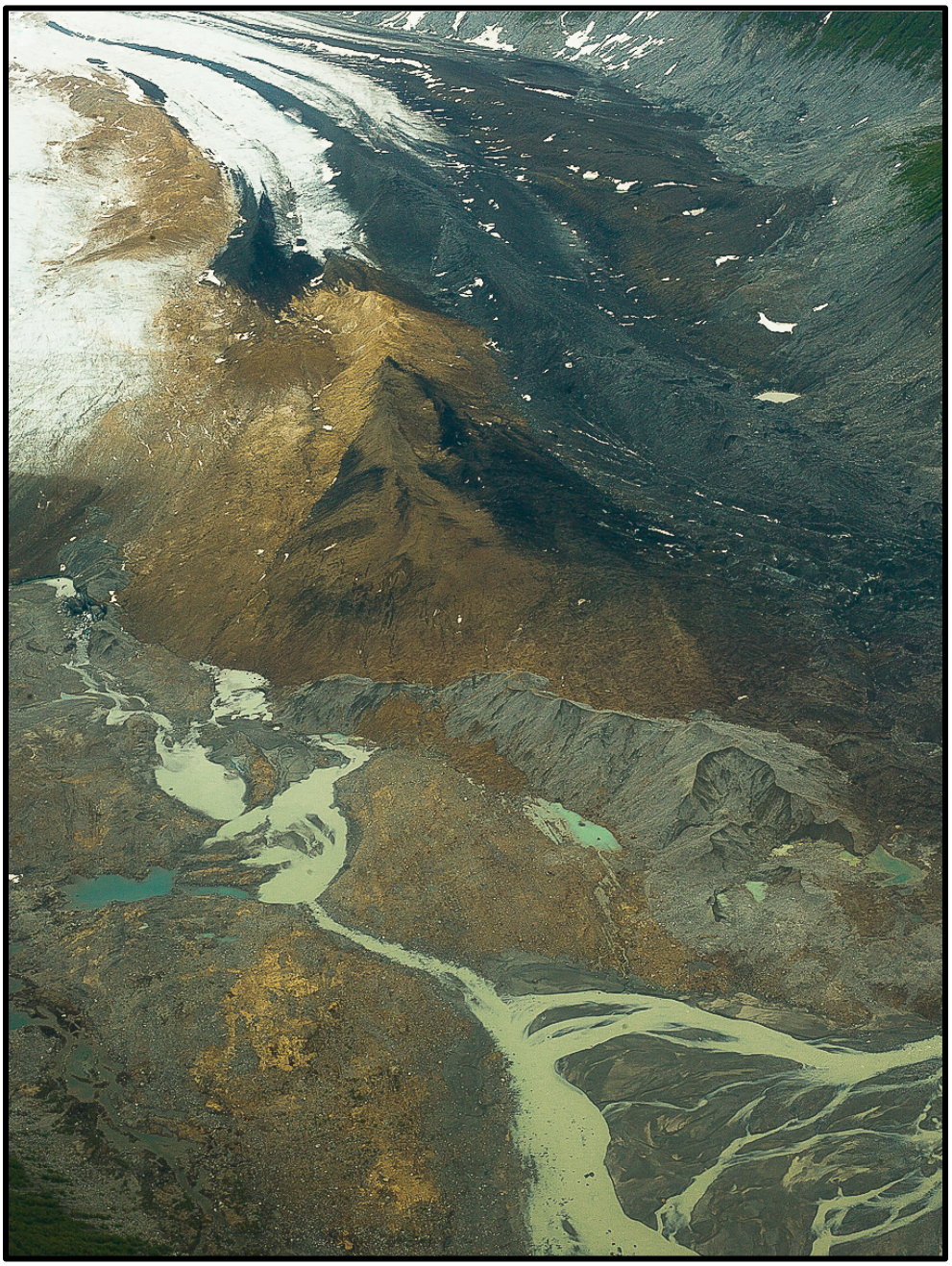
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Alaskan National Park Glaciers - Status and Trends

Third Progress Report

Natural Resource Data Series NPS/AKRO/NRDS—2013/439



ON THE COVER
The colorful, debris-covered terminus of Tuxedni Glacier. Lake Clark National Park and Preserve June 12, 2011.
Photograph by: JT Thomas

Alaskan National Park Glaciers - Status and Trends

Third Progress Report

Natural Resource Data Series NPS/AKRO/NRDS—2013/439

Anthony Arendt, Chris Larsen

Geophysical Institute
University of Alaska Fairbanks
903 Koyukuk Drive
Fairbanks, AK 99775

Michael Loso

Environmental Science Dept
Alaska Pacific University
4101 University Drive
Anchorage, AK 99508

Nate Murphy, Justin Rich

Geophysical Institute
University of Alaska Fairbanks
903 Koyukuk Drive
Fairbanks, AK 99775

January 2013

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available from the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

Please cite this publication as:

Arendt, A., C. Larsen, M. Loso, N. Murphy, and J. Rich. 2013. Alaskan National Park glaciers - status and trends: Third progress report. Natural Resource Data Series NPS/AKRO/NRDS—2013/439. National Park Service, Fort Collins, Colorado.

NPS 953/119665, January 2013

Contents

Contents (continued)

Figures

Page

Figures (continued)

Page

Figures (continued)

Page

Figures (continued)

Page

Tables

Page

Executive Summary

This is the third progress report for a multi-year study of glaciers in Alaskan national parks. The project will be completed in December 2013. Here we present results from mapping of all glacier extents in Gates of the Arctic National Park & Preserve (NP&P), Klondike Gold Rush National Historic Park (NHP), and Aniakchak National Monument & Preserve (NM&P), from measurements of surface elevation changes in Denali NP&P, and from focus glacier research in Denali NP&P, Katmai NP&P, and Lake Clark NP&P. We have accomplished all tasks on schedule for this third deliverable, and we look forward to continued conversation with our colleagues at NPS as the project moves forward. Significant results include the following:

- Gates of the Arctic NP&P was less than 1% glaciated in both mapping periods (nominally 1970s and 2000s), but ice cover diminished 43% (from 95.6 to 54.0 km^2).

- Klondike Gold Rush NHP has almost no glacier cover, but ice cover in watersheds draining into or near the Park diminished 18% from 288 to 237 km^2 (1948-2011/11).

- Aniakchak NM&P was less than 1% glaciated in both mapping periods, but ice cover grew 8% over that period (from 4.1 to 4.4 km^2). This is likely an artifact of mapping errors in the original cartography.

- The total number of glaciers declined in two of the three mapped parks (by 30% in Gates and by 34% in Aniakchak), but glacier numbers increased 26% in in the study area around Klondike. This result in Klondike is likely due to fragmentation of glaciers into multiple smaller ice masses.

- Using laser altimetry, we measured 21 distinct intervals of elevation change among eight glaciers in Denali NP&P from 1994 - 2010. Interpretation of these changes is complicated by collection of the profiles during different portions of the melt season.

- Of the glaciers measured by repeat laser altimetry in Denali, two had positive glacier-wide mass balance rates for some portion of the measured period: Muldrow Glacier (2001-2008) and its tributary Traleika Glacier (2001-2010). We attribute this to thickening of the upper elevations of this surging glacier system during the quiescent post-surge phase. Lower elevations of these glaciers were consistently thinning, and over the entire 1994-2010 period Muldrow had an overall negative mass balance rate.

- All other glaciers and intervals in Denali had negative mass balance rates (overall thinning) ranging from -0.7 to -2.2 m water equivalent per year, but interpretation of these results is complicated by inconsistency in the seasonality of measurements. The lowest measured balance rate was on east Toklat Glacier from 2008-2010.

- We visited and photographed glaciers in Denali, Katmai, and Lake Clark NP&Ps in summer 2011. Sample interpretive themes for their focus glaciers are presented herein.

- A sample vignette from Knife Creek Glacier in Katmai was presented in the Second Progress Report, has now been vetted by NPS personnel and project collaborators, and

will serve as the model as we commence planning for the layout and design phase for the final report. Negotiations are underway to hire a graphic designer for the interpretive report.

Acknowledgments

We acknowledge the advice and contributions of our NPS collaborators Bruce Giffen, Guy Adema, Fritz Klasner, Rob Burrows, and Denny Capps. We also thank all the many scientists whose work has helped build the foundation upon which this project is built.

Introduction

Project Overview

Basic information on the extent of glaciers and how they are responding to climatic changes in Alaska NPS units is lacking. Because glaciers are a central component of the visitor experience for many Alaskan parks, because the complicated relationship between glaciers, humans, and the climate system constitutes a significant interpretive challenge for NPS staff, and because glacier changes affect hydrology, wildlife, vegetation, and infrastructure, this project was initiated to document the status and recent trends in extent of glaciers throughout the nine glaciated park units in Alaska. The work will also be of substantial interest to scientists who recognize recent changes in Alaskan glaciers, including their collective contribution to sea level rise, as both globally significant and under-studied.

Of Alaska's 15 national parks, preserves, and monuments, nine contain or adjoin glaciers: Aniakchak (ANIA), Denali (DENA), Gates of the Arctic (GAAR), Glacier Bay (GLBA), Katmai (KATM), Kenai Fjords (KEFJ), Klondike Gold Rush (KLGO), Lake Clark (LACL), and Wrangell-St. Elias (WRST). Under this project, status and trends of glaciers within (or in isolated cases—adjacent to) these park units will be assessed in three primary ways: changes in extent (area) for all glaciers, changes in glacier volume for all glaciers with available laser altimetry, and an interpretive-style description of glacier and landscape change for 1-3 "focus glaciers" per park unit. These components of the project, summarized in Table 1, are described in more detail in the methods section of this report.

Table 1. Overall scope of project by component: Principal Investigator, glacier coverage, and types of analyses.

	Extent Mapping	Volume Change	Focus Glaciers
Principal Investigator	Dr. Anthony Arendt	Dr. Chris Larsen	Dr. Michael Loso
Affiliation	Geophysical Institute, University of Alaska Fairbanks	Geophysical Institute, University of Alaska Fairbanks	Environmental Science Dept, Alaska Pacific University
Contact	arendta@gi.uaf.edu	chris.larsen@gi.uaf.edu	mloso@alaskapacific.edu
Analyses	Map modern and historic outlines of glaciers from topo maps and satellite imagery	Determine glacier surface elevation changes over time with repeat laser altimetry	Graphic/narrative summary of glacier response to climate and landscape-scale impacts
Glacier Coverage	All glaciers in all units, some park-adjacent glaciers	Existing coverage: ~1000 total flightlines in parks	1-3 per park unit

Project Deliverables and Timeline

The results of our work will be presented in two written products: a technical report and an interpretive report. Dr. Loso has primary responsibility for the content of both publications – including layout and design.

The technical report, published internally as a Natural Resource Technical Report, will be a comprehensive technical document prepared to thoroughly document the data sources, methodology, and results of the project, to analyze those results, and to discuss the implications of those analyses. The technical report will be accompanied by a permanent electronic archive of

geographic and statistical data and is intended to serve a specialized audience interested in working directly with the project's datasets. It will therefore be complete, lengthy, and cumbersome to read for scientists interested primarily in the project's findings and implications. All audiences will find a comprehensive, but more accessible, discussion of the project's results and implications in the interpretive report, discussed below.

The interpretive report will be a non-technical document suitable for glaciologists, park interpretation specialists, park managers, and park visitors with no particular background in science or glaciology. The document will be comprehensive and thorough, however, and is envisioned as graphics and photo-intensive, content rich, and accessibly written. Content will be prepared to fit in a publication similar to an existing model: (Winkler 2000, A Geologic Guide to Wrangell-St. Elias National Park and Preserve, Alaska). Content will include a comprehensive literature review, and also detailed—but accessible—summaries of the key data sources, methodologies, and findings of the technical report. We will utilize the "focus glaciers" as a primary narrative tool to describe status and trends in NPS glaciers.

Separately from these primary publications, the principal investigators—in collaboration with other research associates and NPS staff, as appropriate and willing—will publish the research results of most broad and compelling scientific interest in a more concise form in one or more peer-reviewed journals (e.g. *Journal of Glaciology*). These articles are not considered project deliverables. Interpretive summaries may also be produced based on region-wide and/or park-by-park themes. These two-page (front and back) summaries, published internally by NPS, would summarize the most broad and compelling findings of scientific interest.

The project was initiated with a kickoff meeting held October 11, 2010 and is scheduled for completion December 15, 2013. Interim project tasks and deliverables are summarized in Table 2, and are subject to modification in each year's annual meeting and task agreement.

Scope of Progress Report 3

This is the third of four progress reports due biannually during the first two years of the project (Table 2). These reports are meant to be technical in nature and park-centered. They may contain some analysis on parks with completed data products, and in other cases may simply present data products that remain incomplete. Parks scheduled for presentation in this report are Gates of the Arctic, Klondike Gold Rush, and Aniakchak (extent mapping), Denali (volume change and focus glaciers), and Katmai and Lake Clark (focus glaciers only).

Because it was our first substantive written communication to the project sponsors, the first progress report placed considerable emphasis on defining the project and our approach to it. In this third and subsequent progress reports, we focus our efforts on presentation of data products. Much of the text in the introduction and methods is appropriated from previous reports and has only minor changes.

Table 2. Schedule for project tasks and deliverables. Report is under the direction of Loso, but relies substantially on timely contribution by all collaborators.

Date	Extent Mapping-Arendt	Volume Change-Larsen	Focus Glaciers-Loso	Reporting-Loso et al.
9/30/11	Glacier Bay, Denali	Glacier Bay	Glacier Bay	Progress Report 1
3/30/12	Katmai, Lake Clark	Katmai, Lake Clark	Summary of field efforts*	Progress Report 2
9/30/12	Gates of the Arctic, Klondike, Aniakchak	Denali	Katmai, Lake Clark, Denali	Progress Report 3
3/30/13	Kenai Fjords, Wrangell-St. Elias	Kenai Fjords, Wrangell-St. Elias	Summary of field efforts*	Progress Report 4
5/31/13	Remaining data and analyses	Remaining data and analyses	Remaining data and analyses	Progress Report 5
9/30/13			Report prep	Draft Final Report
11/1/13	Report review	Report review		
12/15/13			Report prep	Final Reports

* only as dictated by actual fieldwork

Study Areas

Alaska is the largest and most heavily glaciated of the fifty United States. With an area of 1,530,693 km^2, approximately 75,000 km^2, or ~5% of the land area, are covered by glacial ice (Post and Meier, 1980). Approximately 18,500 km^2 of the state's glaciers (~25%) are on lands administered by the National Park Service. Statewide, NPS administers 15 national parks, preserves, monuments, and national historical parks; glaciers occur in (or adjacent to, in the case of Klondike Gold Rush) 9 of those units:

- Aniakchak National Monument and Preserve
- Denali National Park & Preserve
- Gates of the Arctic National Park & Preserve
- Glacier Bay National Park & Preserve
- Katmai National Park & Preserve
- Kenai Fjords National Park
- Klondike Gold Rush National Historic Park
- Lake Clark National Park & Preserve
- Wrangell-St. Elias National Park & Preserve

This progress report focuses on several of those units. Overview maps of park and modern glacier boundaries for each unit are presented either here or in previous progress reports, as indicated. We describe these, including those from previous reports, in more detail below.

- Extent Mapping: Gates of the Arctic (this report, Figure 1), Klondike Gold Rush (this report, Figure 2), and Aniakchak (this report, Figure 3)
- Volume Change: Denali (First Progress Report, Figure 1)
- Focus Glaciers: Denali; Katmai and Lake Clark (Second Progress Report, Figures 1-2)

Gates of the Arctic National Park and Preserve

Gates of the Arctic National Park and Preserve (Figure 1) was first established by Congress in 1978 as the Arctic National Monument, and later upgraded to a National Park and Preserve in 1980 for its wild and undeveloped character and its opportunities for solitude and wilderness travel. In total, the Park encompasses 331,944 km^2 of terrain, including portions of six National Wild and Scenic Rivers, the headwaters of an international Biosphere Reserve (the Noatak River drainage), and peaks up to 2594 m (Mt. Igikpak). The Park is almost entirely mountainous, encompassing portions of the central Brooks Range, and the ancillary Schwatka and Endicott Mountains. Glaciers in Gates of the Arctic are unique in this study for being entirely north of the Arctic Circle, and glaciers on the north side of the Brooks Range experience a true Arctic climate with extremely cold temperatures and very light snowfall. In Anaktuvuk Pass, the average January low temperature is -30° C and the average July high is 16° C, with an average total annual precipitation of 36 cm. In the most recent imagery, the unit contains over 175 glaciers scattered throughout the Park, all of which are small (average 0.3 km^2, maximum 2.3 km^2) and land-terminating. Glaciers range from 67°19' to 68° 20' N and from 149° 34' to 155° 54' W.

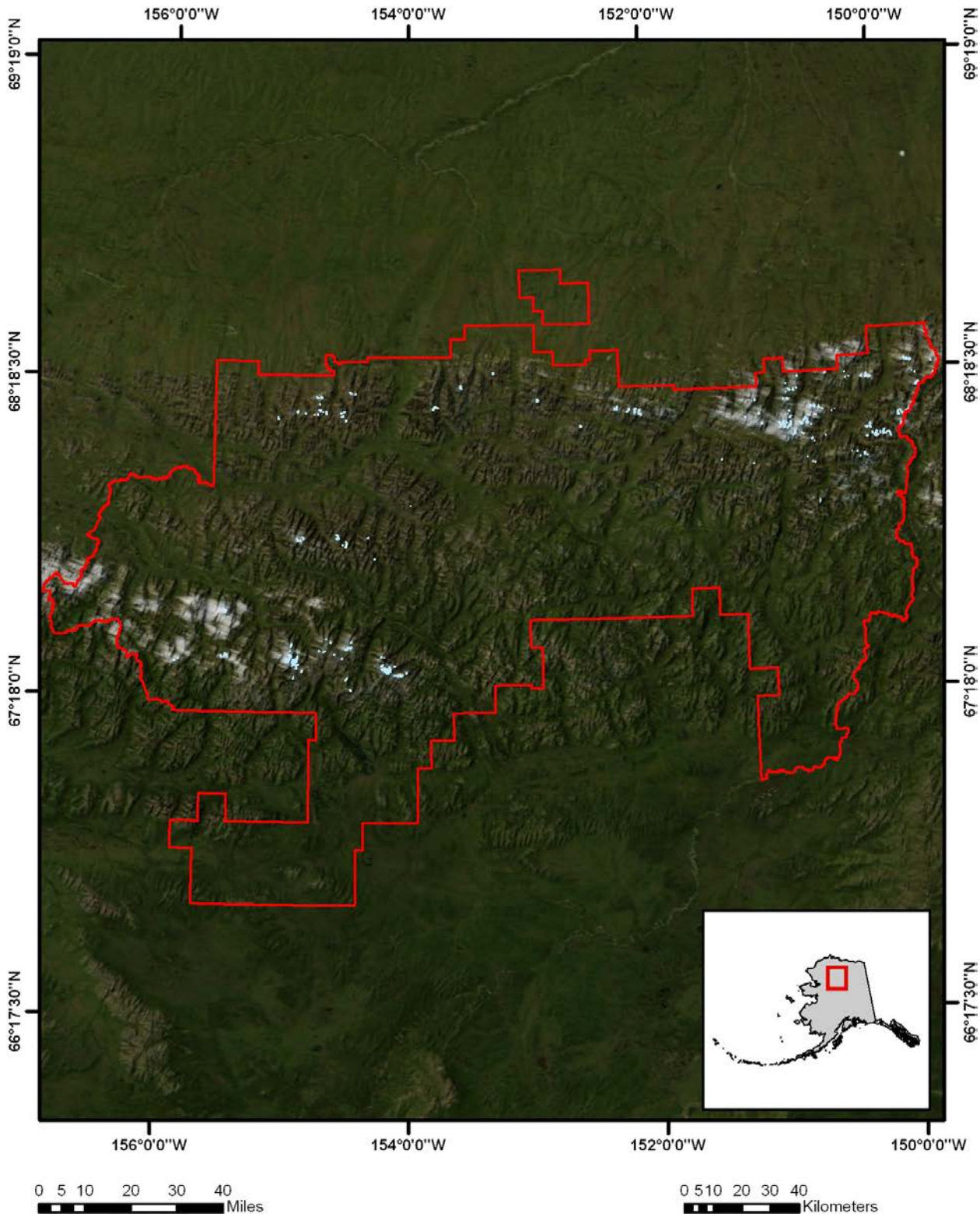


Figure 1. Gates of the Arctic National Park and Preserve. Blue polygons are current ice coverage, and red lines are park unit outlines.

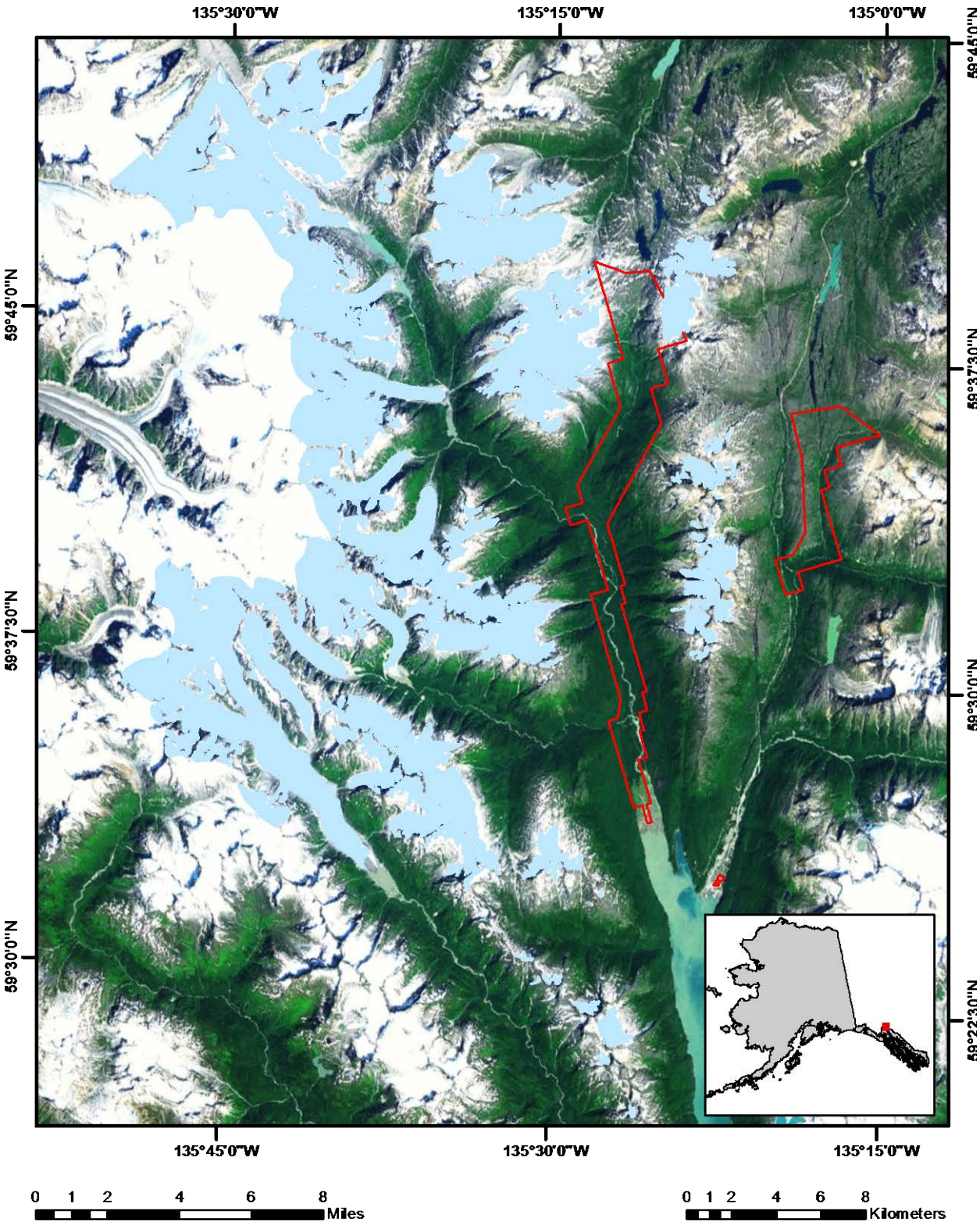


Figure 2. Klondike Gold Rush National Historic Park. Blue polygons are current ice coverage, and red lines are park unit outlines. Note that almost all these glaciers fall outside the park boundaries.

Klondike Gold Rush National Historic Park

Klondike Gold Rush National Historic Park (Figure 2) is the smallest NPS unit in this study at only 13,191 km^2. Congress established it in 1976 to preserve historic structures and trails associated with the Klondike Gold Rush of 1898, and the Park's lands are concentrated around the historic townsites of Skagway and Dyea and in narrow corridors along the Chilkoot Trail and White Pass & Yukon Route Railroad. All these areas lie between tidewater on the Pacific Ocean's Taiya Inlet and ridges of the St. Elias Mountains at elevations over 1800 m. Glacier coverage in the park is minimal, including only a portion (<1 km^2) of a glacier that straddles the international boundary with Canada in the northernmost edge of the Chilkoot Trail corridor at 59° 41' N and 135° 14' W. The status and trends of glaciers outside the park boundary are important, however, because many are visible and relatively accessible to recreational users of the park trails, and also because lakes associated with some of those glaciers have caused damage in the past and continue to threaten historic park resources. In our subsequent analyses, we treat glaciers near the park (most of which drain meltwater into the park boundary) as "KLGO glaciers." Skagway's average January low temperature is -8° C and the average July high is 20° C. Total annual precipitation in Skagway is 67 cm, with as much as 500 cm (and lower temps) in the mountainous reaches of the park.

Aniakchak National Monument and Preserve

Aniakchak National Monument and Preserve (Figure 3) is the remotest and westernmost of the NPS units in this study, 1165 km southwest of Anchorage on the Alaska Peninsula. Visitation averages less than 200 persons per year, arriving mostly by air taxi from King Salmon to float the Aniakchak River, a National Wild and Scenic River, and to hunt moose and brown bear. The Monument is 2371 km^2 and centers on the 750 m deep Aniakchak Caldera, formed by a massive volcanic eruption 3500 years ago, and is located among other volcanoes between Bristol Bay and the Gulf of Alaska. Volcanic activity is ongoing in the region, and the Aniakchak Caldera most recently erupted in 1931. The highest elevation in the park is ~1340 m, and glacier coverage is minimal—only about 4 km^2 of small glaciers exist, located primarily on shaded north-facing slopes. None of the glaciers reach tidewater, and the largest of them (in recent imagery) is about 3 km^2. In Port Heiden, near the south edge of the Monument, average January low temperature is -9° C, average July high is 14° C, and the average total annual precipitation is 29 cm. Glaciers in the park ranges from 56° 51' to 57° 1' N and from 157° 24' to 158° 11' W.

Denali National Park and Preserve

Denali National Park & Preserve is located in interior Alaska, north of Anchorage and south of Fairbanks. The Park was first established in 1917 (as Mt. McKinley National Park) and expanded to its present size and designation in 1980. It contains 24,585 km^2 of federal land. In Denali NP&P, the Alaska Range attains its greatest height, containing the highest mountain in North America (Denali or Mt. McKinley, 6194 m) and numerous summits over 3000 m. The interior climate of Denali is cold in winter and warm in summer, with dry conditions and modest snowfall at low elevations but higher levels of precipitation in the mountains, especially on the south side of the range. Near park headquarters, average January low temperature is -22° C and average July high is 21 C. Annual total precipitation is 37 cm.

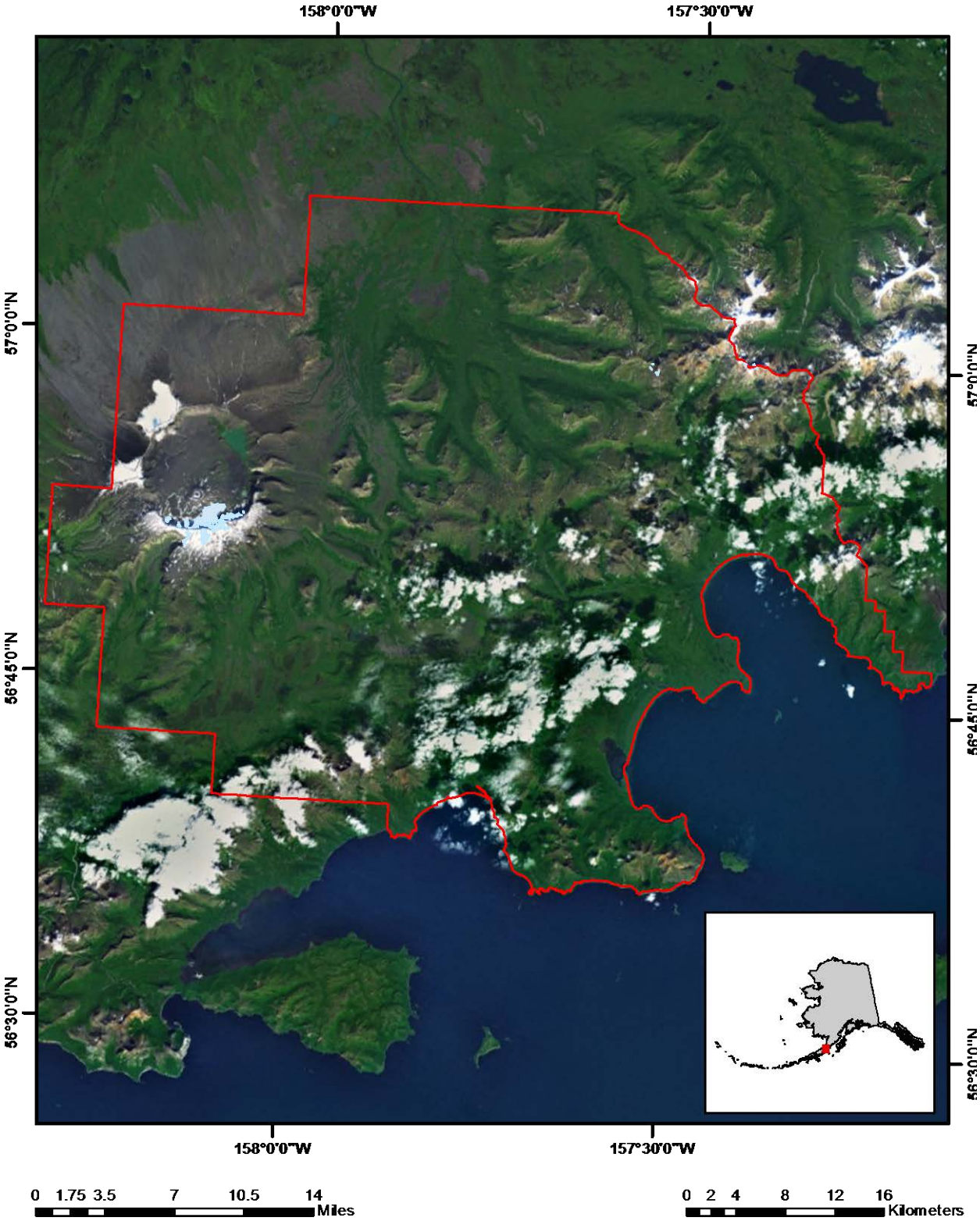


Figure 3. Aniakchak National Monument and Preserve. Blue polygons are current ice coverage, and red lines are park unit outlines.

Katmai National Park and Preserve

Katmai National Park and Preserve was established in 1918 (as Katmai National Monument) to preserve the spectacular and dynamic landscape associated with the 1912 eruption of Novarupta Volcano—the world's largest volcanic eruption of the 20th century. The Valley of Ten Thousand Smokes was and is a central attraction of the Park, but Katmai is now equally famous for its populations of brown bears and fish. The Park encompasses ~20,610 km^2 of federal land. Located on the Alaska Peninsula between Cook Inlet and Bristol Bay, the Park's mountains are relatively low and reach their greatest heights on the eastern edge of the Park where the Aleutian Range crests at 2318 m on Mount Denison. Near park headquarters in King Salmon, average January low temperature is -13° C and average July high is 17° C. Annual precipitation is 48 cm. Katmai NP&P (including glaciers wholly or partly inside of the Park boundary) has an ice-covered area of around 911 km^2 based on satellite imagery mostly from 2009. Glaciers are clustered in three groups: on the Kejulik Mountains to the south, on Fourpeaked Volcano in the east, and scattered in the Walatka Mountains in the north. Collectively, the glaciers range from 58˚06' N to 58˚59' N and spans from 153 27' W to 155˚27' W. Glaciers in the Park are mostly modestly-sized and land-terminating, and stand out in a regional sense mostly for their response to extensive deposition of volcanic ash, especially after the massive 1912 Novarupta eruption.

Lake Clark National Park and Preserve

Lake Clark National Park & Preserve is located in western Alaska, southwest of—and across Cook Inlet from—Anchorage. The Park was first established in 1980 to protect scenic beauty (including volcanoes, glaciers, wild rivers, and waterfalls), populations of fish and wildlife, watersheds essential for red salmon, and the traditional lifestyle of local residents. It contains ~16,390 km^2 of federal land. Along with its signature feature, 66 km long Lake Clark, the Park features two active volcanoes (Redoubt and Iliamna) and the intersection of two major mountain ranges: the Aleutian and Alaska Ranges. Climate is quite variable; elevations range from sea level on the Cook Inlet coast to over 3100 m on Redoubt Volcano. Near park headquarters in Port Alsworth, average January low temperature is -15° C and average July high is 20° C. Annual total precipitation is 36 cm. Lake Clark's glaciers (including glaciers wholly or partly inside of the Park boundary) covered around 3233 km^2 as of 2009. Glaciers are scattered throughout the central and eastern portion of the park, originating on two volcanoes (Iliamna and Redoubt) and three mountain ranges (the Chigmit and Neacola Mountains and the southernmost extension of the Alaska Range). In the northeastern part of the park, glaciers of the Neacola Mountains are contiguous with ice outside the park boundary that adds a substantial amount to the glacier areas measured in this park. Indeed, the two largest glaciers in this inventory, Tanaina Glacier and Blockade Glacier, originate outside the park boundary. The largest glacier contained mostly within the Park boundary is Double Glacier, with a main ice mass area over 137 km^2. Within the Park proper, glaciers range from 59˚52' N to 61˚31' N and from 152˚12' W to 154˚ 04' W. None of the Park's glaciers reach tidewater.

Methods-Mapping

Data

The mapping component of this project aims to delineate the outlines of all glaciers in all Alaskan parks for two time intervals: mid-20th century (based mainly upon USGS topographic mapping from that time period, typically available as Digital Raster Graphics or "DRGs") and the early 2000s (based upon latest available satellite imagery). For simplicity, we commonly refer to these time intervals as "map date" and "modern," or less commonly as "DRGs" and "2000s." Topographic map coverage is based on photography that ranges from 1948 to 1979 (and as late as 1987 for some Canadian glaciers not covered by USGS maps), with some later revisions. Post-2000 (mostly 2006-2008 with some 2010 and 2011) satellite data for this phase of the project are from a combination of Ikonos and SPOT4 imagery. Detailed source information for mapping presented in this report is presented in Appendix A.

Analysis

PI Anthony Arendt and research technician Justin Rich have developed a standardized workflow for the generation and distribution of glacier shapefiles and associated geostatistics for these glaciers (Figure 4). We have automated the procedure whenever possible to minimize errors, and to provide for future outline generation after this project is complete. Justin Rich has developed algorithms that provide for automatic delineation of glacier boundaries from multispectral satellite imagery, and has also produced an algorithm to improve the usability of post-2003 Landsat imagery that is corrupted by scan line correction (SLC) errors.

