jacquemart and others, 2020; Jacquemart and Cicoira, 2021).

Glacier Status and Trends

In 2014, the first comprehensive effort to inventory glaciers within the Alaskan National Parks was completed by cooperators at two Alaskan universities (Arendt and others, 2012a; b, 2013, 2014; Loso and others, 2014). Although strictly outside the boundaries of the written CAKN Glacier Monitoring Protocol, the work accomplished by that report was directly applicable to the objectives of the program, and it is widely agreed that a similar inventory should be done roughly every 10 years. Accordingly, the second Status and Trends report ("GST2.0") is underway, with funding from I&M and other sources. This latest effort involves A) updated mapping of glacier perimeters using automated algorithms—led by Peter Kirchner and collaborators, and B) updated assessment of glacier surface elevations using Operation Icebridge lidar data along with other sources—led by CAKN Glacier Monitoring Program PI Loso and collaborators. The collaborations motivated by initial funding of this effort are taking on a life of their own, and additional data products and analyses are almost certain to come out of this project with minimal additional investment. One such component is the addition of glacier change projections for all NPS Alaska glaciers through 2100 (in a collaboration led by David Rounce), and another is the collection of full-coverage lidar for the four highest-priority glacier clusters in GAAR (led by collaborator Chris Larsen). Work on this project is ongoing.

Traleika Surge Monitoring

An early focus of the CAKN Glacier Monitoring Program was detection of glacier surges, and that focus was motivated in large part by the early recognition that Muldrow Glacier (DENA) had an apparently 50-year return period for its periodic surges (e.g. Harrison, 1964). When Traleika Glacier, a significant tributary of Muldrow Glacier, began speeding up in 2016, the CAKN Glacier Monitoring Program was watching. Early observations, aided by remote sensing of surface velocities

by collaborator Mark Fahnestock, showed that Traleika more than tripled its usual speed in the years after 2016, and it seemed a speed-up of the Muldrow was imminent. The event was publicized through NPS blog posts and resource briefs between 2017 and 2019. But Traleika began slowing down around 2019, and it seemed maybe the Muldrow was not going to surge. That all changed in 2020, when very Muldrow began a very substantial surge that later incorporated the Traleika and other tributaries. The CAKN Glacier Monitoring Program assisted AKRO geologist Chad Hults, who took the lead in coordinating an NPS-led campaign of measurements to document this surge, which has only recently concluded. Publications about this event are pending.

Kennicott Glacier interpretation and Hazard Analysis

Education of visitors about park phenomena is one important justification for I&M monitoring work, along with an emphasis on detecting and understanding geohazards. The CAKN Glacier Monitoring Program took a lead in addressing both these issues at Kennicott Glacier (WRST) through a PMIS-funded project “Protecting infrastructure & visitor safety from hazards associated with Kennicott Glacier retreat.” This project, conducted from 2018-2020, updated a hazards analysis conducted previously by the now-retired park geologist (Rickman and Rosenkrans, 1997) and used the results to complete two primary tasks. The first was design and completion (along with substantial collaborative work by WRST Interpretation staff) of the *Kennicott Glacier Interpretive Concept Plan* (Chambers and others, 2020). This document, now adopted by the park’s leadership team, lays a blueprint for interpretation and outreach related to glacier phenomena in the park, and is being implemented in stages commensurate with funding. The second task was completion of a new hazards analysis, which was done in concert with park maintenance staff. This culminated in an ongoing working relationship between the CAKN Glacier Monitoring Program, the maintenance division, the local community, and the AK State DOT to monitor and assess hazards related specifically to the retreat and change of Kennicott Glacier.