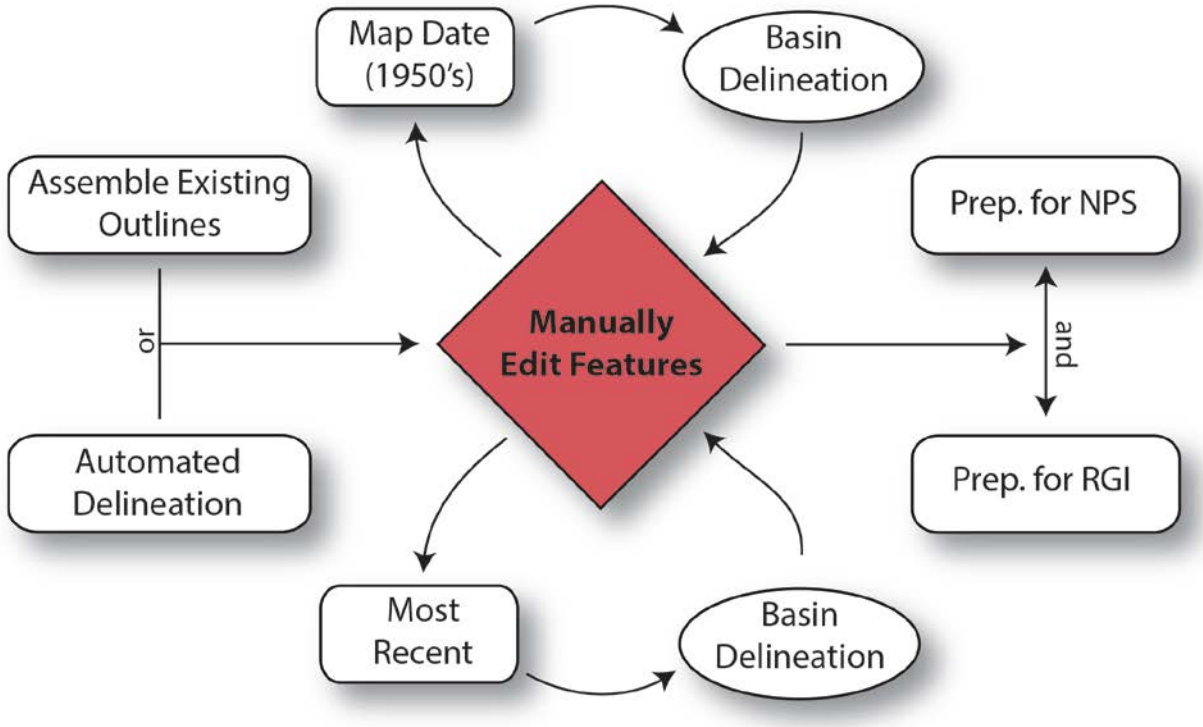


Figure 4. Workflow for the generation of glacier inventory data for NPS glaciers.

Details of the workflow shown in figure 4 are described below, and the steps are shown by example in Figure 5.

Step 1: Existing outlines are assembled if they exist. These may come from previous UAF altimetry work, NPS scientists, or from other colleagues working on these areas. Otherwise, an automated delineation algorithm is run using multispectral satellite imagery to produce a first estimate of glacier extent.

Step 2: We perform heads-up (on-screen) manual digitization on the computer to clean up existing outlines so that they more accurately match map or satellite imagery. Editing is performed at a scale appropriate to the base imagery: between 1:10,000 and 1:20,000 for Landsat imagery, and between 1:1500 and 1:5000 for Ikonos imagery. Once the product is of suitable quality, we run it through a basin delineation algorithm written by UAF PhD student Christian Kienholz. We perform additional manual digitization, primarily to ensure the automatically produced basins match what we would expect in reality. We then populate the attribute table with glacier names (where available), calculate glacier areas, and use a standard "remarks" code to describe anomalous glacier types where this information is known: e.g. surge-type, tidewater, etc. (table 1 in Paul et al. 2009).

Step 3: We run a final series of scripts that set up the files for ingest into a standard data distribution format. As part of this step we write metadata files that describe what imagery was used, what dates are covered, and other information. At present, the products exported from these final scripts include the following, shown by example in Appendix B:

- Glacier ID
- Name (if available)
- Remarks code
- Date of imagery used
- Centroid latitude and longitude
- Glacier area (km^2)
- Min, max, and area-weighted mean/median glacier elevations (m)
- Hypsometry data, presented as glacier areas within 50 m elevation bins

Glacier volumes (and changes over time) are calculated using basic area/volume scaling (Bahr et al. 1997) using coefficient/exponent values of 0.2055/1.375 from Radic and Hock (2010). Work is ongoing to more robustly calculate glacier slope and aspect, and these fields will be included in the final product. We are also improving our hypsometry calculations to ensure that vector and raster data produce comparable results.

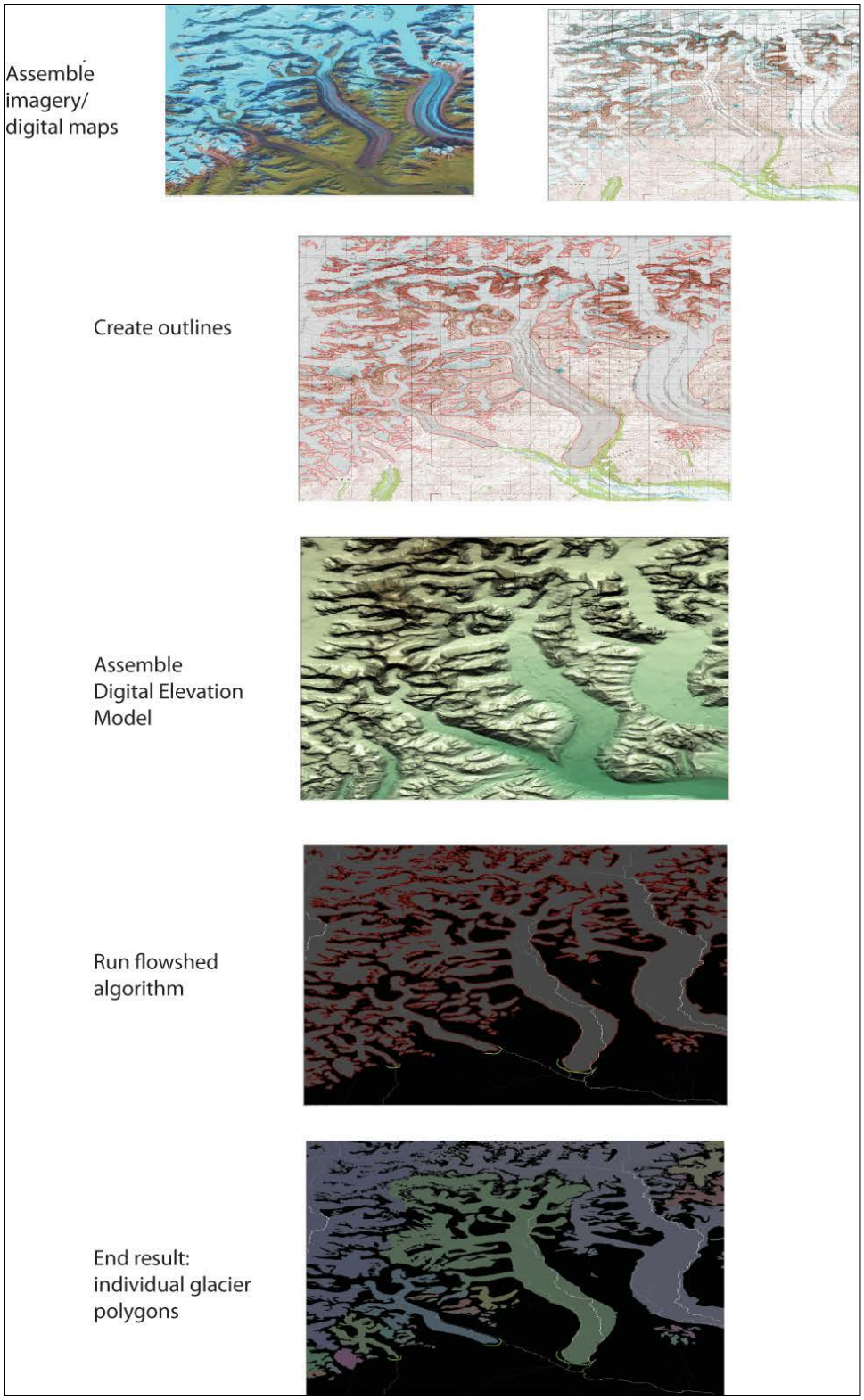


Figure 5. Aerial oblique imagery (from the south viewing Tokositna and Ruth Glaciers, Denali NP&P) demonstrating generation of glacier inventory data for NPS glaciers.

Methods-Elevation Change

The elevation change component of this project aims to characterize changes in surface elevations of all glaciers (within glaciated Alaskan parks) that have existing laser point data from two or more time intervals since this work commenced in the mid-1990s. No new laser altimetry data will be acquired under the scope of this project. Existing laser altimetry profiles (as of January 2011) for Denali are shown in Figure 6 and Table 3. Note that we do not show (or use) data from glaciers that have only one profile flown to date (Dall, Eldridge, Yentna, and Lacuna Glaciers) or data from a few profiles that provide too few crossings with existing profiles on the same glaciers to provide a robust comparison (Ruth Glacier in 2005, Toklat 1 Glacier in 2001 and 2005, and Toklat 2 & 3 Glaciers in 2005).

Dates of elevation data acquisition shown in Table 3 reflect a significant problem with some of the Denali data—differing seasonality of acquisition. Most of the data were acquired at or around the annual mass maximum in late spring or early summer, but for three of the glaciers (Kahiltna, Muldrow, and Traleika), some early observations were acquired around the time of the annual mass minimum in late summer. For these glaciers, calculated changes in surface elevation that use those late summer sampling dates as the "initial condition" will underestimate the actual elevation loss over a given time period. The amount of this underestimate is not exactly known, but can be approximated for any given elevation on a glacier by the typical seasonal reduction in glacier surface elevation determined solely by summer-season ablation. This could amount to many meters of error at higher elevations. We do not attempt to quantify that error in this report, but will address it more thoroughly in the final report.

Data

Elevation change estimates are based upon laser point data acquired from aircraft at discrete time intervals. Laser point data has been acquired with three different systems since data collection began in 1995, including two different laser profilers before 2009 and a scanning laser system since then. The laser profilers have been described in previous publications (Arendt et al. 2002; Echelmeyer et al. 1996; Sapiano et al. 1998). The data acquired during those earlier missions have been reprocessed with the same methods as post-2009 scanning laser system data, which was acquired with a Riegl LMS-Q240i that has a sampling rate of 10,000 points per second, an angular range of 60 degrees, and a wavelength of 900 nm. The average spacing of laser returns both along and perpendicular to the flight path at an optimal height above glacier of 500 m is

Table 3. Date of laser altimetry flights for glaciers located in Denali National Park and Preserve. Note that profile acquisition dates vary considerably from year to year on the Denali NP&P glaciers, so that elevation changes in some cases reflect considerable seasonal (rather than super-annual) differences. See discussion in text. Glacier types are land terminating (L) and surge (S).

Kahiltna (L)	Muldrow (S)	Ruth (L)	Toklat 1 (L)	Toklat 2 (L)	Toklat 3 (L)	Tokositna (S)	Traleika (L)
7/31/94	8/3/94	4/30/01	5/6/96	5/21/01	5/21/01	4/30/01	8/22/01
5/17/08	8/22/01	5/16/08	5/21/01	5/16/08	5/16/08	5/17/08	5/16/08
5/22/10	5/16/08		5/16/08	5/22/10			5/22/10
	5/22/10						

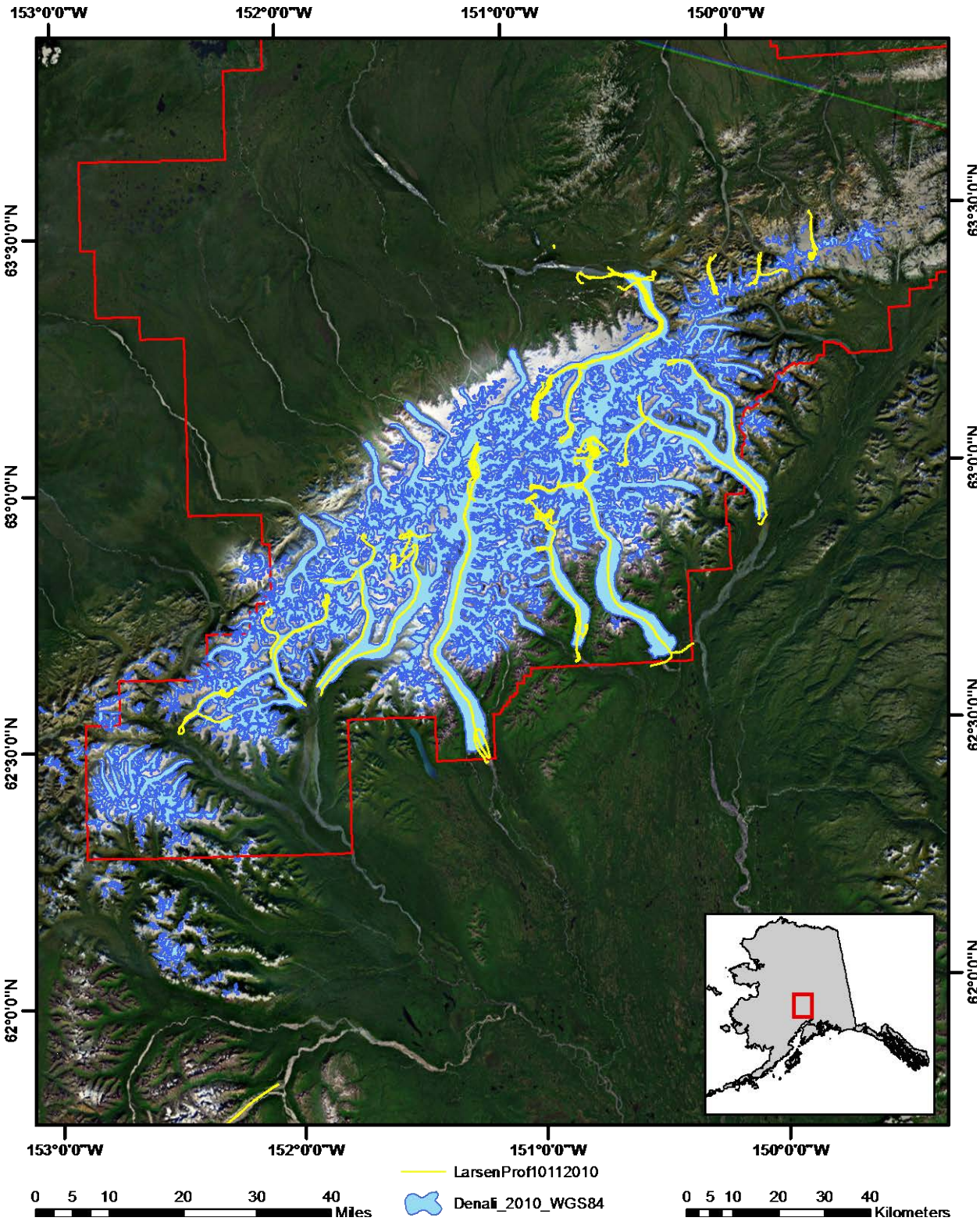


Figure 6. Existing laser altimetry profiles (yellow lines) in Denali National Park and Preserve (red polygon) as of January 2011.

approximately 1 m x 1 m with a swath width of 500 – 600 m. The aircraft is oriented using an inertial navigation system (INS) and global position system (GPS) unit. The INS is an Oxford Technical Solutions Inertial+ unit that has a positioning accuracy of 2 cm, a velocity accuracy of 0.05 km/h RMS, and an update rate of 100 Hz. The GPS receiver is a Trimble R7 that records data at 5 Hz and has an accuracy of 1 cm horizontal and 2 cm vertical in ideal kinematic surveying conditions.

To translate laser point data to estimates of volume change, we require digital elevation models (DEMs) and glacier outlines for measured glaciers. The DEM is derived from the National Elevation Database (NED), a USGS product derived from diverse source data that generally (in Alaska) reflect elevations from the most recent topographic map at 2-arc-second (~60 m) grid spacing. Outlines and surface areas of each glacier are based upon "modern" glacier outlines developed elsewhere in this project.

Analysis

The workflow for calculation of elevation changes and derived volume changes follows these steps:

Step 1: Glacier surface elevations are derived from laser point data by integrating the GPS-based position of the aircraft on its flight path over a glacier, airplane orientation data from an onboard INS, and laser point return positions relative to the airplane. The combination of these data determines the position in 3-dimensional space of the laser point returns from the glacier surface. The points are referenced in ITRF00 and coordinates are projected to WGS84, with a coordinate accuracy in x, y, and z position of +/- 30 cm. Elevation data are recorded as height above ellipsoid.

Step 2: Glacier surface elevation profiles from different years can then be differenced to find the cumulative thickness change (dz, meters) over that time interval. Division by the time elapsed (dt, years) gives the rate of thickness change Δz (m/yr). This is determined with slightly different methods depending on whether data from the laser profiler (1995 – 2009) or laser scanner (2010 – 2011) are being used.

Step 3a: For laser profiler to laser profiler differencing, points that are located within 10 m of each other in the x-y plane are selected as common points between the different years. If more than one point is located within that 10 m grid, then the mode of the elevation is used for each grid point. These common points are then used in the determination of Δz. Since there are data points recorded only along the flight track at nadir with the laser profiler it is critical that these earlier flight paths were repeated as accurately as possible to obtain a large number of common points. Sometimes the flights were not repeated closely enough to provide extensive elevation change, and dz plots using this data typically exhibit many fewer points than comparable plots based on the laser scanning system (described below in step 3b). This limits the robustness of the interpolated line that is fit to the data, especially if there is variability within the data.

Step 3b: For laser scanner to laser profiler differencing, a grid is made of the laser scanner swath at a resolution of 10 m. Elevation values in this grid are based upon the mode of all the points within each of the grid cells, which helps to filter out laser returns from crevasse bottoms. Then, the coordinates from each point in the old profile are used to extract an elevation from this grid

(for all laser profiler points that fall within the new LiDAR swath extents). This laser scanner elevation is differenced with the laser profiler elevation at that point, giving the change in elevation. The same idea is used for laser scanner to laser scanner comparisons, but instead of using every point from the older laser scanner swath, an average value on a 10 m x 10 m is calculated out of the old swath, then the value for that point location is also extracted from the newer laser scanner grid.

Step 4: The complete series of Δz measurements at specific elevations along the glacier flight line is plotted as the median of a smoothing window with a typical width of twelve data points from the bottom to the top of the glacier. Plotted confidence intervals are based upon the interquartile range of the moving window. At both the lower and upper elevation limits of the glacier, Δz is forced to zero and the confidence interval is presented as an average of the interquartile ranges calculated along the entire profile.

Step 5: The NED-based DEM is used to develop an area-altitude distribution (AAD) for the glacier in 30 m bins. Volume change is found by performing a numerical integration wherein the binned Δz line is multiplied by the binned AAD.

To facilitate comparison of volume changes among glaciers of different sizes, we convert volume changes to glacier-wide mass balance rates ($\dot{B}$), adhering to terminology in the *Glossary of Mass Balance Terms* (Cogley et al. 2011). The mass change is calculated assuming that the lost (or gained) volume was composed entirely of ice, e.g. Sorge's law (Bader, 1954). The mass change can then be converted to water equivalent (w.e.) by assuming a constant ice density of 900 kg/m^3, and the mass change presented as Gt/yr. Glacier-wide mass balance rate is then just mass change divided by glacier surface area. Note that where profiles were collected at significantly different times of year (as many were in Denali), Sorge's law is significantly violated and glacier-wide mass balance rates should be interpreted as limiting values, and with caution. We address this issue in more detail in our results section.

Methods-Focus Glaciers

The focus glacier component of this project aims to provide additional information about a small subset of glaciers in each glaciated Alaskan park for the purpose of demonstrating the potentially unique ways in which A) glaciers change in response to climate and other forcings, and B) landscapes respond to glacier change. The focus glacier portion of the final report will include a narrative description of each glacier and a collection of photos, maps, figures, and other graphical information. In comparison with the other components of this project, which are directed clearly towards generating and analyzing new or existing data, the focus glacier component is focused more on interpretation and synthesis. No new data will be acquired, but collection of existing materials is a central task for the PI Michael Loso. For each glacier, this collection of materials will ultimately be presented as a "vignette" in the final document. A sample vignette was presented in the Second Progress Report.

Focus Glacier Selection

The final list of focus glaciers is included below (Table 4) and mapped in Figure 7. The focus glaciers are not intended to be statistically representative of Alaskan glaciers as a whole, but rather were selected to collectively represent the diversity of glacier types and climatic responses evident statewide. Additional supporting criteria for inclusion in the list were a rich history of visitation/ documentation and public accessibility. Since October 2010, the list evolved some under the advice and guidance of NPS staff, particularly including NPS unit resource staff and regional I&M staff. No changes have occurred since the Second Progress Report.

Fieldwork, Resource Collection, and Development of Vignettes

In summer 2011, PI Loso visited several NPS units to collect existing resource materials and develop first-hand familiarity with some of the focus glaciers. The objectives were to understand the field site geography, collect photographs (including, in some cases, repeat photographs of historic imagery), interview researchers and NPS staff working on or near each glacier, and qualitatively document the diverse evidence of landscape change.

The diverse historic and contemporary reference materials necessary for development of the focus glacier vignettes cannot be found solely through traditional library and internet resources; many resources are available only from NPS/NPS-affiliated personnel at AKRO and at the individual parks. Examples of collected materials include:

- Published, peer-reviewed journal articles
- Internal NPS (and occasionally other agency) reports
- Internal NPS unpublished data, when available
- Historic maps
- Satellite and aerial imagery
- Interviews with knowledgeable persons
- Original and historic photography

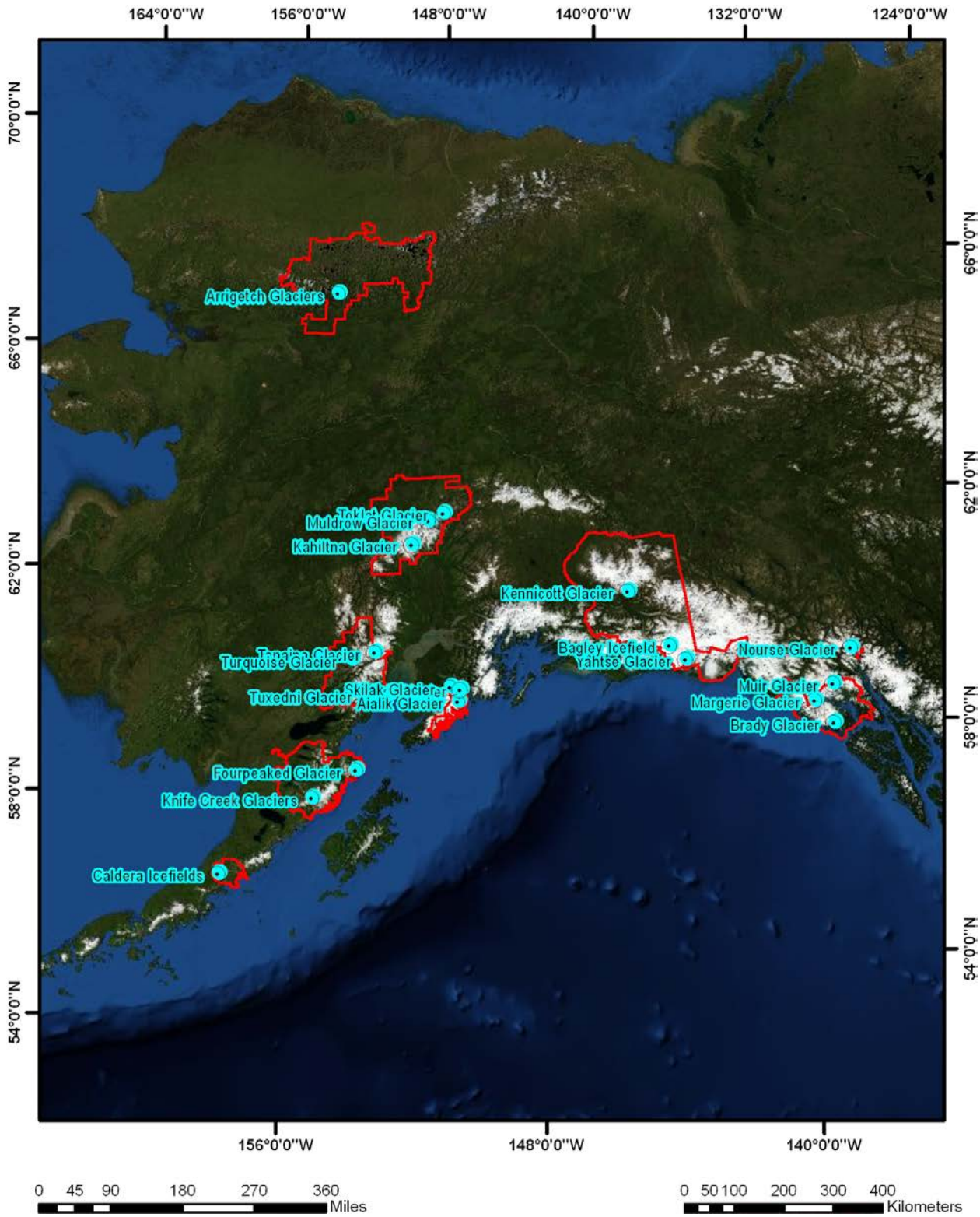


Figure 7. Overview of focus glacier locations. Red polygons are NPS unit outlines.

While on site at the various parks, Loso tried, within logistical and budgetary constraints, to personally visit as many focus glaciers as possible. Here, we summarize field efforts germane to the Katmai, Lake Clark, and Denali vignettes. Other fieldwork conducted in 2011 was detailed in the Second Progress Report.

Loso and one colleague, professional photographer JT Thomas, visited the three parks in summer 2011. Thomas served in a volunteer capacity, donating his time and making his images available for use in all publications associated with this project in exchange for travel expenses (covered out of Loso's travel budget under this agreement). Our work was conducted under Scientific Research and Collecting Permits issued by the respective parks.

Thomas and Loso visited Katmai from June 13-19, 2011. The 13th, 14th, and 19th were used for travel to and from Brooks Camp, our base for visiting the Knife Creek Glaciers. While in Brooks Camp, we stayed at the NPS yurt. From the 15th to the 18th, we hiked on foot to the Knife Creek glaciers, backcountry camping during the trip. Fourpeaked Glacier was not visited.

Table 4. Focus glaciers for each of Alaska's 9 glaciated park units. "Snapshot" briefly denotes unique aspects of each glacier. PI Loso has personal knowledge of "visited" glaciers. Glaciers with a "poor" historic record may require additional work, outside the original scope, if they are to be included in the final report.

Park	Glacier(s)	Snapshot	Visited	Historic record
ANIA	Caldera icefields	Only permanent ice in Aniakchak. Virtually unstudied. Tiny.	no	poor
DENA	Kahiltna Glacier	Popular climbing and flightsee route. Non-surging valley glacier.	yes	good
	Muldrow Glacier	Backcountry accessible surge-type valley glacier.	yes	good
	Toklat Glacier	Backcountry accessible cirque glacier with history of NPS study.	no	good
GAAR	Arrigetch glaciers	High visitation for a remote park. Small, arctic cirque glaciers.	yes	good
GLBA	Brady Glacier	Remote tidewater glacier with very low-elev accumulation zone.	yes	good
	Margerie Glacier	Cruise-ship visible, tidewater. High-elev accumulation zone.	yes	good
	Muir Glacier	Formerly tidewater glacier with spectacular retreat history.	yes	excellent
KATM	Fourpeaked Glacier	Valley glacier on an active volcano. Remote.	no	poor
	Knife Creek Glaciers	Unusual tephra-covered glacier with long historic record.	yes	good
KEFJ	Aialik Glacier	Tidewater glacier with historically stable terminus position.	no	moderate
	Exit Glacier	Tourist-popular, on coastal side of Harding Icefield.	yes	excellent
	Skilak Glacier	Backcountry glacier draining interior side of Harding Icefield.	no	moderate
KLGO	Nourse Glacier	Outside park; moraine-dammed threatens infrastructure.	no	moderate
LACL	Tanaina Glacier	On flightseeing route at Lake Clark Pass. Changing hydroogy.	yes	moderate
	Turquoise Glacier	Cirque glacier with simple geometry. Remote.	no	good
	Tuxedni Glacier	Valley glacier on an active volcano. Remote.	yes	moderate
WRST	Bagley Icefield	Huge icefield with multiple distributaries. Remote.	yes	good
	Kennicott Glacier	Highly visited, tourist-friendly valley glacier. Jokulhlaup history.	yes	excellent
	Yahtse Glacier	Tidewater glacier that is currently advancing.	yes	good

From June 10-12, 2011, Thomas and Loso visited Lake Clark and stayed with NPS ranger Rich Richotte in Port Alsworth. We examined archived data with Richotte and also retired NPS staff member Page Spencer at the headquarters there, and on June 12 did an overflight of the focus glaciers with Richotte and Spencer. No landings were made. On June 6 and 7, 2011, Thomas and

Loso visited Kahiltna Glacier with UAF collaborators Anthony Arendt and Joanna Young. Travel to the Kahiltna was provided by NPS helicopter, which was used while en route to complete research work permitted separately by Arendt. We stayed one night at basecamp and in the morning completed additional fieldwork before returning to Talkeetna by fixed wing.

The target objective for each focus glacier is a vignette that uses text, photos, maps, and other information to highlight unique aspects of that glacier and ways that the glacier reflects broader trends in glacier change statewide. A sample vignette was presented in the Second Progress Report. Most of these vignettes will be written during PI Loso's sabbatical year (fall 2012 – spring 2013). Until that time, the interim objectives for each focus glacier are to gather all available resources (as described above), to organize and digest those resources, and to identify the dominant themes for later presentation in vignettes. In this report we summarize progress on this process with an annotated resource list organized by the tentative interpretive themes for the focus glaciers.

Results-Mapping

Maps of glacier outlines, with associated geostatistics, were completed for all glaciers in GAAR, KLGO, and ANIA. In all three parks, modern outlines are based upon high-quality imagery (Ikonos or SPOT4) and we do not anticipate significant further refinements of these outlines. The full datasets upon which these results are based will be delivered in electronic format when the project is finalized, but NPS investigators may contact the mapping team (Arendt and Rich) if they wish to obtain preliminary data in advance of that time. We tentatively estimate errors in glacier area to be approximately 10%, with the primary sources of error in the relatively small glaciers of these park units being interpretive challenges posed by debris cover and shading, particularly on north facing slopes in the Brooks Range. The analysis presented here is focused on basic metrics of glacier change, but we ultimately plan a more robust analysis of the geostatistical component of the datasets (e.g. Bolch et al. 2010). Note that additional, higher resolution maps of glacier change are presented in Appendix C.

Gates of the Arctic NP&P

Mapped outlines for Gates of the Arctic NP&P are shown in Figure 8 and summarized in Table 5. Note that map era photography dates range 1970-1990 for Gates, meaning the described changes are from a shorter time period than in some of the other park units in this study. In total, Gates had 253 glaciers mapped on the DRGs and 30% fewer in modern satellite imagery. In that same time, total glacier area decreased 43% from 96 km^2 to 54 km^2. Estimated total ice volume decreased a similar amount (47%), as would be expected since volumes are here calculated simply by scaling known area changes (Bahr et al. 1997; Radic and Hock 2010). These changes in area and inferred volume are largely due to the complete disappearance of many glaciers, especially in the northern portion of the park (Appendix C, Figures B1 and B2). Generalized terminus retreat, though common in many glaciers as well, is probably less important in Gates than in other Alaska region parks.

Table 5. Summary statistics for glaciers in Gates of the Arctic NP&P.

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1970-1990)	253	95.6	16.7
Modern (2006-2009)	178	54.0	8.9
Absolute Change	-75	-41.5	-7.9
Percent Change	-30%	-43%	-47%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using coefficient/exponent values of 0.2055/1.375 from Radic and Hock (2010).

These overall changes are summarized on a per-glacier basis in Figure 9. Glaciers of all sizes diminished roughly equally in abundance (right panel), but ranking glaciers by mean elevation we see that the lowest and highest elevation glaciers were the least changed in abundance, while glaciers with a moderate mean elevation diminished most strongly (right panel). This result may be explained in part by the diminished role of warming temperatures in heavily shaded north-facing cirques (favored by the lowest elevation glaciers), and near summits of the Arctic mountains (occupied by the highest elevation glaciers). This pattern is also reflected by Figure 10, which shows change in total glacier coverage (rather than individual glaciers) as a function of elevation. Ice at and above the modal elevation (1500-1600 m in the DRGs, 1600-1700 m in satellite imagery) diminished most noticeably, with the least proportional change at the lowest elevations.

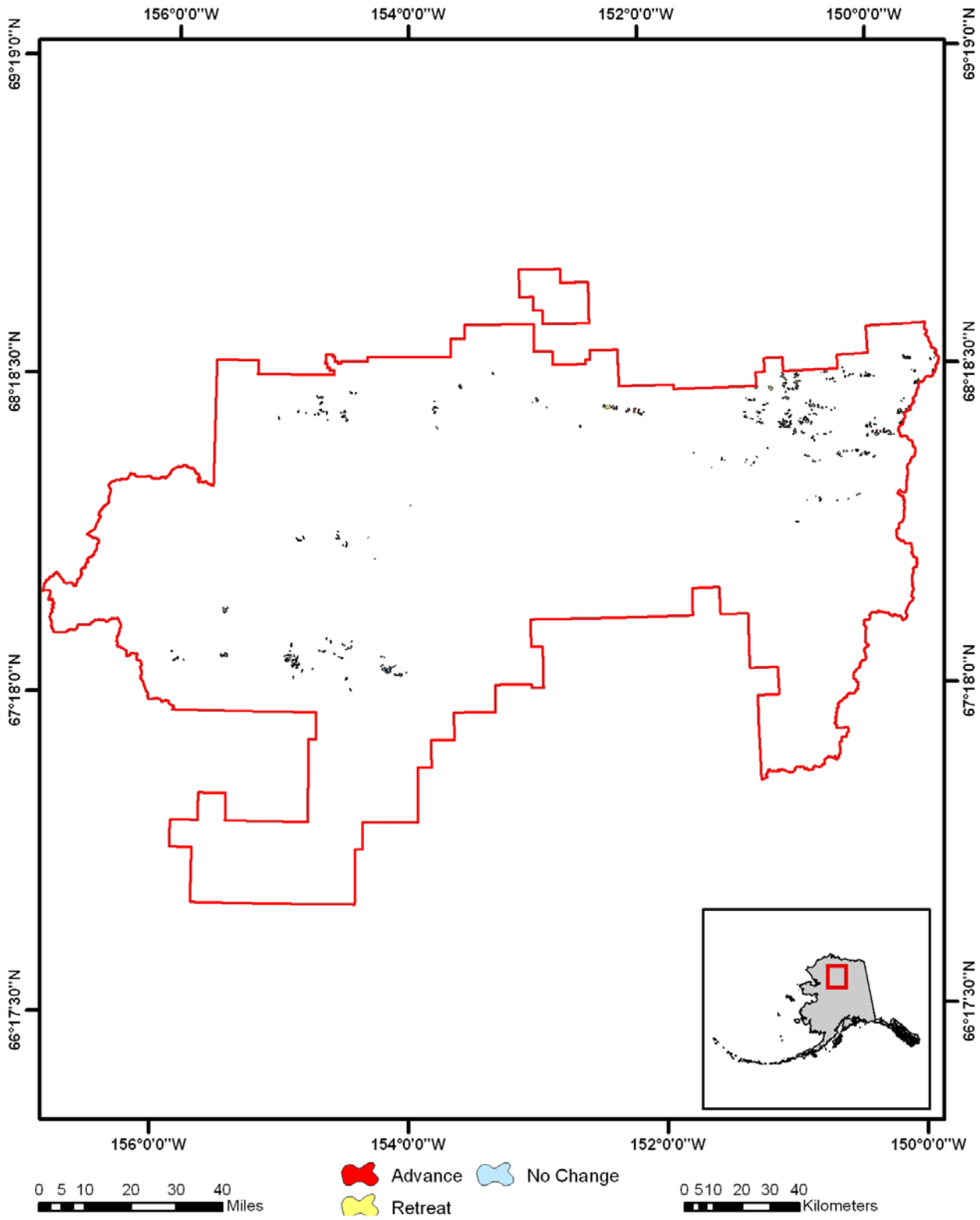


Figure 8. Changes in glacier area between map date and modern in Gates of the Arctic NP&P. See Appendix C for close-up maps.

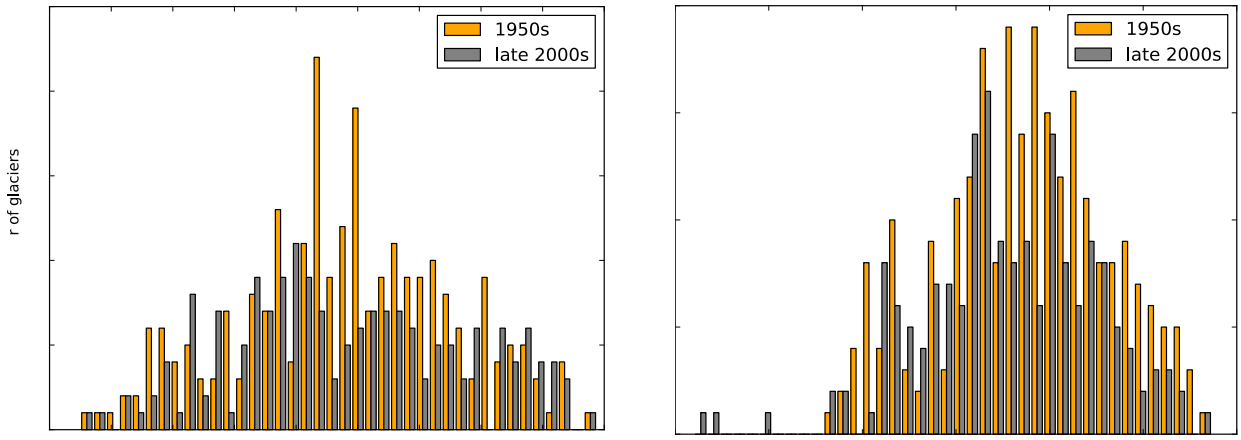


Figure 9. Histograms of changes in number of individual glaciers by area-weighted mean elevation (left) and area (right) in Gates of the Arctic between map date (1970s-1990s) and modern (2006-2009). Note that in this and subsequent figures in this section, legend labels are general and dates should not be interpreted strictly. This will be corrected in the final reports.

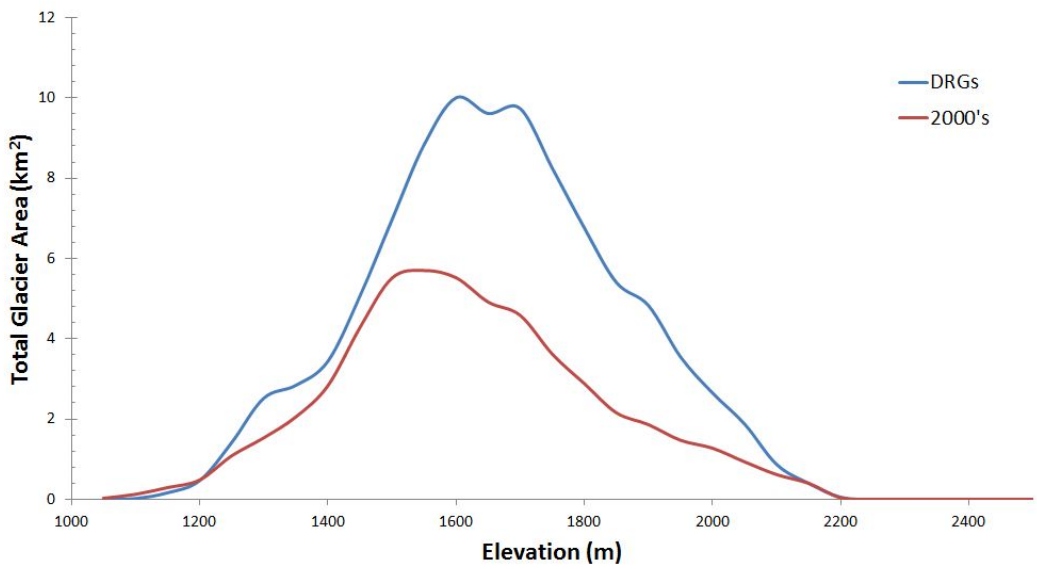


Figure 10. Total area of glacier-covered terrain in Gates of the Arctic by elevation between map date (1970s-1990s) and modern (2006-2009).

Klondike Gold Rush NHP

Mapped outlines for Klondike Gold Rush NHP are shown in Figure 11 and summarized in Table 6. Map era photography dates are all 1948 for Klondike, with the significant exception of a relatively small number of glaciers on the Canada side of the border, which were photographed in 1987 (Appendix A). We emphasize here that because the boundary defining this population of glaciers was chosen somewhat arbitrarily (it is not defined even loosely by the NHP boundary), our change statistics could vary substantially if that population was redefined. Having said that, our population of glaciers grew 26% from 133 to 168 over the measured interval, while simultaneously losing 18% of its total glacier area and an inferred 28% of its volume, ending with 237.1 km^2 of ice coverage and 110.7 km^3 of ice volume.

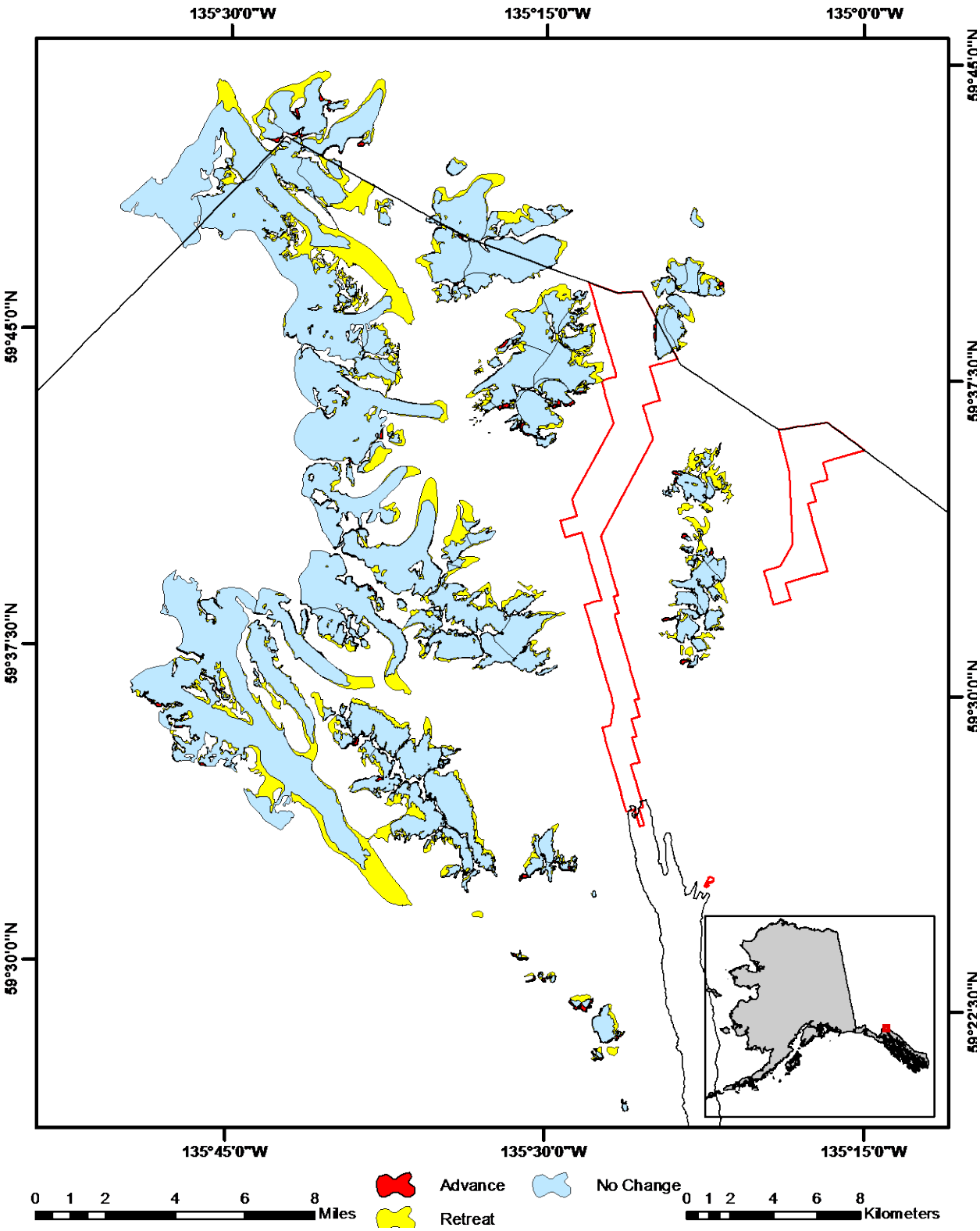


Figure 11. Changes in glacier area between map date (1948 US, 1987 Canada) and modern in and around Klondike Gold Rush NHP. The glaciers shown in this figure are the subset included in calculations of glacier change presented elsewhere in this report. See Appendix C for close-up maps.

The map of glacier changes (Figure 11) suggests that the increase in glacier numbers is not due to appearance of many new ice masses, but is rather due to the shrinkage and dissection of existing larger glaciers into numerous smaller ice masses. The change in average glacier size over this interval, from 2.16 km^2 to 1.41 km^2, supports this interpretation. So does Figure 12, which shows the appearance of many new small and medium sized glaciers (right panel) concurrent with the loss of a small number of what we infer to be "parent" glaciers in the larger size classes.

Table 6. Summary statistics for glaciers in and around Klondike Gold Rush NHP.

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1948-1987)	133	287.6	153.4
Modern (2010-2011)	168	237.1	110.7
Absolute Change	35	-50.6	-42.7
Percent Change	26%	-18%	-28%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using coefficient/exponent values of 0.2055/1.375 from Radic and Hock (2010).

The Ferebee Glacier (largest glacier in the southwest portion of Figure 11) provides an example: by shrinking over the last ~50 years, this single glacier broke up into three smaller glaciers. As expected with such changes, which arise from widespread terminus retreat, the typical mean elevation of individual glaciers in KLGO grew over the measured interval (left panel), and total ice coverage shrank significantly only in the lowest and middle elevations (Figure 13).

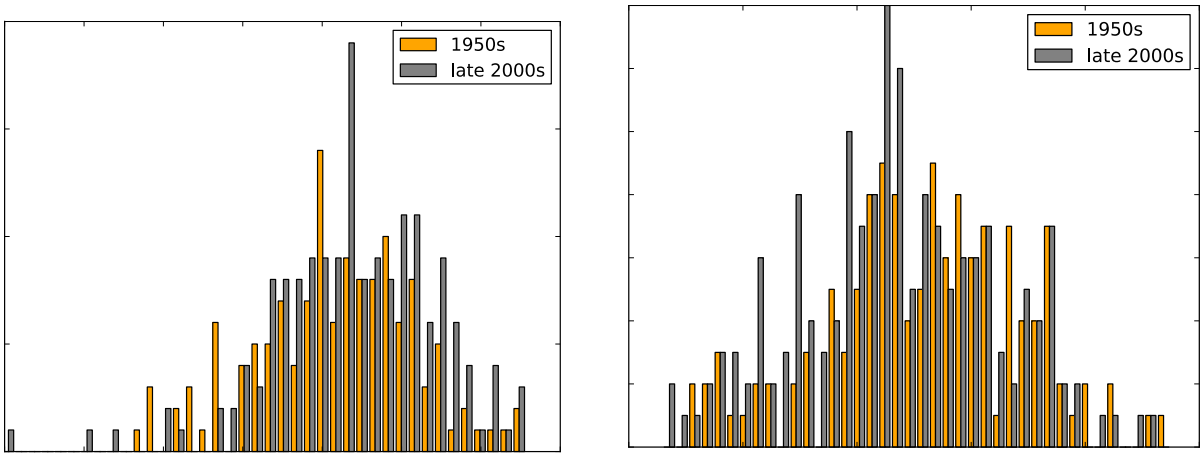


Figure 12. Histograms of changes in number of individual glaciers by area-weighted mean elevation (left) and area (right) in and around Klondike Gold Rush between map date (mostly 1948) and modern (2010-2011). For the purposes of this analysis, "around" is loosely defined as glaciers that contribute meltwater to land within the Park boundaries.

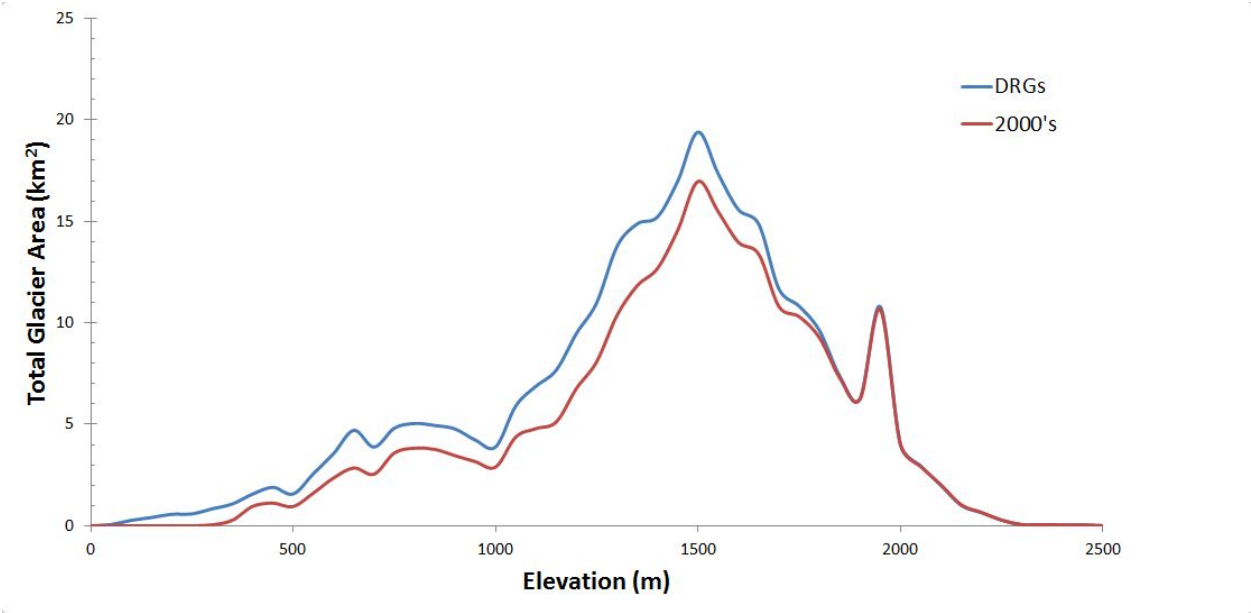


Figure 13. Total area of glacier-covered terrain in and around Klondike Gold Rush by elevation between map date (1948) and modern (2010-2011).

Aniakchak NM&P

Mapped outlines for Aniakchak NM&P are shown in Figure 14 and summarized in Table 7. Map era photography dates range from 1957-1962, and we reiterate that the exact capture dates for the satellite imagery are currently unknown but are in the 2005-2008 range. Aniakchak has few glaciers overall—19 in modern imagery—but that number has diminished over time, from 29 in the map era. Total glacier area, on the other hand, increased slightly from 4.1 to 4.4 km^2. Interestingly, the changes in glacier number and coverage differ strongly across the park: small glaciers in the low peaks of the Aleutian Range on the eastern boundary of the park primarily shrank or disappeared, while larger glaciers in the caldera proper either grew or were mapped for the first time in satellite imagery (also seen in Figure 15). At this time, we cannot say definitively whether the "appearance" of ice in the Caldera reflects incorrect original mapping—perhaps due to enhanced tephra cover following the 1931 eruption of a small vent in the Caldera, but more likely due to an early summer aerial photo with heavy snowcover—or instead indicates that glaciers were in fact melted by that same eruption and have since returned. We are working on this through acquisition of additional photography, and will address this more completely in the final report.

Table 7. Summary statistics for glaciers in Aniakchak NM&P.

Time Period	Number of glaciers	Total glacier area (km^2)	Estimated volume (km^3)*
Map date (1957-1962)	29	4.1	0.5
Modern (post-2000)	19	4.4	1.1
Absolute Change	-10	0.3	0.5
Percent Change	-34%	8%	106%

*volumes and volume changes are preliminary and subject to change. They are derived from area/volume scaling (Bahr, 1997) using coefficient/exponent values of 0.2055/1.375 from Radic and Hock (2010).

The histogram of changes in number of individual glaciers by mean elevation (Figure 15) and a plot of total glacier area by elevation (Figure 16) also show that the glaciers forming or growing in the caldera are higher in elevation, generally, than those shrinking and/or disappearing in the eastern part of the park. This makes sense climatically, and suggests that the glaciers in the Caldera were indeed impacted by the 1931 eruption event (whether destroyed or simply covered by debris) and have since regrown. We again caution that this intriguing result may also be simply a function of mapping errors (omission of existing glaciers) in the original maps, and we are trying to locate the original aerial photography to confirm this result before the publishing the final report.

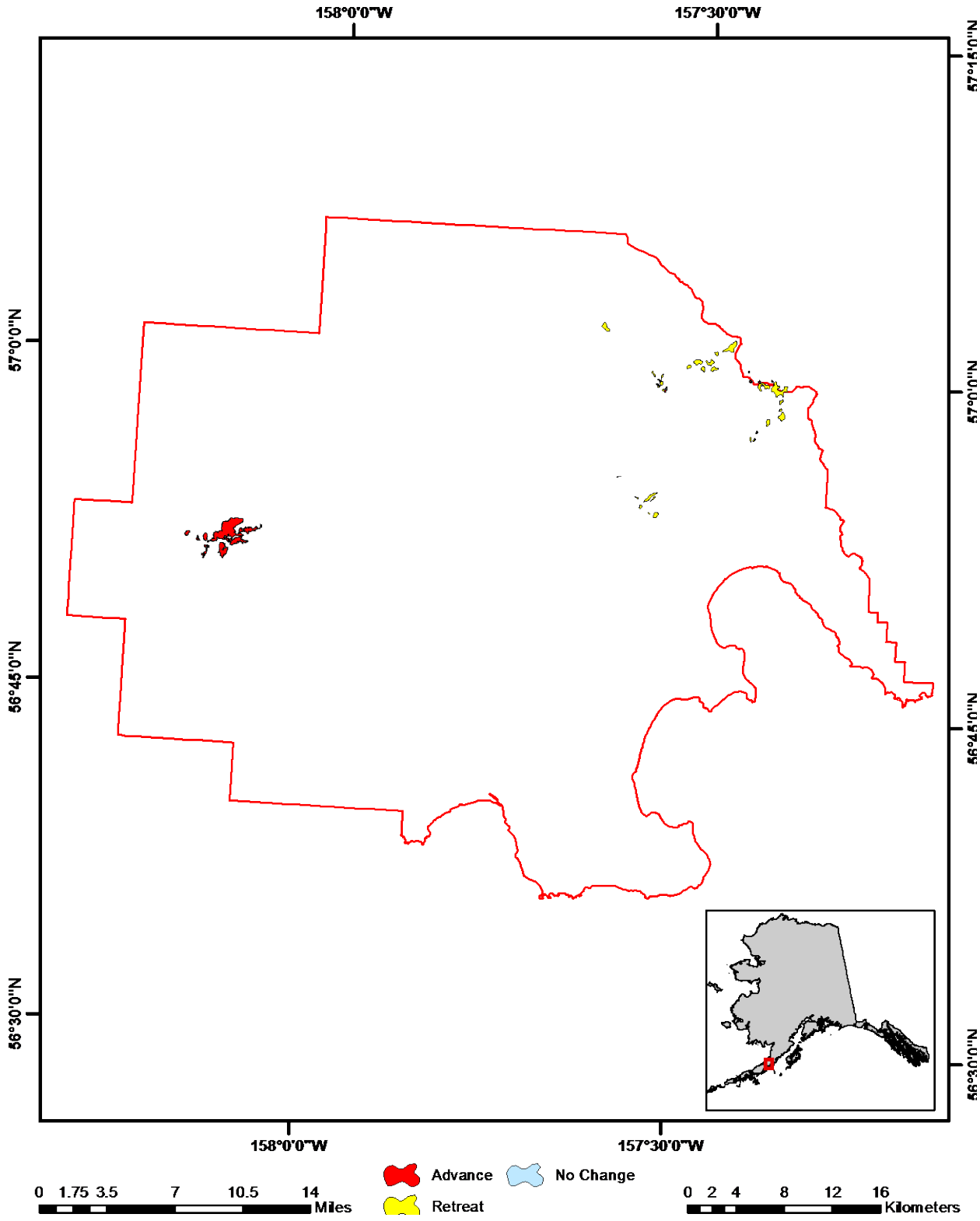


Figure 14. Changes in glacier area between map date and modern in Aniakchak NM&P. See Appendix C for close-up maps.

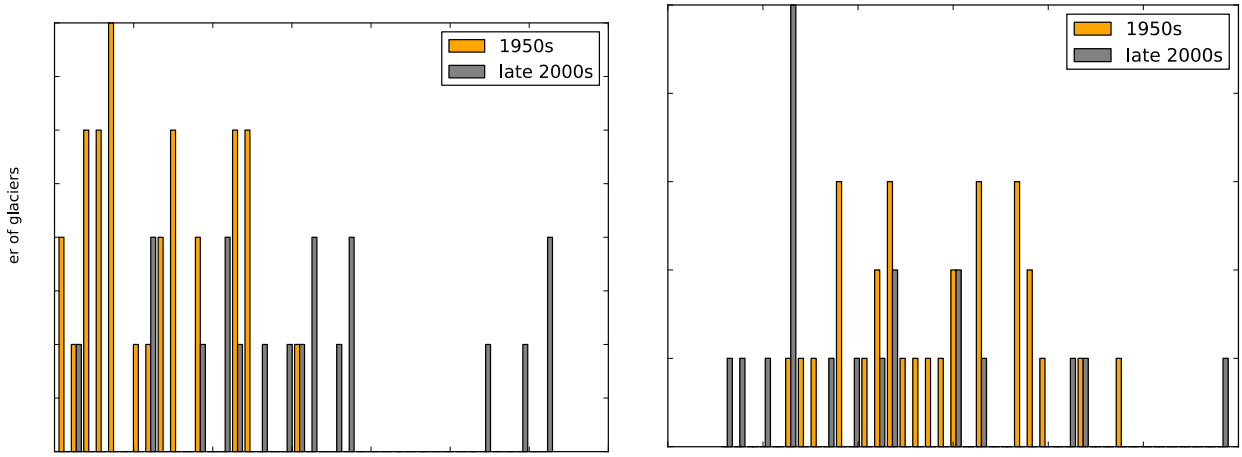


Figure 15. Histograms of changes in number of individual glaciers by area-weighted mean elevation (left) and area (right) in Aniakchak between map date (1957-1963) and modern (late 2000s).

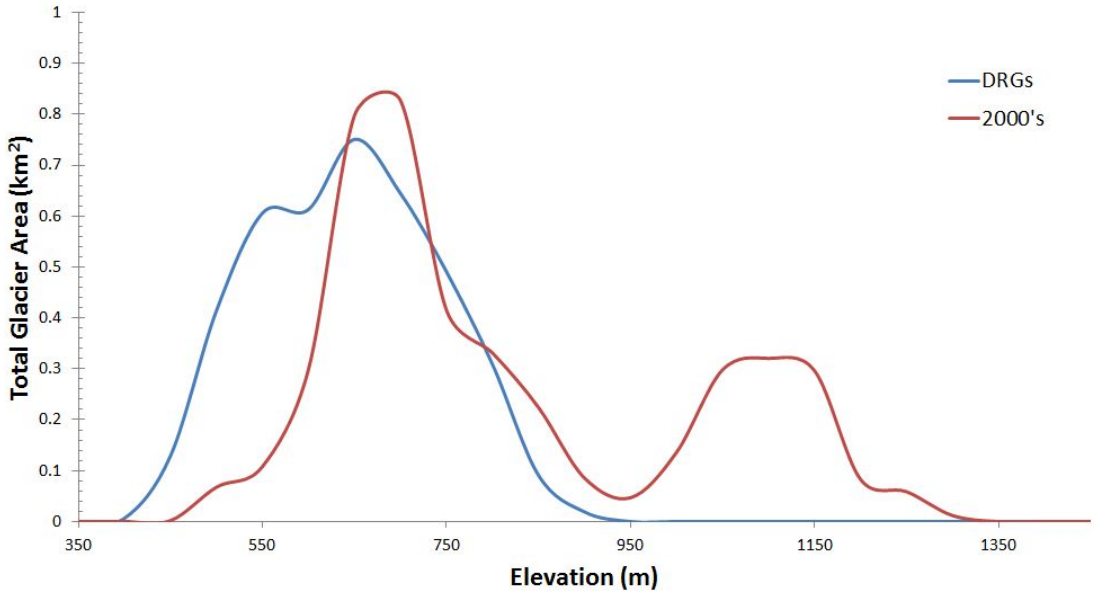


Figure 16. Total area of glacier-covered terrain in Aniakchak by elevation between map date (1957-1963) and modern (late 2000s).

Results-Elevation Change

We have completed analysis of surface elevation changes and inferred volume changes for eight glaciers in Denali NP&P over one to three intervals for each glacier, as shown in Table 3. Complete results for those 21 individual analyses are presented in narrative and graphic form in Appendix D. Below, we begin with the example of Muldrow Glacier over two time intervals between 1994 and 2010 and then move on to summarize broader trends.

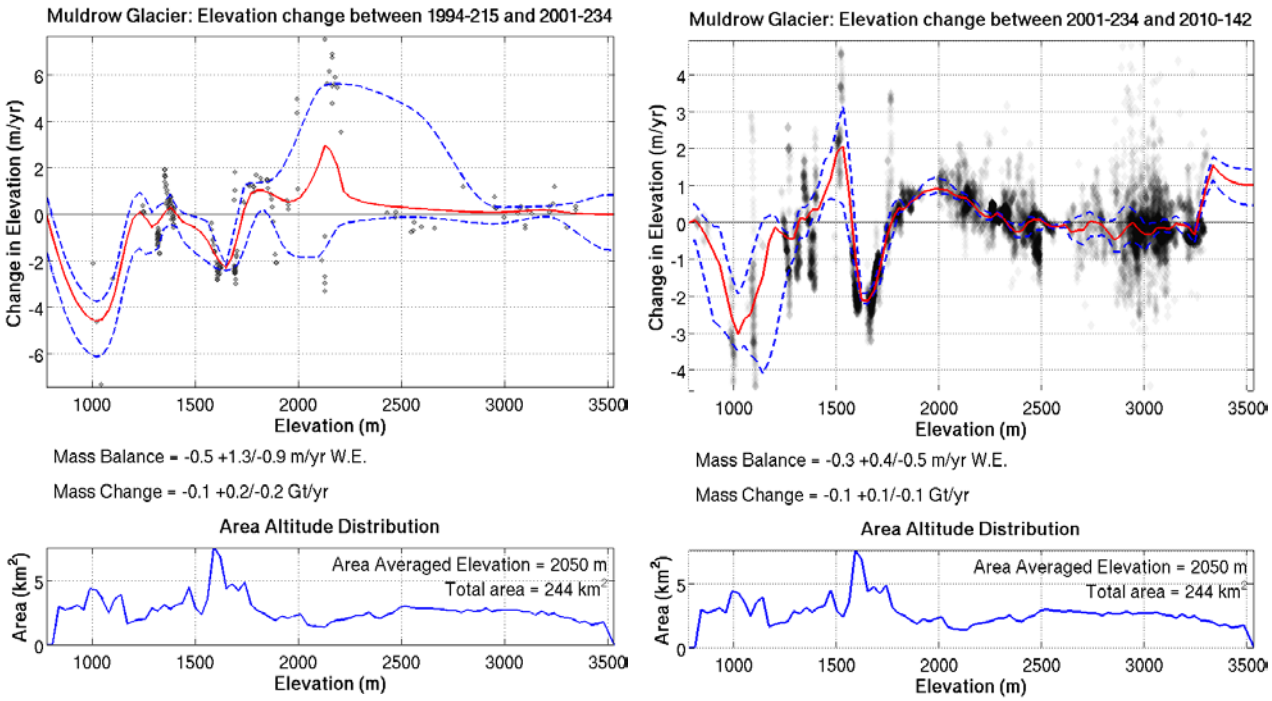


Figure 17. Elevation difference results (upper panel) and area altitude distributions (below) from Muldrow Glacier during two time periods: 1994-2001 (left) and 2001-2010 (right). In upper plots, points are derived from raw laser point data, red lines are median values of a moving window of twelve datapoints, and dashed blue lines are upper and lower quartile values of the moving window. More points are visible in the right hand plot because it is based on a denser network of points from a laser scanning system. Other intervals for this glacier, and other glaciers, are shown in Appendix D.

Muldrow Glacier (Figure 17) is one of two glaciers that actually gained mass (positive glacier-wide mass balance) during some phases of our study period. The other is Traleika Glacier, a tributary to Muldrow Glacier that is affected by the same long-period surge cycle that affects Muldrow. Muldrow Glacier surged in 1956-1957 (Post 1960), and, as is typical of surging glaciers in their quiescent phase, has since then been replacing the mass lost from the Muldrow's upper elevations (including the Traleika). This trend is exhibited in both panels of Figure 17, with thickening above ~1750 m in both time periods. Importantly, lower elevations of both glaciers have been losing mass throughout the time period, and the overall glacier-wide mass balance averaged over these two periods has been slightly negative (Figure 17), but for one short period within that time (2001-2008; Figure 18) the balance was actually positive. This is anomalous, in comparison with most other (non-surging) glaciers in the Alaska Range, but serves to illustrate the value of surface elevation profiles, which preserve the complicated details of glacier behavior masked by mapped surface extents alone.

As mentioned above, Muldrow and Traleika Glaciers are anomalous with respect to most glaciers in Denali, and the broader trends are better represented by a plot of glacier-wide mass balance rates: the most direct way of comparing volume changes on glaciers of different size (Figure 18). Compared with some other parks discussed in previous progress reports, however, these results are difficult to interpret for two reasons:

1) Measurements on Denali Glaciers were not made at a uniform time in the melt season, as shown in Table 3 and Appendix D. This confounds our calculations of glacier-wide mass balance, as discussed in the methods section.

2) Flights on different glaciers were conducted in different years, so that the intervals of comparison differ for each glacier.

With these caveats in mind, the trends shown in Figure 18 reflect the expected pattern of general mass loss throughout the park. Besides Muldrow and Traleika, other glaciers sampled between 1994 and 2010 exhibited modestly negative glacier-wide balance rates between -0.7 and -2.2 m/yr w.e. If more profiles are flown in the next year, we will include those data in the final project report.

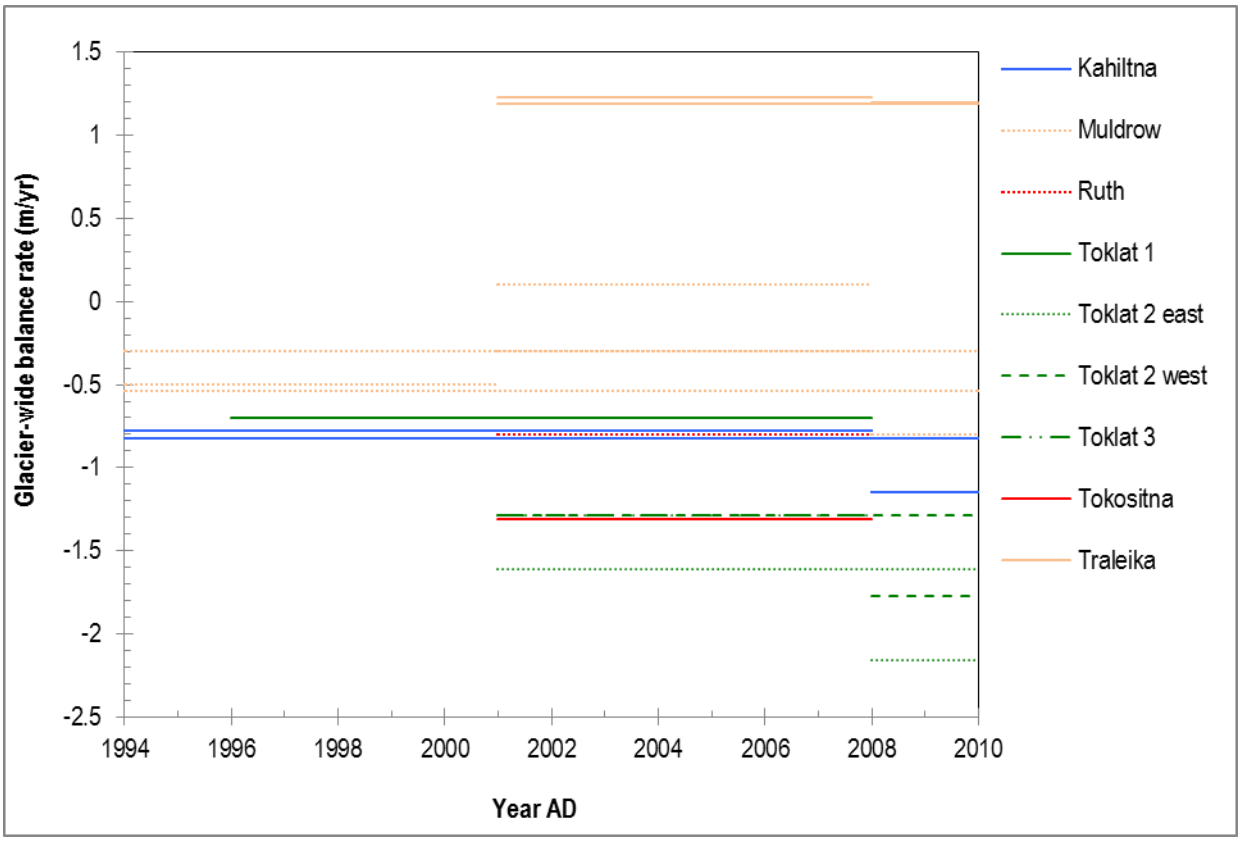


Figure 18. Glacier-wide mass balance rates (m/yr) for nine glaciers from Denali NP&P over multiple time periods between 1994 and 2010. Rates are averaged over the period spanned by each bar—note that some glaciers have overlapping averages from multiple intervals. See Appendix D and text for complete details, including confidence intervals that are excluded here for clarity and discussion of problems with seasonality of data acquisition.