Kahiltna Glacier Focused Condition Assessment

As mentioned previously, glacier monitoring has been occurring continuously on Kahiltna Glacier since 1991. Due to numerous changes in principal investigator, methodology, and archival strategy since that time, the glacier monitoring records inherited by the current CAKN Glacier Monitoring Program PI (Loso) in 2016 were complete, but not all mutually comparable. Seeking assistance in organizing, interpreting, and homogenizing those data, the Program sought and received I&M Focused Condition Assessment money in 2018-19 to solicit outside assistance. Those funds helped to procure the service of Emily Baker, a geophysicist and glaciologist with the USGS Alaska Science Center in Anchorage. Emily took a deep dive into the records and produced a completely revised and homogenized dataset of Kahiltna Glacier mass balances from 1991-2015. Those data, as described earlier, are now incorporated into the Glacier Monitoring Program’s SQL Server database. Now that they are incorporated into the database, a NRDS report is being prepared to describe Emily’s work and the resulting datasets. One enjoyable portion of that project was motivated by the need to transform Larry Mayo’s original optical survey records (from the early-mid 1990s) into modern GPS-compatible coordinates referenced to a consistent datum. That required a collaborative field effort involving USGS, the Glacier Monitoring Program, and South District Ranger Tucker Chenoweth. We located and visited three optical survey monuments in high-angle terrain

surrounding the Kahiltna Glacier to measure them with modern survey-grade GPS units—a project that successfully brought the historic survey data into a tight modern reference frame.

Malaspina Glacier Collaborative Forecasting Project

Malaspina Glacier, along with the Seward Glacier which feeds it (this is unusual for a single glacier to have two names), is the largest glacier in Alaska. It is also very vulnerable to imminent catastrophic tidewater glacier retreat, poised perhaps to begin a decades-long phase of rapid retreat culminating in the creation of a new large embayment on the south coast of Alaska. To assess the probability and nature of such an event, the CAKN Glacier Monitoring Program and a large number of academic collaborators have initiated a 3-year research project with both internal NPS funding and substantial National Science Foundation Support. The NPS component ("Characterize landscape and park loss from retreat of globally significant Malaspina Glacier") provides $210k over 3 years, leveraging the ~$1 million in NSF funding to do a comprehensive study and numerical model of this unique glacier's present and future dynamics. The first year of fieldwork is complete and the numerous important findings from that early work were summarized by seven separate presentations at the 2021 American Geophysical Union annual meeting.

Kahiltna Glacier Human Waste Monitoring

One early use of the CAKN Glacier Monitoring Program data culminated in the publication of two widely-cited papers documenting the 'fate' of human waste deposited into crevasses on Denali by mountaineers (Goodwin and others, 2012; Loso and others, 2013). That work motivated DENA to procure Rec Fee funds for follow-up monitoring that was conducted by the CAKN Glacier Monitoring Program since 2016. That proposal (*Monitoring Human Waste Contamination on Kahiltna Glacier*) supported three years of water quality sampling on the upper Kahiltna River, a human waste deterioration experiment on the surface of the Kahiltna Glacier ablation zone, and most importantly, ongoing direct collaboration with the Denali rangers to educate and consult with staff and visitors about the consequences of various waste management strategies. Data collection for this project is complete, and writing of a technical report is proceeding, albeit slowly. Completion is expected before fy2023.

Lidar and SfM Acquisitions

Geospatial data is increasingly important for glacier monitoring, and the CAKN Glacier Monitoring Program is taking advantage of opportunities to catalyze or leverage new acquisitions of data using both lidar and Structure-from-Motion (SfM) technologies. This is occurring under the auspices of numerous different projects and funding sources, and the products themselves are listed here (Table 2) for convenience. Ultimate ownership, disposition, and availability of each dataset varies, but many are in the process of being incorporated into the NPS/AKRO Theme Manager and/or the State of Alaska's Division of Geological and Geophysical Surveys Elevation Portal <DGGS Elevation Portal (alaska.gov)>.

Table 2. DEMs acquired by the CAKN Glacier Monitoring Program since 2016.

Location	Park	Source	Date
Denali Summit area	DENA	Matt Nolan SfM	2018_04_08
Flat Creek	WRST	Larsen SfM	2016_06_01 2019_08_30
Gates of the Arctic Glaciers	GAAR	Larsen lidar	2020_08_11
Icy Bay landslide and coastline	WRST	Larsen lidar and SfM	2016_05_29
Kahiltna Glacier	DENA	SfM	2020_10_13
Kennicott Glacier	WRST	AKRO Hults SfM	2018_09_13
Kennicott Glacier	WRST	Larsen lidar and SfM	2019_05_13 2019_09_05 2020_05_17
Malaspina Glacier	WRST	Larsen lidar	2020_06_10
103 glaciers	All	NASA Operation Icebridge lidar	Multi-epoch since 1990s

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