Spatial and temporal trends in volume change, by elevation, are shown in Figures 19 and 20. Figure 19 shows changes in Toklat Glacier over several time periods, and the pattern is typical: thinning over most of the glacier surface, but most accentuated at the terminus. From 2008-2010, the Middle Toklat Glacier did show slight thickening at its highest elevations, but at all other elevations the thinning is actually enhanced relative to earlier periods. Several larger (than Toklat) glaciers are shown in Figure 20. Patterns vary among these glaciers. Muldrow and Traleika exhibit the overall pattern of accumulation zone thickening and ablation zone thinning summarized previously, while the other glaciers on the south side of the Alaska Range (which are all non-surging) show a more generalized pattern of thinning. There are two notable exceptions: the terminus of Kahiltna Glacier thickened from 2008-2010, and from 2001-2008 Tokositna Glacier thickened in two distinct areas: at the terminus and at mid-elevations from 800-1000 m. We don't have a clear interpretation for either of these observations, but both present questions about ice dynamics that additional profiles may help to answer. Overall, temporal trends are difficult to discern, especially with the complications mentioned previously, but it is clear that thinning is the predominant behavior of surveyed glaciers since 1994, even including the observations of Muldrow and Traleika.

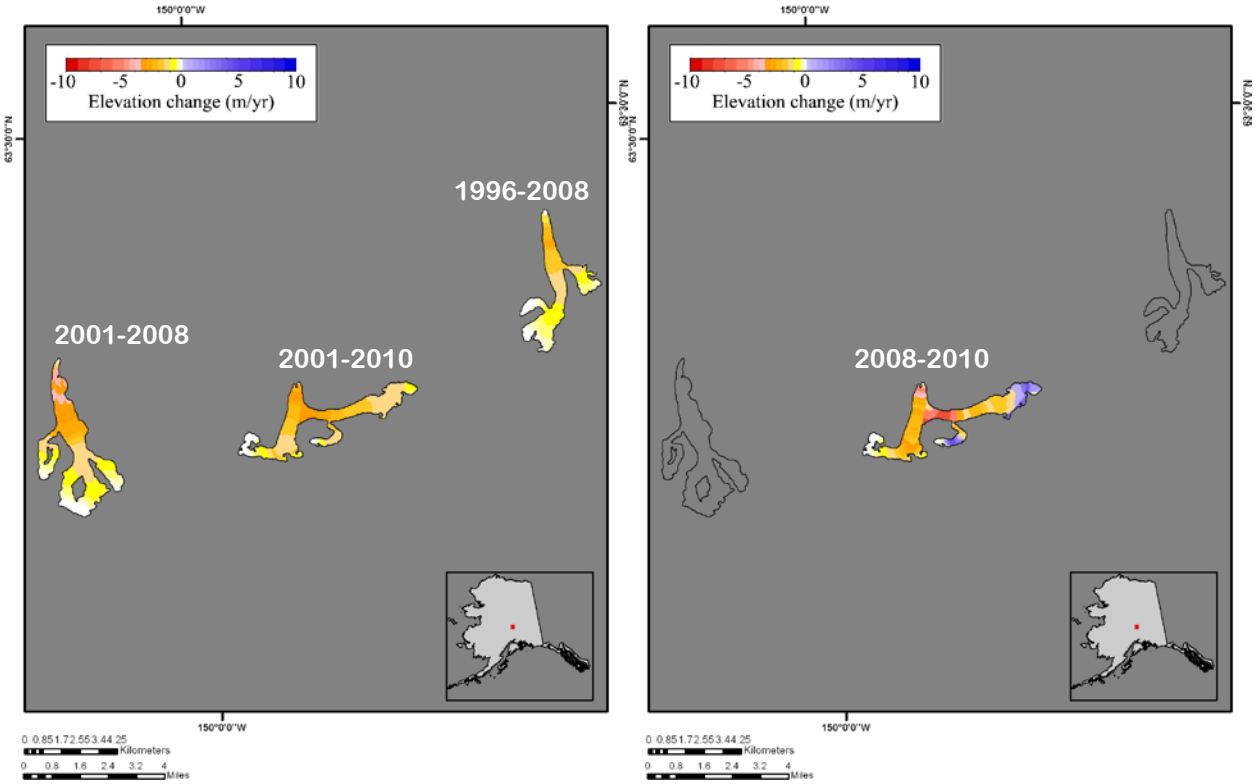


Figure 19. Annual rate of ice thickness change, by elevation, for Toklat Glaciers (1, 2, and 3, from east to west respectively) in Denali National Park & Preserve. Mapped values reflect averages over time periods shown by white text on figures. See Appendix D for underlying data.

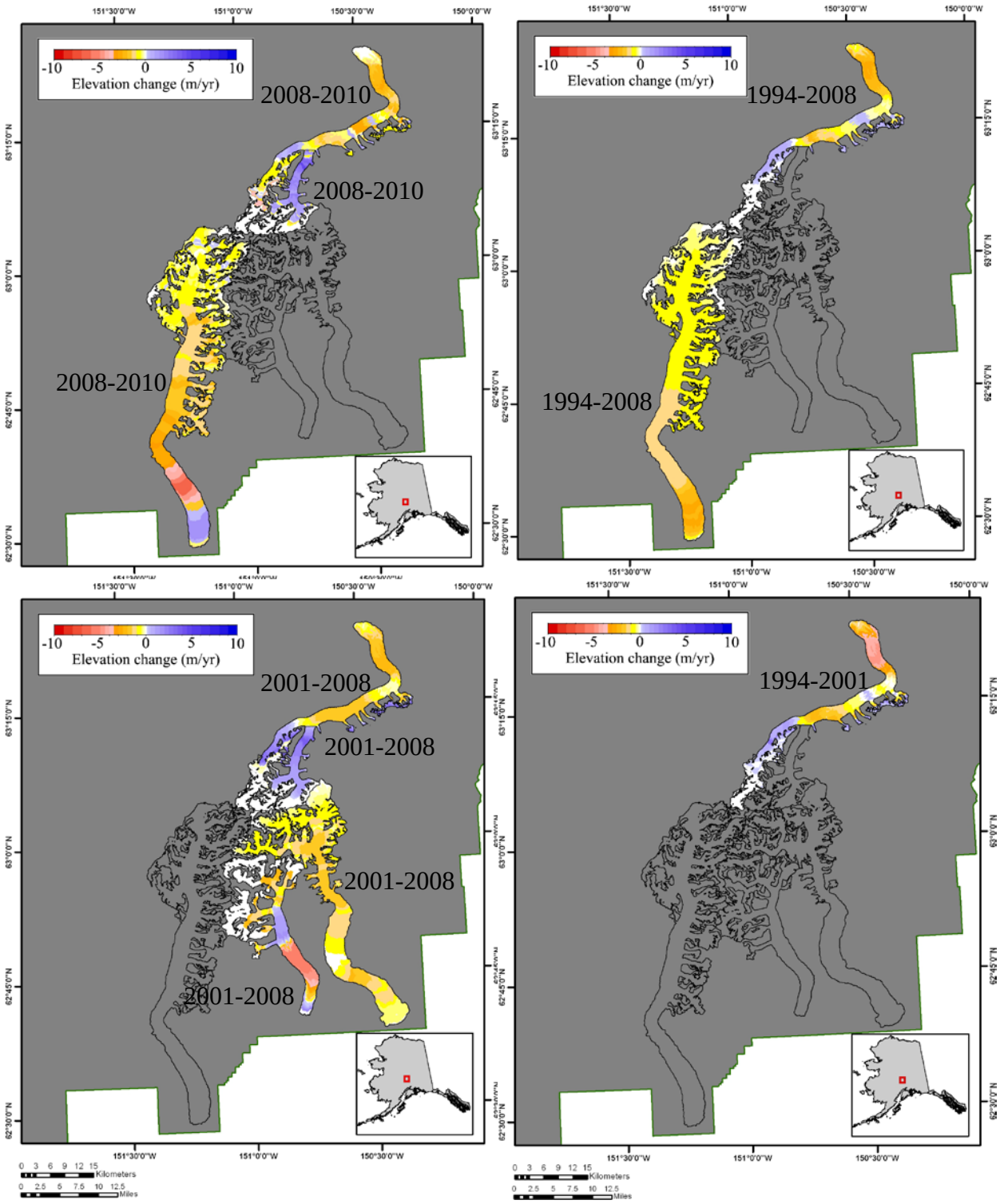


Figure 20. Annual rate of ice thickness change, by elevation, for selected glaciers in Denali National Park & Preserve. Clockwise from lower left, mapped glaciers are Kahiltna, Muldrow, Traleika, Ruth, and Tokositna. Mapped values reflect averages over time periods shown by white text on figures. See Appendix D for underlying data.

Results-Focus Glaciers

As described earlier, the focus glacier component of this project will culminate in creation of a narrative-based and graphic rich vignette for each glacier. Fieldwork and resource collection associated with creation of these vignettes was described in the methods sections, and included field visits to some (not all) of the focus glaciers in Parks targeted in this report: Denali, Katmai, and Lake Clark.

Creation of the vignettes for each focus glacier will primarily be completed during Loso's sabbatical year (fall 2012 – spring 2013), but a sample vignette was constructed for Knife Creek Glacier (Katmai NP&P) to present (in poster form) at the *National Park Service Southwest Alaska Science Symposium*, November 2-4 2011 in Anchorage, AK. The poster was then edited and vetted by NPS personnel and project collaborators and the revised version was included in the Second Progress Report. We do not present it again here, but reference it for two reasons:

1) The Knife Creek Glacier vignette will serve as a model for creation of further vignettes as we commence planning for the layout and design phase for the final report. Individual vignettes will vary from 4-8 pages, depending on the amount of information available for each glacier.

2) The vignette happened to be for a glacier in Katmai National Park, a unit scheduled for presentation in this Third Progress Report. We refer to it here for the sake of completeness.

As in the first progress report, when focus glacier results for Glacier Bay NP&P were presented, our approach here is to summarize, by glacier, the interpretive themes that will serve to document the most unique aspects of the focus glaciers presented in this report: those in Denali, Katmai, and Lake Clark NP&P. In this context, we also cite those resources (documents, maps, reports) we have accessed to support our efforts. We welcome suggestions of additional resources not included in this section, particularly from our NPS collaborators, and will highlight below those focus glaciers where resources are so scarce as to potentially compromise the suitability of a given glacier as a "focus glacier."

Denali NP&P

Focus glaciers in Denali NP&P include Kahiltna, Muldrow, and Toklat Glaciers.

Kahiltna Glacier

Kahiltna Glacier is a very large (over 70 km long) valley glacier that arises on the south and west flank of Mt. McKinley, the highest mountain in North America. It is notable for its size (only the Bagley Icefield is larger among the focus glaciers), but the Kahiltna is probably most unique in Alaska for hosting the state's most popular mountaineering route: the West Buttress (Coombs 1997). Over 1200 climbers per year, including many international groups, spend an average of 18 days on the West Buttress route, and it is further the subject of many hundreds of flightseeing overflights and landings each climbing season. It is intimately experienced by a large number of people and is also highly visible to the public. There is a large amount of data available for the Kahiltna: it is an index glacier monitored by NPS (Adema 2006), it has been studied by many scientific expeditions (e.g. Campbell et al. 2012), and it has been repeatedly mapped and imaged.

The narrative we will focus on, however, is the effect of warmer temperatures (and the consequent rise in ELA) on climbing and flightseeing activity. Changes in mass balance have been documented by the park's index glacier program and by ongoing work under the direction of coauthor Arendt, and will be used to validate anecdotal evidence (primarily from air taxi operators) of the decreasing quality of available glacier landing strips on the Southeast Fork Kahiltna Glacier, and the shortened season in which those strips are even usable. On a related note, we will discuss the impacts of enhanced melting on emergence of trash and human waste disposed by climbers (Goodwin et al 2012).

Muldrow Glacier

Muldrow Glacier is the north-draining counterpart to Kahiltna Glacier, emerging from the Mt. McKinley summit to flow towards Wonder Lake and the most heavily-visited part of the Park. It is most unique in the focus glacier group for being a well-known surging glacier, and this will form the primary narrative theme for this glacier. The surges of the Muldrow were first noted by Post (1960), and were later addressed further by Harrison (1964, 1970), and the post-surge evolution of the glacier (and its tributary, Traleika Glacier) is being addressed, using repeat altimetry data, by coauthors Murphy and Larsen. We hope to use preliminary results from that investigation in our final report. We will complement that narrative with repeat photography, including original photos by S. Capps and B. Washburn, and repeat imagery by G. Adema and R. Karpilo. With permissions, we will use these in the vignette.

Toklat Glacier

Toklat Glacier is the name given to three distinct glaciers on the north side of the Alaska Range. These glaciers are much smaller (<10 km length) than the Kahiltna and Muldrow, to the west, and more rarely visited. Denali NPS staff has been surveying the changes to Toklat Glacier (East Fork and Middle Fork) for some time (Adema 2007), and these results will be included in a more extensive set of extent maps for these glaciers. We also have altimetry profiles for these glaciers. It is not clear to us, at this time however, what a primary narrative theme for the Toklat Glaciers should be. Debris cover has played a role in mapping challenges on the Toklat Glaciers for some time, and medial moraines on Toklat Glacier have served as examples of medial moraine evolution (Anderson 2000). This may serve as one narrative theme, and allows inclusion of novel research on microbial (as opposed to botanical) succession on moraines of the Toklat Glacier (Concienne 2008, Darcy et al 2011). Nonetheless, we would appreciate feedback from our agency collaborators on the best approach to the vignette for these glaciers.

Katmai NP&P

Focus glaciers in Katmai NP&P include Fourpeaked and Knife Creek Glaciers.

Fourpeaked Glacier

Fourpeaked Glacier is a lake-terminating, calving glacier that flows east off of Fourpeaked Mountain in northeastern Katmai NP&P. Fourpeaked Mountain is a stratovolcano that was considered dormant prior to a several month period of moderate seismic and venting activity that began in September 2006. The activity tapered in June 2007, and never deposited a significant (cm to meters) layer of tephra on the glacier (Gardine et al 2011, McGimsey et al 2011). For this reason, Fourpeaked Glacier provides an interesting (and more typical, when viewed in the context of other southern Alaskan glaciers) contrast to the effects of the catastrophic Novarupta eruption on nearby Knife Creek Glaciers. It did, however, involve disruption of glacier ice on the

north flank of the mountain, generating significant debris flows that disrupted some portions of the glacier (Cervelli and West 2007) and represent another narrative theme: the hazards posed by debris flows and, in particular, lahars associated with volcanic eruptions on glaciated mountains (e.g. Huggel 2009). This narrative theme will afford some opportunity to discuss the well-studied Drift River lahars associated with the 1989-1990 eruption of Mount Redoubt (Dorava and Meyer 1994). We note, however, that at this time we have essentially no reports, articles, laser altimetry, or first-hand accounts of the Fourpeaked Glacier with which to make these narrative themes clear and accessible. Furthermore, Tuxedni Glacier (Lake Clark NP&P—see below) offers a much better documented opportunity to discuss these same themes. It is unclear what Fourpeaked would add to the narrative. Additional data from NPS collaborators would be very welcome.

The Knife Creek Glaciers

The Knife Creek Glaciers, as summarized in the vignette presented in the Second Progress Report, are a complex of related (but not all connected) ice masses that drain north and west from Katmai, Trident, and Griggs Volcanoes at the head of the Valley of Ten Thousand Smokes. The glaciers are small, and were unremarkable until they were blanketed with many meters of volcanic tephra and pyroclastic debris after the catastrophic eruption of nearby Novarupta volcano in 1912 (Griggs 1922). The eruption was only kilometers away, and was the largest of the 20th century. Knife Creek Glaciers therefore provide an “end-member” representation of how volcanic eruptions and associated tephra-fall can affect glaciers. No other Alaskan glacier has been so thoroughly buried by volcanic debris, and the effects of this burial constitute the primary narrative for them. Fortunately, the Knife Creek Glaciers were visited and described shortly after the eruption (Griggs 1922, Fenner 1926) and were photographed and more thoroughly examined again in 1957 (Muller and Coulter 1957). We revisited and re-photographed the Knife Creek Glaciers in 2011, and spoke with John Eichelberger, a contemporary field scientist with a long history in the Valley (Eichelberger 2006), for his perspective. We will also utilize a shuttle radar topography mission (SRTM) DEM to provide a new analysis of elevation change over the last ~decade, taking advantage of existing laser altimetry profiles for these glaciers too.

Lake Clark NP&P

Focus glaciers in Lake Clark NP&P include Tanaina, Turquoise, and Tuxedni Glaciers.

Tanaina Glacier

Tanaina Glacier is a local, informal name for a large (~30 km long) glacier flowing south from the Neacola Mountains (just outside the park boundary) towards Lake Clark Pass. Lake Clark Pass is heavily traveled by aircraft flying to Port Alsworth and other areas in western Alaska, and Tanaina is thus frequently seen and photographed. At the glacier terminus, meltwater historically discharged both west (into Tlikakila River) and east (into North Fork Big River), but it now drains primarily east. Tlikakila River contributes over one-half of the inflow to Lake Clark, and provides important salmon habitat that prompted early studies by Brabets (2002) and Brabets et al (2004). Brabets described the effects of Tanaina and other glaciers in the watershed on the hydrology of the river, and especially focused on the effects that changes to these glaciers (primarily retreat) have on salmon productivity. Documentation of these effects is mostly anecdotal for Tanaina Glacier proper, but provides an opportunity to describe the more

generalized hydrologic effects of glacier changes, and the concomitant effects on salmon productivity elsewhere. We have existing laser altimetry profiles for this glacier, and also contemporary photography collected in 2011.

Turquoise Glacier

Turquoise Glacier is a small (~12 km long), relatively simple valley glacier that feeds Turquoise Lake via a 6 or 7 km long proglacial stream. We have existing laser altimetry profiles for this glacier, and can reconstruct changes via map extents using historical imagery, but beyond this we have no information with which to construct a coherent narrative theme for this glacier. Due to weather, we were unable to visit this glacier in 2011, and we have found no published resources describing the glacier or unique aspects of its behavior. We welcome contributions from our collaborators.

Tuxedni Glacier

Tuxedni Glacier is a surge-type glacier (Post 1969) on the slopes of Mount Iliamna—an active 3053 m high stratovolcano. Evidence of multiple debris avalanches and lahars on Mount Iliamna glaciers—including Tuxedni—has been well studied (Waythomas et al 2000). On Iliamna, extensive exposures of hydrothermally altered / weakened granitic rocks combined with high heat flow near the summit region combine to favor glacier activity (surging, ice and debris avalanches, lahars) that suggest a narrative focus on volcanic hazards. Surging will also be discussed in the context of the Muldrow Glacier, where the surge cycle has been more thoroughly documented, so we will focus more on the hazards aspect with Tuxedni. Tuxedni also has good datasets available, including existing laser altimetry profiles, an early map we are working on acquiring (it was evidently mapped for the first time on or just before 1912 on Coast Survey Chart 8554 according to Reid 1915), and extensive satellite image analyses (Huggel et al 2007). A completely separate narrative theme is suggested for Tuxedni by recent monitoring of vascular plant populations on nunataks in southwest Alaska, including a nunatak on the Tuxedni Glacier (Miller et al 2006). Nunataks are common throughout glaciated Alaska, but few have been carefully studied, and Tuxedni happens to be one of the few. While no endemic species or range extensions were documented in the Miller study, it does present an opportunity to discuss the ecological role of nunataks, and/or refugia, in Alaska ecology (e.g. Petit et al 2003).

Discussion

Preliminary Highlights

The data presented here are preliminary, but serve well to document our approach to, and progress on, this project. Some of the details of our analytical techniques are still evolving, but the general presentation has now been vetted in several meetings and two prior progress reports. Accordingly, the language and structure of this progress report is largely similar to the previous one and our focus here has been on documenting new datasets. The following trends emerge from this preliminary work.

- Gates of the Arctic NP&P was less than 1% glaciated in both mapping periods (nominally 1970s and 2000s), but ice cover diminished 43% (from 95.6 to 54.0 km^2).

- Klondike Gold Rush NHP has almost no glacier cover, but ice cover in watersheds draining into or near the Park diminished 18% from 288 to 237 km^2 (1948-2011/11).

- Aniakchak NM&P was less than 1% glaciated in both mapping periods, but ice cover grew 8% over that period (from 4.1 to 4.4 km^2). This is likely an artifact of mapping errors in the original cartography.

- The total number of glaciers declined in two of the three mapped parks (by 30% in Gates and by 34% in Aniakchak), but glacier numbers increased 26% in in the study area around Klondike. This result in Klondike is likely due to fragmentation of glaciers into multiple smaller ice masses.

- Using laser altimetry, we measured 21 distinct intervals of elevation change among eight glaciers in Denali NP&P from 1994 - 2010. Interpretation of these changes is complicated by collection of the profiles during different portions of the melt season.

- Of the glaciers measured by repeat laser altimetry in Denali, two had positive glacier-wide mass balance rates for some portion of the measured period: Muldrow Glacier (2001-2008) and its tributary Traleika Glacier (2001-2010). We attribute this to thickening of the upper elevations of this surging glacier system during the quiescent post-surge phase. Lower elevations of these glaciers were consistently thinning, and over the entire 1994-2010 period Muldrow had an overall negative mass balance rate.

- All other glaciers and intervals in Denali had negative mass balance rates (overall thinning) ranging from -0.7 to -2.2 m water equivalent per year, but interpretation of these results is complicated by inconsistency in the seasonality of measurements. The lowest measured balance rate was on east Toklat Glacier from 2008-2010.

- We visited and photographed glaciers in Denali, Katmai, and Lake Clark NP&Ps in summer 2011. Sample interpretive themes for their focus glaciers are presented herein.

- A sample vignette from Knife Creek Glacier in Katmai was presented in the Second Progress Report, has now been vetted by NPS personnel and project collaborators, and will serve as the model as we commence planning for the layout and design phase for the

final report. Negotiations are underway to hire a graphic designer for the interpretive report.

Challenges

As this project progresses, new challenges and questions emerge. Our goal in including them here is to open a discussion about these items. We emphasize that these progress reports are not intended to present final results or conclusions, but to stimulate discussion that will improve the final reports. To emphasize these points for discussion, we itemize some of these challenges below, in no particular order.

- Extreme sun angle and debris cover combine in Gates of the Arctic to make this region more difficult to map. Differences between map data and modern may just as likely be the result of incorrect mapping as it is ice loss or gain.

- Early topographic mapping at Aniakchak may have omitted some existing glaciers, particularly in the caldera, and incorrectly added some others that were merely snowfields in the eastern portion of the Monument. As with Gates, this makes interpretation of extent differences problematic. In both cases, we will examine additional imagery to assist us with our interpretation. At Aniakchak, a field visit might also be very valuable prior to the conclusion of this project.

- We are still working with the NPS to assign more accurate dates to the mosaicked imagery used to generate outlines in Lake Clark and Aniakchak.

- Denali elevation change data are compromised by seasonal variations. We may be able to quantify some of these changes more thoroughly in subsequent reports, but the interpretation challenge is not completely solvable with existing data. If additional profiles are flown before completion of the final project, we may be able to augment our conclusions with that new data.

- Additional quantification of these and all other errors are of obvious importance for the final report, but especially in the case of archival maps not created by our group (such as the Aniakchak topographic maps), it may be impossible for us to quantify the errors of other cartographers.

- NPS has expressed interest in extrapolation of volume change results to other glaciers, but we question the utility of such an extrapolation. This will require further discussion.

Literature Cited

Adema G (2006) Glacier monitoring in Denali National Park and Preserve: Background and study plan. Denali National Park and Preserve, Denali Park AK 27 pp.

Adema G (2007) Glacier monitoring in Denali National Park and Preserve. *Alaska Park Science* 6: 28-32

Anderson RS (2000) A model of ablation-dominated medial moraines and the generation of debris-mantled glacier snouts. *Journal of Glaciology* 46: 459-469

Arendt AA, Echelmeyer KA, Harrison WD, Lingle CS, Valentine VB (2002) Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* 297: 382-386

Bahr DB, Meier MF, Peckham SD (1997) The physical basis of glacier volume-area scaling. *Journal of Geophysical Research* 102: 20355-20362

Bolch T, Menounos B, Wheate R (2010) Landsat-based inventory of glaciers in western Canada, 1985-2005. *Remote Sensing of Environment* 114: 127-137

Brabets TP (2002) Water quality of the Tlikakila River and five major tributaries to Lake Clark, Lake Clark National Park and Preserve, Alaska, 1999-2001. US Geological Survey Water-Resources Investigations Report 02-4127, Anchorage AK 29 pp

Brabets TP, March RS, Trabant DC (2004) Glacial history and runoff components of the Tlikakila River Basin, Lake Clark National Park and Preserve, Alaska. US Geological Survey Scientific Investigations Report 2004-5057, Reston VA 24 pp

Campbell S, Kreutz K, Osterberg E, Arcone S, Wake C, Volkening K, Winski D (2012) Flow dynamics of an accumulation basin: a case study of upper Kahiltna Glacier, Mount McKinley, Alaska. *Journal of Glaciology* 58: 185-195

Cervelli PF, West M (2007) The 2006 eruption of Fourpeaked Volcano, Katmai National Park, Alaska. American Geophysical Union Fall Meeting 2007, abstract #V31E-0719

Concienne B (2008) Microbial succession within a pro-glacial zone: the Middle Fork Toklat Glacier, Denali National Park & Preserve, Alaska, USA. Thesis. University of Colorado, Boulder CO 51 pp

Coombs C (1997) Denali's West Buttress: A Climber's Guide to Mount McKinley. Mountaineers Books, Seattle WA 128 pp

Darcy JL, Lynch RC, King AJ, Robeson MS, Schmidt SK (2011) Global distribution of *Polaromonas* phyolotypes – evidence for a highly successful dispersal capacity. PLoS ONE 6: doi:10.1371/journal.pone.0023742

Denali National Park and Preserve, 2010: Annual Mountaineering Summary. Denali National Park & Preserve, Denali Park AK 10 pp.

Dorava JM, Meyer DF (1994) Hydrologic hazards in the lower Drift River basin associated with the 1989-1990 eruptions of Redoubt Volcano, Alaska. *Journal of Volcanology and Geothermal Research* 62: 387-407

Echelmeyer KA, Harrison WD, Larsen CF, Sapiano J, Mitc hell JE, DeMallie J, Rabus B, Adalgeirsdottir G, Sombardier L (1996) Airborne surface profiling of glaciers: a case-study in Alaska. *Journal of Glaciology* 42: 538-547

Eichelberger J (2006) The Valley of Ten Thousand Smokes, Alaska, including Katmai, Trident, and Novarupta Volcanoes, Katmai National Park. Alaska, The Alaska Volcano ObservatoryFenner CN (1926) The Katmai magmatic province. *Journal of Geology* 34: 675-771

Gardine M, West M, Werner C, Doukas M (2011) Evidence of magma intrusion at Fourpeaked volcano, Alaska, in 2006-2007 from a rapid-response seismic network and volcanic gases. *Journal of Volcanology and Geothermal Research* 200: 192-200

Goodwin K, Loso MG, Braun M (2012) Glacial transport of human waste and survival of fecal bacteria on Mt. McKinley's Kahiltna Glacier, Denali National Park, Alaska. *Arctic, Antarctic, and Alpine Research* 44: 00-00 (in press)

Griggs RF (1922) The Valley of Ten Thousand Smokes. National Geographic Society, Washington DC

Harrison AE (1964) Ice surges on the Muldrow Glacier, Alaska. *Journal of Glaciology* 5: 365-368

Harrison AE (1970) Renewed activity of Muldrow Glacier, Alaska, after the 1956 surge. *Journal of Glaciology* 57: 397-400

Huggel C, Caplan-Auerbach J, Waythomas CF, Wessels RL (2007) Monitoring and modeling ice-rock avalanches from ice-capped volcanoes: A case study of frequent large avalanches on Iliamna Volcano, Alaska. *Journal of Volcanology and Geothermal Research* 168: 114-136

Huggel C (2009) Recent extreme slope failures in glacial environments: effects of thermal perturbation. *Quaternary Science Reviews* 28: 1119-1130

McGimsey RG, Neal CA, Dixon JP, Malik N, Chibisova M (2011) 2007 volcanic activity in Alaska, Kamchatka, and the Kurile Islands: Summary of events and response of the Alaska Volcano Observatory. US Geological Survey Scientific Investigations Report 2010-5242. Washington DC 110 pp

Miller A, Spencer P, Carlson ML, Lipkin R (2006) Vascular plant inventory & baseline monitoring of nunatak communities (2005). Lake Clark National Park and Preserve and Kenai Fjords National Park. Southwest Alaska Network, National Park Service, Anchorage AK 43 pp

Muller EH, Coulter HW (1957) The Knife Creek Glaciers of Katmai National Monument, Alaska. *Journal of Glaciology* 3: 116-122

Paul F, Barry RG, Cogley JG, Frey H, Haeberli W, Ohmura A, Ommanney CSL, Raup B, Rivera A, Zemp M (2009) Recommendations for the compilation of glacier inventory data from digital sources. *Annals of Glaciology* 50: 119-126

Petit RJ, Aguinagalde I, de Beaulieu JL, Bittkau C, Brewer S, Cheddadi R, Ennos R, Fineschi S, Grivet D, Lascoux M, Mohanty A, Müller-Starck G, Demesure-Musch B, Palmé A, Martín JP, Rendell S, Vendramin GG. 2003. Glacial refugia: hotspots but not melting pots of diversity. *Science* 300: 1563-1565

Post A (1969) Distribution of surging glaciers in western North America. *Journal of Glaciology* 8: 229-240

Post A, Meier MF (1980) A preliminary inventory of Alaskan glaciers, in World Glacier Inventory Workshop, 17–22 September 1987, Reideralp, Switzerland, Proceedings: International Association of Hydrological Sciences (IAHS) Publication No. 126, p. 45–47

Post, A (1960) The exceptional advances of the Muldrow, Black Rapids, and Susitna Glaciers. *Journal of Geophysical Research* 65: doi:10.1029/JZ065i011p03703

Radic V, Hock R (2010) Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. *Journal of Geophysical Research* 115: doi:10.1029/2009JF001373

Reid HF (1915) Variations of Glaciers XIX. *The Journal of Geology* 23: 548-553

Sapiano JJ, Harrison WD, Echelmeyer KA (1998) Elevation, volume and terminus changes of nine glaciers in North America. *Journal of Glaciology* 39: 582-590

Waythomas CF, Miller TP, Beget JE (2000) Record of late Holocene debris avalanches and lahars at Iliamna Volcano, Alaska. *Journal of Volcanology and Geothermal Research* 104: 97-130

Winkler GR, MacKevett EM Jr., Plafker G, Richter DH, Rosenkrans DS, Schmoll HR (2000) A geologic guide to Wrangell-St. Elias National Park and Preserve, Alaska. USGS Professional Paper 1616, 166 pp.

Appendix A: Data Sources for Mapping

Park	FileID	Date	Long (center)	Lat (center)	Type
ANIA	unknown mosaic	between 08/17/2004 and 08/09/2007			
KLGO	s4_13605_5937_20100914	9/14/2010	-135.088738	59.612540	SPOT 4
KLGO	s4_13604_5937_20100919	9/19/2010	-136.061033	59.611450	SPOT 4
KLGO	po_669666_bgm_0000000	8/24/2011	-135.401844	59.572813	Ikonos
KLGO	po_669666_bgm_0000001	8/24/2011	-135.422325	59.399692	Ikonos
KLGO	po_669666_bgm_0000100	8/24/2011	-135.126148	59.583847	Ikonos
GAAR	20060825_452_0070001.tif	08/25/2006	-150.486999	67.342597	Ikonos
GAAR	20060826_792_0080000.tif	08/26/2006	-153.740005	68.330596	Ikonos
GAAR	20060826_792_0080001.tif	08/26/2006	-152.936996	68.305496	Ikonos
GAAR	20060826_792_0080002.tif	08/26/2006	-152.326995	68.393501	Ikonos
GAAR	20060826_806_0110000.tif	08/26/2006	-153.878997	66.927696	Ikonos
GAAR	20060828_926_0120000.tif	08/28/2006	-151.003005	67.423797	Ikonos
GAAR	20060828_926_0120001.tif	08/28/2006	-150.464996	67.424499	Ikonos
GAAR	20060831_920_0130000.tif	08/31/2006	-153.625000	67.546898	Ikonos
GAAR	20060831_920_0130001.tif	08/31/2006	-152.910995	67.546897	Ikonos
GAAR	20060831_920_0130002.tif	08/31/2006	-152.214996	67.543403	Ikonos
GAAR	20060902_610_0150000.tif	09/02/2006	-151.069000	67.196899	Ikonos
GAAR	20060902_610_0150001.tif	09/02/2006	-150.537994	67.194198	Ikonos
GAAR	20060902_612_0140000.tif	09/02/2006	-150.988998	67.257202	Ikonos
GAAR	20060902_612_0140001.tif	09/02/2006	-150.524002	67.253997	Ikonos
GAAR	20060903_148_0190000.tif	09/03/2006	-151.005004	67.344001	Ikonos
GAAR	20060903_148_0190001.tif	09/03/2006	-150.483993	67.344200	Ikonos
GAAR	20060903_158_0180000.tif	09/03/2006	-153.723007	67.460601	Ikonos
GAAR	20060903_158_0180001.tif	09/03/2006	-153.156997	67.460296	Ikonos
GAAR	20060903_159_0170000.tif	09/03/2006	-153.690994	67.379203	Ikonos
GAAR	20060903_159_0170001.tif	09/03/2006	-153.139007	67.370300	Ikonos
GAAR	20060925_755_0220000.tif	09/25/2006	-153.610000	68.258096	Ikonos
GAAR	20060925_755_0220001.tif	09/25/2006	-152.932006	68.255401	Ikonos
GAAR	20060925_755_0220002.tif	09/25/2006	-152.240005	68.256301	Ikonos
GAAR	20060928_806_0230000.tif	09/28/2006	-153.611999	68.176803	Ikonos
GAAR	20060928_806_0230001.tif	09/28/2006	-152.919006	68.179298	Ikonos
GAAR	20060928_806_0230002.tif	09/28/2006	-152.253005	68.178901	Ikonos
GAAR	20070702_411_0250000.tif	07/02/2007	-151.548004	68.166397	Ikonos
GAAR	20070702_407_0240003.tif	07/02/2007	-149.770996	68.262199	Ikonos
GAAR	20070702_407_0240002.tif	07/02/2007	-150.341995	68.264602	Ikonos
GAAR	20070702_407_0240001.tif	07/02/2007	-150.955001	68.264602	Ikonos
GAAR	20070702_407_0240000.tif	07/02/2007	-151.583999	68.262496	Ikonos
GAAR	20070702_393_0260002.tif	07/02/2007	-150.113006	68.082000	Ikonos
GAAR	20070702_393_0260001.tif	07/02/2007	-150.841995	68.084297	Ikonos
GAAR	20070702_393_0260000.tif	07/02/2007	-151.533996	68.083297	Ikonos
GAAR	20070925_430_0420000.tif	09/25/2007	-150.833999	67.056900	Ikonos
GAAR	20070925_429_0410001.tif	09/25/2007	-150.591995	67.150199	Ikonos
GAAR	20070925_429_0410000.tif	09/25/2007	-151.005004	67.150696	Ikonos
GAAR	20070920_973_0390000.tif	09/20/2007	-150.761993	68.333800	Ikonos
GAAR	20070920_959_0400001.tif	09/20/2007	-152.626998	68.359901	Ikonos
GAAR	20070920_959_0400000.tif	09/20/2007	-153.552993	68.360496	Ikonos
GAAR	20070920_958_0380001.tif	09/20/2007	-152.744995	68.428100	Ikonos
GAAR	20070920_958_0380000.tif	09/20/2007	-153.380996	68.428298	Ikonos
GAAR	20070810_695_0360000.tif	08/10/2007	-153.850997	67.102203	Ikonos
GAAR	20070810_694_0370000.tif	08/10/2007	-153.867996	67.020300	Ikonos
GAAR	20070809_489_0350000.tif	08/09/2007	-152.800003	68.621101	Ikonos
GAAR	20070809_488_0340001.tif	08/09/2007	-152.692993	68.528297	Ikonos
GAAR	20070809_488_0340000.tif	08/09/2007	-153.268005	68.528396	Ikonos
GAAR	20070809_484_0330001.tif	08/09/2007	-149.697006	68.356101	Ikonos
GAAR	20070809_484_0330000.tif	08/09/2007	-150.179992	68.356498	Ikonos
GAAR	20070723_218_0320000.tif	07/23/2007	-149.848007	68.423202	Ikonos
GAAR	20070708_458_0310000.tif	07/08/2007	-153.766998	67.183203	Ikonos
GAAR	20070707_088_0290002.tif	07/07/2007	-150.134002	67.612701	Ikonos
GAAR	20070707_088_0290001.tif	07/07/2007	-150.839996	67.614303	Ikonos
GAAR	20070707_088_0290000.tif	07/07/2007	-151.529006	67.611801	Ikonos
GAAR	20070707_087_0280002.tif	07/07/2007	-150.126007	67.681701	Ikonos
GAAR	20070707_087_0280001.tif	07/07/2007	-150.819000	67.684097	Ikonos
GAAR	20070707_087_0280000.tif	07/07/2007	-151.505004	67.685096	Ikonos
GAAR	20070707_085_0300002.tif	07/07/2007	-150.162994	67.531303	Ikonos
GAAR	20070707_085_0300001.tif	07/07/2007	-150.839996	67.532997	Ikonos
GAAR	20070707_085_0300000.tif	07/07/2007	-151.511993	67.531898	Ikonos
GAAR	20070705_595_0030001.tif	07/05/2007	-154.384994	68.357299	Ikonos
GAAR	20070705_595_0030000.tif	07/05/2007	-155.250000	68.356796	Ikonos
GAAR	20070705_592_0020001.tif	07/05/2007	-154.425003	68.060699	Ikonos
GAAR	20070705_592_0020000.tif	07/05/2007	-155.229003	68.061599	Ikonos
GAAR	20070705_578_0040000.tif	07/05/2007	-155.570999	67.027999	Ikonos
GAAR	20070704_068_0270002.tif	07/04/2007	-150.139007	67.881797	Ikonos
GAAR	20070704_068_0270001.tif	07/04/2007	-150.850006	67.883300	Ikonos
GAAR	20070704_068_0270000.tif	07/04/2007	-151.564992	67.881896	Ikonos
GAAR	20070702_411_0250002.tif	07/02/2007	-150.061004	68.164901	Ikonos
GAAR	20070702_411_0250001.tif	07/02/2007	-150.805999	68.168999	Ikonos
GAAR	20090713_093_0000000.tif	07/13/2009	-154.572006	67.770202	Ikonos
GAAR	20090817_860_0000000.tif	08/17/2009	-154.412002	66.993896	Ikonos
GAAR	20090817_861_0030000.tif	08/17/2009	-155.414993	66.674497	Ikonos
GAAR	20090817_861_0030001.tif	08/17/2009	-154.746994	66.674497	Ikonos
GAAR	20090817_862_0020000.tif	08/17/2009	-155.501998	66.831497	Ikonos
GAAR	20090817_862_0020001.tif	08/17/2009	-154.671005	66.832496	Ikonos
GAAR	20090817_863_0010000.tif	08/17/2009	-155.401992	66.682098	Ikonos
GAAR	20090817_863_0010001.tif	08/17/2009	-154.733993	66.681800	Ikonos
GAAR	20090825_066_0040002.tif	08/25/2009	-154.311004	66.915802	Ikonos
GAAR	20090828_616_0000000.tif	08/28/2009	-155.470001	66.918302	Ikonos
GAAR	20080914_012_0260001.tif	09/14/2008	-156.100399	67.475601	Ikonos
GAAR	20080914_012_0260000.tif	09/14/2008	-156.639999	67.475196	Ikonos
GAAR	20080914_010_0270002.tif	09/14/2008	-156.175994	67.565499	Ikonos
GAAR	20080914_010_0270001.tif	09/14/2008	-156.921005	67.565498	Ikonos
GAAR	20080914_009_0250002.tif	09/14/2008	-156.145004	67.663902	Ikonos
GAAR	20080914_009_0250001.tif	09/14/2008	-156.884994	67.665000	Ikonos
GAAR	20080913_744_0210001.tif	09/13/2008	-154.382003	68.164497	Ikonos
GAAR	20080913_744_0210000.tif	09/13/2008	-155.236999	68.164100	Ikonos
GAAR	20080913_743_0240001.tif	09/13/2008	-154.192001	67.094596	Ikonos
GAAR	20080913_743_0240000.tif	09/13/2008	-154.632996	67.093803	Ikonos
GAAR	20080913_737_0220001.tif	09/13/2008	-154.429992	67.961700	Ikonos
GAAR	20080913_737_0220000.tif	09/13/2008	-155.343002	67.961601	Ikonos
GAAR	20080913_735_0230001.tif	09/13/2008	-154.425994	67.866600	Ikonos
GAAR	20080913_735_0230000.tif	09/13/2008	-155.319000	67.865798	Ikonos

Park	FileID	Date	Long (center)	Lat (center)	Type
GAAR	20080911_124_0200002.tif	09/11/2008	-154.328002	67.283500	Ikonos
GAAR	20080911_124_0200001.tif	09/11/2008	-155.052001	67.285102	Ikonos
GAAR	20080911_124_0200000.tif	09/11/2008	-155.796005	67.283401	Ikonos
GAAR	20080910_888_0160002.tif	09/10/2008	-154.274002	67.578796	Ikonos
GAAR	20080910_888_0160001.tif	09/10/2008	-154.888000	67.579299	Ikonos
GAAR	20080910_888_0160000.tif	09/10/2008	-155.514007	67.577698	Ikonos
GAAR	20080910_887_0150002.tif	09/10/2008	-154.281997	67.674797	Ikonos
GAAR	20080910_887_0150001.tif	09/10/2008	-154.893005	67.674102	Ikonos
GAAR	20080910_887_0150000.tif	09/10/2008	-155.503005	67.674097	Ikonos
GAAR	20080908_382_0170001.tif	09/08/2008	-154.371002	68.256301	Ikonos
GAAR	20080908_382_0170000.tif	09/08/2008	-155.236999	68.256401	Ikonos
GAAR	20080908_369_0190002.tif	09/08/2008	-154.324996	67.278900	Ikonos
GAAR	20080908_369_0190001.tif	09/08/2008	-155.089996	67.280998	Ikonos
GAAR	20080908_369_0190000.tif	09/08/2008	-155.837997	67.279502	Ikonos
GAAR	20080908_368_0180002.tif	09/08/2008	-154.324996	67.347503	Ikonos
GAAR	20080908_368_0180001.tif	09/08/2008	-155.093994	67.349197	Ikonos
GAAR	20080908_368_0180000.tif	09/08/2008	-155.873001	67.347396	Ikonos
GAAR	20080906_923_0130002.tif	09/06/2008	-156.300997	67.764701	Ikonos
GAAR	20080906_923_0130001.tif	09/06/2008	-156.985992	67.763998	Ikonos
GAAR	20080906_922_0120002.tif	09/06/2008	-156.098007	67.856399	Ikonos
GAAR	20080906_922_0120001.tif	09/06/2008	-156.882003	67.857299	Ikonos
GAAR	20080902_963_0290002.tif	09/02/2008	-154.343994	67.392303	Ikonos
GAAR	20080902_963_0290001.tif	09/02/2008	-155.020996	67.393302	Ikonos
GAAR	20080902_963_0290000.tif	09/02/2008	-155.688003	67.391899	Ikonos
GAAR	20080902_959_0280002.tif	09/02/2008	-154.354003	67.487098	Ikonos
GAAR	20080902_959_0280001.tif	09/02/2008	-155.027999	67.487701	Ikonos
GAAR	20080902_959_0280000.tif	09/02/2008	-155.707992	67.485702	Ikonos
GAAR	20080825_690_0510000.tif	08/25/2008	-153.647994	67.283096	Ikonos
GAAR	20080825_688_0490002.tif	08/25/2008	-152.266006	67.911796	Ikonos
GAAR	20080825_688_0490001.tif	08/25/2008	-152.953002	67.913200	Ikonos
GAAR	20080825_688_0490000.tif	08/25/2008	-153.662002	67.911903	Ikonos
GAAR	20080825_687_0500002.tif	08/25/2008	-152.274002	67.834297	Ikonos
GAAR	20080825_687_0500001.tif	08/25/2008	-152.975997	67.835700	Ikonos
GAAR	20080825_687_0500000.tif	08/25/2008	-153.667999	67.835296	Ikonos
GAAR	20080822_404_0480002.tif	08/22/2008	-150.106994	67.790000	Ikonos
GAAR	20080822_404_0480001.tif	08/22/2008	-150.820999	67.791999	Ikonos
GAAR	20080822_404_0480000.tif	08/22/2008	-151.554992	67.791000	Ikonos
GAAR	20080820_739_0470002.tif	08/20/2008	-152.218994	67.652999	Ikonos
GAAR	20080820_739_0470001.tif	08/20/2008	-152.932006	67.654800	Ikonos
GAAR	20080820_739_0470000.tif	08/20/2008	-153.658996	67.653503	Ikonos
GAAR	20080820_738_0460002.tif	08/20/2008	-152.233001	67.748901	Ikonos
GAAR	20080820_738_0460001.tif	08/20/2008	-152.964996	67.750000	Ikonos
GAAR	20080820_738_0460000.tif	08/20/2008	-153.658996	67.748497	Ikonos
GAAR	20080819_569_0430002.tif	08/19/2008	-150.119995	67.972099	Ikonos
GAAR	20080819_569_0430001.tif	08/19/2008	-150.832992	67.973800	Ikonos
GAAR	20080819_569_0430000.tif	08/19/2008	-151.559997	67.972702	Ikonos
GAAR	20080819_563_0440002.tif	08/19/2008	-152.257995	67.969299	Ikonos
GAAR	20080819_563_0440001.tif	08/19/2008	-152.962005	67.970896	Ikonos
GAAR	20080819_563_0440000.tif	08/19/2008	-153.666000	67.969100	Ikonos
GAAR	20080819_562_0450002.tif	08/19/2008	-152.236992	68.069000	Ikonos
GAAR	20080819_562_0450001.tif	08/19/2008	-152.947998	68.070602	Ikonos
GAAR	20080819_562_0450000.tif	08/19/2008	-153.673995	68.069198	Ikonos
GAAR	20080808_696_0070000.tif	08/08/2008	-154.408996	67.187599	Ikonos
GAAR	20080809_177_0100001.tif	08/09/2008	-156.888000	67.946701	Ikonos
GAAR	20080809_177_0100002.tif	08/09/2008	-156.119003	67.944198	Ikonos
GAAR	20080809_178_0090002.tif	08/09/2008	-156.123001	68.039802	Ikonos
GAAR	20080814_838_0110000.tif	08/14/2008	-155.676994	67.766098	Ikonos
GAAR	20080814_838_0110001.tif	08/14/2008	-155.212997	67.765403	Ikonos

Park	FileID	Pub Year	Photo Year	Revisions	Type
ANIA	SOTWIK ISLAND D-5	1963	1960		USGS 1:63360
ANIA	UGASHIK A-5	1963	1962	1981	USGS 1:63360
ANIA	CHIGNIK D-1	1963	1960		USGS 1:63360
GAAR	KILLIK RIVER B-3	1986	1973		USGS 1:63360
GAAR	CHANDLER LAKE A-4	1986	1973		USGS 1:63360
GAAR	CHANDLER LAKE A-5	1986	1973		USGS 1:63360
GAAR	SURVEY PASS B-3	1990	1979		USGS 1:63360
GAAR	SURVEY PASS C-6	1990	1979		USGS 1:63360
GAAR	KILLIK RIVER A-2	1986	1973		USGS 1:63360
GAAR	CHANDLER LAKE B-2	1971	1970		USGS 1:63360
GAAR	CHANDLER LAKE A-2	1971	1970		USGS 1:63360
GAAR	CHANDLER LAKE A-1	1971	1970		USGS 1:63360
GAAR	SURVEY PASS B-4	1990	1979		USGS 1:63360
GAAR	PHILIP SMITH MTNS A-5	1971	1970	1975	USGS 1:63360
GAAR	SURVEY PASS D-4	1986	1973		USGS 1:63360
GAAR	WISEMAN D-1	1971	1970		USGS 1:63360
GAAR	SURVEY PASS B-6	1990	1979		USGS 1:63360
GAAR	SURVEY PASS C-5	1990	1979		USGS 1:63360
GAAR	CHANDLER LAKE B-1	1971	1970		USGS 1:63360
GAAR	CHANDLER LAKE A-3	1971	1970	1984	USGS 1:63360
GAAR	KILLIK RIVER A-3	1986	1973		USGS 1:63360
GAAR	PHILIP SMITH MTNS B-5	1971	1970	1975	USGS 1:63360
GAAR	WISEMAN D-2	1971	1970		USGS 1:63360
GAAR	SURVEY PASS B-5	1990	1979		USGS 1:63360
GAAR	KILLIK RIVER B-1	1986	1973		USGS 1:63360
GAAR	SURVEY PASS D-2	1986	1973		USGS 1:63360
KLGO	HOMAN LAKE	2012	1987		GOVT of CA 1:50000
KLGO	ROTHWELL PEAK	2012	1987		GOVT of CA 1:50000
KLGO	SKAGWAY C-2	1948	1948	1973	USGS 1:63360
KLGO	SKAGWAY C-3	1954	1948	1963	USGS 1:63360
KLGO	SKAGWAY D-2	1949	1948		USGS 1:63360
KLGO	SKAGWAY C-4	1954	1948	1963	USGS 1:63360
KLGO	SKAGWAY B-3	1954	1948	1963	USGS 1:63360
KLGO	SKAGWAY C-1	1948	1948	1966	USGS 1:63360
KLGO	SKAGWAY B-2	1954	1948	1977	USGS 1:63360
KLGO	SKAGWAY B-4	1954	1948	1972	USGS 1:63360

Appendix B: Data Products Exported From Extent Mapping

OBJECTID	ID	Name	Code	Date_	Latitude	Longitude	Area	Volume	Elev_Min	Elev_Max	Median	Mean	B0	B50	B100	B150	B200	B250	B300	B350	B400	B450	B500	B550
1	G135301W59699N		0	20100914	59.699537	-135.30172	1.436	0.33799	1183	1753	1402	1454	0	0	0	0	0	0	0	0	0	0	0	0
2	G135297W59693N		0	20100914	59.693573	-135.29711	0.392	0.0567	1362	1791	1685	1629	0	0	0	0	0	0	0	0	0	0	0	0
3	G135313W59673N		0	20110826	59.673788	-135.313434	3.318	1.0691	1127	1849	1548	1526	0	0	0	0	0	0	0	0	0	0	0	0
4	G135345W59659N	Saussure Glacier	0	20110826	59.659415	-135.345909	2.914	0.8943	1147	1732	1593	1548	0	0	0	0	0	0	0	0	0	0	0	0
5	G135364W59657N		0	20110826	59.657427	-135.364276	0.204	0.0231	1345	1632	1498	1512	0	0	0	0	0	0	0	0	0	0	0	0
6	G135362W59665N		0	20110826	59.665528	-135.362217	0.026	0.00136	1778	1822	1800	1800	0	0	0	0	0	0	0	0	0	0	0	0
7	G135387W59667N		0	20110826	59.667703	-135.387324	0.002	4E-05	1297	1297	1297	1297	0	0	0	0	0	0	0	0	0	0	0	0
8	G135389W59669N		0	20100914	59.669004	-135.389808	0.002	4E-05	1195	1195	1195	1195	0	0	0	0	0	0	0	0	0	0	0	0
9	G135380W59669N		0	20110826	59.668097	-135.380815	0.153	0.01555	1314	1638	1446	1457	0	0	0	0	0	0	0	0	0	0	0	0
10	G135353W59677N		0	20110826	59.677261	-135.353489	4.286	1.52014	892	1802	1463	1456	0	0	0	0	0	0	0	0	0	0	0	0
11	G135365W59684N		0	20110826	59.684847	-135.365607	0.158	0.01625	1307	1454	1383	1383	0	0	0	0	0	0	0	0	0	0	0	0
12	G135328W59693N		0	20100914	59.693048	-135.328286	2.874	0.87747	1182	1689	1488	1466	0	0	0	0	0	0	0	0	0	0	0	0
13	G135408W59463N		0	20110826	59.463169	-135.40805	0.037	0.00221	1324	1463	1406	1397	0	0	0	0	0	0	0	0	0	0	0	0
14	G135191W59695N		0	20100914	59.695909	-135.19166	0.892	0.17562	1459	1836	1705	1682	0	0	0	0	0	0	0	0	0	0	0	0
15	G135227W59676N		0	20110826	59.676496	-135.227473	1.363	0.31459	1280	1669	1475	1478	0	0	0	0	0	0	0	0	0	0	0	0
16	G135214W59695N		0	20100914	59.695619	-135.214304	0.551	0.09055	1198	1746	1479	1498	0	0	0	0	0	0	0	0	0	0	0	0
17	G135422W59477N		0	20110826	59.477275	-135.422506	0.264	0.03292	1286	1696	1483	1495	0	0	0	0	0	0	0	0	0	0	0	0
18	G135434W59487N		0	20110826	59.487549	-135.434088	0.749	0.13811	1233	1608	1420	1433	0	0	0	0	0	0	0	0	0	0	0	0
19	G135447W59482N		0	20110826	59.482899	-135.447621	0.705	0.12708	1231	1580	1396	1398	0	0	0	0	0	0	0	0	0	0	0	0
20	G135395W59557N		0	20110826	59.557001	-135.395253	0.13	0.01243	1266	1631	1514	1476	0	0	0	0	0	0	0	0	0	0	0	0
21	G135174W59718N		0	20100914	59.718421	-135.174589	0.221	0.02578	1265	1524	1394	1402	0	0	0	0	0	0	0	0	0	0	0	0
22	G135269W59550N		0	20110826	59.550109	-135.269288	0.283	0.03623	1570	1813	1674	1678	0	0	0	0	0	0	0	0	0	0	0	0
23	G135243W59584N		0	20110826	59.584284	-135.243043	0.247	0.03004	1426	1750	1646	1633	0	0	0	0	0	0	0	0	0	0	0	0
24	G135236W59578N		0	20110826	59.57821	-135.236462	0.506	0.08054	1541	1869	1724	1732	0	0	0	0	0	0	0	0	0	0	0	0
25	G135256W59554N		0	20110826	59.554675	-135.256277	0.01	0.00037	1816	1879	1834	1841	0	0	0	0	0	0	0	0	0	0	0	0
26	G135250W59554N		0	20110826	59.554075	-135.250368	0.038	0.00229	1531	1850	1702	1691	0	0	0	0	0	0	0	0	0	0	0	0
27	G135252W59558N		0	20110826	59.558682	-135.252988	0.488	0.07663	1599	1960	1768	1772	0	0	0	0	0	0	0	0	0	0	0	0
28	G135270W59544N		0	20110826	59.544076	-135.270847	0.007	0.00022	1629	1659	1629	1639	0	0	0	0	0	0	0	0	0	0	0	0
29	G135280W59544N		0	20110826	59.544006	-135.280058	0.175	0.01871	1280	1644	1437	1448	0	0	0	0	0	0	0	0	0	0	0	0
30	G135274W59558N		0	20110826	59.558634	-135.274298	0.991	0.20296	1387	1889	1615	1617	0	0	0	0	0	0	0	0	0	0	0	0
31	G135267W59568N		0	20110826	59.568611	-135.267223	0.631	0.10911	1327	1969	1628	1638	0	0	0	0	0	0	0	0	0	0	0	0
32	G135254W59573N		0	20110826	59.573886	-135.254609	1.773	0.45163	1159	1963	1680	1631	0	0	0	0	0	0	0	0	0	0	0	0
33	G135255W59583N		0	20110826	59.583746	-135.255556	0.112	0.01013	1500	1673	1600	1597	0	0	0	0	0	0	0	0	0	0	0	0
34	G135256W59589N		0	20110826	59.588935	-135.256269	0.113	0.01025	1323	1532	1403	1403	0	0	0	0	0	0	0	0	0	0	0	0
35	G135254W59593N		0	20110826	59.593837	-135.25488	0.08	0.00638	1216	1442	1281	1302	0	0	0	0	0	0	0	0	0	0	0	0
36	G135244W59591N		0	20110826	59.59195	-135.244258	0.014	0.00058	1553	1634	1600	1597	0	0	0	0	0	0	0	0	0	0	0	0
37	G135242W59594N		0	20110826	59.59443	-135.24227	0.039	0.00237	1459	1552	1514	1510	0	0	0	0	0	0	0	0	0	0	0	0
38	G135308W59736N		0	20100914	59.736347	-135.308602	1.513	0.36315	1488	1694	1667	1649	0	0	0	0	0	0	0	0	0	0	0	0
39	G135327W59724N		0	20100914	59.72424	-135.327271	6.634	2.77174	1262	1992	1658	1654	0	0	0	0	0	0	0	0	0	0	0	0
40	G135361W59719N		0	20100914	59.719123	-135.361211	0.782	0.14655	1727	1988	1912	1892	0	0	0	0	0	0	0	0	0	0	0	0
41	G135373W59716N		0	20100914	59.716585	-135.373316	0.167	0.01754	1755	1976	1906	1889	0	0	0	0	0	0	0	0	0	0	0	0
42	G135380W59715N		0	20100914	59.715639	-135.380363	0.179	0.0193	1793	2038	1908	1913	0	0	0	0	0	0	0	0	0	0	0	0
43	G135389W59717N		0	20100914	59.717895	-135.389867	0.354	0.04928	1424	1778	1660	1649	0	0	0	0	0	0	0	0	0	0	0	0
44	G135377W59731N		0	20100914	59.731844	-135.377819	3.667	1.2767	1216	2089	1788	1750	0	0	0	0	0	0	0	0	0	0	0	0
45	G135354W59748N		0	20100914	59.748293	-135.35425	4.442	1.59673	1228	2071	1548	1582	0	0	0	0	0	0	0	0	0	0	0	0
46	G135353W59766N		0	20100914	59.766454	-135.353114	0.418	0.06193	1448	1883	1635	1639	0	0	0	0	0	0	0	0	0	0	0	0
47	G135231W59601N		0	20110826	59.601913	-135.23181	0.019	0.00088	1649	1771	1730	1722	0	0	0	0	0	0	0	0	0	0	0	0
48	G135259W59613N		0	20110826	59.613681	-135.259147	0.077	0.00605	1610	1830	1711	1710	0	0	0	0	0	0	0	0	0	0	0	0
49	G135239W59613N		0	20110826	59.613605	-135.239363	1.212	0.26769	1141	1810	1496	1476	0	0	0	0	0	0	0	0	0	0	0	0
50	G135427W59794N		0	20100914	59.794289	-135.427589	3.755	1.26736	1064	1985	1203	1319	0	0	0	0	0	0	0	0	0	0	0	0
51	G135482W59585N		0	20110826	59.585448	-135.482601	0.18	0.01945	1249	1639	1482	1481	0	0	0	0	0	0	0	0	0	0	0	0
52	G135625W59584N		0	20100914	59.584679	-135.625111	0.07	0.00531	1116	1354	1264	1242	0	0	0	0	0	0	0	0	0	0	0	0
53	G135536W59609N		0	20110826	59.608183	-135.536501	8.691	4.01821	417	2266	1641	1517	0	0	0	0	0	0	0	0	93657	64389	64389	46829
54	G135576W59565N		0	20100914	59.565246	-135.576691	0.18	0.01945	1226	1449	1341	1336	0	0	0	0	0	0	0	0	0	0	0	0
55	G135494W59599N		0	20110826	59.599986	-135.494148	0.137	0.01336	1514	1805	1642	1646	0	0	0	0	0	0	0	0	0	0	0	0
56	G135535W59775N		0	20100914	59.775764	-135.535881	26.92	19.018	735	2323	1736	1682	0	0	0	0	0	0	0	0	0	0	0	0
57	G135490W59803N		0	20100914	59.803534	-135.490677	0.921	0.18351	1512	2025	1728	1748	0	0	0	0	0	0	0	0	0	0	0	0
58	G135557W59793N		0	20100914	59.793051	-135.557787	14.83	8.38092	1414	2288	1980	1861	0	0	0	0	0	0	0	0	0	0	0	0
59	G135432W59804N		0	20100914	59.804496	-135.432777	0.244	0.02954	1218	1400	1297	1295	0	0	0	0	0	0	0	0	0	0	0	0
60	G135461W59806N		0	20100914	59.806251	-135.461952	4.341	1.54703	1221	2107	1722	1679	0	0	0	0	0	0	0	0	0	0	0	0
61	G135462W59775N		0	20100914	59.775729	-135.46221	2.309	0.64941	1254	1602	1492	1484	0	0	0	0	0	0	0	0	0	0	0	0
62	G135454W59728N		0	20100914	59.728363	-135.454447	0.012	0.00047	1299	1403	1363	1350	0	0	0	0	0	0	0	0	0	0	0	0
63	G135455W59707N		0	20100914	59.707159	-135.455428	0.905	0.17914	1270	2001	1653	1655	0	0	0	0	0	0	0	0	0	0	0	0
64	G135438W59702N		0	20100914	59.702317	-135.438183	0.005	0.00014	1190	1229	1210	1210	0	0	0	0	0	0	0	0	0	0	0	0
65	G135449W59695N		0	20100914	59.69574	-135.449835	0.342	0.047	1307	1584	1458	1463	0	0	0	0	0	0	0	0	0	0	0	0
66	G135461W59665N		0	20100914	59.665906	-135.46167	0.149	0.01499	1423	1766	1555	1572	0	0	0	0	0	0	0	0	0	0	0	0
67	G135464W59668N		0	20100914	59.668596	-135.464419	0.032	0.00181	1452	1641	1570	1565	0	0	0	0	0	0	0	0	0	0	0	0
68	G135497W59682N		0	20100914	59.682628	-135.497049	15.77	9.11337	391	2509	1744	1586	0	0	0	0	0	0	0	5854	122925	178534	201948	166827
69	G135505W59657N		0	20100914	59.657496	-135.505284	0.185	0.02019	1427	1944	1690	1693	0	0	0	0	0	0	0	0	0	0	0	0
70	G135513W59647N		0	20100914	59.647595	-135.513486	6.983	2.9742	698	2197	1556	1467	0	0	0	0	0	0	0	0	0	0	0	0
71	G135483W59618N		0	20100914	59.618594	-135.483248	8.397	3.8325	645	2071	967	1053	0	0	0	0	0	0	0	0	0	0	0	0
72	G135422W59623N		0	20100914	59.623728	-135.422807	0.212	0.02435	1232	1565	1467	1447	0	0	0	0	0	0	0	0	0	0	0	0
73	G135416W59617N		0	20100914	59.617626	-135.416679	0.513	0.08208	1093	1542	1405	1375	0	0	0	0	0	0	0	0	0	0	0	0
74	G135442W59609N		0	20100914	59.609582	-135.442944	0.27	0.03396	1343	1552	1468	1468	0	0	0	0	0	0	0	0	0	0	0	0
75	G135437W59590N		0	20110826	59.590055	-135.437006	4.699	1.72512	640	1851	1354	1335	0	0	0	0	0	0	0	0	0	0	0	0
76	G135407W59575N	Irene Glacier	0	20110826	59.575266	-135.407562	2.737	0.82047	806	1700	1520	1477	0	0	0	0	0	0	0	0	0	0	0	0
77	G135405W59563N		0	20110826	59.563298	-135.405855	1.092	0.23194	1101	1701	1554	1509	0	0	0	0	0	0	0	0	0	0	0	0
78	G135432W59570N		0	20110826	59.570791	-135.432879	1.286	0.29041	1137	1788	1581	1567	0	0	0	0	0	0	0	0	0	0	0	0
79	G135460W59577N		0	20110826	59.577328	-135.460353	2.407	0.68761	1094	1615	1318	1337	0	0	0	0	0	0	0	0	0	0	0	0
80	G135484W59579N		0	20110826	59.579017	-135.484665	0.097	0.00831	1294	1549	1467	1462	0	0	0	0	0	0	0	0	0	0	0	0
81	G135532W59589N		0	20110826	59.588656	-135.532301	0.083	0.00671	1450	1658	1575	1568	0	0	0	0	0	0	0	0	0	0	0	0
82	G135553W59599N		0	20110826	59.599944	-135.5533	1.705	0.42799	1173	2043	1577	1599	0	0	0	0	0	0	0	0	0	0	0	0
83	G135583W59599N		0	20110826	59.599052	-135.583055	4.701	1.72613	648	2247	976	1230	0	0	0	0	0	0	0	0	0	0	0	0
84	G135550W59534N		0	20110826	59.534175	-135.550558	1.849	0.47846	752	1636	1247	1213	0	0	0	0	0	0	0	0	0	0	0	0
85	G135553W59546N		0	20110826	59.546461	-135.553047	0.317	0.04234	1300	1786	1540	1522	0	0	0	0	0	0	0	0	0	0	0	0
86	G135568W59552N		0	20110826	59.552407	-135.568966	0.484	0.07577	1128	1769	1365	1375	0	0	0	0	0	0	0	0	0	0	0	0
87	G135564W59564N		0	20110826	59.564644	-135.564088	0.081	0.00649	1269	1529	1396	1400	0	0	0	0	0	0	0	0	0	0	0	0
88	G135541W59553N		0	20110826	59.553693	-135.541277	3.437	1.12217	973	1914	1372	1388	0	0	0	0	0	0	0	0	0	0	0	0
89	G135515W59537N		0	20110826	59.537169	-135.515108	2.615	0.77061	695	1888	1391	1380	0	0	0	0	0	0	0	0	0	0	0	0
90	G135490W59536N		0	20110826	59.536221	-135.490688	0.177	0.019	1278	1434	1383	1379	0	0	0	0	0	0	0	0	0	0	0	0
91	G135496W59532N		0	20110826	59.532227	-135.496904	0.104	0.00915	1287	1571	1427	1427	0	0	0	0	0	0	0	0	0	0	0	0
92	G135502W59483N		0	20110826	59.48306	-135.502824	0.19	0.02095	1164	1379	1310	1292	0	0	0	0	0	0	0	0	0	0	0	0
93	G135499W59493N		0	20110826	59.493415	-135.499363	1.072	0.22612	999	1620	1323	1321	0	0	0	0	0	0	0	0	0	0	0	0
94	G135497W59511N		0	20110826	59.511793	-135.49741	4.828	1.79057	1138	1787	1403	1435	0	0	0	0	0	0	0	0	0	0	0	0
95	G135612W59543N	Ferebee Glacier	200	20100914	59.543287	-135.612833	37.7	30.2224	341	2238	1224	1174	0	0	0	0	0	0	49755	269264	743404	872182	687795	1381443

Appendix C: Close-up Maps of Glacier Extent Changes

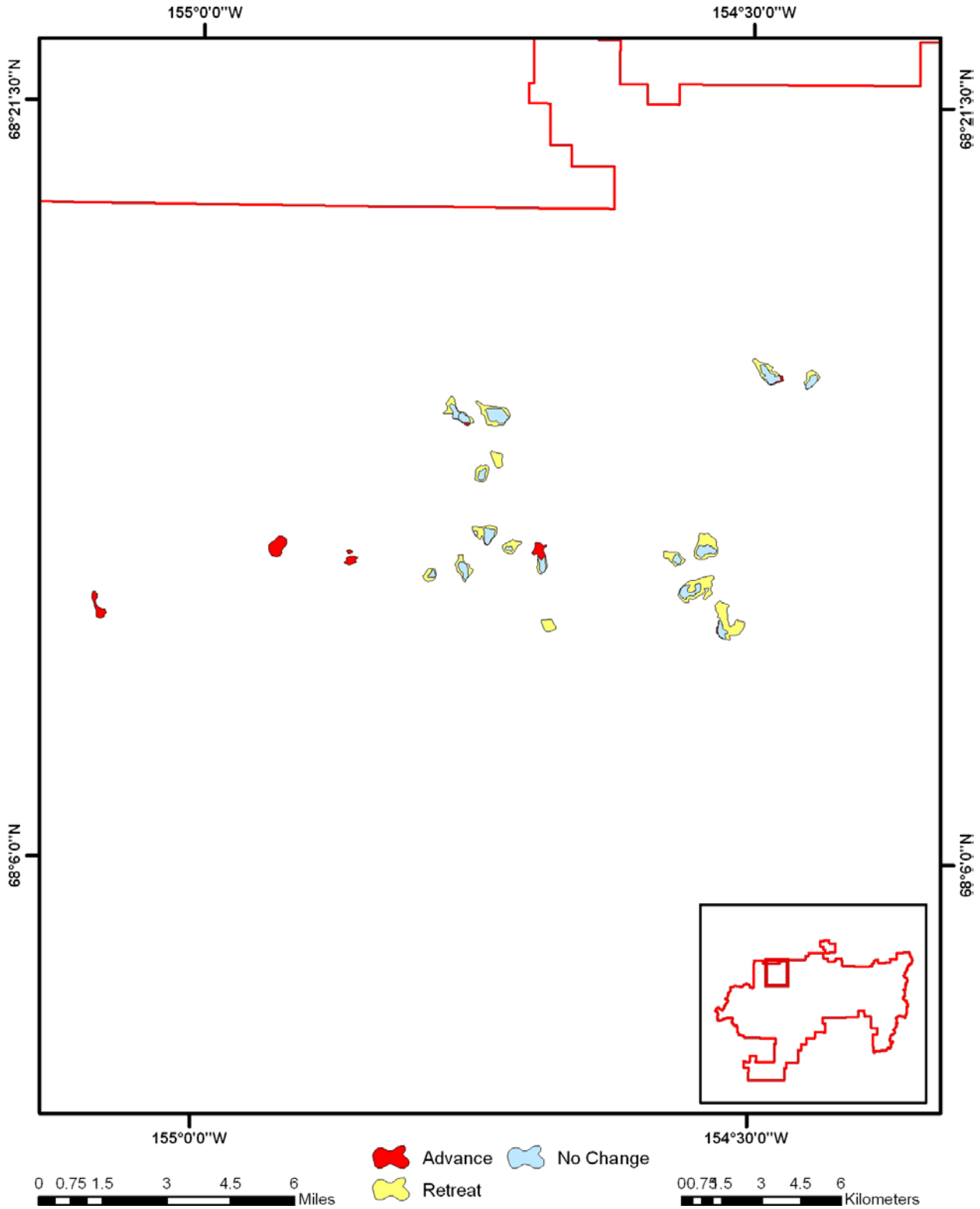


Figure C1. Close-up of northwestern Gates of the Arctic glaciers.

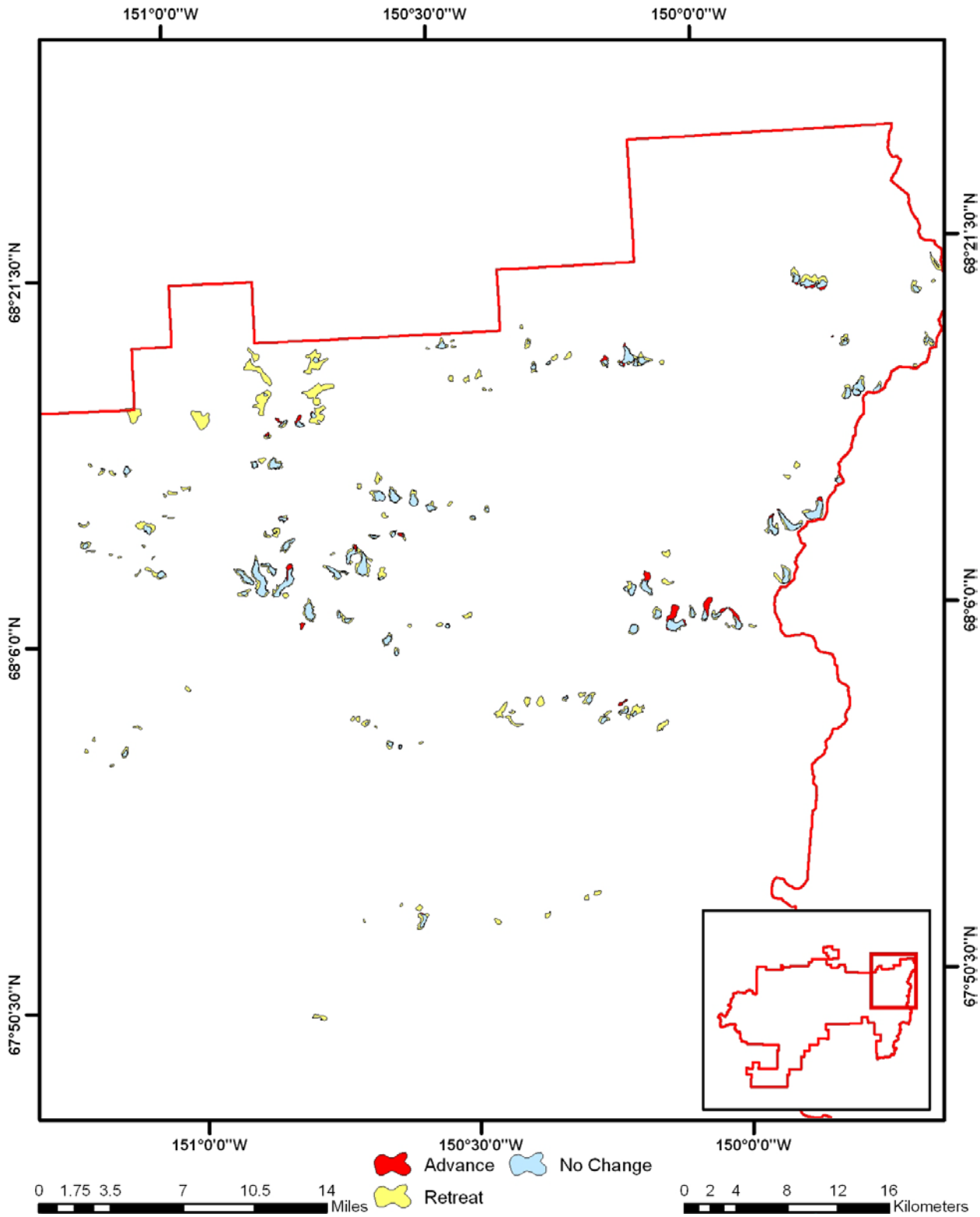


Figure C2. Close-up of NE Gates of the Arctic glaciers.

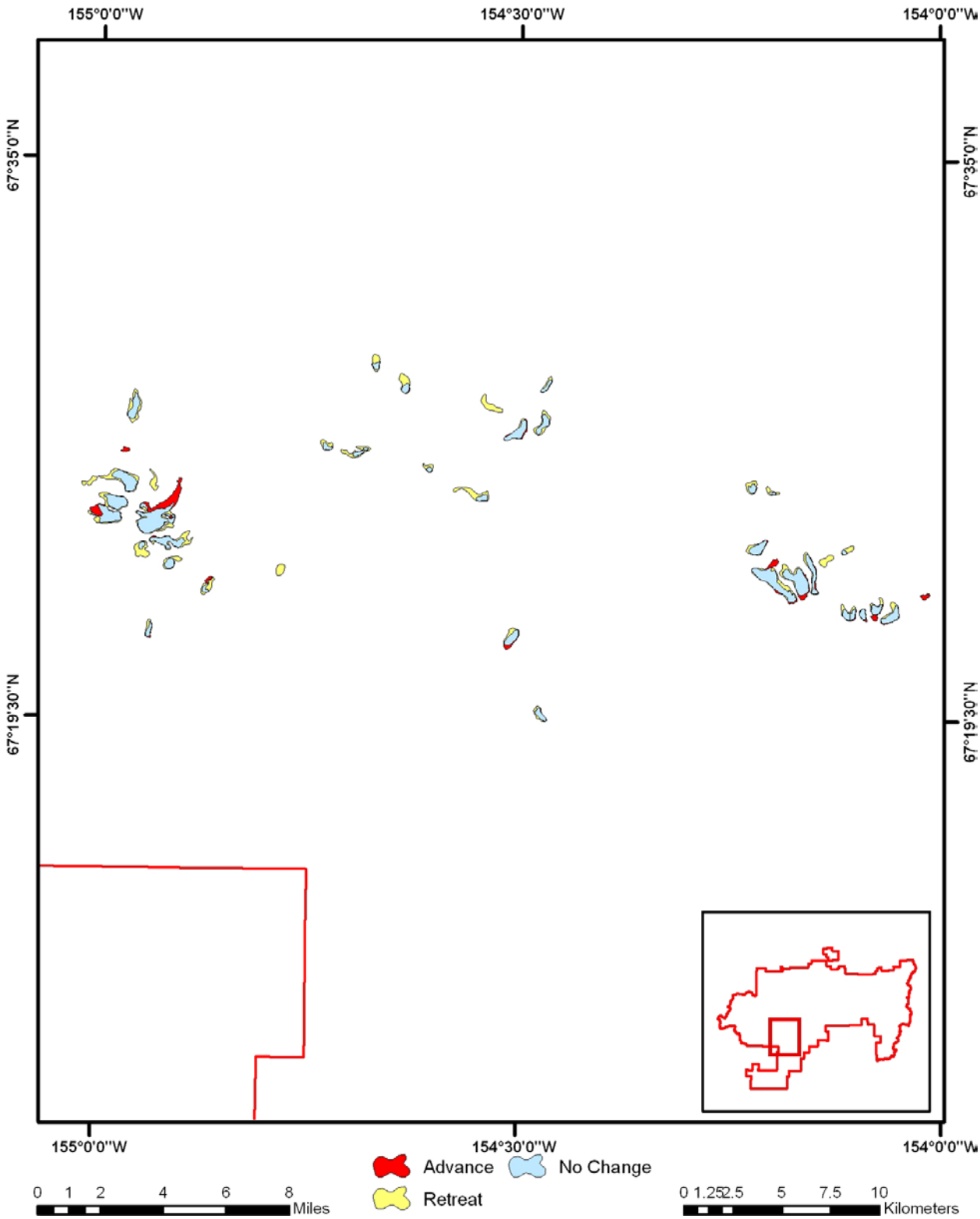


Figure C3. Close-up of southwestern Gates of the Arctic glaciers.

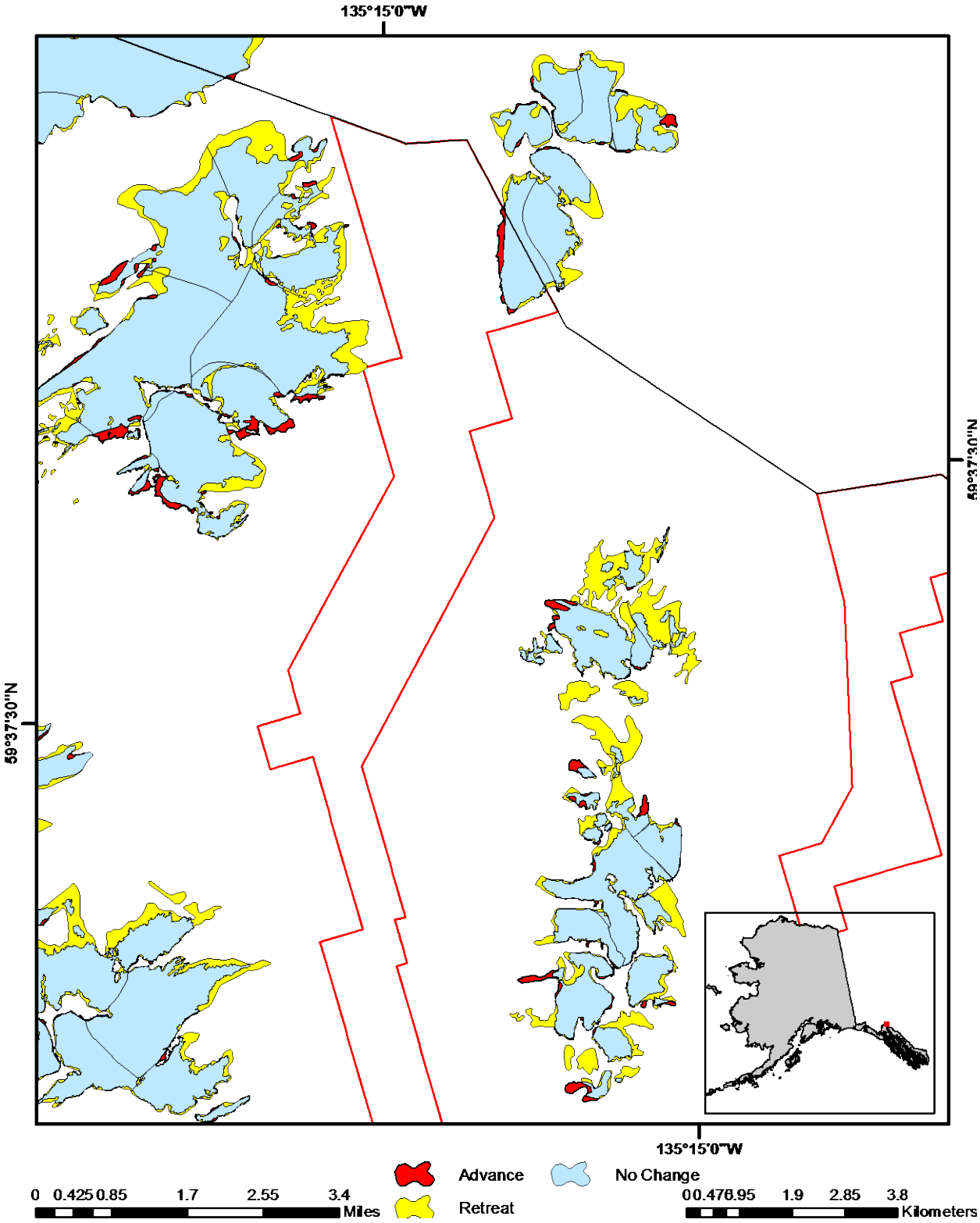


Figure C4. Close-up of northern Klondike Gold Rush glaciers.

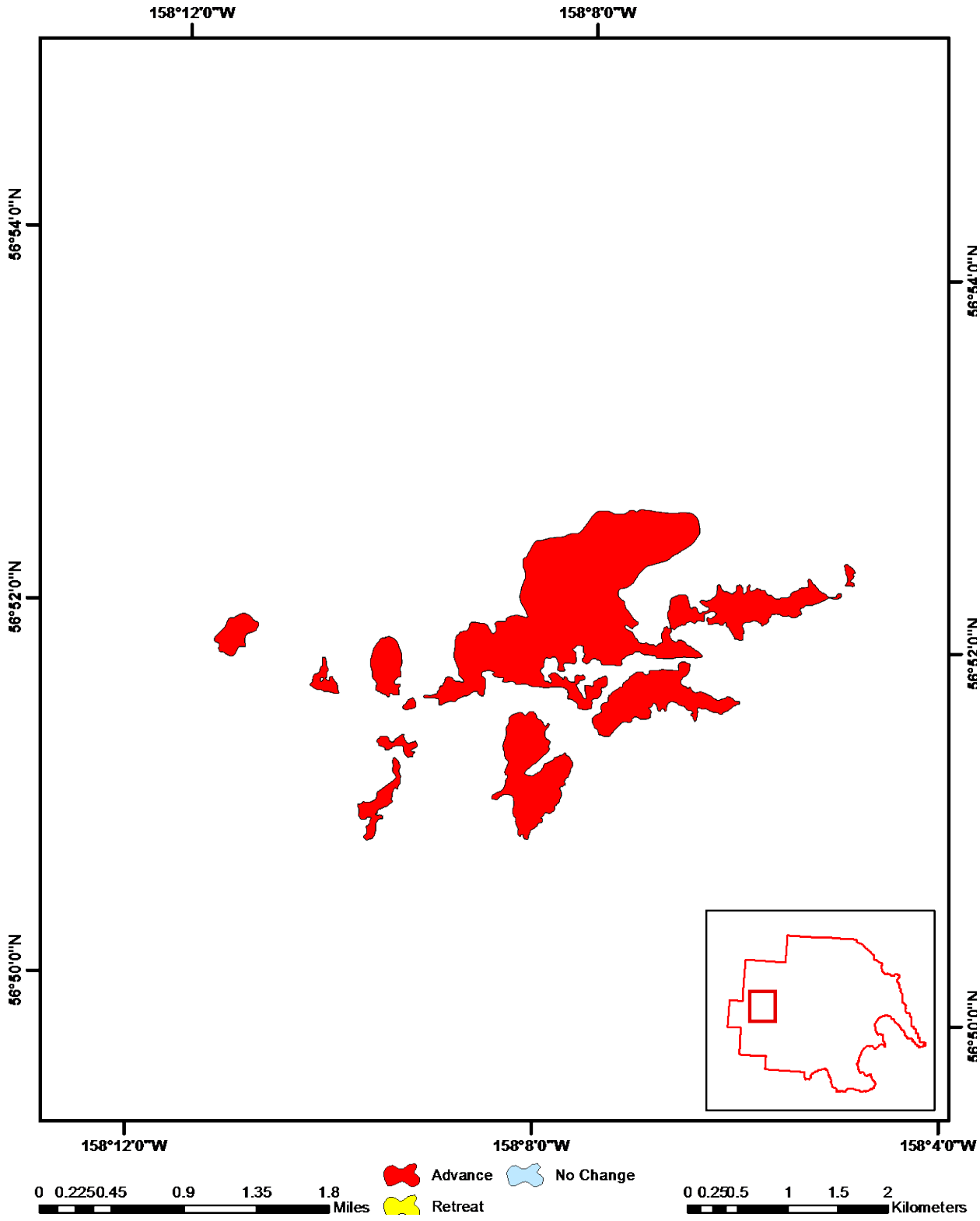


Figure C5. Close-up of western Aniakchak glaciers.

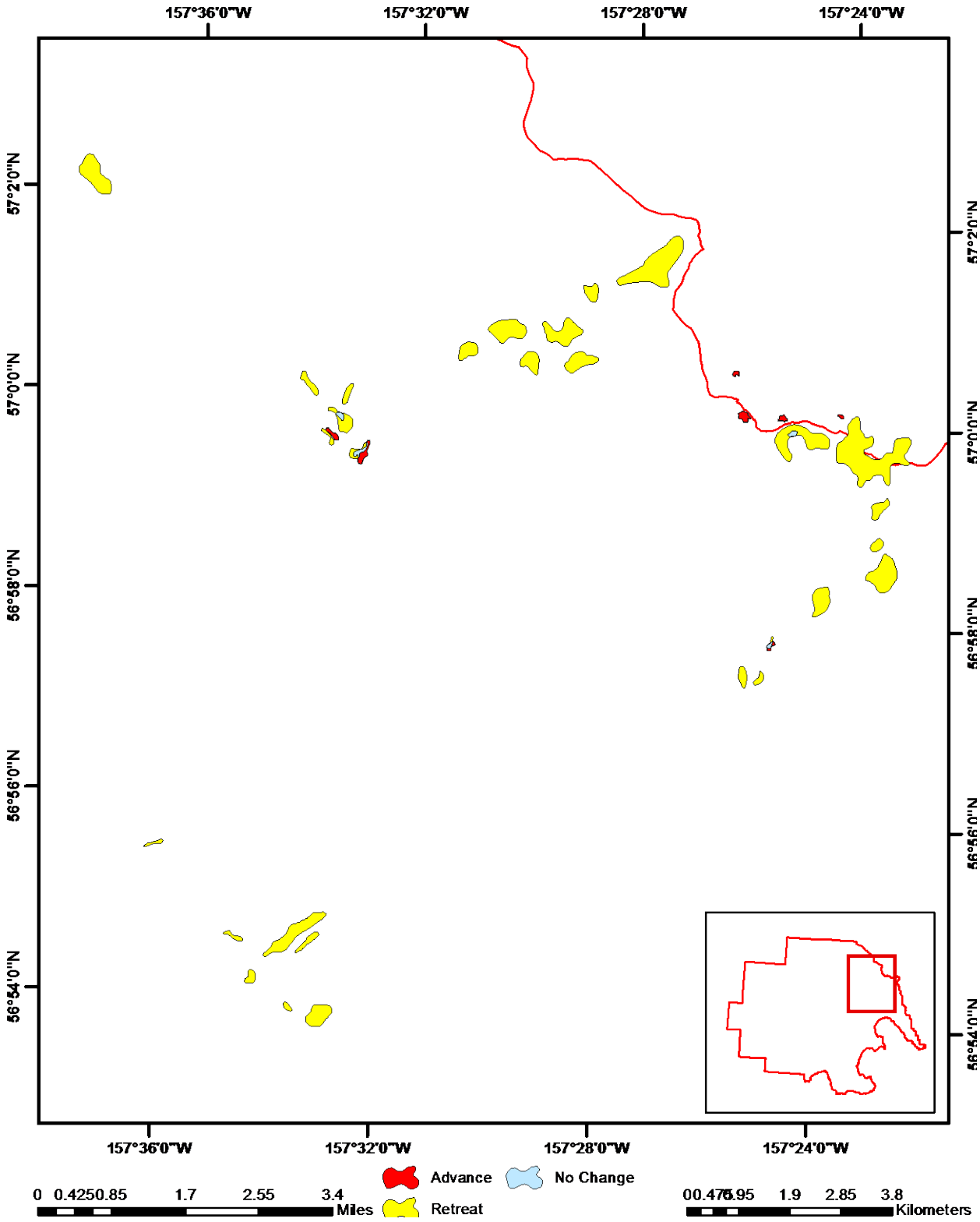


Figure C6. Close-up of eastern Aniakchak glaciers.

Appendix D: Elevation and Volume Change Analyses

Narrative summaries of elevation changes for individual glaciers during discrete time intervals are followed by plots of all summarized data.

Kahiltna Glacier (1994, 2008, 2010)

1994 – 2008: Overall good coverage for a laser profiler to laser profiler comparison. The data show a generally consistent story with more negative change lower on the glacier. The Kahiltna extends up to elevations of ~4700 m and so we miss about 47 sq. km of the glacier. However, the missed areas are all the highest elevations (typically the cirques, etc. at the head of the glacier) and likely have little consequence for the overall values. The mass balance and change estimates are based on the measured area only (the elevation range included in the plot).

1994 – 2010: Excellent data coverage and spread. This is a laser profiler to scanning LiDAR comparison. It's a fall to spring comparison, but covers a period of 16 years, which should reduce the impact of the snow effect. We don't include any corrections for the difference in seasons for these cases, preferring instead to present the data as is.

2008 – 2010: About 50% greater loss rate compared to the 1994 – 2010 comparison, so it's likely that wastage rates are increasing. Joanna Young (Anthony Arendt's master's student who is working on Kahiltna) believes they've seen a kinematic wave moving through the toe of the glacier. The positive elevation change < 500 m may reflect passage of this wave.

Muldrow (and Traleika) Glacier (1994, 2001, 2008, 2010) Traleika (2001, 2008, 2010)

Brief summary of Muldrow: Muldrow is a long-period surging glacier and last surged over 1956 – 57 (documented by Post, 1960). The elevation changes we're seeing here are consistent with typical elevation changes during the quiescent phase of a surging glacier and increasing wastage over the years—especially noticeable in the last 5-10 years. The upper Muldrow (above the Traleika confluence) and Traleika glaciers have maintained an overall positive mass change for all periods measured, but this positive mass change is typically overwhelmed by the negative mass change in the lower Muldrow. However, the total mass change stays close to zero, which is typical for a surging glacier in a quiescent phase. Long story short, the elevation changes we're seeing are only partially influenced by climate due to the surging nature of Muldrow.

1994 – 2001: Data coverage is pretty sparse and the large medial moraines on Muldrow (especially lower Muldrow) hurt the precision of the difference measurements by creating large spreads in the DZ data at a given elevation (example at about ~1350 m in this plot). The old profiler system, with its single point measurements, was vulnerable to these types of topography effects. Despite the sparse data and medial moraine complication, the elevation changes tell a fairly consistent story of elevation loss at lower elevations and gains at high elevations.

1994 – 2010: The scanning LiDAR data tend to appear worse since the LiDAR provides matching points with every profiler point and creates an even more pronounced vertical spread. Since the medial moraines are larger and more common on the lower Muldrow, the vertical spreads are more pronounced < ~1700 m. However, the data do show enough clumping of

elevation changes that we're fairly confident with the modeled line (red line). On the upper Muldrow (> ~1700 m) the elevation changes show variation between +2 m/yr to slightly negative values (max of -1 m/yr at ~2800 m), but overall the upper Muldrow shows relatively smaller elevation changes compared to the lower Muldrow.

The Traleika was not flown in 1994 and so there are no profiles previous to 2001 for the Traleika. Also, since the 2001 – 2008 and 2001 – 2010 profiles are so similar we only the 2001 – 2010 and 2008 – 2010 profiles.

2001 – 2010: Overall a similar story to the 1994 – 2010 plot. Wastage on the lower Muldrow, the medial moraines and entrance of the Brooks Glacier (it shifts the moraines around on Muldrow) tend to throw off elevation change measurements in some areas. The positive elevation change from ~1700 m to 2400 m includes the entrance of the Traleika up to above the Muldrow icefall. The positive bump at the upper limit of the profile (>3300 m) is an artifact of the smoothing code and the spread of the DZ data and is unlikely a real change. This is an area of the code I'm still working on perfecting, but still causes some problems in cases like this (basically there's a clump of DZ values at ~2 m/yr at the top elevation of the data range that distort the top end of the model line).

The Traleika shows significant elevation increase at about 1 – 2 m/yr for most of its main trunk. The large elevation increase at its confluence with the Muldrow may be due to ice flowing down the Traleika and dramatically slowing or even stopping when it hits the Muldrow. At 2100 – 2180 m there are two different trends in the elevation data about 0.5 m/yr different. However, this split in the elevation measurements has little effect on the glacier-wide calculations, and so we have not yet attempted to identify and remove the bad data.

2008 – 2010: The vertical spread in the data on this plot is a combination of the effects of shifting medial moraines (2008 was still the old laser profiler) and the much shorter two-year period (dividing by more years mutes the vertical spread). However, there's still decent clumping of data that the modeled line follows reasonable well and so we're reasonably confident in these elevation change measurements. Similar story to previous years, wastage on the lower Muldrow with a bump from the Traleika confluence (~1700 m) to the base of the Muldrow icefall (~2100 m) and near zero changes above the icefall. The dip of the model line at the uppermost elevations (3300 – 3500 m) is an artifact similar to the positive artifact in the 2001 – 2010 plot.

The Traleika shows similar overall behavior as the 2001 – 2010 changes, but with more variation in the elevation changes. The data are well sampled throughout the profile. Similar to the Muldrow plots, the deviation at the top of the profile is an artifact of the spread in DZ values and modeling code. The section of code responsible for these deviations at the upper boundary will be fixed in the future.

Ruth Glacier (2001, 2008)

2001 – 2008: Over this period Ruth shows a fairly consistent story as other non-surging Denali glaciers: wastage generally higher at lower elevation and decreasing with increasing elevation.

Toklat 1 (East) Glacier (1996, 2001, 2008)

1996 – 2001: It's a very sparse profile , but shows what are fairly typical negative elevation changes for the Denali glaciers.

1996 – 2008: Also a sparse profile, but it's currently the best we have. The 2001 – 2008 comparison is not included because it's even sparser than either of the included profiles. Same story as elsewhere: elevation loss. However, with no measurements for much of the glacier this is likely an overestimate of the wastage (if we assume there is less wastage at higher elevations).

Toklat 2 (Middle) Glacier (2001, 2008, 2010)

Toklat 2 has the benefit of being flown with the scanning LiDAR in 2010, which essentially makes all previous profiles useful. Unfortunately though, there aren't many other profiles for Toklat 2. The 2005 profile has extremely limited coverage and is essentially useless.

Even though it's small, Toklat 2 has two roughly equal-area branches, designated east branch and west branch. The laser altimetry data cover both branches and so we present them separately to avoid contaminating the results of one branch with elevation changes from the other branch.

2001 – 2010: Overall the east and west branches are both robust profiles with continuous data points and little variation in DZ at any given elevation. The toe of the glacier is included in the west branch. Similar elevation changes as other glaciers in Denali: more loss at lower elevation and less loss at higher elevations.

2008 – 2010: Elevation losses have increase slightly (30 – 40 %) compared to the longer period from 2001 – 2010, which suggests mass balances are increasingly negative— Which is similar to the cases of other Denali glaciers in the study.

Toklat 3 (West) Glacier (2001, 2008)

Toklat 3 is a similar story to Toklat 1—without a 2010 scanning LiDAR profile we don't have many points of comparison. Only the 2001 – 2008 data provide enough points to be worth showing and they show the usual story of elevation loss decreasing with increasing elevation.

Tokositna Glacier (2001, 2008)

The Tokositna data are difficult to interpret. Elevation changes from 2001 to 2008 bounce from strongly negative up to 700 m and then hover around zero up the glacier. This may be due in part to the clumpiness of the data (clumps at ~750 m, ~1100 m, and ~1400 m) and the scatter of the data within the clumps. At this point it's difficult to know if anything beyond is driving these elevation changes. Once we can have a scanning LiDAR profile of Tokositna in the future, we should have more continuous coverage of the glacier and have a better idea of the Tokositna's behavior.

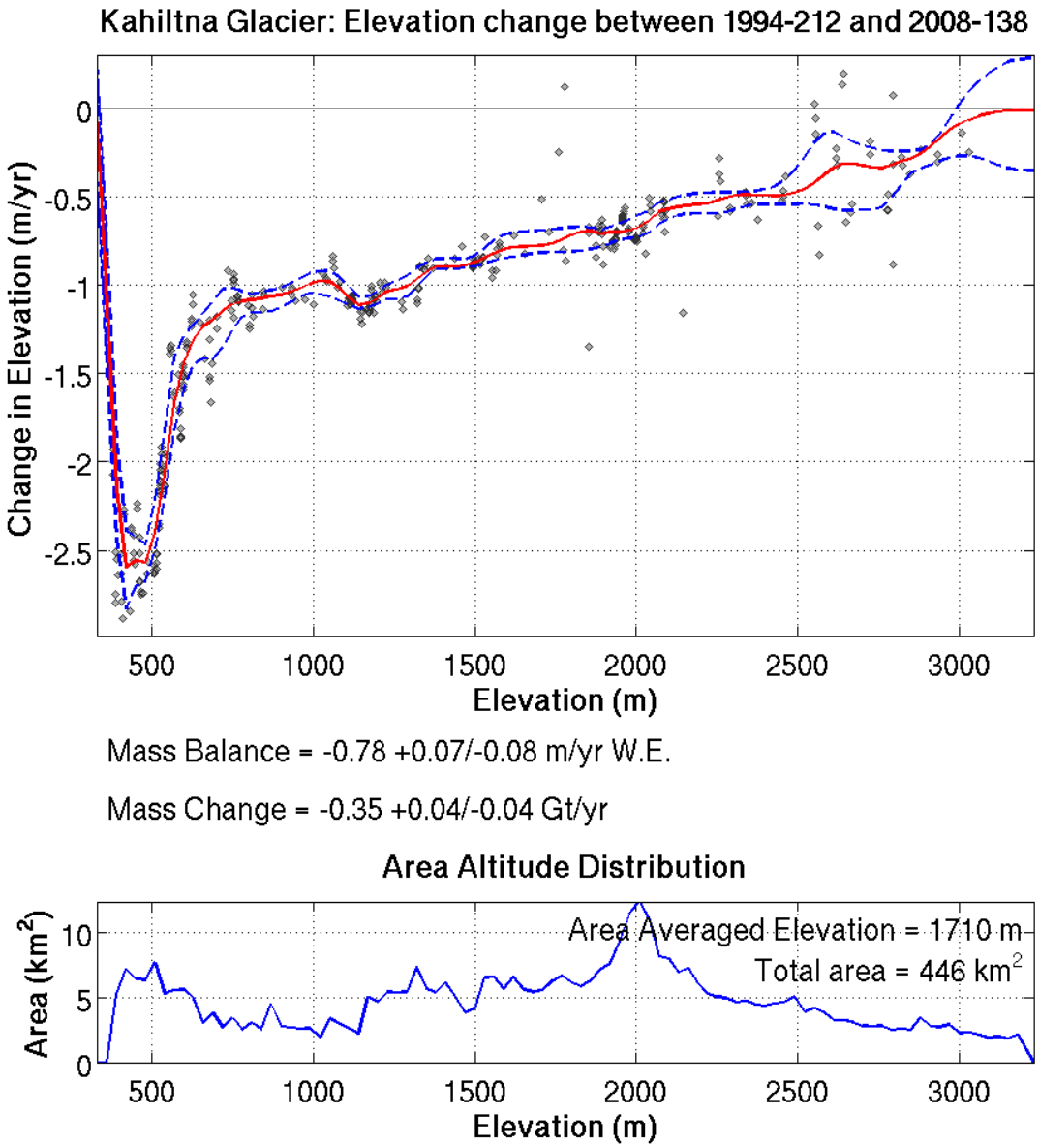


Figure D1. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Kahiltna Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

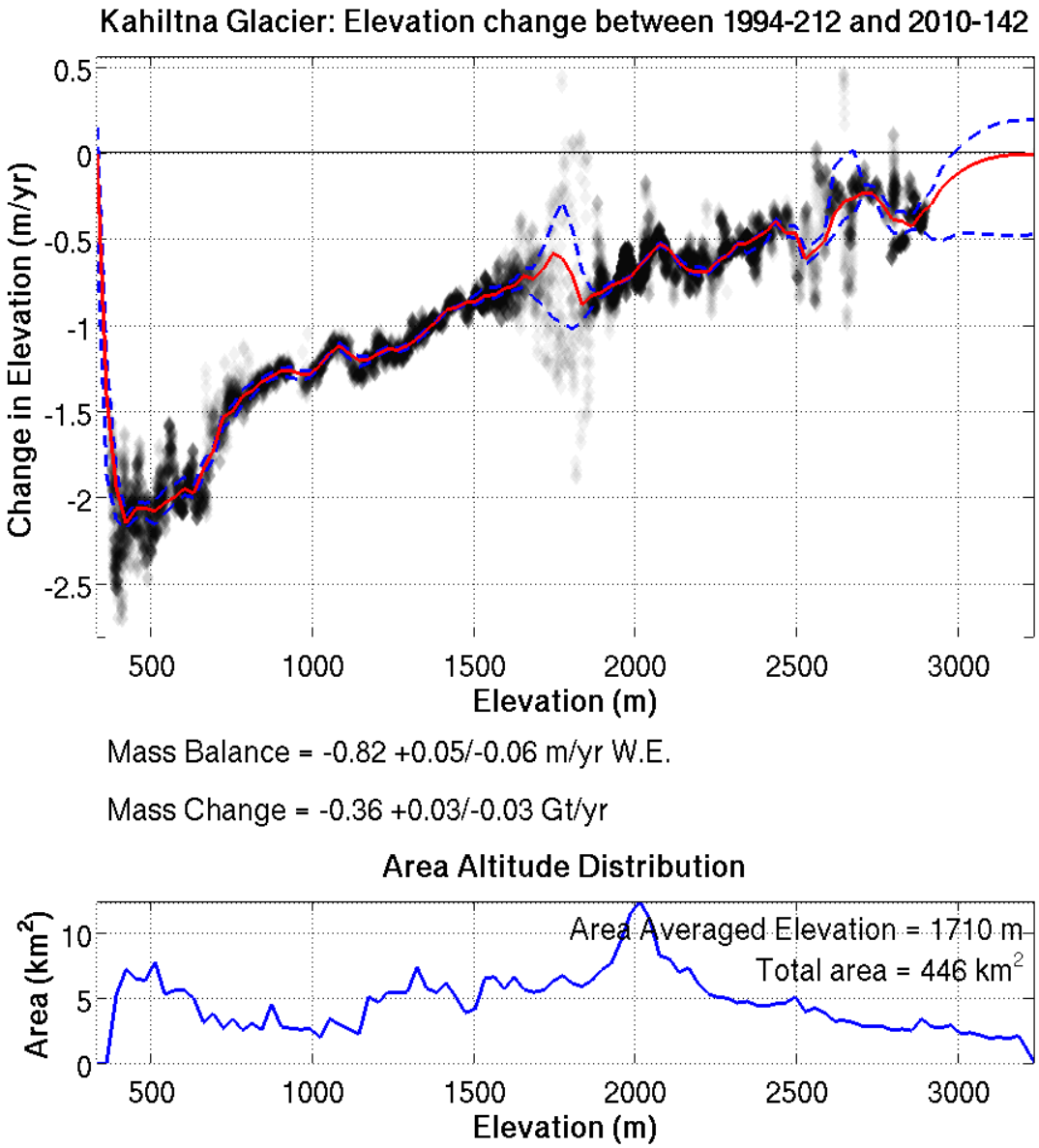


Figure D2. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Kahiltna Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

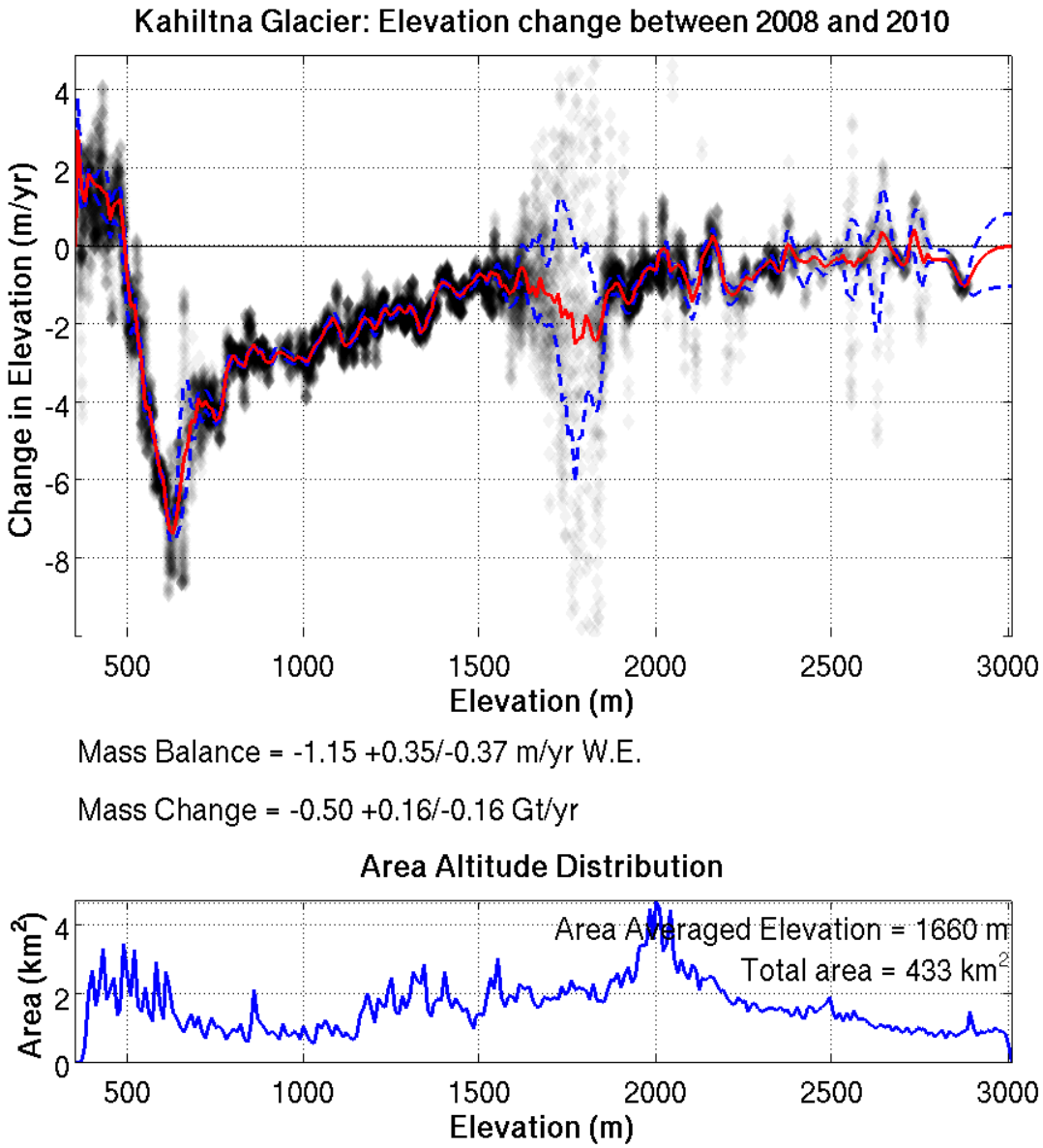


Figure D3. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Kahiltna Glacier. Beginning and ending dates are 2008-138 and 2010-143.

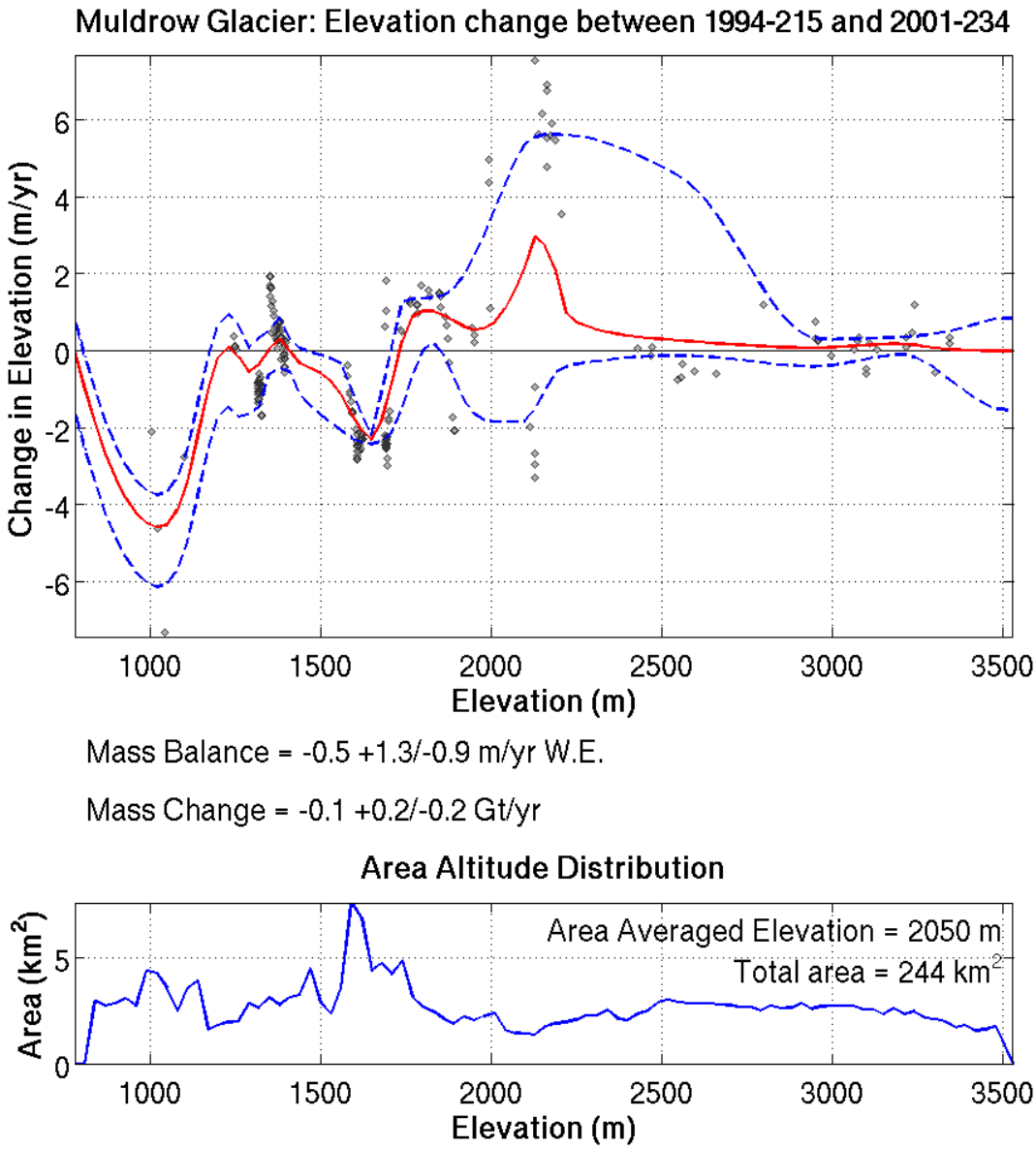


Figure D4. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Muldrow Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

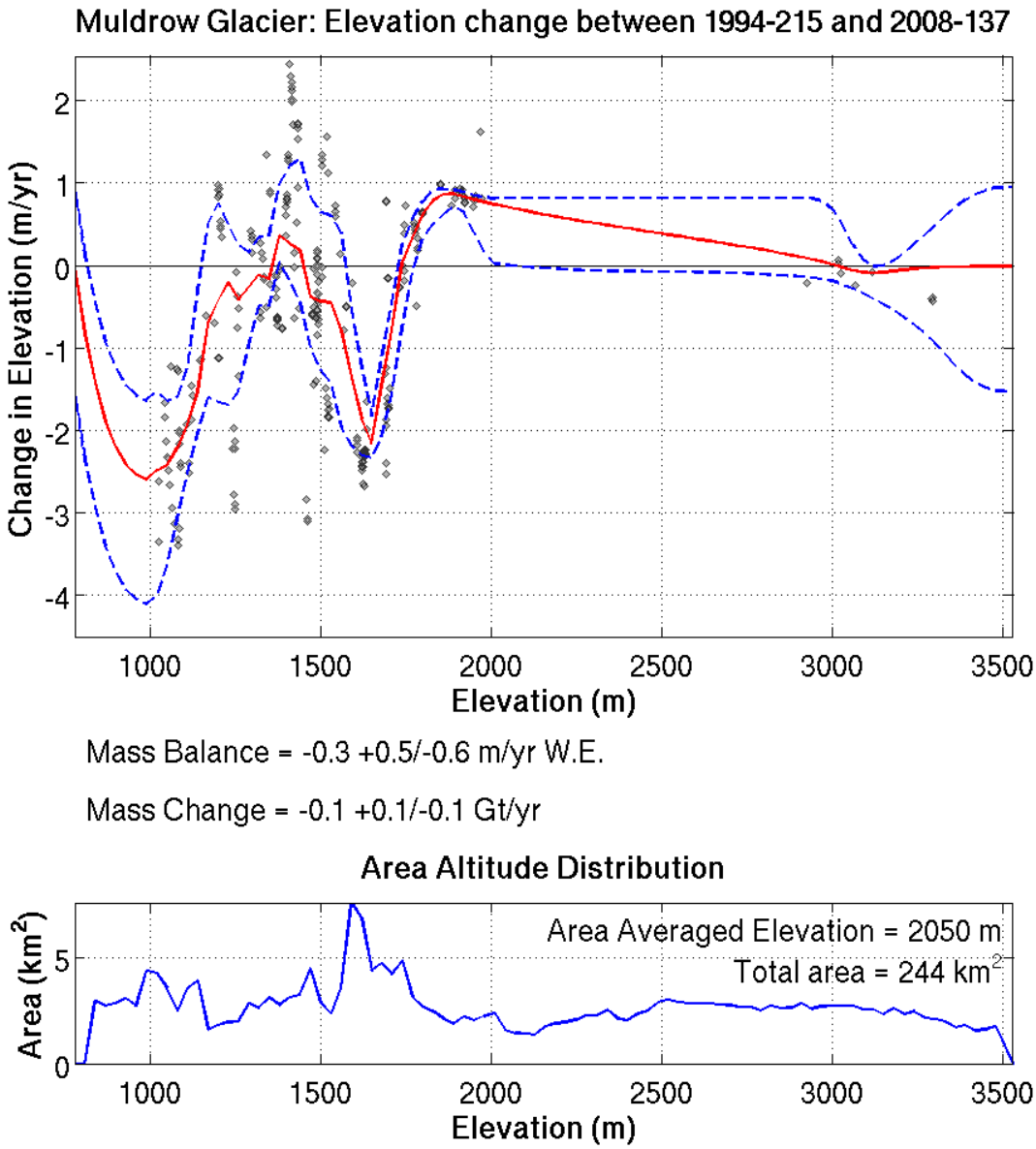


Figure D5. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Muldrow Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

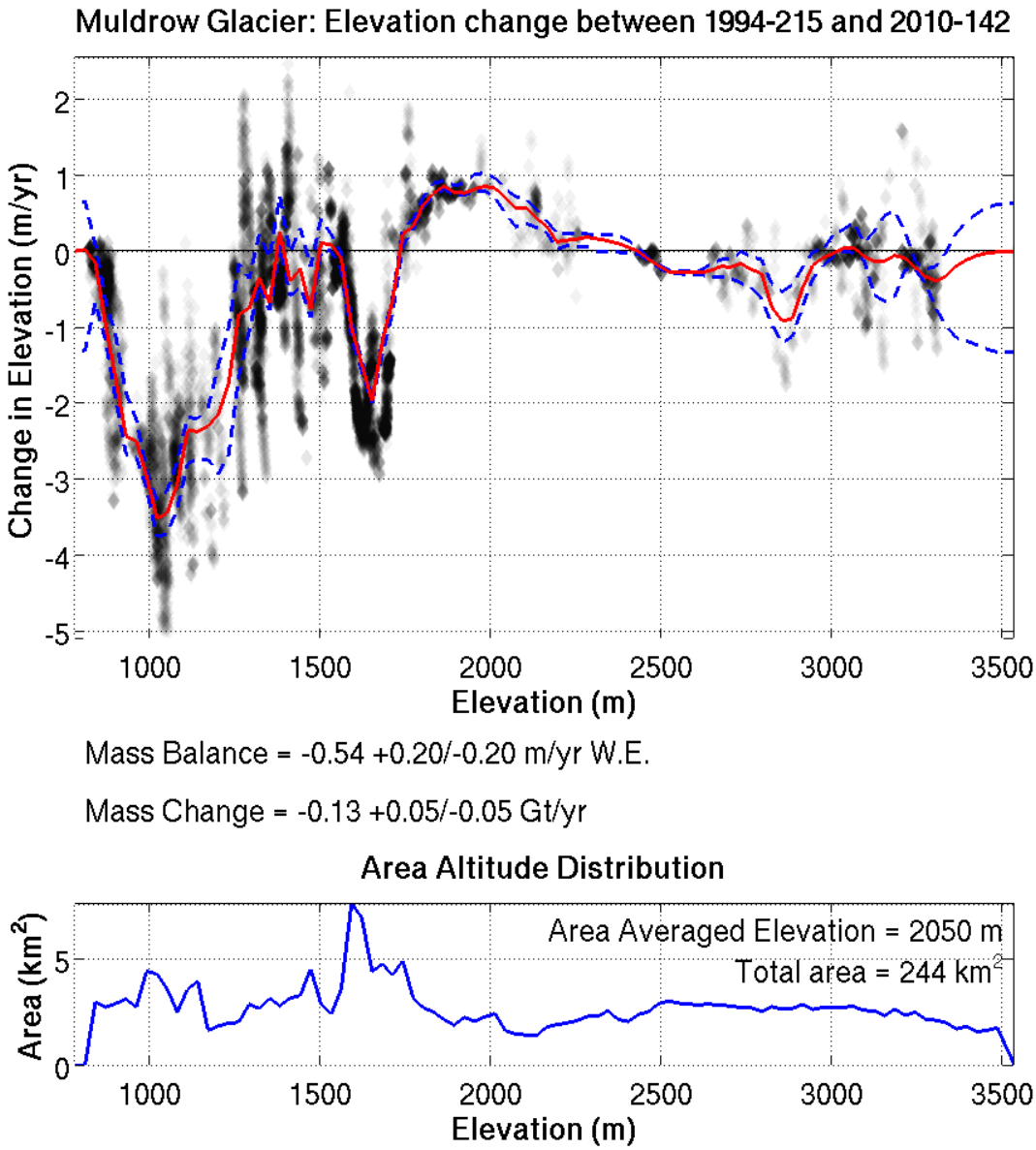


Figure D6. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Muldrow Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

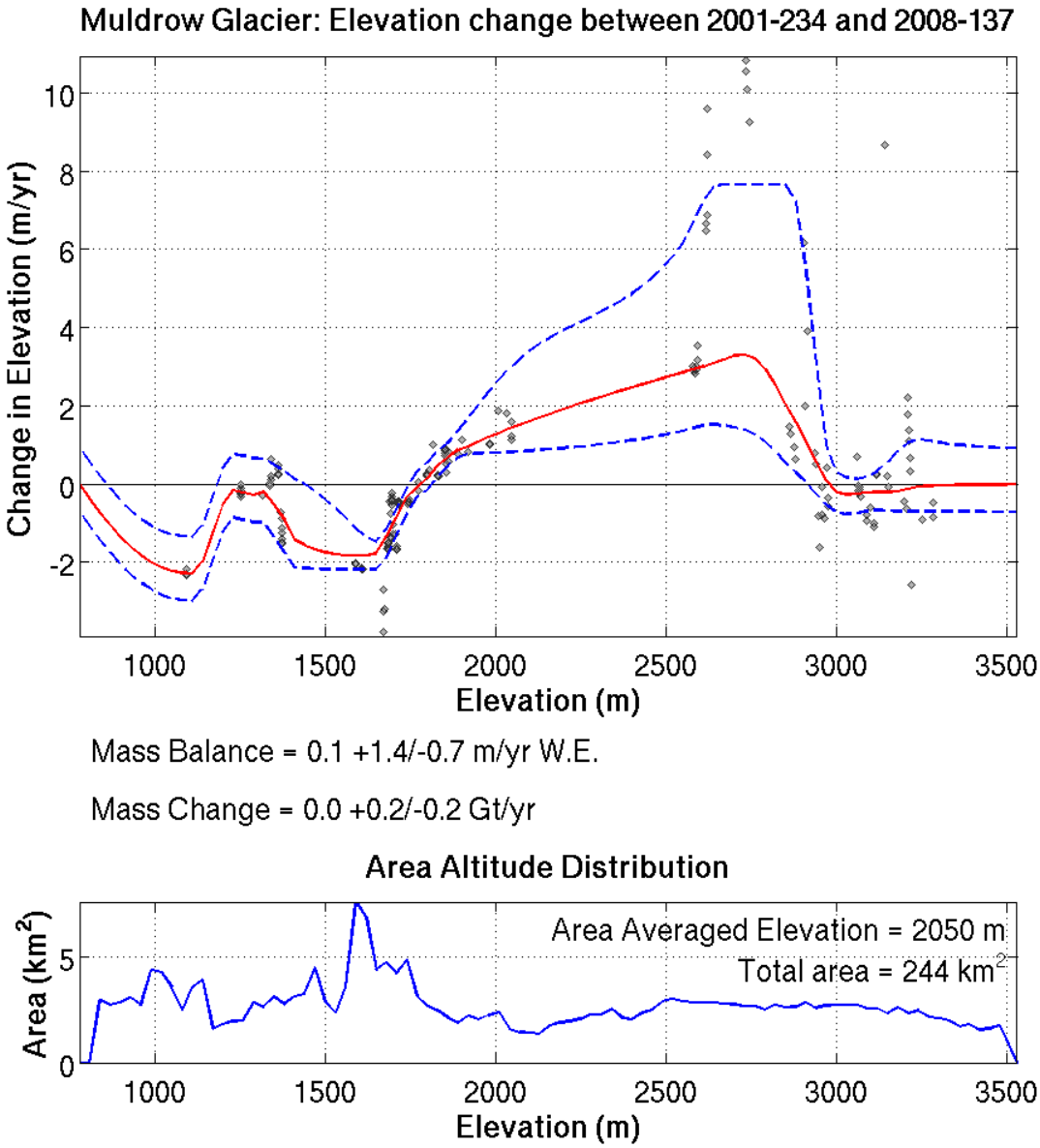


Figure D7. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Muldrow Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

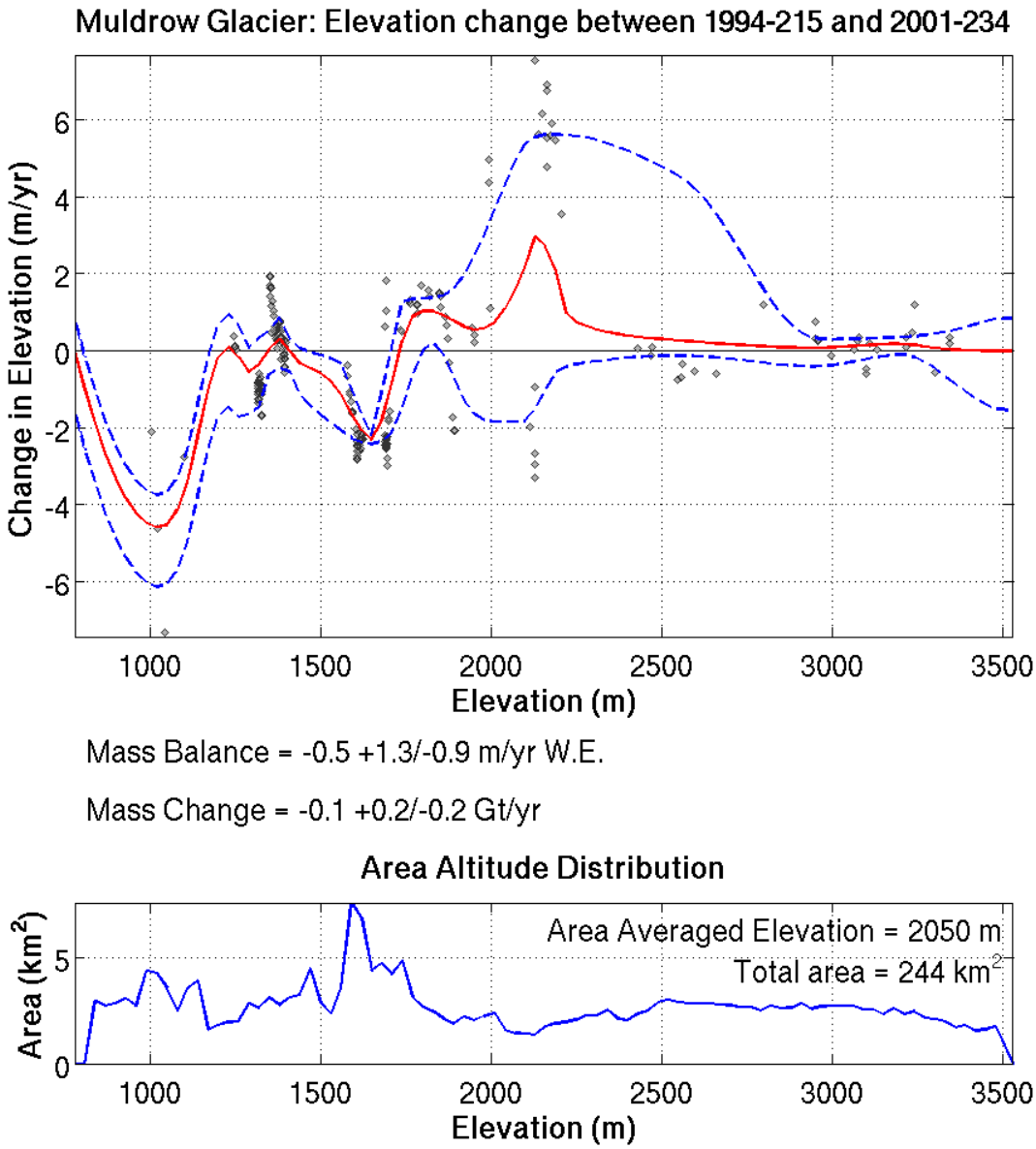


Figure D8. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Muldrow Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

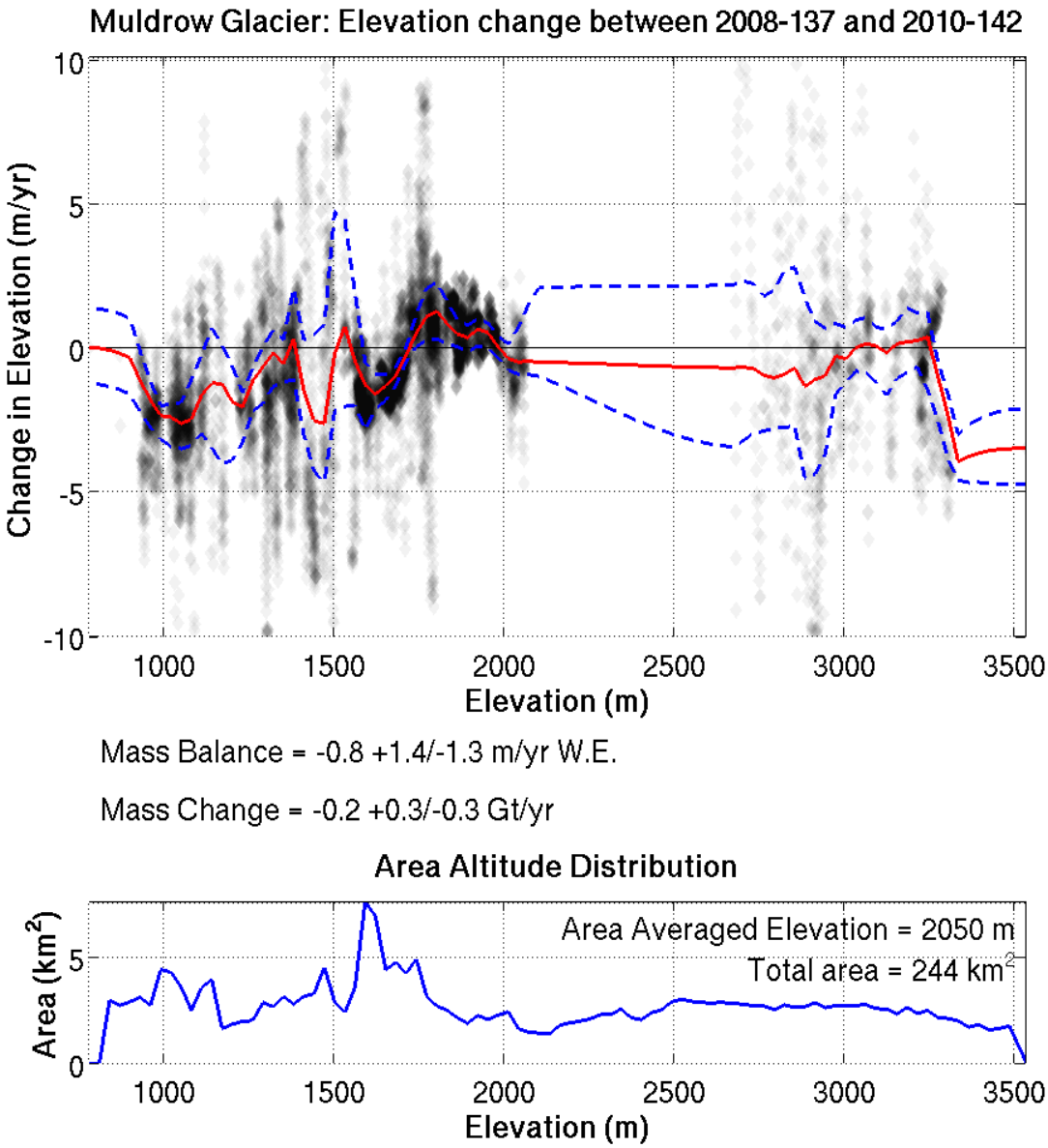


Figure D9. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Muldrow Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

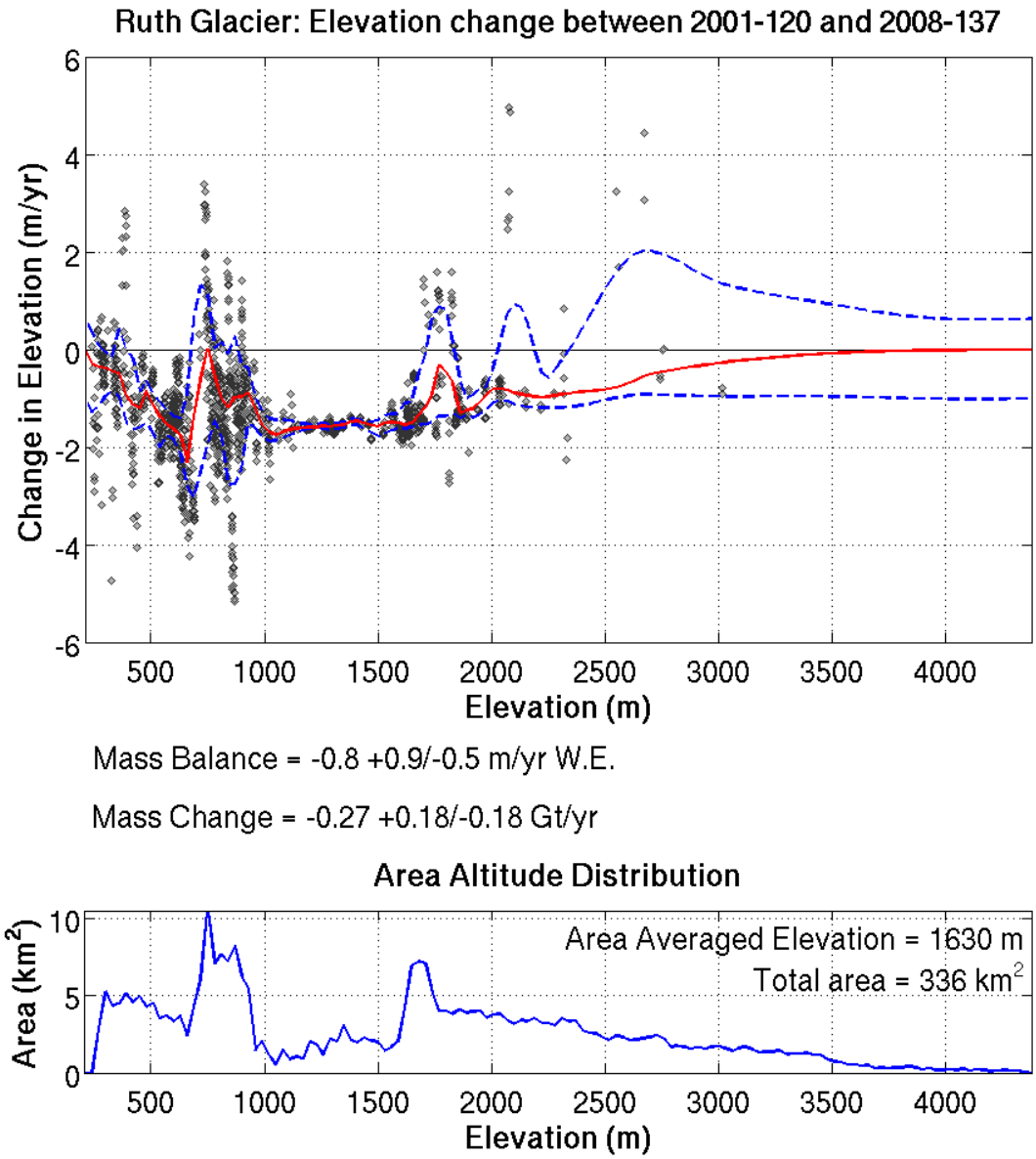


Figure D10. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Ruth Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

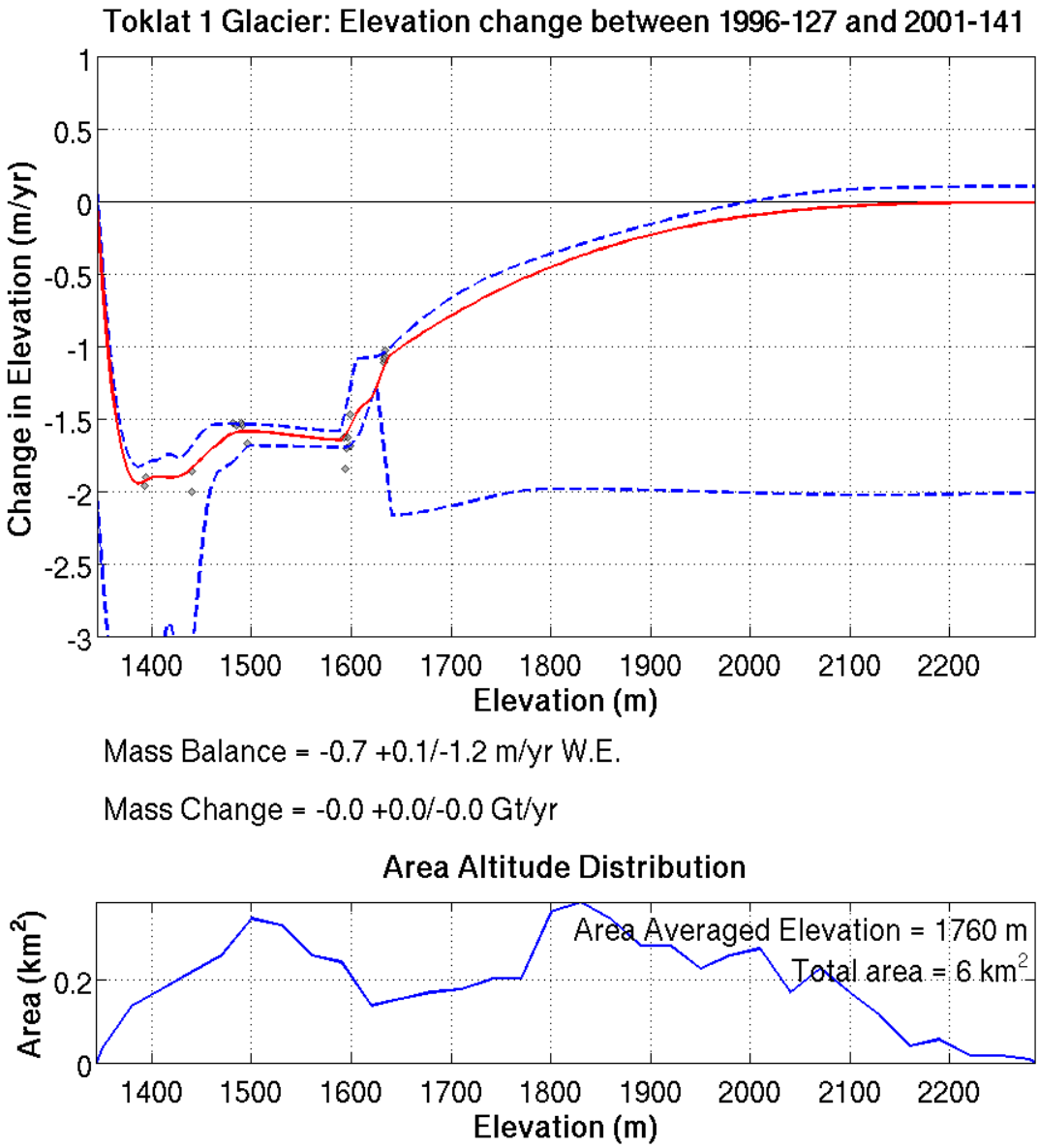


Figure D11. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Toklat 1 Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

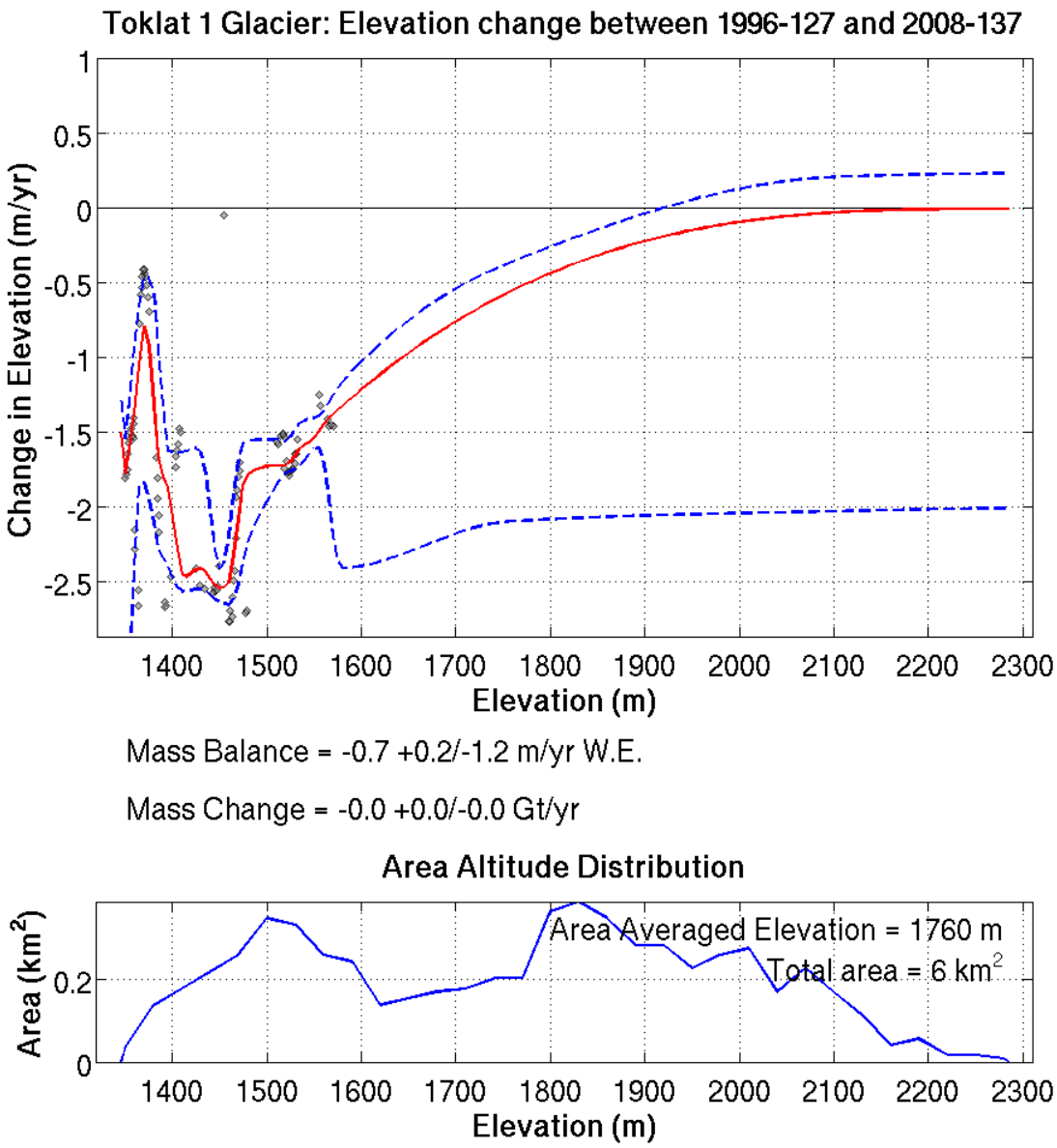


Figure D12. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Toklat 1 Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

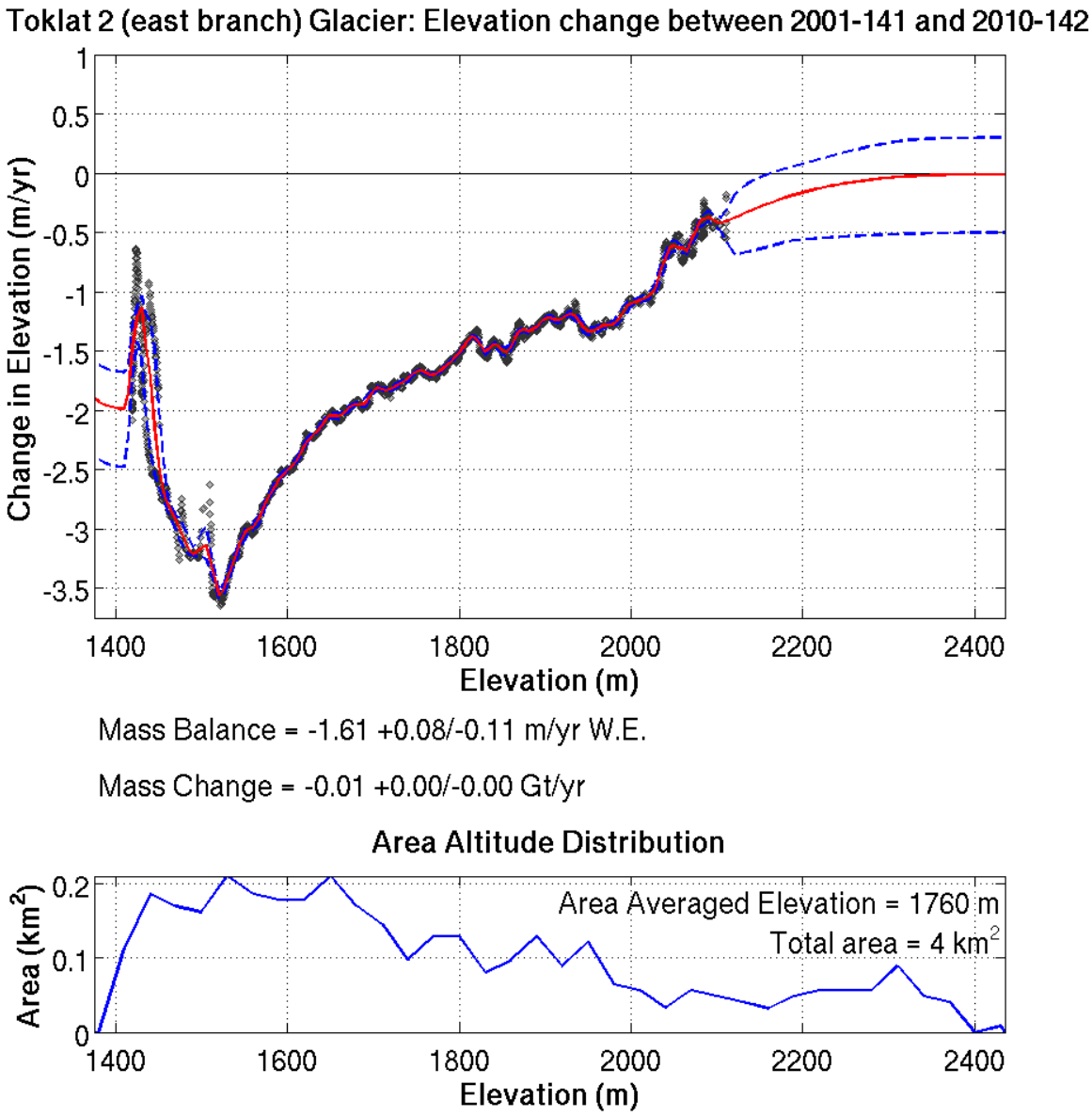


Figure D13. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Toklat 2 (east branch) Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

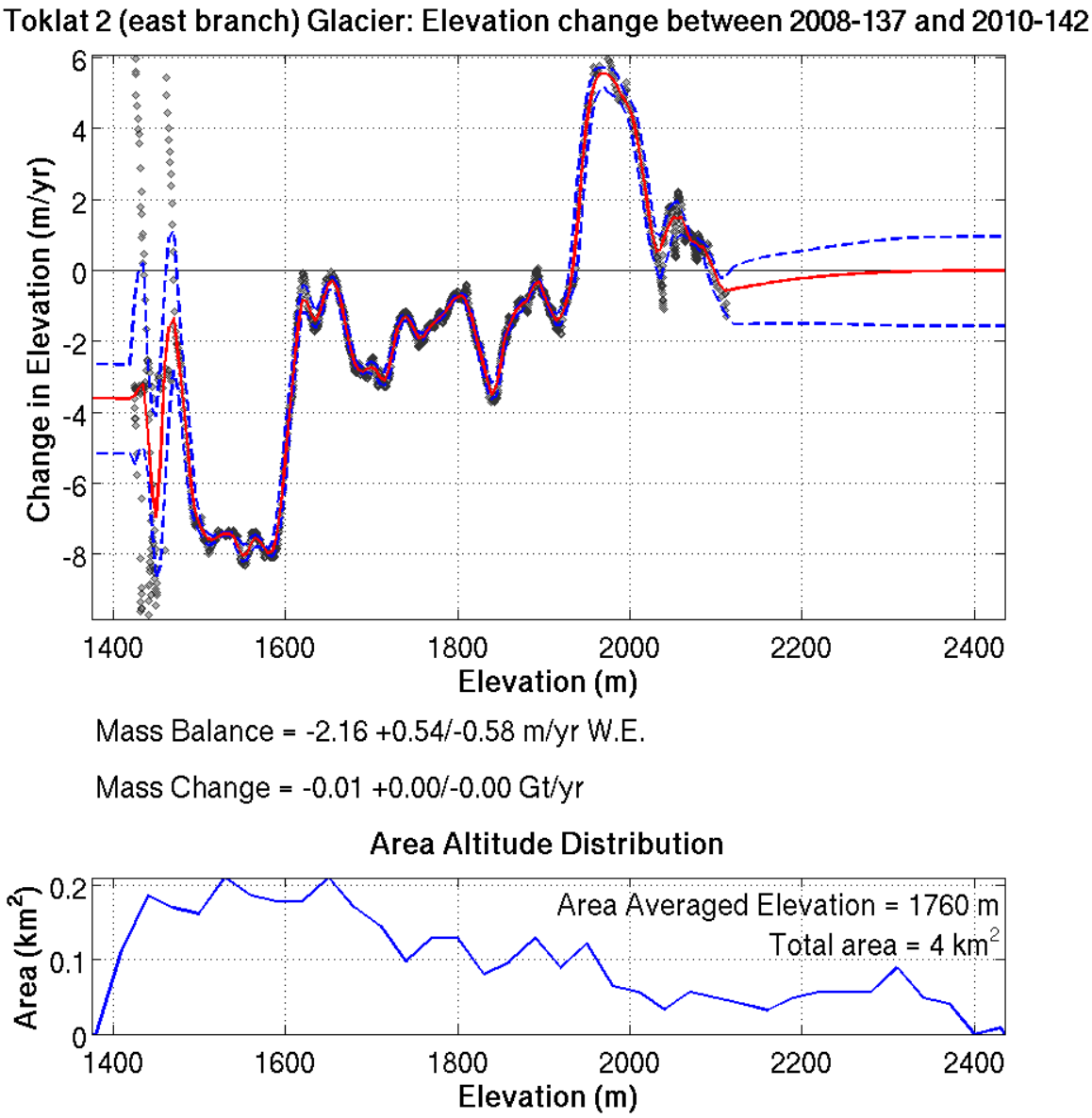


Figure D14. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Toklat 2 (east branch) Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

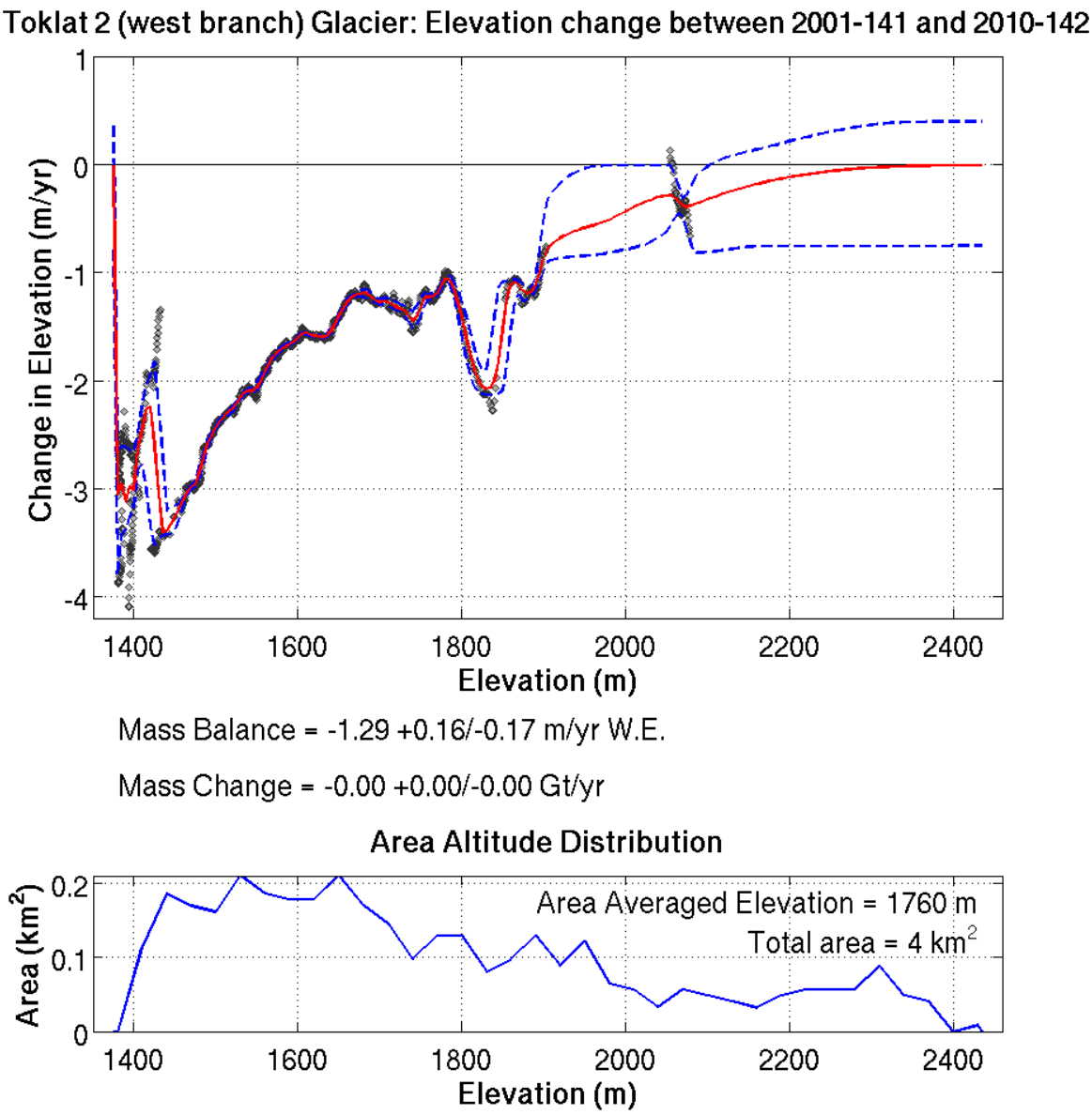


Figure D15. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Toklat 2 (west branch) Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

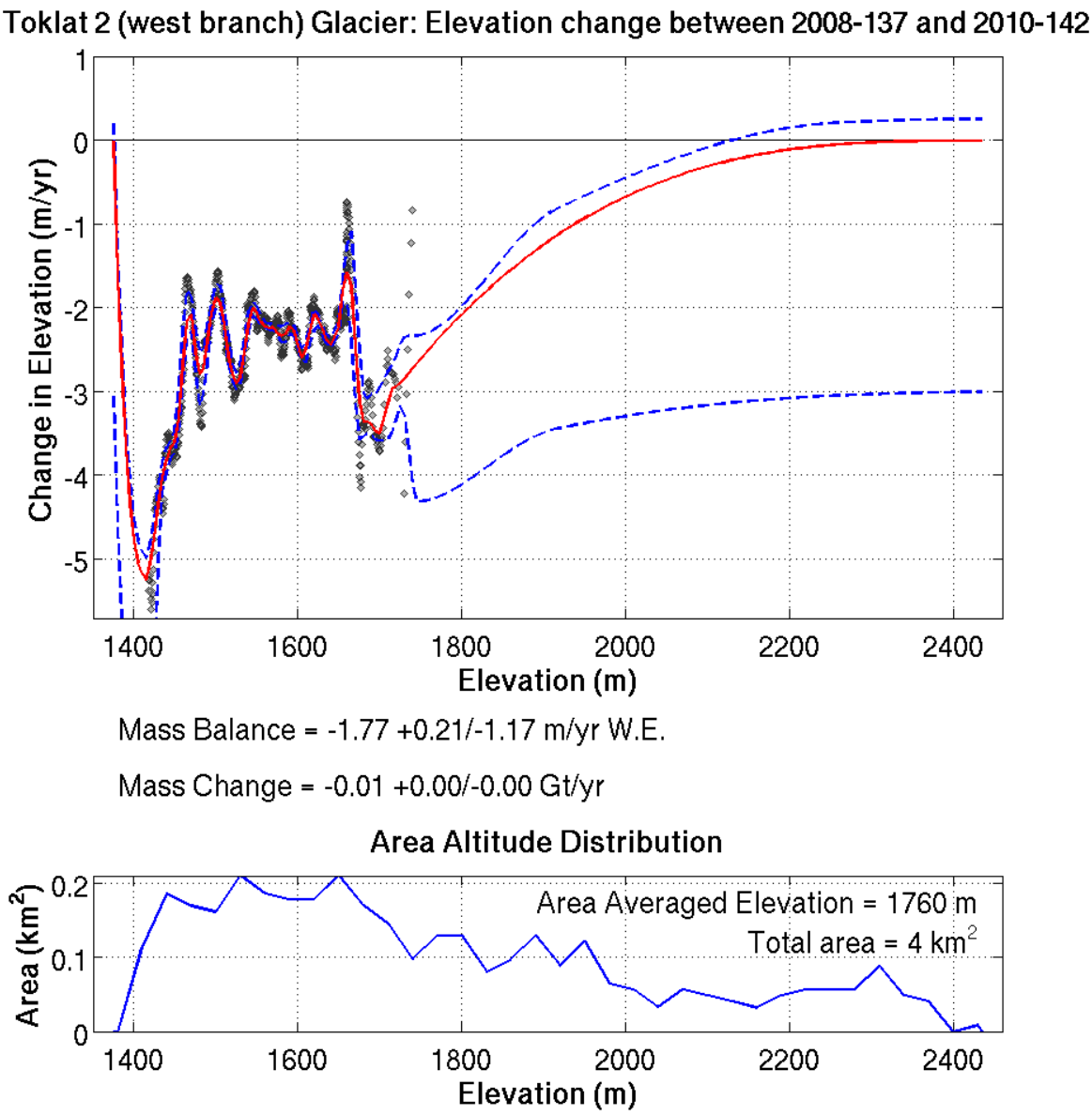


Figure D16. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Toklat 2 (west branch) Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

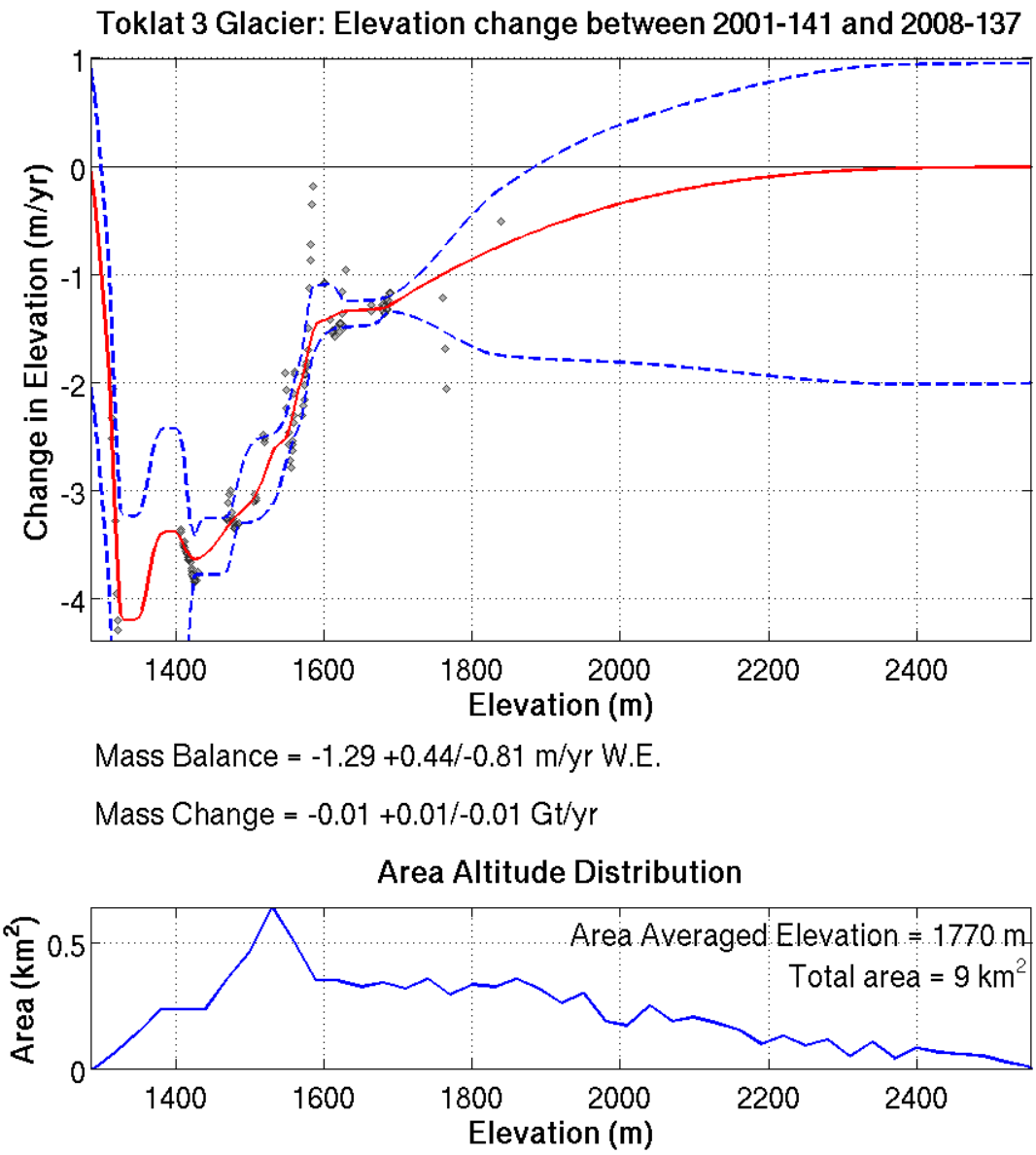


Figure D17. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Toklat 3 Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

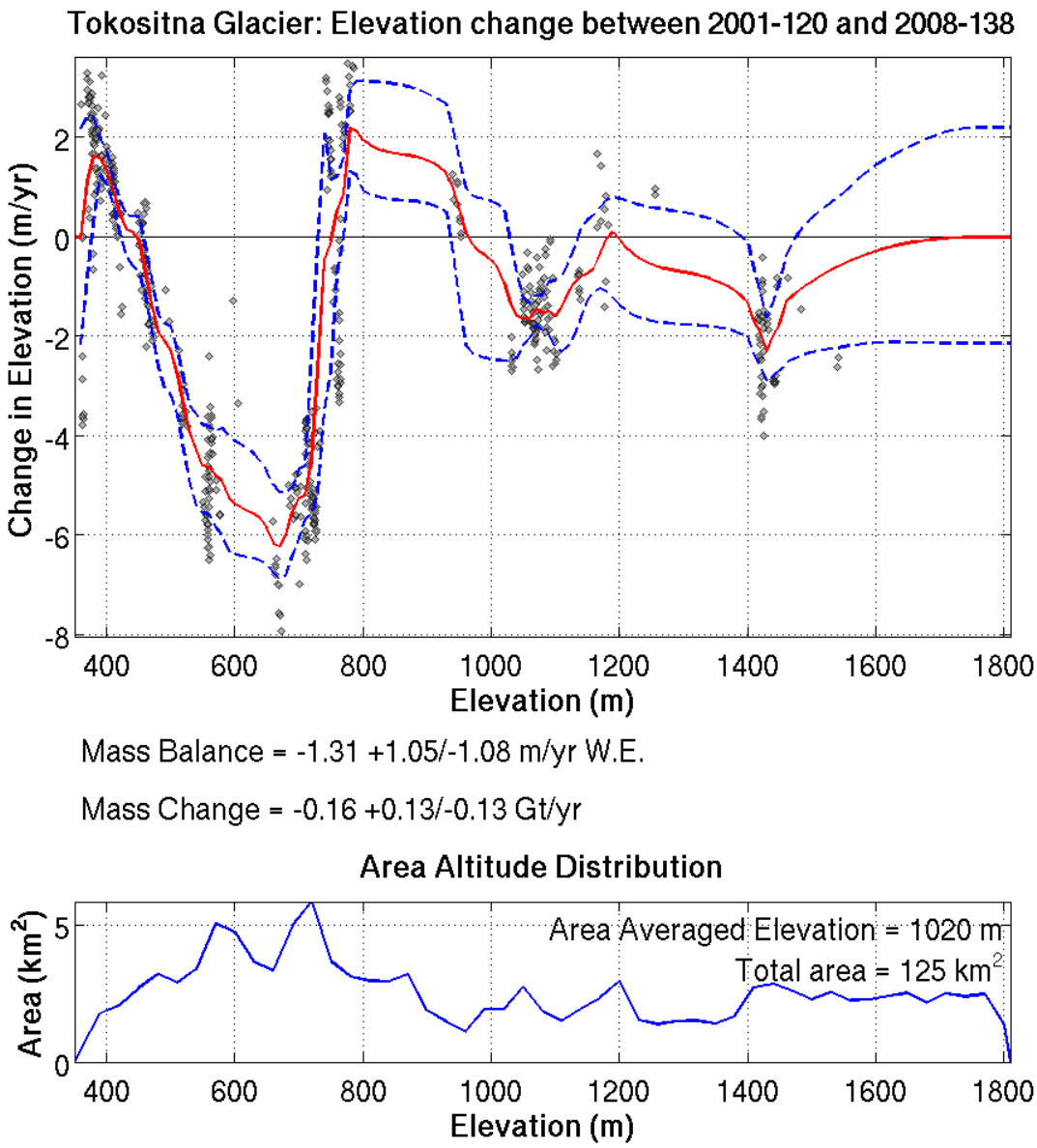


Figure D18. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Tokositna Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

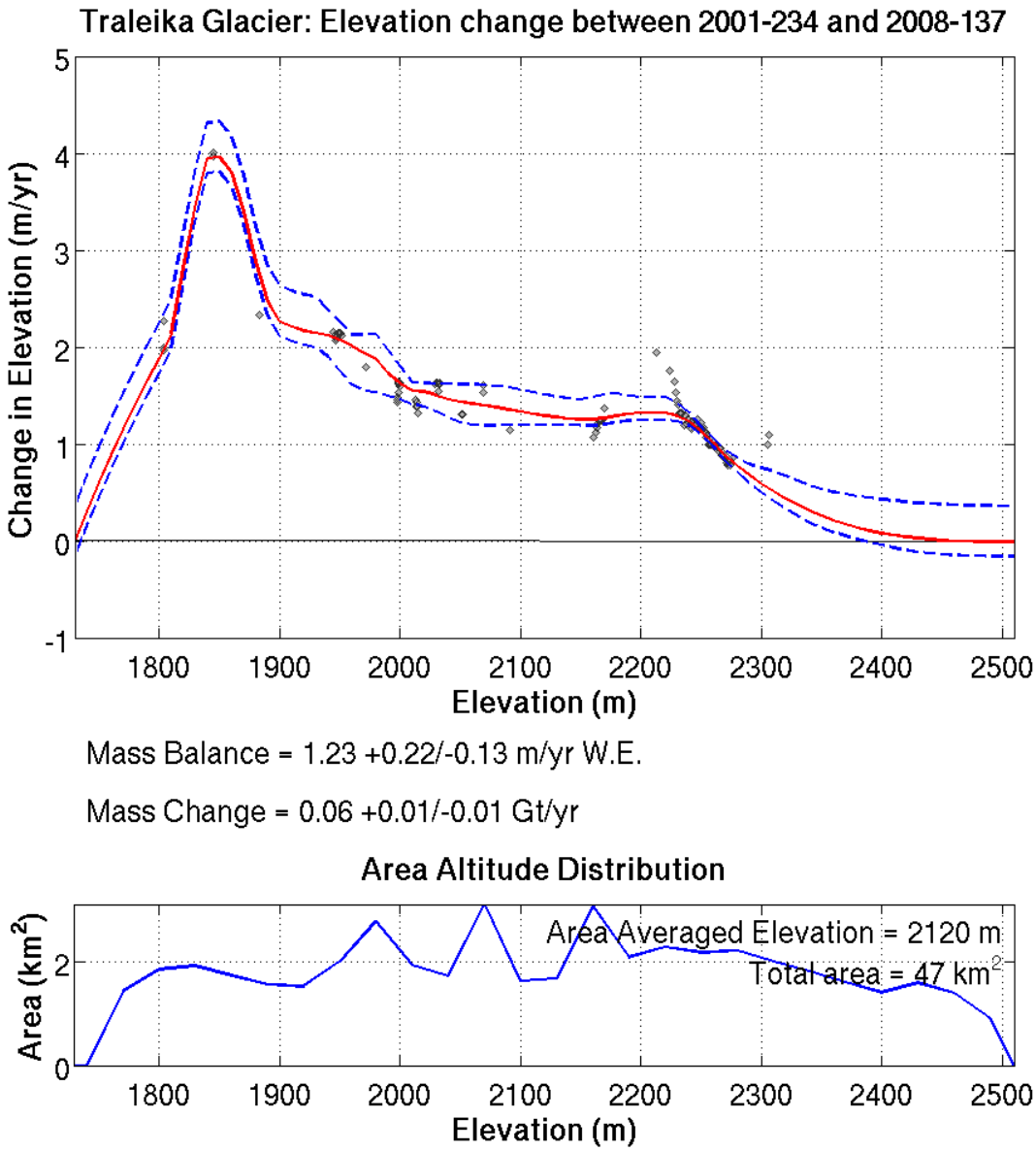


Figure D19. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Traleika Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

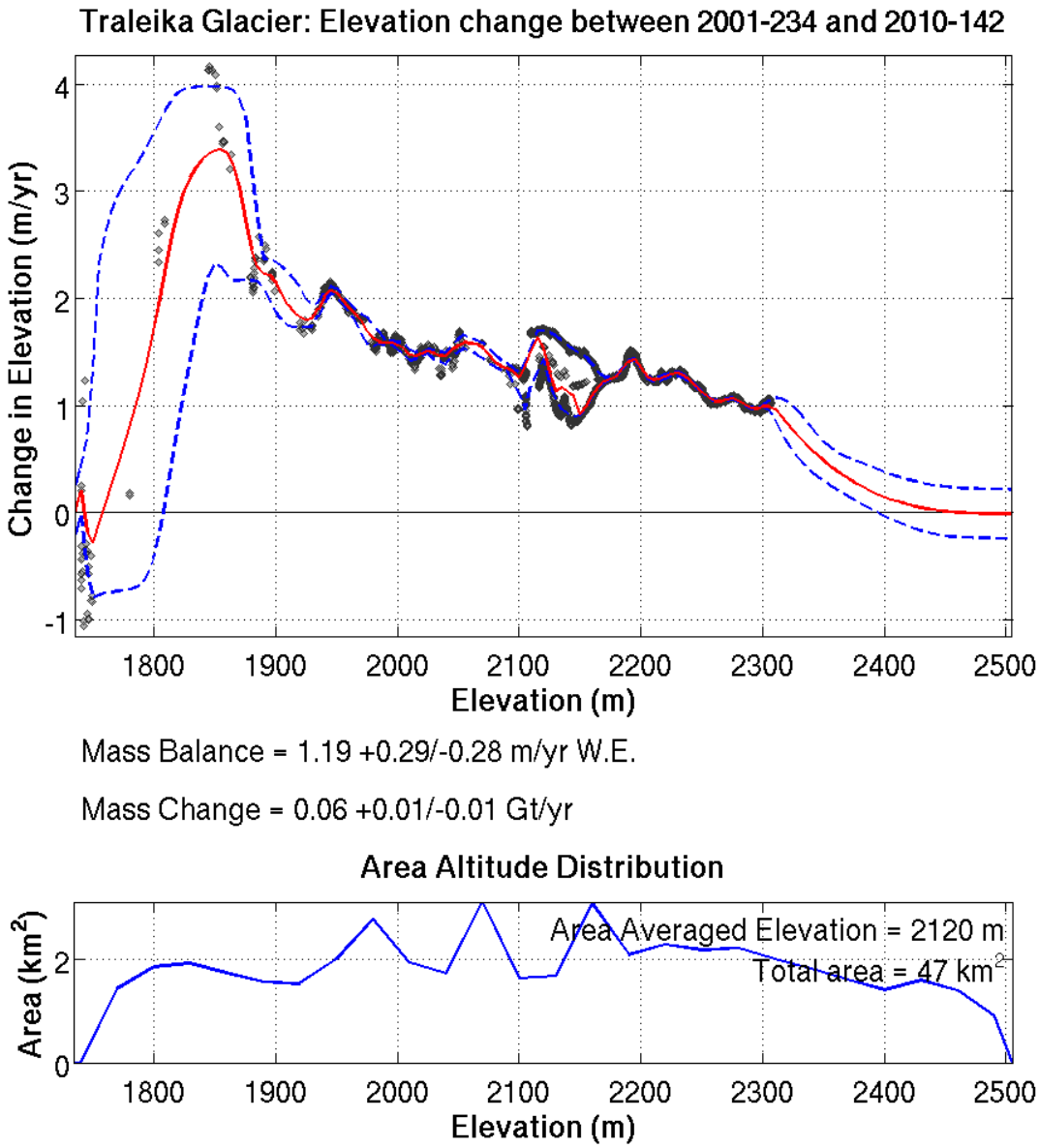


Figure D20. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Traleika Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

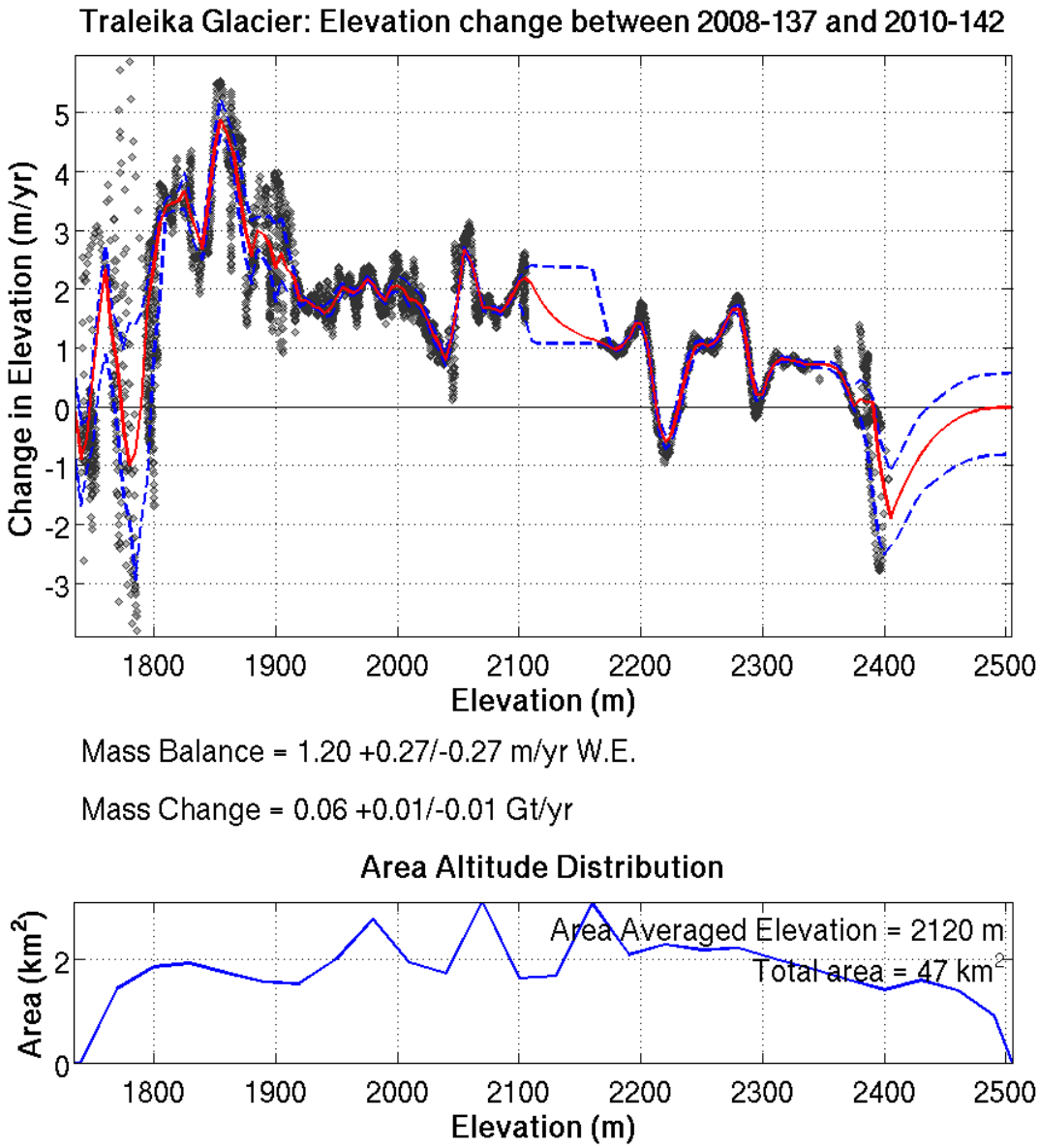


Figure D21. Details of calculated elevation changes by elevation (upper panel) and the area altitude distribution (lower panel) for Traleika Glacier. Beginning and ending dates are given in the figure title, with year before the hyphen and day of year after.

NPS 953/119665, January 2013

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov