



# Report on Vital Signs Monitoring of Glaciers in the Central Alaska Network, 2011-2013

Natural Resource Technical Report NPS/CAKN/NRTR—2014/905



**ON THE COVER**

**Rob Burrows and Sam Herreid collect index stake data on Kahiltna Glacier, August 15, 2011**

Photograph by: Rob Burrows/NPS

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# **Report on Vital Signs Monitoring of Glaciers in the Central Alaska Network, 2011-2013**

Natural Resource Technical Report NPS/CAKN/NRTR—2014/905

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# Contents

|                                                                            | Page |
|----------------------------------------------------------------------------|------|
| Figures.....                                                               | v    |
| Tables.....                                                                | ix   |
| Appendices.....                                                            | ix   |
| List of Acronyms .....                                                     | xi   |
| List of Variables.....                                                     | xi   |
| Executive Summary .....                                                    | xiii |
| Acknowledgments.....                                                       | xv   |
| Introduction: Background .....                                             | 1    |
| Selected Glaciers: .....                                                   | 1    |
| Methods.....                                                               | 3    |
| Extent.....                                                                | 3    |
| Comparative Photography .....                                              | 5    |
| Index Station Measurements .....                                           | 6    |
| Equilibrium Line Altitude .....                                            | 8    |
| Glacier Motion.....                                                        | 9    |
| Glacier Surface Height .....                                               | 9    |
| 2011 Surge-type Glacier Observations.....                                  | 9    |
| Results.....                                                               | 13   |
| Extent.....                                                                | 13   |
| Panoramic and Comparative Photography .....                                | 13   |
| Extent, Debris-Cover, and Surface Elevation Change of Focus Glaciers ..... | 16   |
| West Fork Toklat Glacier .....                                             | 16   |
| Middle Fork Toklat Glacier.....                                            | 21   |
| Sources for Error and Uncertainty.....                                     | 24   |
| Estimating Ice Loss Rates in the Toklat Watershed.....                     | 26   |
| West Fork Teklanika Glacier.....                                           | 29   |
| West Fork Cantwell Glacier .....                                           | 31   |
| Surging Glacier Observations.....                                          | 32   |

## Contents (continued)

|                                            | Page |
|--------------------------------------------|------|
| Index Stations Mass Balance Summary .....  | 32   |
| Index Station Measurements .....           | 32   |
| <i>Index Station Data Discussion</i> ..... | 35   |
| Balances Calculated at Long-term ELA.....  | 36   |
| Glacier Stake velocities .....             | 39   |
| Literature Cited .....                     | 43   |

# Figures

Page

|                                                                                                                                                                                             |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 1.</b> An illustration of the measurements taken and instruments used at an index stake. See text and protocol for further explanation. ....                                      | 6  |
| <b>Figure 2.</b> The Kahiltna Glacier system and surrounding glaciers with 2010 IFSAR DTM hillshade from 2000 Landsat imagery and associated mapped glacier margin (Loso et al 2014) .....  | 10 |
| <b>Figure 3.</b> The Muldrow Glacier system and surrounding glaciers on the 2010 IFSAR DTM hillshade from 2000 Landsat imagery and associated mapped glacier margin (Loso et al 2014) ..... | 11 |
| <b>Figure 4.</b> Changes in glacier area in Denali between the 1950s and ~2010. ....                                                                                                        | 14 |
| <b>Figure 5.</b> Changes in glacier area between map date and modern in Wrangell-St. Elias NP&P (from Arendt et al. 2013). ....                                                             | 15 |
| <b>Figure 6.</b> West fork Toklat glacier .....                                                                                                                                             | 16 |
| <b>Figure 7.</b> Two views of the west fork Toklat glacier and locations of the GPS surface elevations surveys (red dots and lines) .....                                                   | 18 |
| <b>Figure 8.</b> These maps illustrate the change in area of debris-covered ice on west fork Toklat glacier from 2004 to 2010 .....                                                         | 19 |
| <b>Figure 9.</b> West fork Toklat glacier hypsometry of the entire glacier (on left) and the subset area of debris-covered ice (on right) .....                                             | 20 |
| <b>Figure 11.</b> A plot of points derived from the August 2013 GPS survey minus the 2010 IFSAR DTM of debris-covered ice areas only on west fork Toklat glacier. ....                      | 20 |
| <b>Figure 10.</b> A plot of points derived from the August 2013 GPS survey minus the 2010 IFSAR DTM of bare ice areas only on west fork Toklat glacier. ....                                | 20 |
| <b>Figure 12.</b> Map showing extent and debris-covered ice from 2004 imagery of middle fork Toklat glacier.....                                                                            | 21 |
| <b>Figure 14.</b> Mapped glacier termini and retreat rates for middle fork Toklat glacier.....                                                                                              | 22 |
| <b>Figure 13.</b> Glacier hypsometry of the entire middle fork Toklat glacier as well as the subsets of bare ice and debris-covered ice .....                                               | 22 |
| <b>Figure 16.</b> A plot of points for debris-covered ice of middle fork Toklat glacier from the August 2012 GPS survey minus the 2010 IFSAR DTM. ....                                      | 23 |
| <b>Figure 15.</b> A plot of points on bare ice only of middle fork Toklat glacier derived from the August 2012 GPS survey minus the 2010 IFSAR DTM. ....                                    | 23 |
| <b>Figure 17.</b> A plot of points derived from the 2002 and 2012 GPS surveys minus the 2010 IFSAR of bare ice areas only on middle fork Toklat glacier. ....                               | 24 |

## Figures (continued)

Page

|                                                                                                                                                                                                                                                                                                          |    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 18.</b> Error distribution histograms of differences between Trimble R6 GPS measurements and the IFSAR DTM elevations at Middle Fork Toklat (MFT) and West Fork Toklat (WFT) glaciers.....                                                                                                     | 25 |
| <b>Figure 19.</b> Comparison graphs showing elevation change rates vs. elevation for all glaciers and time periods in the Toklat Watershed .....                                                                                                                                                         | 27 |
| <b>Figure 20.</b> Map showing the upper west fork and middle fork Toklat watershed in relation to the Denali Park Road and the gravel harvest area .....                                                                                                                                                 | 28 |
| <b>Figure 21.</b> Area-Altitude distribution (hypsoetry) of glaciers and subsets of bare ice and debris-covered ice for the upper west Toklat watershed.....                                                                                                                                             | 29 |
| <b>Figure 22.</b> Glacier at the head of the west fork of the Teklanika River on June 29, 2011. Photo by Brian Schmidt.....                                                                                                                                                                              | 30 |
| <b>Figure 23.</b> Comparison of extents between mapping dates (1950s, 2003, and 20040), methods, and resolution. On this small (~4 km <sup>2</sup> ), debris-covered glacier, mapping extent is difficult and ambiguous without the ability to ground truth or a DTM that matches the terminus date..... | 31 |
| <b>Figure 24.</b> Terminus positions and retreat rates of the lower west fork Cantwell glacier. Retreat rates (meters/year) are measured along the light blue line between each successive terminus position.....                                                                                        | 32 |
| <b>Figure 25.</b> Annual, winter, and summer balances at the index stakes of Kahiltna and Traleika Glaciers.....                                                                                                                                                                                         | 37 |
| <b>Figure 26.</b> The calculated ELAs at the long-term ELA at each glacier. These values serve as an index of the entire glacier annual balance for each balance year.....                                                                                                                               | 38 |
| <b>Figure 27.</b> Cumulative balance graphs from the annual balances calculated at the long-term ELA for Kahiltna and Traleika glaciers.....                                                                                                                                                             | 39 |
| <b>Figure 28.</b> Surface speeds of Kahiltna and Traleika Glaciers from 1991 to 2013 as calculated from the long term index stake positions.....                                                                                                                                                         | 40 |
| <b>Figure 29.</b> Stake velocities on Kahiltna and Traleika Glaciers during the 2013 summer season (except the upper Traleika stake which was the previous summer's velocity).....                                                                                                                       | 41 |
| <b>Figure A-1.</b> A 360 degree panorama near the index station on Kahiltna Glacier, 06/08/2011 .....                                                                                                                                                                                                    | 47 |
| <b>Figure A-2.</b> A 360 degree panorama near the index station on Kahiltna Glacier, 08/15/2011 .....                                                                                                                                                                                                    | 48 |
| <b>Figure A-3.</b> A 360 degree panorama on the lower glacier near Joanna Young's KT5 stake .....                                                                                                                                                                                                        | 49 |
| <b>Figure A-4.</b> The lowermost glacier and terminus area of Kahiltna Glacier, 09/14/2011.                                                                                                                                                                                                              | 50 |

## Figures (continued)

Page

|                                                                                                                                                                                               |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure A-5.</b> The lowermost glacier and terminus area of Kahiltna Glacier, 09/14/2011.                                                                                                   | 50 |
| <b>Figure A-6.</b> The Kahiltna Glacier Index site, 08/13/2012. Camera location: 62.9415 degrees N, 151.24605 degrees W, 1937 m (6354 ft) .....                                               | 51 |
| <b>Figure A-7.</b> A 360 degree panorama on the medial moraine near the index station on Traleika Glacier, spring 2011 .....                                                                  | 51 |
| <b>Figure A-8.</b> A 360-degree panorama on the Muldrow Glacier at the new “two-mile moraine” marker .....                                                                                    | 52 |
| <b>Figure A-9.</b> Comparison of photography of Polychrome glaciers originally taken by Stephen R. Capps on July 18, 1916 (top ) and June 26, 2011 by Ron Karpilo (bottom).....               | 53 |
| <b>Figure A-10.</b> Comparison of photography of East Fork Toklat Glacier originally taken by Stephen R. Capps on August 22, 1919 (top ) and June 30, 2011 by Ron Karpilo (bottom).....       | 54 |
| <b>Figure A-11.</b> Comparison of photography of a glacier in Windy Creek originally taken by Stephen R. Capps in 1919 (top ) and July 30, 2011 by Ron Karpilo (bottom). .....                | 55 |
| <b>Figure A-12.</b> Comparison of the lower section of West Fork Cantwell Glacier between 1928 (top by S. R. Capps) and 2011 (bottom photo by Sam Hooper). .....                              | 56 |
| <b>Figure A-13.</b> Comparison of the lower section of West Fork Cantwell Glacier between 1928 (top by S. R. Capps) and 2011 (bottom photo by Sam Hooper). .....                              | 57 |
| <b>Figure A-14.</b> Comparison of the terminus of Kahiltna Glacier and small glaciers in the surrounding mountains between summer 1916, summer 2004, and September 14, 2011.                  | 58 |
| <b>Figure A-15.</b> Comparison of panoramic photography of middle fork Toklat glacier originally taken by Stephen R. Capps in summer 1919 (top) and July 7, 2012 (bottom by Rob Burrows)..... | 59 |



## Tables

|                                                                                                                                                                                     | Page |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| <b>Table 1.</b> Long-term mass balance monitoring continued for the 23 <sup>rd</sup> consecutive year in 2013 on Kahiltna and Traleika Glaciers in Denali National Park.....        | xiii |
| <b>Table 2.</b> Cumulative errors for each glacier-averaged value in meters water equivalent. These were calculated based on Equation 1.....                                        | 26   |
| <b>Table 3.</b> Watershed-wide loss rates calculated from individual glaciers for time spans between 2002 and 2013. ....                                                            | 27   |
| <b>Table 4.</b> Differences between 2010 DTM and 2011 GPS heights and debris thicknesses at the GPS points on west fork Teklanika glacier.....                                      | 30   |
| <b>Table 5.</b> Summary tables for Kahiltna glacier index stakes .....                                                                                                              | 34   |
| <b>Table 6.</b> Summary tables for Traleika glacier index stakes.....                                                                                                               | 34   |
| <b>Table 7.</b> Results of a correlation analysis between the seasonal balances and annual balance from the period of 1991 to 2013 for the Kahiltna and Traleika index stakes. .... | 36   |
| <b>Table B-1.</b> Balance Data from the worksheet used to calculate the balances from the data collected in the field.....                                                          | 61   |
| <b>Table B-2.</b> Ice motion and glacier surface height data from the long-term observation sites on Kahiltna Glacier from index stakes.....                                        | 65   |
| <b>Table B-3.</b> Ice motion and glacier surface height data from the long-term observation sites on Traleika Glacier from index stakes. ....                                       | 66   |

## Appendices

|                                                                    | Page |
|--------------------------------------------------------------------|------|
| Appendix A –Panoramas and Comparative Photography.....             | 47   |
| Appendix B – Index Data .....                                      | 61   |
| Appendix C – Short report for DENA Current Resource Projects ..... | 69   |



## List of Acronyms

|      |                                               |
|------|-----------------------------------------------|
| APU  | Alaska Pacific University                     |
| BY   | Balance Year                                  |
| CAKN | Central Alaska Network                        |
| DENA | Denali National Park and Preserve             |
| ELA  | Equilibrium Line Altitude                     |
| GPS  | Global Positioning System                     |
| IHOG | Interagency Helicopter Operations Guidelines  |
| NPS  | National Park Service                         |
| PPK  | post processed kinematic GPS survey           |
| RPRS | Research Permit Reporting System              |
| UAF  | University of Alaska                          |
| WRST | Wrangell-St. Elias National Park and Preserve |

## List of Variables

|                         |                                                                                                                                                                                   |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $b'$                    | height of snow surface on stake                                                                                                                                                   |
| $b'_0$                  | height of snow surface on stake at initial time                                                                                                                                   |
| $b'_1$                  | height of snow surface on stake at time 1                                                                                                                                         |
| $b'_{ss}$               | height of summer surface on stake                                                                                                                                                 |
| $b_n(f)$                | new firn with transient water subtracted out                                                                                                                                      |
| $b_a$                   | annual balance                                                                                                                                                                    |
| $b_{al}$                | the annual balance at the index stake                                                                                                                                             |
| $b_{aAELA}$             | the annual balance at the ELA                                                                                                                                                     |
| $b_s$                   | summer balance                                                                                                                                                                    |
| $b_w$                   | winter balance                                                                                                                                                                    |
| $\Delta b_a / \Delta Z$ | balance gradient                                                                                                                                                                  |
| $h_s$                   | snow height/depth                                                                                                                                                                 |
| $h$                     | glacier surface elevation                                                                                                                                                         |
| $\Delta h / \Delta t$   | glacier surface elevation rate of change                                                                                                                                          |
| $\rho$                  | snow density                                                                                                                                                                      |
| $S_{wi}$                | the irreducible water-volume constant, in other words the water retained in snow by capillary retention this is considered to be a ratio of 0.07 of the void space (Colbeck 1974) |
| $t_0$                   | initial time                                                                                                                                                                      |
| $t_1$                   | time 1                                                                                                                                                                            |
| $V_e$                   | emergence velocity                                                                                                                                                                |
| $Z_0$                   | glacier surface height at initial time                                                                                                                                            |
| $Z_1$                   | glacier surface height at time 1                                                                                                                                                  |
| $Z_{AELA}$              | the elevation of the long-term (average) ELA                                                                                                                                      |
| $Z_I$                   | the elevation at the index stake                                                                                                                                                  |



## Executive Summary

Glaciers are a significant resource of mountain range ecosystems in Alaska and a fundamental resource of Alaska's National Parks. The glacier covered area of Denali National Park (DENA) and Wrangell-St. Elias National Park (WRST) are vast. Glaciers in DENA cover ~4,000 km<sup>2</sup>, approximately one sixth of the area of the park. Glaciers in WRST cover ~13,000 km<sup>2</sup>, approximately 25% of the park's area. They are integral components of the region's hydrologic, ecologic, and geologic systems. Glaciers continue to be monitored as a prominent and integral Vital Sign of the Central Alaska Network Inventory and Monitoring program (CAKN) in the landscapes and ecosystems of these parks.

This report details results of monitoring efforts at DENA for the 2010/11, 2011/12, and 2012/13 balance years. A balance year extends from October 1 to September 30. No ground based monitoring has been done by the NPS at WRST to date.

**Table 1.** Long-term mass balance monitoring continued for the 23<sup>rd</sup> consecutive year in 2013 on Kahiltna and Traleika Glaciers in Denali National Park. A summary of 2011 to 2013 balance data for the index monitoring sites of these two glaciers are reported in the table below. Balances are reported in meters water equivalent.

| Glacier  | year | stake<br>winter<br>balance | winter<br>balance<br>percent<br>of<br>average | stake<br>summer<br>balance | summer<br>balance<br>percent<br>of<br>average | stake<br>annual<br>balance | Equilibrium<br>line altitude<br>(meters) | Annual stake<br>velocity<br>(meters/year) |
|----------|------|----------------------------|-----------------------------------------------|----------------------------|-----------------------------------------------|----------------------------|------------------------------------------|-------------------------------------------|
| Kahiltna | 2011 | 0.43                       | 42                                            | -1.03                      | 111                                           | -0.61                      | 2116                                     | 208                                       |
|          | 2012 | 0.72                       | 70                                            | -0.82                      | 87                                            | -0.10                      | 1948                                     | 213                                       |
|          | 2013 | 1.29                       | 127                                           | -0.56                      | 60                                            | 0.73                       | 1676                                     | 217                                       |
| Traleika | 2011 | 0.39                       | 60                                            | -1.89                      | 138                                           | -1.49                      | 2410                                     | 100                                       |
|          | 2012 | 0.75                       | 114                                           | -0.86                      | 63                                            | -0.11                      | 2108                                     | 100                                       |
|          | 2013 | 0.72                       | 110                                           | -1.35                      | 99                                            | -0.63                      | 2168                                     | 109                                       |

New glacier extent maps, glacier inventories, and volume change estimates for DENA and WRST were delivered in 2011-2014 via a cooperative agreement established with University of Alaska, Fairbanks (UAF) and Alaska Pacific University (APU) (Loso et al 2014). Results from this study indicate the area of glaciers in DENA decreased by 8% between 1952 and 2010, with most of this loss occurring on small to medium size glaciers at mid-elevations (1400-1800 meters elevation). A maximum estimate for volume change is a loss of 12%. A few glaciers increased in area during the same time period but this was due to surging, most notably Muldrow and Peters Glaciers. Area of glaciers in WRST decreased by 5% between ~1957 and ~2010. A maximum estimate for volume change in WRST is a loss of 20%.

Several groups of citizen scientists contributed to the effort of tracking glacier change of five different glaciers using repeat photography and GPS mapping of terminus positions and surface elevation change. In 2011 Sam Hooper conducted repeat photography and took GPS points of the terminus of the west fork Cantwell glacier; Brian Schimdt and friends collected GPS points that mark

the current terminus of the west Teklanika glacier; and in a larger repeat photography effort Ron Karpilo repeated several Stephen R. Capps photos of glaciers in Denali, originally taken in the early 20<sup>th</sup> century. These include the Polychrome glaciers and small glaciers in the Sanctuary River watershed. In 2012 seven participants joined the first Murie Science and Learning Center seminar, titled “Glaciology: Backcountry Citizen Science” to explore and map the middle fork Toklat glacier. In 2013 seven participants joined the seminar to explore and map the west fork Toklat glacier. The results from the mapping using survey-grade GPS are compared with a new digital terrain model mapped in 2010. Between 2010 and 2012 middle fork Toklat glacier on a glacier-wide average lost ice volume at  $1.22 \pm 1.82$  m w.e./yr and west fork Toklat lost  $0.74 \pm 1.04$  m w.e./yr between 2010 and 2013.

Panoramic photos of multiple images stitched together were taken in 2011 and 2012 at the index glaciers and other select glacier-related sites. Many of these are being incorporated into DENA’s public website where they offer the opportunity for exploration and a virtual, nearly immersive experience (<http://www.nps.gov/dena/photosmultimedia/360-panos.htm>).

In 2011 we published and discussed results to date of DENA glacier monitoring in the Summer 2011 issue of Park Science: Glacier trends and response to climate in Denali National Park and Preserve, by Rob Burrows, Samuel Herreid, Guy Adema, Anthony Arendt, and Chris Larsen (<http://www.nature.nps.gov/parkscience/index.cfm?ArticleID=509>).

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Special thanks to Don Burrows for processing and analyzing the data from the Toklat glaciers and for his support and inspiration as a father



## Introduction: Background

Glaciers are a significant resource of mountain range ecosystems in Alaska and a fundamental resource of Alaska's National Parks. The glacier covered area of Denali National Park (DENA) and Wrangell-St. Elias National Park (WRST) are vast. Glaciers in DENA cover ~4,000 km<sup>2</sup>, approximately one sixth of the area of the park. Glaciers in WRST cover ~13,000 km<sup>2</sup>, approximately of the park's area. They are integral components of the region's hydrologic, ecologic, and geologic systems. Compellingly, recent research indicates ice loss from Alaska mountains has been accelerating and contributing to global sea level rise (Arendt et al 2002, 2008, Larsen et al 2009). Glaciers continue to be monitored as a prominent and integral Vital Sign of the Central Alaska Network Inventory and Monitoring program (CAKN) in the landscapes and ecosystems of these parks.

There are ten measurable objectives for glacier monitoring listed below. This report details results of monitoring efforts at DENA leading to these objectives for the 2010/11, 2011/12, and 2012/13 balance years. A balance year extends from October 1 to September 30. No ground based monitoring has been done by the NPS at WRST to date. This report adds to the published long-term record of CAKN glacier monitoring data. The last report was completed by Burrows and Adema (2011).

### **All Glaciers:**

- Extent/area at 10-year intervals (equilibrium line altitudes (ELAs) are determined when possible);

### **Selected Glaciers:**

- Terminus morphology and longitudinal profile/surface elevation mapping.
- General condition of selected glaciers via repeat photography;
- Assess ELAs on a yearly basis at selected glaciers throughout;
- Identify surging glaciers and take measurements when possible;

### **Index Glaciers:**

- Winter balance at index stations;
- Summer balance at index stations;
- Net mass balance at index stations;
- Twice yearly surface elevation at index stations;
- Twice yearly glacier surface velocity near index stations;
- Assess surface cover in late fall for each index glacier;



# Methods

## Extent

Glacier extent mapping of all CAKN glaciers and volume change analysis of selected CAKN glaciers was accomplished under a cooperative agreement with University of Alaska Fairbanks and Alaska Pacific University and separately reported in detail (Arendt et al. 2012, Arendt et al. 2014). Some of the results of that study are reported here in order to summarize and widen the reach of results for glaciers in CAKN. The most recent extent was mapped using the best available satellite imagery from 2003 to 2010 with automated algorithms and manual adjustment. Area changes were compared against the glacier boundaries mapped from the US Geological Survey Alaska quadrangle maps produced from 1950s aerial photography. In addition, Arendt et al. (2012) developed automated methods to define separate glaciers at drainage divides and hence for the first time allow the creation of an inventory of glaciers coupled with basic geographic attributes (area, aspect, elevation range, etc.).

Also under cooperative agreement with University of Alaska Fairbanks and Alaska Pacific University and separately reported in detail (Arendt et al. 2014), volume change at various times since the 1990s was determined on select glaciers using profiles and swaths of surface elevation using airborne lidar altimetry (Arendt et al. 2014). The altimetry data is then extrapolated by 30 meter elevation bins to the entire glacier to calculate a glacier-wide mass balance change. This volume estimate was divided by the total area of the entire glacier to find the area averaged mass balance and divided by the time elapsed between successive measurements to find the rate of change. (Arendt et al. 2014).

In addition the author, Rob Burrows, mapped total areal and debris-covered extent of the middle and west fork Toklat glaciers in Denali. Mapping debris-covered ice allows for a more refined calculation of volume loss when coincident changes in surface elevation are mapped. Ablation rates of debris-covered ice are usually substantially different than bare ice. Most of the debris cover has sufficient thickness so that the primary effect is decreased ice melt rates. However, debris cover on ice tends to enhance melting up to a certain thickness called the effective thickness which is between 1–2 cm in most empirical studies (e.g. Nakawo and Rana 1999). The critical thickness is defined as the debris thickness in which ice melt is equal to that of bare ice. This occurs between 2 and 4 cm in the study cited above. When the debris cover is thicker than the critical thickness, ice change in melt rates decrease quickly then follow an asymptotic curve where the curve approximately stabilizes at a thickness of 15 to 20 cm.

Ice extent and cover was mapped using optical IKONOS satellite imagery taken in 2004 (Space Imaging LLC 2011) and SPOT 5 imagery in 2010 (Open Geospatial Consortium 2011). However, the 2010 imagery only had coverage for west fork Toklat Glacier. Areal extent and debris-covered ice was mapped by on screen digitizing Debris that insulates the ice is discerned by having higher topographic height than the surrounding ice. Such areas are easily discerned by comparing the optical imagery and a 2010 digital terrain model (DTM) hillshade map created using Interferometric Synthetic Aperture Radar (IFSAR) (Fugro EarthData Inc. 2011). In addition, ground truthing during

field work, reviewing field photos and the DTM hillshade allowed overall reduction in error and uncertainty when mapping seemingly ambiguous boundaries, particularly of debris-covered ice.

Ground-based surface elevation mapping allows for an estimate of glacier volume change rates. During citizen science courses the active terminus of each glacier was mapped and surface elevations were collected on the deglaciated fore field below the current terminus, debris-covered ice connected to the active glacier, and bare ice. Mapping was accomplished using both mapping grade GPS (Trimble GeoXH) and survey grade (Trimble R6). One Trimble R6 receiver was established at a ground control point to serve as a base station. A second R6 rover was used to conduct the survey in both real time kinematic (RTK) and post processed kinematic (PPK) mode (depending on radio connectivity). Data collected with the GeoXH was post processed against the R6 base station. Base station data was processed through the Online Positioning User Service (OPUS, <http://www.ngs.noaa.gov/OPUS/>) to find the GPS solution and tie the position to the National Spatial Reference System.

To compare recent surface elevation change, the GPS data collected on middle fork Toklat glacier in 2012 and west fork Toklat glacier in 2013 were compared to the most recent digital terrain model (IFSAR DTM) mapped in July 2010 (Fugro EarthData Inc. 2011). The GPS data was post processed to reflect the same horizontal geodetic model and vertical datum as the DTM (NAD 83 CORS96 Epoch 2003.00 and Geoid09-Alaska respectively).

Volume change amounts and rates between 2010 and 2012/13 of the two Toklat glaciers were calculated by first finding the elevation change ( $\Delta h$ ) between the 2010 IFSAR DTM and each GPS point collected. And then finding the rate of change ( $\Delta h/\Delta t$ ) by dividing by the time elapsed between the DTM and the GPS survey. Elapsed time is counted to the nearest year (i.e. 1,2,3...) Points were separated into two categories whether they fell on bare-ice or debris-covered ice based on the latest available cover mapping (from 2004 or 2010 imagery). Next, a best fit function using regression analysis was found between GPS point elevation and elevation change rate ( $\Delta h/\Delta t$ ) for bare and debris-covered ice areas respectively. These functions were then applied to the mid elevation of 30-meter elevation bins for bare and debris-covered ice on the glacier to calculate a glacier-wide mass balance. The 30-meter bins were chosen to match similar efforts using airborne laser altimetry (Loso et al 2014, Das et al 2014). Note that surface elevation data may not be collected for the entire glacier elevation range (particularly the upper accumulation area). In this case, the surface elevation change for the area above surveyed points may be extrapolated or estimated on a case by case basis. This volume estimate was divided by the total area of the entire glacier to find the area-averaged mass balance and divided by the time elapsed between the DTM and the GPS survey to find the rate of change.

Volume change rates for the entire Toklat watershed are estimated by applying the regression equations ( $\Delta h/\Delta t$  versus  $h$ ) from a single glacier across the 30-meter bins for all glaciers in the watershed. The variable  $h$  is the 2010 elevation. The simplest way to estimate ice loss rates across the watershed is to apply the  $\Delta h/\Delta t$  versus  $h$  curves from middle fork and west fork Toklat glaciers to the glacier area altitude distribution (AAD; also termed hypsometry) for the entire Toklat Watershed. Johnson et al. (2013) applied a normalized elevation to “regionalize”  $\Delta h/\Delta t$  curves to best extrapolate

airborne laser altimetry data (similar data to this study) across the Glacier Bay region. Such normalization is not necessary for this data because the area of extrapolation is much smaller and all glaciers occupy similar elevation ranges and topographic positions.

Several sources of error feed uncertainty about interpreting elevation change data. Each data source has a unique suite of errors associated with it. The IFSAR DTM has elevations captured every 5 meters (or a 5 meter resolution) with a reported horizontal positional accuracy of 2 meters and a vertical positional accuracy ( $E_{DTM}$ ) of 1 meter or better in areas of unobstructed flat ground (Fugro EarthData Inc. 2011). Each type of GPS unit used has a different accuracy. The Trimble GeoXH has a horizontal and vertical accuracy of  $\pm 0.50$  m (or better), whereas under ideal conditions the Trimble R6 system is  $\pm 0.01$  to  $0.05$  m. However, many of the points surveyed with the R6 system were done with the receiver backpack-mounted in “continuous topo” mode collected while the operator was hiking, hence such movement likely introduced additional error. Overall GPS error ( $E_{GPS}$ ) is estimated for each survey based the type of GPS used and the measurement technique.

Comparing horizontal positional accuracy between the GPS and the DTM is problematic because of the relatively coarse resolution of the DTM compared to the much more precise GPS measurements. However, vertical accuracy is much more useful since the aim of the measurements is to capture glacier surface elevation changes. Error estimation reflects the cumulative effect of GPS measurement error and differences in height between GPS and DTM at any given point. Some of the GPS measurements were made on areas of stable ground not underlain by ice. There are enough of these measurements from the Trimble R6 that by differencing these with the DTM elevations, a distribution of residual values emerges for each survey. Assuming a normal distribution of the residuals, the 95% confidence interval is used to represent the error of the GPS and DTM difference for each survey ( $E_{DIFF}$ ). Since  $E_{DIFF}$  is a measure of the accuracy of the DTM with reference to GPS measurements it is used instead of  $E_{DTM}$  in the error propagation equation below.

Extrapolating the survey results across each glacier and the watershed requires accounting for additional errors and error propagation. The volume to mass conversion error is  $(E_D) \pm 0.60 \text{ kg/m}^3$  (Huss 2013). The representation error ( $E_R$ ) is due to the assumption that the regression equation derived from GPS data represent the entire glacier and that the single glacier data used represents glaciers in the entire watershed. Since separate calculations are done for bare ice and debris-covered ice, the  $E_R$  is divided into two components for bare and debris-covered ice ( $E_{BR}$  and  $E_{DR}$ ). Each of these is represented by the standard error of the estimate based on the regression line or mean used for each component.

All errors discussed above are combined in quadrature (Das et al. 2014).

$$E_{TOT} = (E_{GPS}^2 + E_{DIFF}^2 + E_D^2 + E_{BR}^2 + E_{DR}^2)^{1/2} \quad (\text{eq. 1})$$

### ***Comparative Photography***

Comparative or repeat oblique photography was conducted on select glaciers with historical photos for qualitative comparisons of area and volume changes (Karpilo 2009). In addition recent comparative photography was taken at the index sites. This uses high resolution digital panoramic

photography (also known as gigapixel panoramic photography). Details of these methods are described in the corresponding standard operating procedure of the draft protocol (Burrows and Adema, in progress).

### Index Station Measurements

The methods for index stations on Kahiltna and Traleika glaciers are described in detail Burrows and Adema (in progress). See Figure 1 for a visual representation of the methods and instruments, Figures 2 and 3 for locations of stakes near index stations (pages 9 & 10 and 11), and Figure 4 for locations of the glaciers in DENA (page 12,13). The index stations are monitored twice a year, once in the spring and once in the fall. The spring visit is designed to capture the maximum winter balance and occurs sometime in late May to early June each year. This spring field campaign collects snow depth, snow density, glacier stake height (in relation to the glacier surface), glacier surface height, stake position data at each index station, and 360-degree gigapixel panoramas. Three new stakes were placed on each glacier in spring 2013 to provide more data about spatial variability and balance gradients. The new stakes on Kahiltna were placed above the two existing index stakes (Figure 2). The new stakes on Traleika were placed near the confluence of the Traleika Glacier with the Muldrow Glacier (Figure 3).

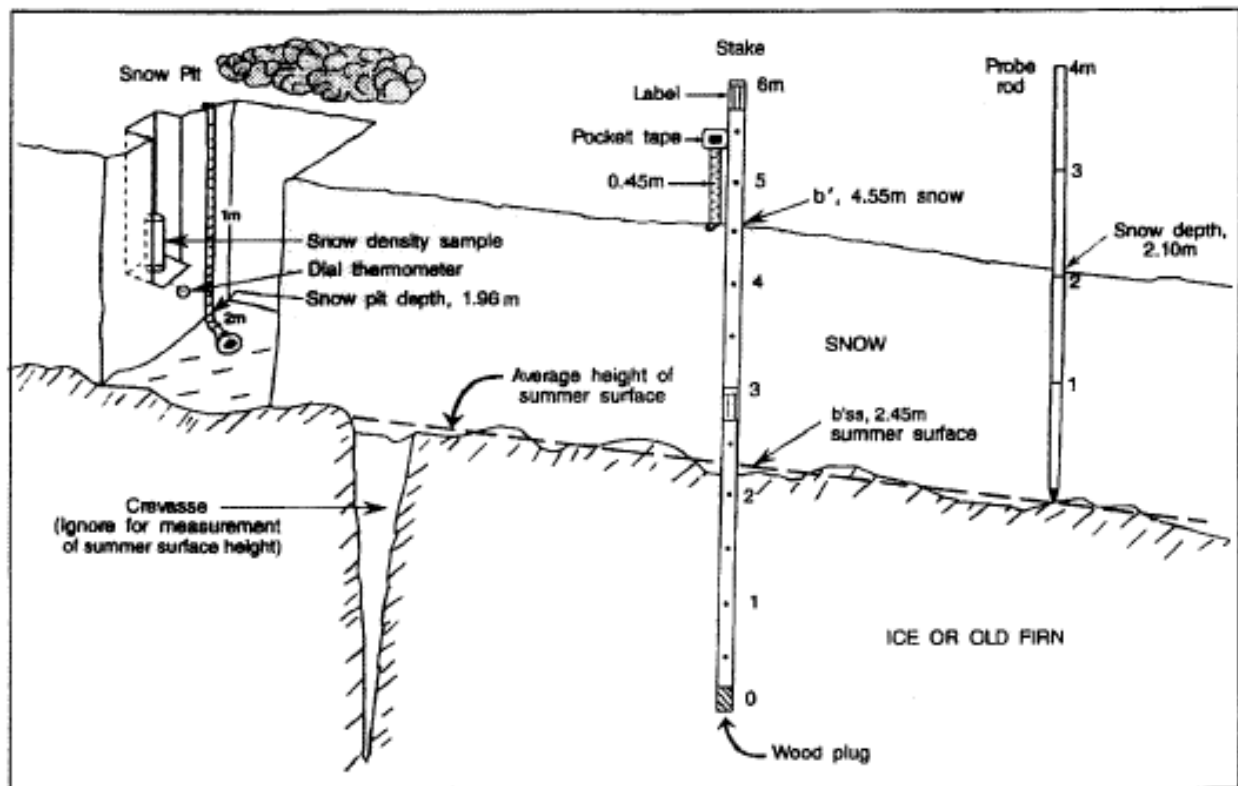


**Figure 1.** An illustration of the measurements taken and instruments used at an index stake. See text and protocol for further explanation. From Mayo (2001).

The fall visit, designed to capture the minimum balances for the year, occurs sometime from early-August to mid-September. The fall field campaign collects snow depth and density (if any remains),

glacier stake height (in relation to the glacier surface), glacier surface height, stake position data at each index station, and 360-degree gigapixel panoramas.

Glacier stake position and surface height have been measured at each seasonal visit using primarily survey-grade GPS (Trimble R6 two-receiver system), however in 2012 and 2013 mapping grade GPS was used on the fall visits (Trimble GeoXH 2005 Series) and will become the primary method at seasonal visits in future years. The cost of additional time to set up and post process the survey-grade data does not outweigh the benefits of the increased precision.

Glacier mass balance terms and variables used in this report follow the convention of Ostrem and Brugman (1991) with some revisions made to variables based on Cogley et al (2011). Balance (b) is a change in mass measured at a point (at a stake) on the glacier for one or more periods of time. By convention the balance year (BY) is the period between two successive times of minimum balance in late fall. The BY is designated by the calendar year in which it ends.

Accumulation includes all processes that add mass to the glacier such as snowfall, wind drifting, avalanching, rime ice buildup, rainfall, superimposed ice, and internal accumulation. Winter balance ( $b_w$ ) is the sum of all accumulation and ablation during the winter season (also referred to as the accumulation season). At the equilibrium lines of the index glaciers the time of maximum winter balance typically occurs in mid-May to early June. The  $b_w$  is the product of accumulated snow depth or height of snow, ( $h_s$ ) between the upper surface to the previous year's summer surface and the snow density ( $\rho$ ) at a single point on the glacier surface.

$$b_w = h_s \quad \square \quad (eq. 22)$$

The summer surface is the surface of firn and/or ice on which the new winter season's snow is deposited. A dirty layer and significant change in density typically identify it. The height of the summer surface, as measured by the distance from the base of the stake, is designated  $b'ss$ . Likewise the height of the snow surface is designated  $b'$  (Figure 1), such that:

$$h_{snow} = b' - b'ss \quad (eq. 33)$$

Ablation includes all processes that remove mass from the glacier such as melting and runoff, evaporation, sublimation, calving, and wind erosion. The summer balance ( $b_s$ ) includes the total of all ablation and accumulation during the summer season at a single point on the glacier surface (always a negative value as indicated below).

$$b_s = - (h_{snow}\rho_{snow} + h_{firm}\rho_{firm} + h_{ice}\rho_{ice}) \quad (eq. 44)$$

Summer balance is determined at the end of the BY. At the equilibrium line of the index glaciers this typically occurs during the period of early-August to mid-September. The symbols  $b_w$  and  $b_s$  refer to values measured and/or calculated at a stake or other measurement point. Likewise the annual balance ( $b_a$ ) is the change in balance calculated at a measurement point during one BY. These balance values are expressed in meters water equivalent (m w.e.).

$$b_a = b_w + b_s \quad (\text{eq. 55})$$

Note that the annual balance ( $b_a$ ) is in new usage with this report. Annual balance is used instead of net balance ( $b_n$ ) following the newly published Glossary of Glacier Mass Balance and Related Terms (Cogley et al 2011).

In positive balance years the seasonal snow remaining at the end of the summer season is assumed to be new firm. This remaining quantity is equivalent to a positive  $b_a$  calculated in eq. 4. Snow that becomes new firm is a mixture of ice crystals, liquid water, and air. However, the liquid component is in temporary storage. Some of it is converted into internal accumulation by freezing during the next winter (Trabant and Mayo 1985); the rest is thought to drain from the glacier as the firm gradually compresses into glacier ice. The liquid component of new firm creates a potential problem in glacier mass balance accounting, because the same material could be counted twice, once in the new firm, and a second time when it freezes. To account for this, the following calculation is applied to the annual balance. The liquid component is subtracted from the snow balance when snow becomes new firm. The amount of ice (without water) in new firm,  $b_n(f)$ , is found by subtracting the water volume retained by capillary retention from the arithmetic  $b_n$  of eq. 4.

$$b_n(f) = b_a - S_{wi} [h_{\text{snow}}(1 - \rho_{\text{snow}}/\rho_{\text{ice}})] \quad (\text{eq. 6}) \text{ where:}$$

$h_{\text{snow}}$  of eq. 2, is the remaining snow at the end of the summer season.

$S_{wi}$  is the irreducible water-volume constant, in other words the water retained in snow by capillary retention this is considered to be a ratio of 0.07 of the void space (Colbeck 1974).

### **Equilibrium Line Altitude**

Fluctuations in the ELA from year to year signal annual fluctuations in climate and given the limited mass balance data available for these glaciers is the best indicator for comparison of long-term trends and with other glaciers in Alaska. The annual ELA can be determined in two ways. The first method is to observe the elevation of the transient snow line at the end of the summer season. This may be ambiguous if this is not a well-defined line or zone and/or if one cannot discern the current year's snow from previous years. In addition, it may become completely obscured with early snow fall. The more accurate method to determine the annual ELA is to find the altitude at which  $b_a = 0$ . Ideally this is calculated using two or more mass balance stakes to determine the balance gradient,  $\Delta b_a/\Delta Z$ , for the glacier for the year. In the case where balance is measured at one site, a balance gradient is assumed. Fortunately, balances were measured at two sites on both Kahiltna and Traleika glaciers for 4 and 5 years, respectively in the 1990s (Mayo 2001). The average balance gradient,  $\Delta b_a/\Delta Z$ , from this data is used to find the ELA:

$$\text{ELA} = Z_I - b_{aI}/(\Delta b_a/\Delta Z) \quad (\text{eq. 77})$$

Where:  $Z_I$  is the elevation at the index stake and  $b_{aI}$  is the annual balance at the index stake.

Similarly, the net balance at the long term average ELA is found using the same principles and is also a useful value to compare with results from monitoring programs on other glaciers:

$$B_{aAELA} = b_{al} - [(\Delta b_a / \Delta Z) (Z_1 - Z_{AELA})] \quad (\text{eq. 88})$$

Long-term average ELAs for the Kahiltna and Traleika glaciers are shown in Figures 2 and 3.

### **Glacier Motion**

Glacier motion was measured by repeat GPS measurements on the ablation stake at each visit. Glacier speed is calculated simply by taking the quotient of the distance traveled and time between measurements. Emergence velocity ( $V_e$ ) is the rate at which ice is emerging or firn is being buried at the stake location.

$$V_e = [(Z_1 - Z_0) - (b'_1 - b'_0)] / (t_1 - t_0) \quad (\text{eq. 99})$$

Where:  $t_1$  and  $t_0$  are the later time and initial time, respectively.

$Z_1$  and  $Z_0$  are the glacier surface heights at a later time and an initial time, respectively.

$b'_1$  and  $b'_0$  are the glacier stake heights at a later time and an initial time, respectively.

### **Glacier Surface Height**

Glacier surface height at each index station is measured at minimum by taking GPS measurements on the surface at approximately equidistant points of a triangle surrounding a fixed coordinate that is returned to at least once a year. Surface height at the index station for that visit is then simply the average height of those three measurements. Changes in surface height are then the difference of the average height. This approach allows for a consistent measurement from year to year, but covers a very small area of the entire glacier. When time allows during a field visit, a transect of surface elevations are collected across part of the glacier through the index point in order to sample a larger area. Results of these height surveys are not reported here but will be covered in a future report.

### **2011 Surge-type Glacier Observations**

Every two years a glacier surge search flight is made via NPS fixed-wing aircraft. This can often be conveniently combined with the March or April snow surveys flight. In addition signs of glacier surges are searched for while on monitoring flights in DENADENA. No glaciers are known to be surging in WRST.

Movement markers are tracked by repeat GPS surveys on Muldrow Glacier to track velocity on different parts of the glacier (Figure 3). These markers may not be visited at every seasonal visit, but when time and logistics allow. These are a lower priority in comparison to the index station data collection.

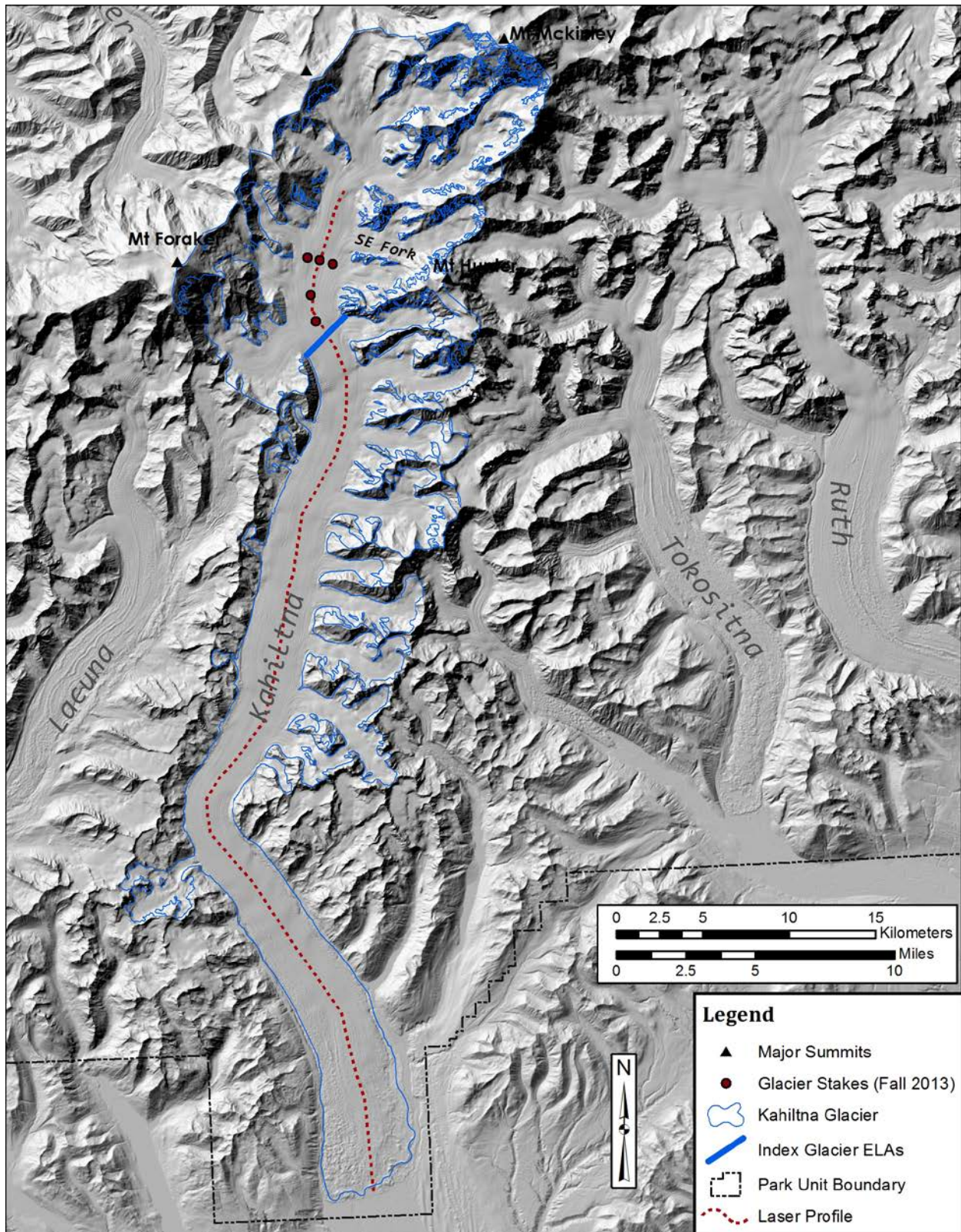


**Figure 2.** The Kahiltna Glacier system and surrounding glaciers with 2010 IFSAR DTM hillshade from 2000 Landsat imagery and associated mapped glacier margin (Loso et al 2014). The glacier equilibrium line altitude (ELA) is approximate, based on over 20 years of long term mass balance monitoring.

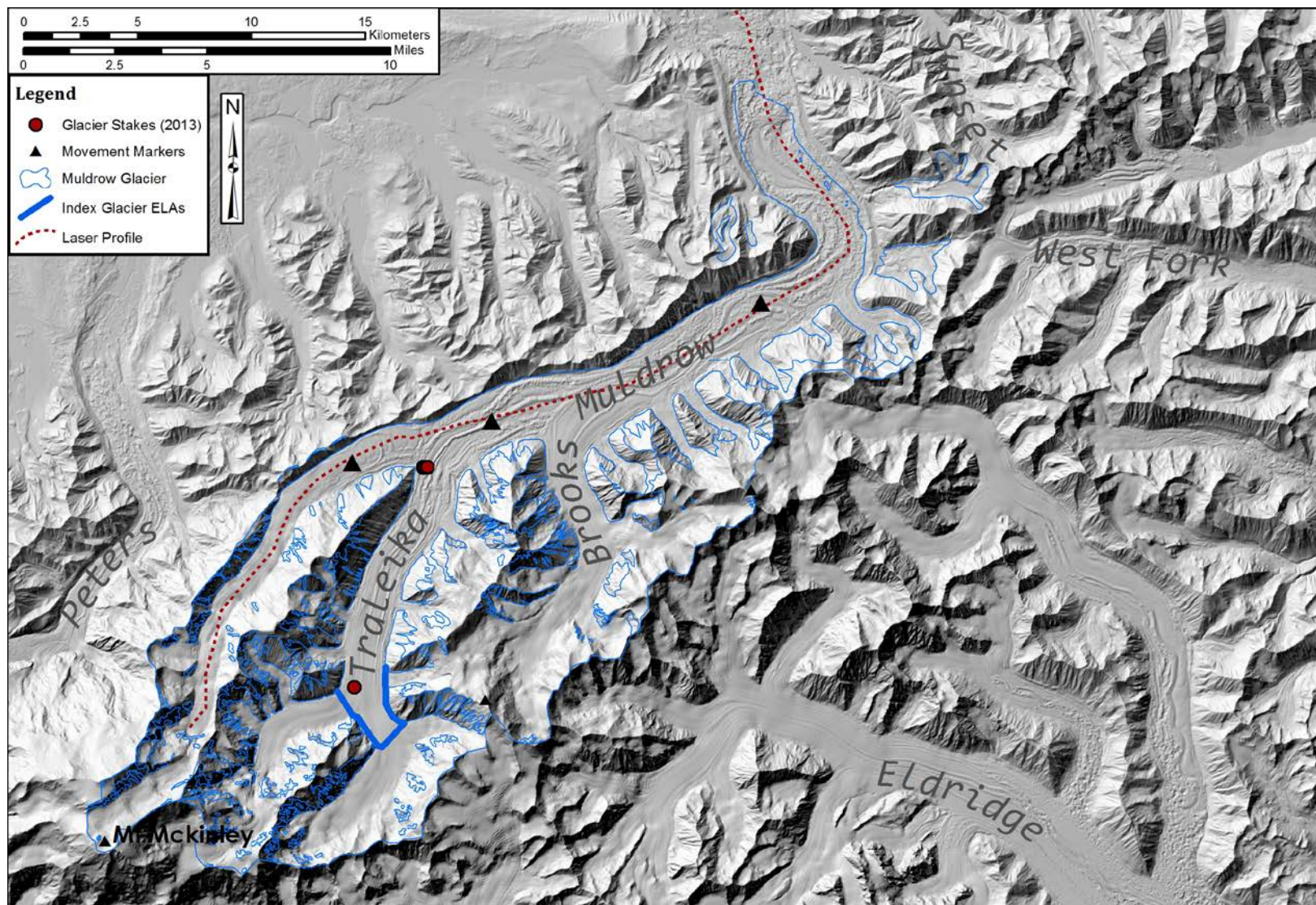


**Figure 3.** The Muldrow Glacier system and surrounding glaciers on the 2010 IFSAR DTM hillshade from 2000 Landsat imagery and associated mapped glacier margin (Loso et al 2014). The glacier equilibrium line altitude (ELA) is approximate and based on almost 20 years of long term mass balance monitoring. The laser profile refers to the path flown and line measured for repeat surface elevation surveys by UAF researchers.



# Results

## Extent

Via a cooperative agreement with the NPS Alaska Regional Office, the University of Alaska, Fairbanks and Alaska Pacific University (Anthony Arendt, Chris Larsen, Mike Loso and others) are completing work and reporting in 2014 on the status and trends of glaciers in all glacier-clad national parks in Alaska (Arendt et al 2012, 2013, 2014; Loso et al 2014).

In the First Progress Report for Alaskan National Park Glaciers: Status and Trends, Arendt et al. (2012) report on a new glacier extent map and inventory for DENA. The new extents are mapped from satellite imagery from ~2010 and show that glaciers in DENA have lost approximately 8% (330 km<sup>2</sup>) of their area since the 1950s (Figure 4). This data is available worldwide in the Global Land Ice Measurements from Space database (GLIMS; <http://www.glims.org/>) This data was also reported on an article about DENA glaciers in Park Science (Burrows et. al 2011).

In the Fourth Progress Report for Alaska National Park Glaciers: Status and Trends, Arendt et al. (2014) report that WRST and surrounding area with mapped glacier cover lost ~5% of its glacier area (Figure 5). This loss is calculated for the entire park for a broad range of years because of early map photography ranging from 1948 to 1973. The second inventory is from satellite imagery taken from 2006-2011. Five percent is a relatively small percentage but because of the huge area of ice in WRST this results in approximately 1660 km<sup>2</sup> of ice area lost.

## ***Panoramic and Comparative Photography***

Multi-image panoramas were photographed from eight sites during the field campaigns from 2011-2012 (See Appendix A; Figures A-1 to A-8). See Figure 4 for locations of these glaciers in DENA. At the date of this writing, the panoramas can be viewed from any computer with a high-speed internet connection on the Gigapan website, <http://www.gigapan.org/profiles/27054/>. The Gigapan platform allows the viewer to zoom in on any area of interest at up to the level of detail captured by the camera lens.

Several new repeat photographs were made in 2011-2013 (Appendix A; Figures A-9 to A-14). See Figure 4 for locations of these glaciers in DENA. In 2011, Ron Karpilo repeated photographs originally taken by Stephen R. Capps of the Polychrome glaciers, east fork Toklat glacier, and a small glacier in upper Windy Creek. Sam Hooper on a backcountry ranger patrol repeated two photos in 2011 of west fork Cantwell glacier originally photographed by Stephen R. Capps in summer 1928. In 2011 Rob Burrows repeated a photo of the lower Kahiltna Glacier originally photographed by S.R. Capps in summer 1916, and again by Ron Karpilo in summer 2004. In 2012 Rob Burrows and citizen scientists repeated a photo of the middle fork Toklat glacier originally taken by Stephen R. Capps in 1919.

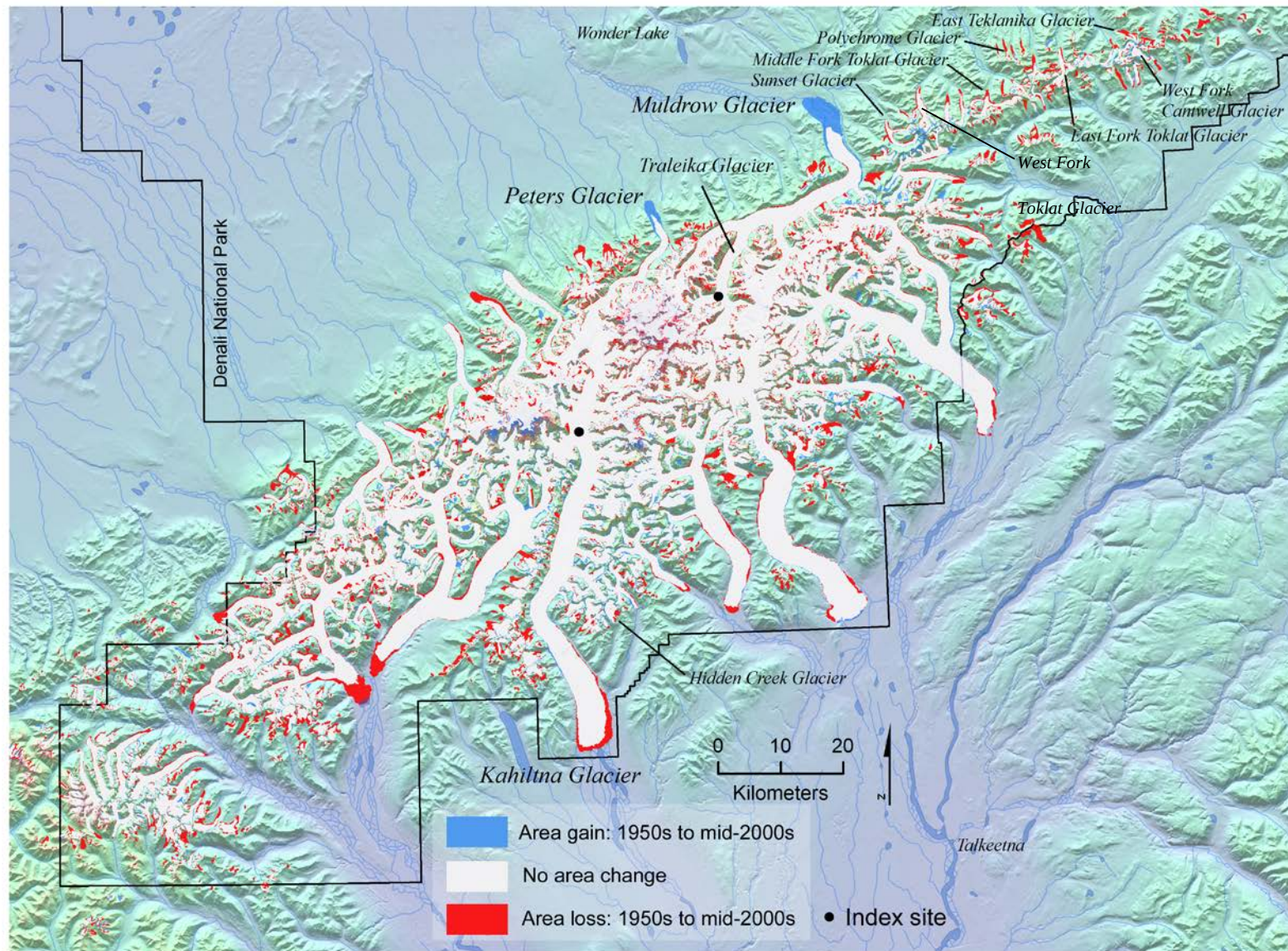


**Figure 4.** Changes in glacier area in Denali between the 1950s and ~2010. Map courtesy of Sam Herreid, University of Alaska Fairbanks.

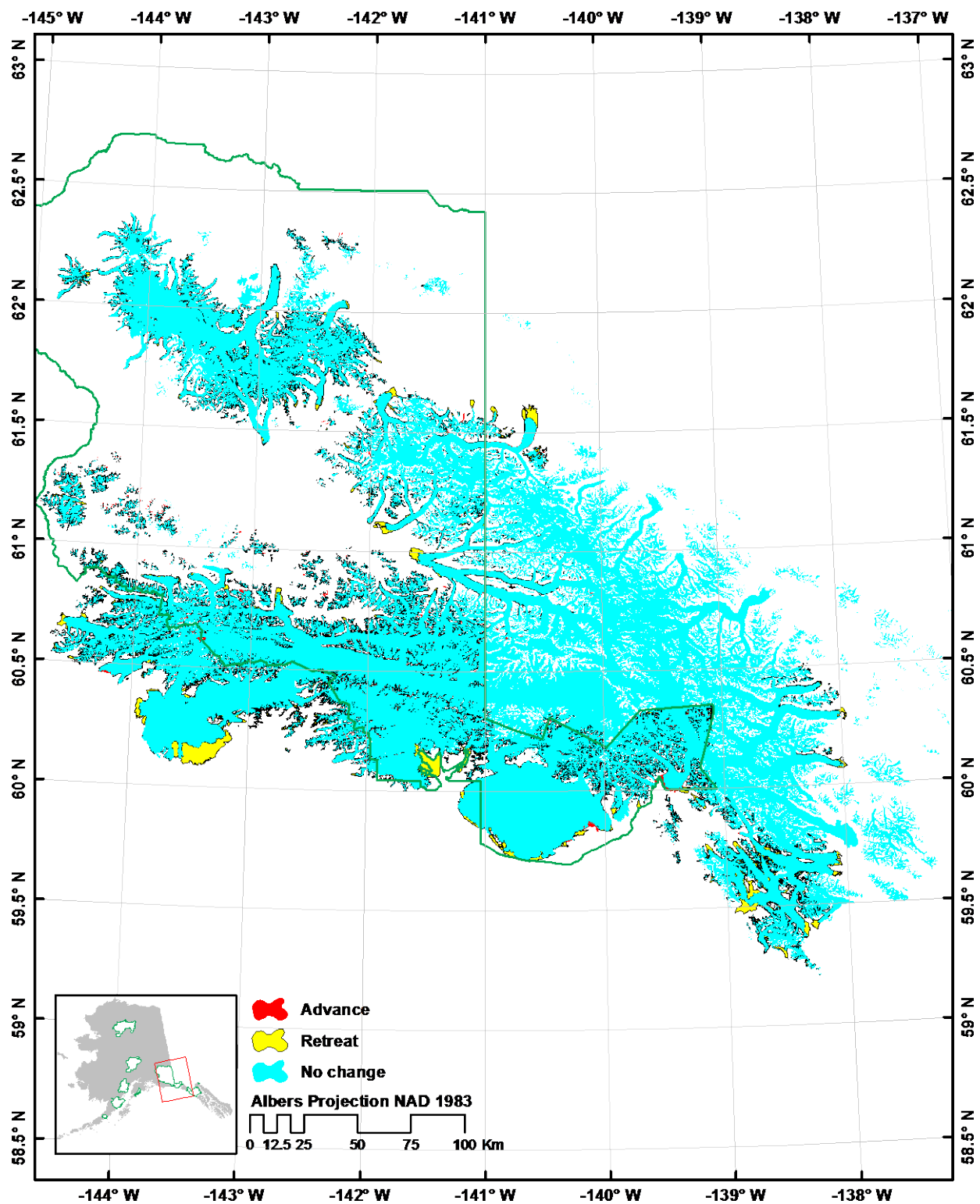


**Figure 5.** Changes in glacier area between map date and modern in Wrangell-St. Elias NP&P (from Arendt et al. 2013).

## Extent, Debris-Cover, and Surface Elevation Change of Focus Glaciers

### *West Fork Toklat Glacier*

The west fork Toklat glacier (WFT) is a 9.7 km<sup>2</sup> glacier in the western most branch of the upper Toklat River watershed (Figure 4 and 66). The terminus in 2013 was at 1255 m elevation and the highest point of the glacier was 2675 m.



**Figure 6.** West fork Toklat glacier. This photo was taken near a survey point established in 1992. The photo point and view will serve as a reference for future repeat photography. Photo by Don Burrows

This glacier was visited twice during the summer of 2013. First July 5-8 by Rob Burrows and Denny Capps for reconnaissance and second from August 12-16 with Rob Burrows leading a Murie Science and Learning Center Field Seminar: Glaciology, Backcountry Citizen Science. Four participants along with two field assistants joined the field seminar. The group learned about glaciers and climate change in Denali and collected over 9500 data points recording precise position and elevation data using mapping grade and survey grade GPS systems (Figure 77). The primary scientific contribution the citizen scientists on the glaciology course made was to collect mapping and survey grade quality elevation measurements with GPS.

Between 2004 and 2010 the total glacier area decreased by 3% from 10.0 km<sup>2</sup> to 9.69 km<sup>2</sup>, while the percentage of the glacier debris-covered area increased by 4.5% (to 41% of the total glacier area) (Figures 7 and 8). Hypsometry of bare and debris-covered ice areas was calculated for each year using cover type maps and the 2010 IFSAR digital terrain model and the results are presented in Figure 9. Surface elevation loss on the glacier ranged from 12.6 meters on the lower glacier to 0 meters at higher elevations.

### Ice Loss Estimates 2010-2013

Elevation change rates were determined from the GPS data for both bare ice and debris-covered ice and plotted against 2010 elevation. Bare ice elevation change rates show a strong dependence on elevation (Figure 10). The best fit function where  $h$  is the 2013 glacier surface elevation and  $\Delta h/\Delta t$  is the rate of change of elevation in meters/year then,

$$\Delta h/\Delta t = 0.00865h - 15.937$$

with a correlation  $R^2 = 0.939$ . This implies that  $\Delta h/\Delta t$  goes to zero at 1842 meters.

Plotting  $\Delta h/\Delta t$  versus  $h$  for debris-covered ice shows they are nearly independent with significant variability (Figure 11). The best option for calculating  $\Delta h/\Delta t$  for all debris-covered ice on the glacier is to use the mean rate, -1.26 m/yr.

Applying the  $\Delta h/\Delta t$  bare ice function and debris-covered ice mean loss rate above to elevation band areas for bare and debris-covered ice of the entire glacier yields an estimate of integrated ice loss rate of the entire glacier of 7,940,000 m<sup>3</sup>/year. Dividing by the entire area of the glacier results in an area averaged loss rate of 0.82 m/yr. Using 0.9 as the ratio between the density of water and ice this results in 0.74 m w.e./yr.

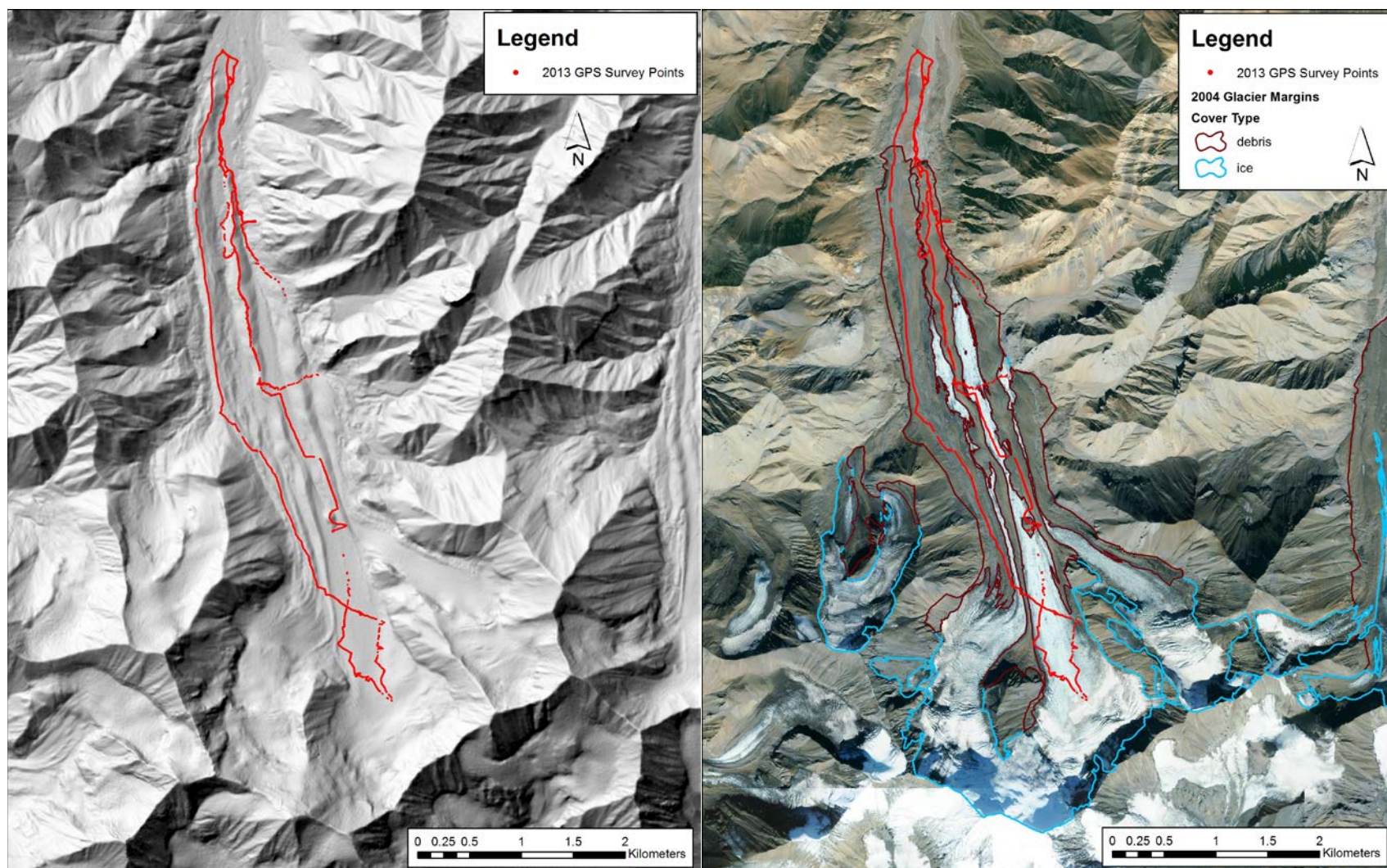


**Figure 7.** Two views of the west fork Toklat glacier and locations of the GPS surface elevations surveys (red dots and lines). The map on the left shows the hillshade of the 2010 IFSAR DTM. The map on the right is optical satellite imagery in 2004 from IKONOS with the GPS survey and mapped margins of the glacier and debris-covered ice that is part of the active glacier.

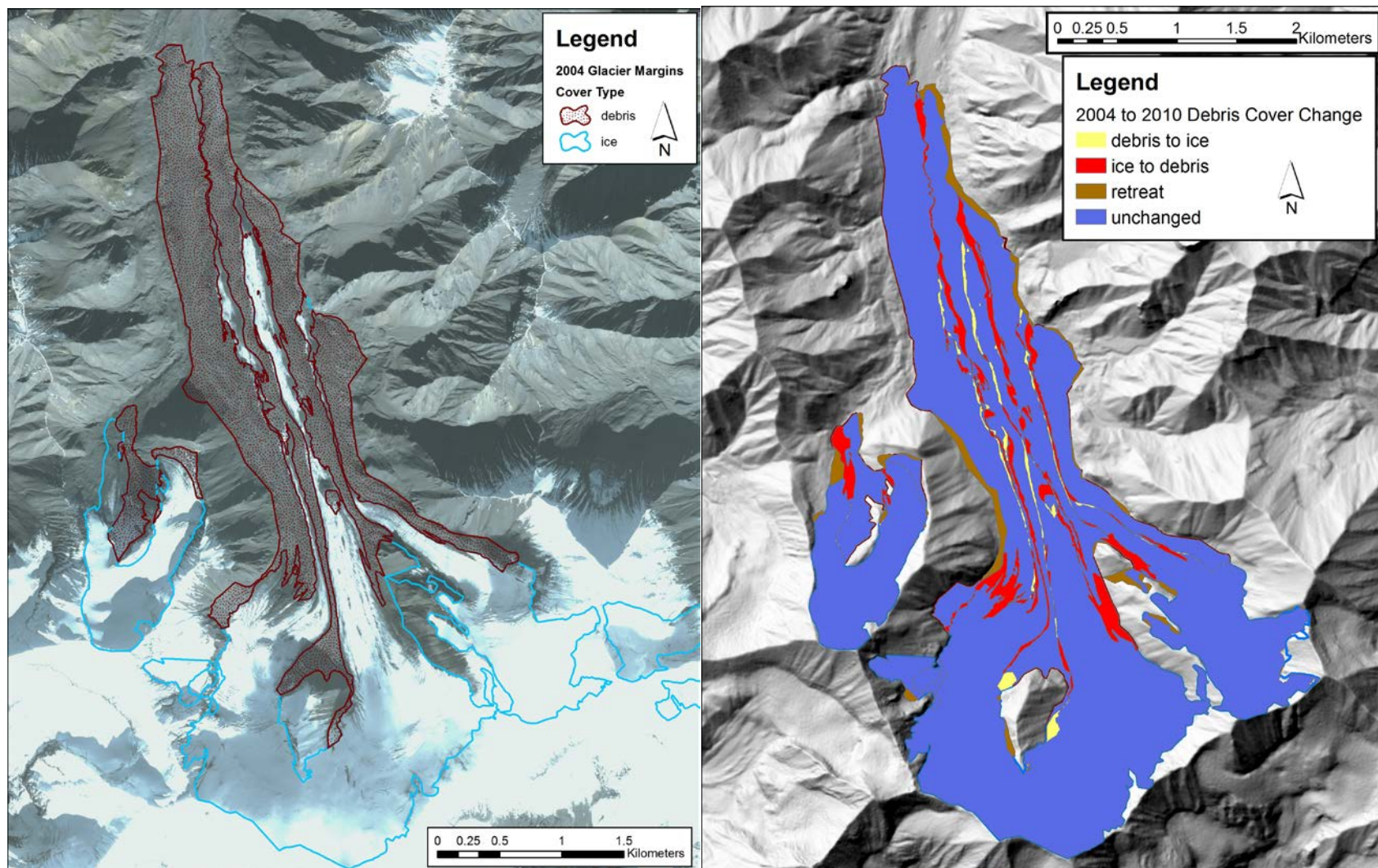


**Figure 8.** These maps illustrate the change in area of debris-covered ice on west fork Toklat glacier from 2004 to 2010. The map on the left shows 2010 SPOT satellite imagery with the 2004 polygons overlaid so that changes in debris cover are visually apparent, particularly on the mid and lower glacier. The map on the right quantifies the changes in debris cover (red and yellow) and glacier area loss (brown). The trend from 2004 to 2010 is of increasing debris cover (in red), a 4.5% percent increase. Yellow areas that show ice exposed in 2010 where there was debris in 2004 are a result of glacier flow moving debris-covered areas down the glacier and two areas mapped as ice that were likely snow covered in 2010.

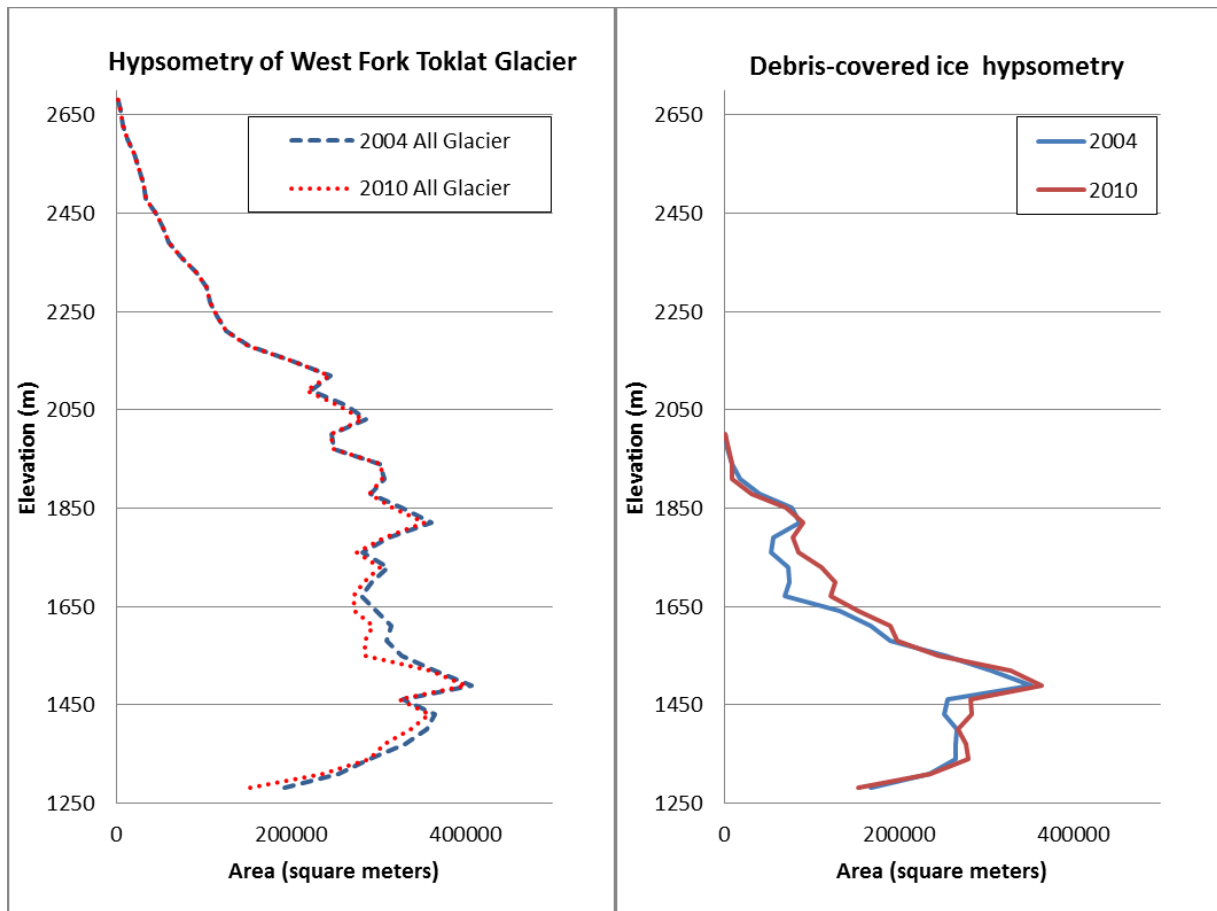


**Figure 9.** West fork Toklat glacier hypsometry of the entire glacier (on left) and the subset area of debris-covered ice (on right). A 30 m cell size was used for both 2004 and 2010 extents, thus differences in hypsometry are reflective of area changes only. A 30 m cell size was chosen to correspond to similar studies by different authors (i.e. Arendt et al 2014).

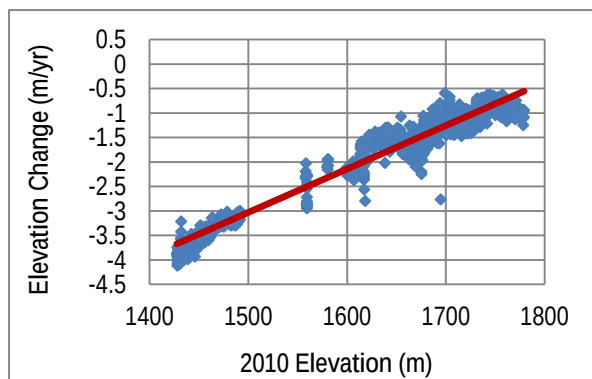


**Figure 10.** A plot of points derived from the August 2013 GPS survey minus the 2010 IFSAR DTM of bare ice areas only on west fork Toklat glacier.

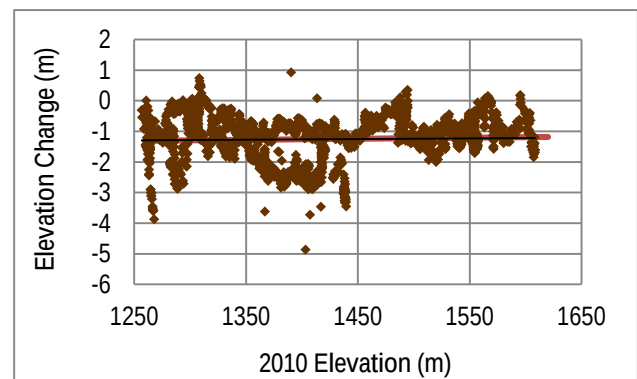


**Figure 11.** A plot of points derived from the August 2013 GPS survey minus the 2010 IFSAR DTM of debris-covered ice areas only on west fork Toklat glacier.

### **Middle Fork Toklat Glacier**

The middle fork Toklat glacier (MFT) is a 10.5 km<sup>2</sup> glacier in the middle branch of the upper Toklat River watershed (Figure 4 and 12). The terminus in 2013 was at ~1370 m elevation and the highest point of the glacier was ~2370 m. The glacier has two major branches that are now likely glaciologically separated by stagnant debris-covered ice (shown as debris-covered ice between the east and west branches in Figure 12). Colloquially scenic air tour pilots call the west branch the “blue glacier” and east branch the “white glacier” or collectively “the blue and white glaciers” (Denali Air, personal communication).

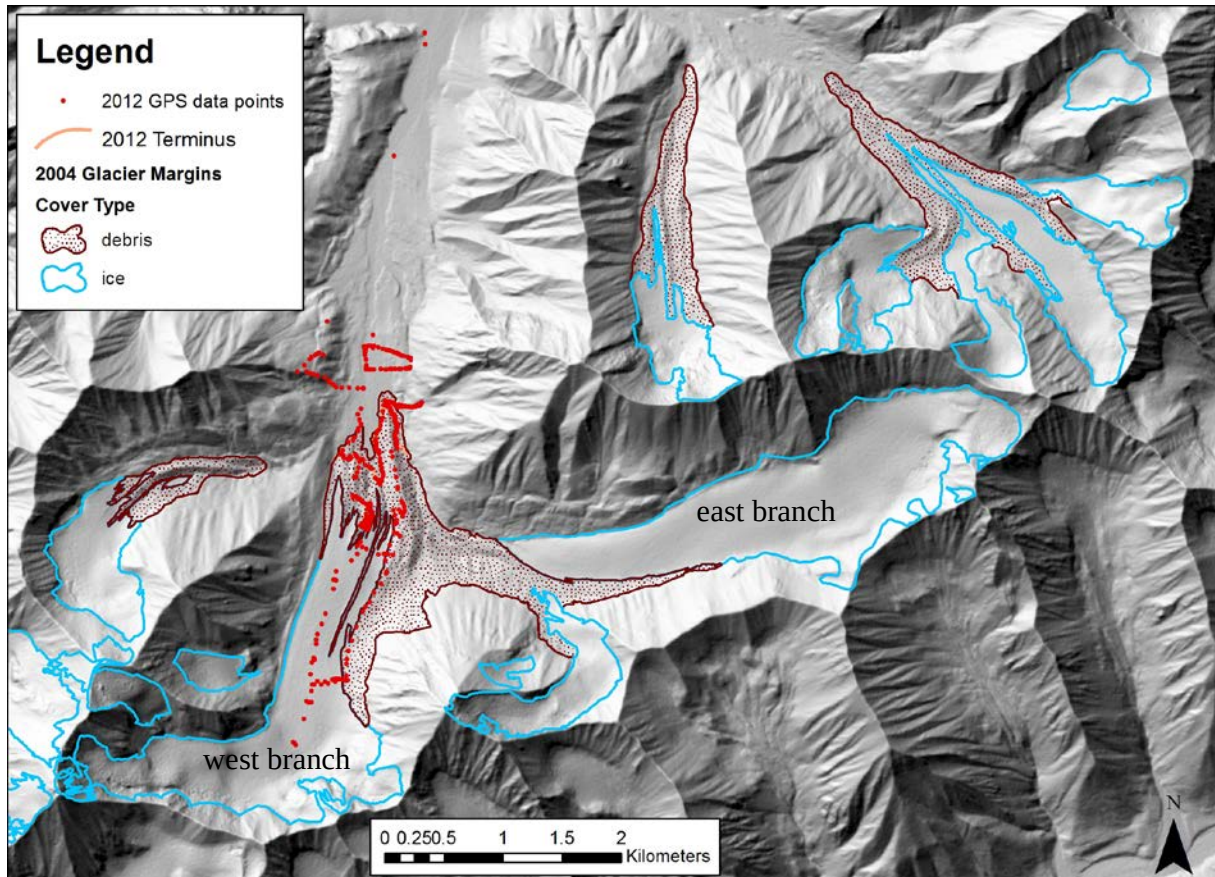


**Figure 12.** Map showing extent and debris-covered ice from 2004 imagery of middle fork Toklat glacier. Points collected during the 2012 GPS survey are in red.

This glacier was visited twice during the summer of 2012. First, July 6-8 for reconnaissance and a second trip from August 12-16 with Rob Burrows leading a Murie Science and Learning Center Field Seminar: Glaciology, Backcountry Citizen Science. Five participants signed up along with one field assistant joining the field seminar. The group learned about glaciers and climate change in Denali and collected 124 data points recording precise position and elevation data using a mapping grade and survey grade GPS system (Figure 12). The primary scientific contribution the citizen scientists on the glaciology course was to collect mapping and survey quality elevation measurements with GPS. To compare recent surface elevation changes, data are compared to the 2010 IFSAR DTM. The GPS data was post processed to reflect the same horizontal geodetic model and vertical datum as the

DTM (NAD 83 CORS96 Epoch 2003.00 and Geoid09-Alaska respectively). Measured surface elevation loss on the glacier ranged from 14.5 meters on the lower glacier to near 0 meters at higher elevations.

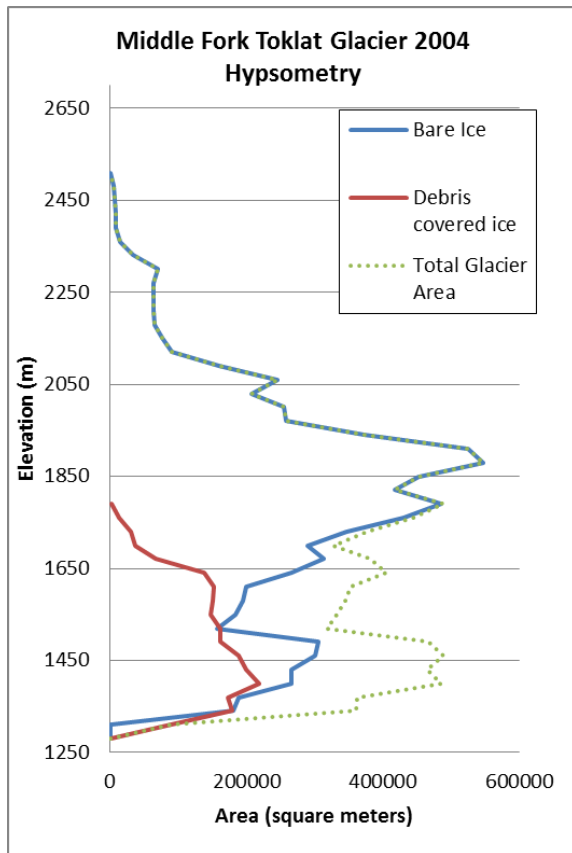


**Figure 13.** Glacier hypsometry of the entire middle fork Toklat glacier as well as the subsets of bare ice and debris-covered ice. The IFSAR DTM using a 30 m cell size was used for 2010 extent.

Glacier and debris-covered ice area was mapped from satellite imagery taken in 2004 (GeoEye 2004) (Figure 12). Twenty percent of the total glacier area is covered by debris thick enough to insulate the ice. Hypsometry of bare and debris-covered ice areas was calculated from the cover-type maps and the DTM (Figure 13).

#### Terminus Change

Middle fork Toklat glacier has a good series of imagery from which to reconstruct terminus positions (of the main west branch of the glacier). Figure 14 shows terminus positions and their successive retreat distances and rates from 1954 to 2012. The terminus retreat rate appears to have nearly halved from 31 to 15 m/yr after 1981 until 2010, but from 2010 to 2012 appears to have increased by three times (13 to 42 m/yr). Distances between successive termini were measured along three different

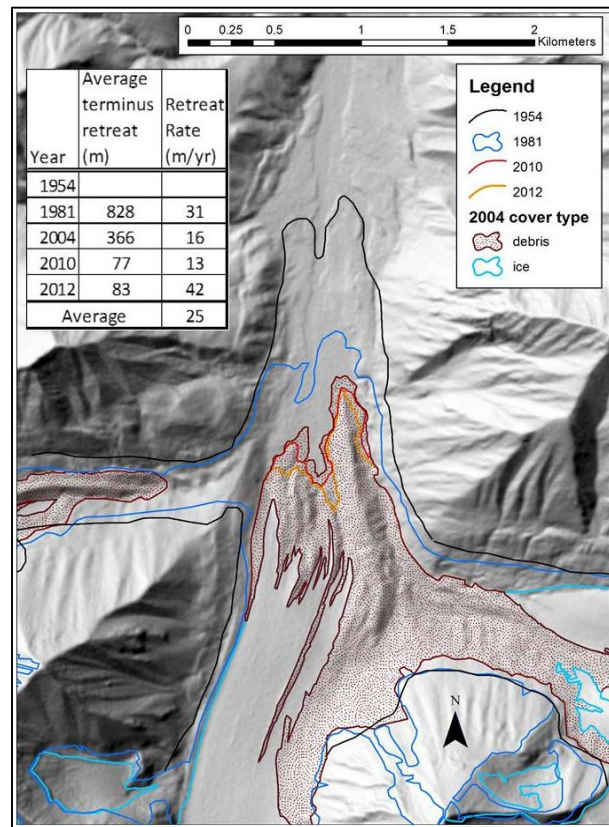


**Figure 14.** Mapped glacier termini and retreat rates for middle fork Toklat glacier.

lines in order to approximate an “average” retreat rate. These lines were located near the point of each of the two prominent lobes with the third line in the recess between.

#### Ice Loss Estimates 2010-2012

Elevation change rates were determined from the GPS data for both bare ice and debris-covered ice and plotted against 2012 elevations. Bare ice elevation change rates show a strong dependence on elevation (Figure 15). The best fit function where  $h$  is the 2012 glacier surface elevation and  $\Delta h/\Delta t$  is the rate of change of elevation in meters/year then,

$$\Delta h/\Delta t = 0.00760h - 14.151$$

with a correlation  $R^2 = 0.738$ . This implies that  $\Delta h/\Delta t$  goes to zero at 1861 meters.

Plotting  $\Delta h/\Delta t$  versus  $h$  for debris-covered ice shows significant variability with a large range at the lower glacier (Figure 16). There appears to be an asymptotic pattern to the lower bound of the data, with significantly less variability above 1400 meters. The following regression is used for debris covered ice. Although a poor correlation ( $R^2 = 0.738$ ) it fits the pattern better than using the mean.

$$\Delta h/\Delta t = 0.0043h - 8.0248$$

Applying the  $\Delta h/\Delta t$  bare ice function and debris-covered ice mean loss rate above to elevation band areas for bare and debris-covered ice of the entire glacier yields an estimate of integrated ice loss rate of the entire glacier of 14,300,000 m<sup>3</sup>/year. Dividing by the entire area of the glacier results in an area averaged loss rate of 1.26 m/yr. Using 0.9 as the ratio between the density of water and ice this results in 1.13 m w.e./yr.

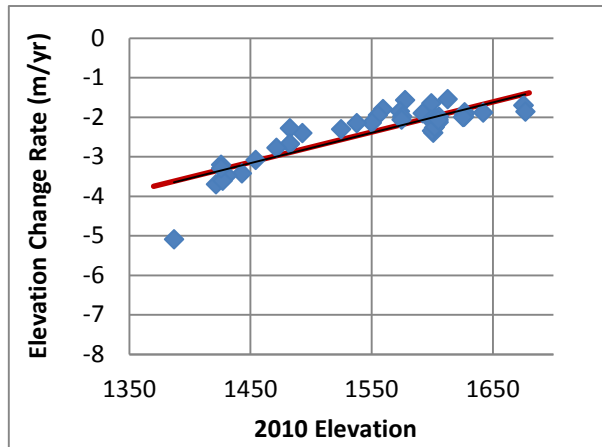


**Figure 15.** A plot of points on bare ice only of middle fork Toklat glacier derived from the August 2012 GPS survey minus the 2010 IFSAR DTM.

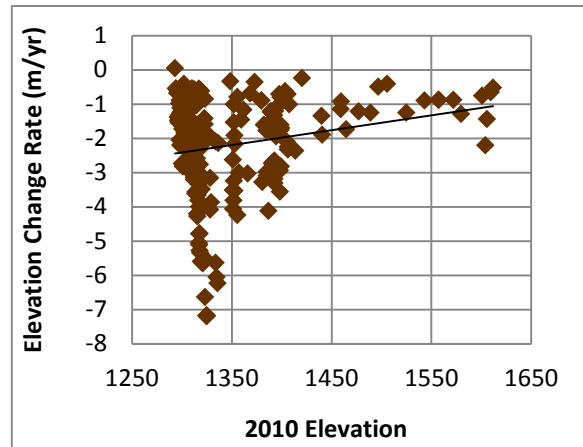


**Figure 16.** A plot of points for debris-covered ice of middle fork Toklat glacier from the August 2012 GPS survey minus the 2010 IFSAR DTM.

### Ice Loss Estimates 2002-2010

On July 29, 2002 Chad Hults and Amanda Peacock conducted a GPS survey of the terminus and centerline of the west branch of the MFT glacier using a mapping-grade Trimble Geo-3 GPS unit. The 2002 terminus mapping from this effort differs slightly from the author's mapping from 2004 IKONOS imagery, likely due to different interpretations of terminus position. Thus the 2002 points were not used to delineate the terminus. However, the centerline survey points are useful for calculating rates of surface elevation change on the lower bare ice (Figure 17). The best fit function where  $h$  is the 2012 glacier surface elevation and  $\Delta h/\Delta t$  is the rate of change of elevation in meters/year then,

$$\Delta h/\Delta t = 0.011497 h - 19.0469$$

with a correlation  $R^2 = 0.949$ . This implies that  $\Delta h/\Delta t$  goes to zero at 1657 meters, which is substantially lower than from 2010 to 2012.

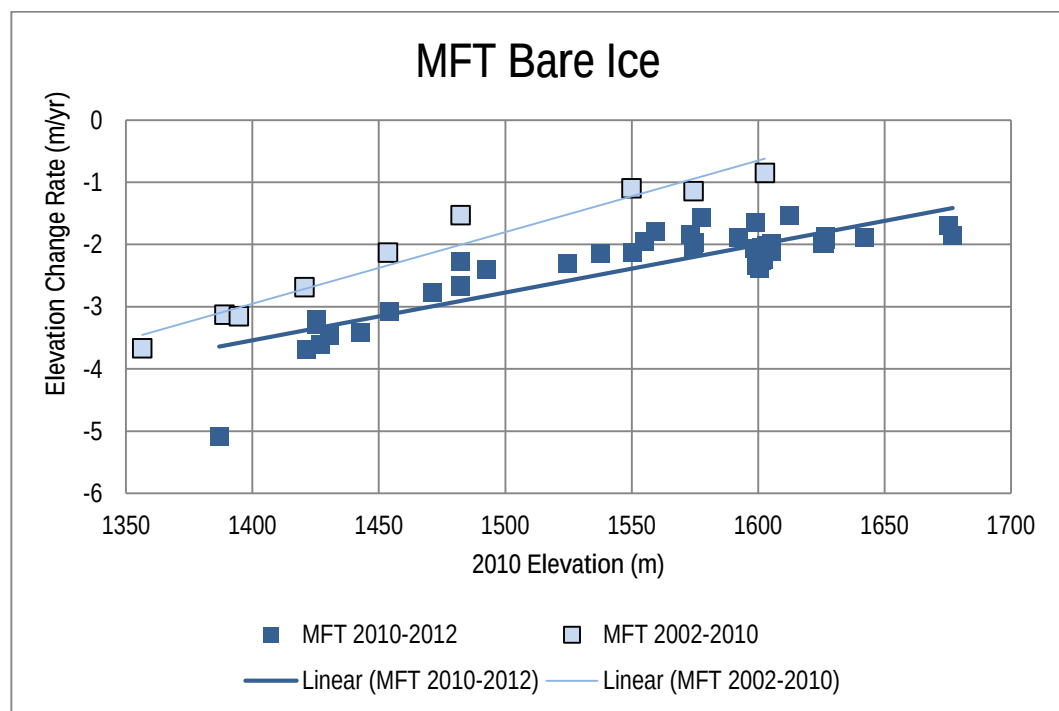


**Figure 17.** A plot of points derived from the 2002 and 2012 GPS surveys minus the 2010 IFSAR of bare ice areas only on middle fork Toklat glacier.

### **Sources for Error and Uncertainty**

The largest single uncertainty in these estimates for west fork and middle fork glaciers is the assumption that there is no ice gain or loss above the calculated ELA from the bare ice loss functions. The areas above these elevations are primarily firm and bare ice and comprise 30-40% of each glacier's area. This error is not quantitatively accounted for.

While there are likely some differences in relative positional accuracy between the 2004 IKONOS and 2010 SPOT imagery, it is treated as negligible in this analysis. Errors in glacier extent and

debris-covered ice mapping are reduced with having a single mapper (the author). However, there are ambiguities discerning glacier margins with debris-covered ice, shadows, and snow covered areas. Mapping debris-covered ice was informed as much as possible from the satellite imagery, field observations, photos, and the IFSAR DTM hillshade, however, in the end there are many areas that were mapped subjectively. Again, given a single operator these areas are treated as systematic and shouldn't significantly affect the 2004 and 2010 comparison.

#### GPS and DTM Height Comparison

Error associated with the difference in resolution between the GPS point heights and the IFSAR DTM elevations are evaluated for each GPS survey done on each glacier. Some of the GPS measurements were made on areas of stable ground not underlain by ice. There are enough of these measurements from the Trimble R6 that by differencing these with the DTM elevations, a distribution of values emerges for each survey on west fork and middle fork Toklat glaciers (Figure 18). Assuming a normal distribution, the expected error with a 95% confidence interval is  $\pm 1.55$  m for the data collected below west fork Toklat glacier ( $n = 1510$  points). Likewise for middle fork Toklat glacier the expected error at the 95% confidence interval is  $\pm 2.35$  m ( $n = 116$  points). The sample sizes are much smaller for data collected with the GeoXH and the best that can be reported is the range of differences: MFT survey is -0.6 to 2.56 m ( $n = 8$ ); WFT survey is -2.16 to 4.65 m ( $n = 15$ ).

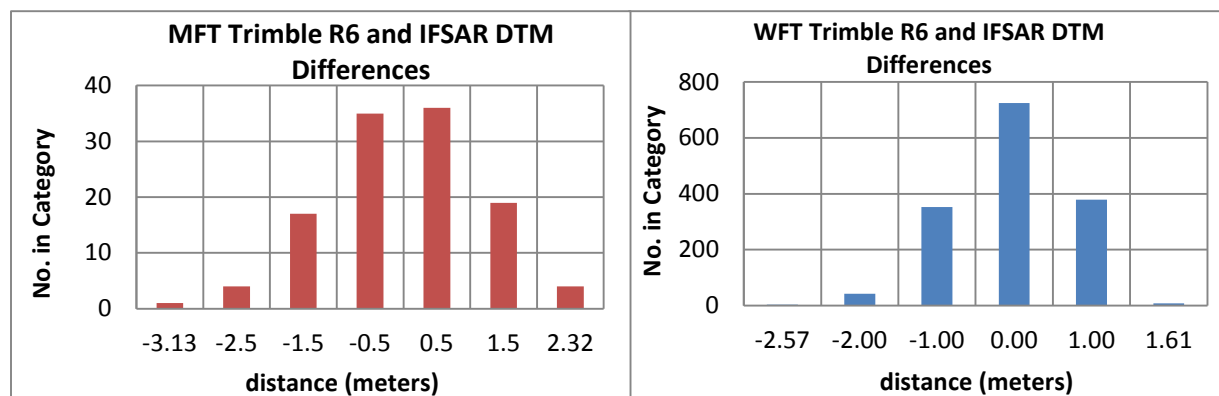


**Figure 18.** Error distribution histograms of differences between Trimble R6 GPS measurements and the IFSAR DTM elevations at Middle Fork Toklat (MFT) and West Fork Toklat (WFT) glaciers.

#### Cumulative Error Analysis

Several sources of error feed uncertainty about interpreting the elevation change data presented above. Each data source has a unique suite of errors associated with it that are combined cumulatively ( $E_{TOT}$ ) in quadrature (Table 2).

**Table 2.** Cumulative errors for each glacier-averaged value in meters water equivalent. These were calculated based on Equation 1. Where ETOT is total error, EGPS is the average GPS precision for the given survey, EDIFF is the comparison.

| Glacier     | E <sub>TOT</sub> | E <sub>GPS</sub> | E <sub>DIFF</sub> | E <sub>D</sub> | E <sub>BR</sub> | E <sub>DR</sub> |
|-------------|------------------|------------------|-------------------|----------------|-----------------|-----------------|
| WFT 2010-13 | 1.00             | 0.07             | 0.52              | 0.60           | 0.22            | 0.74            |
| MFT 2010-12 | 1.76             | 0.03             | 1.18              | 0.60           | 0.36            | 1.40            |
| MFT 2002-10 | 1.76             | 0.22             | 1.18              | 0.60           | 0.25            | 1.40            |

### ***Estimating Ice Loss Rates in the Toklat Watershed***

Determining ice loss for the Toklat watershed is useful in estimating the contribution of glacier ice melt to runoff on an annual and multi-year basis. In addition there has been recent interest by staff at DENA as to the contribution of water and sediment fluxes from glacier retreat as it pertains to sediment delivery to the Toklat gravel harvest area. The NPS harvests 22,200 cubic yards of gravel every other year from the braided floodplain of the Toklat River just downstream from the road causeway (Figure 19). The Toklat watershed (excluding Polychrome Glaciers and East Fork Toklat) has 31.5 sq. km of glacier ice, 33% of which is debris-covered (Figure 20). The simplest way to estimate ice loss rates across the watershed is to apply the  $\Delta h/\Delta t$  versus  $h$  curves from Middle Fork and West Fork Toklat glaciers to the glacier AAD for the entire Toklat Watershed (Figure 20 and 21). Johnson et al. (2013) applied a normalized elevation to “regionalize”  $\Delta h/\Delta t$  curves to best extrapolate airborne laser altimetry data (similar data to this study) across the Glacier Bay region. Such normalization is not necessary for this data because the area of extrapolation is much smaller and all glaciers occupy similar elevation ranges and topographic positions.

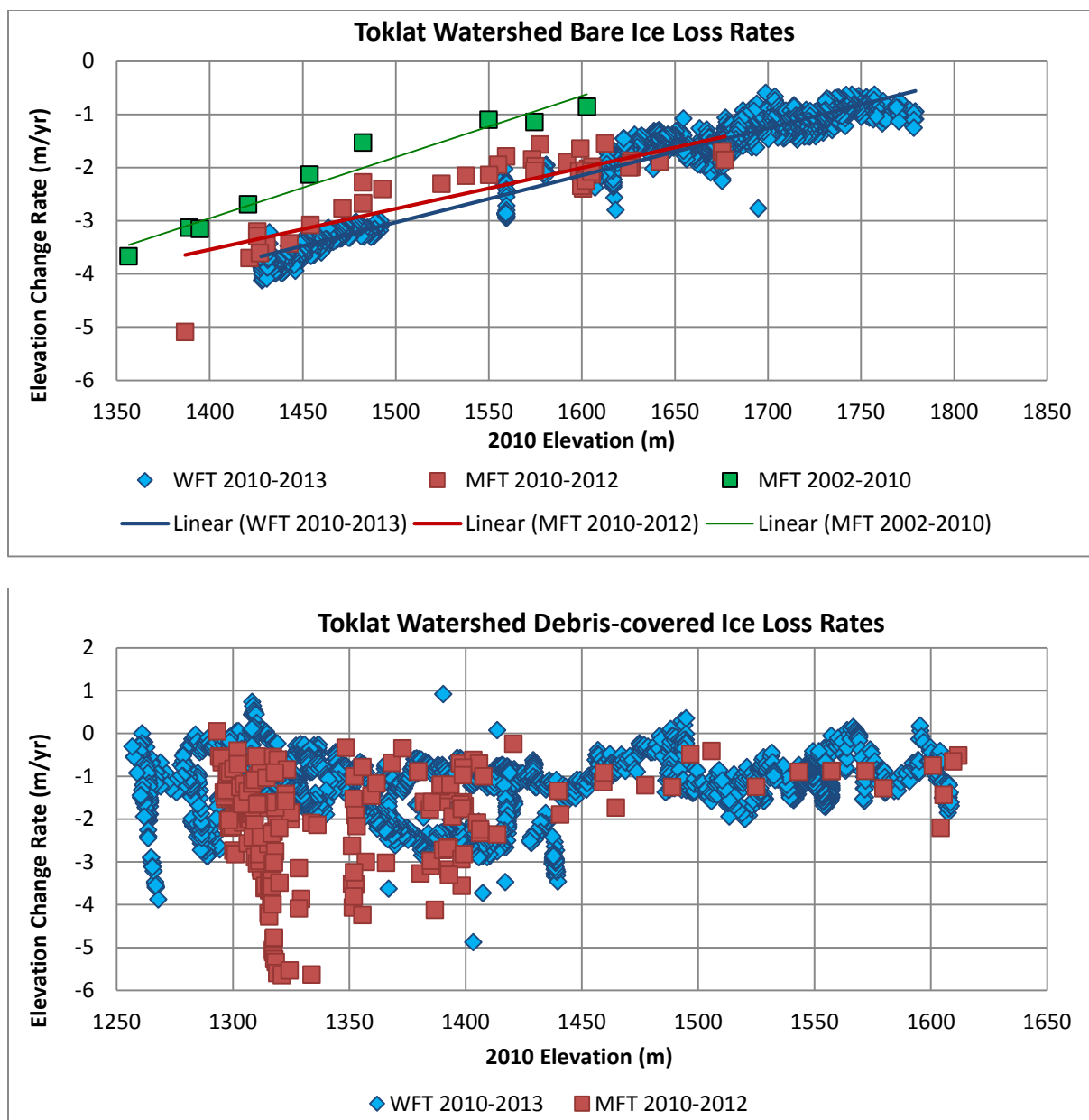


**Figure 19.** Comparison graphs showing elevation change rates vs. elevation for all glaciers and time periods in the Toklat Watershed. Watershed-wide rates of ice water loss have increased 40% from 2002 to 2013 (Table 3 and Figure 26).

**Table 3.** Watershed-wide loss rates calculated from individual glaciers for time spans between 2002 and 2013.

| Timespan | Watershed-wide loss rate (m w.e./year) |
|----------|----------------------------------------|
| 2010-13  | -0.99                                  |
| 2010-12  | -0.98                                  |
| 2002-10  | -0.71                                  |

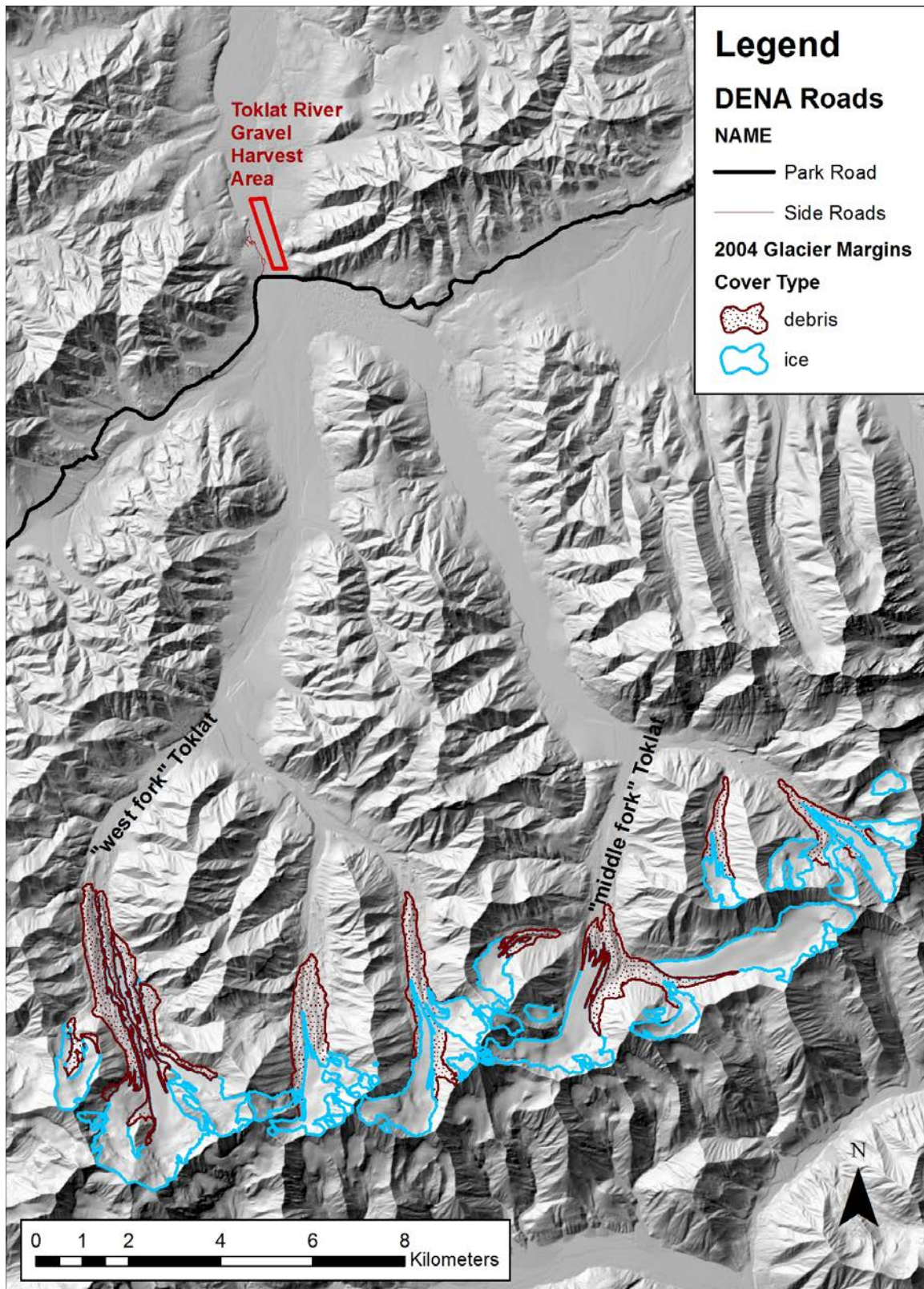


**Figure 20.** Map showing the upper west fork and middle fork Toklat watershed in relation to the Denali Park Road and the gravel harvest area. The map also shows areas of bare and debris-covered ice as mapped from 2004 IKONOS imagery.

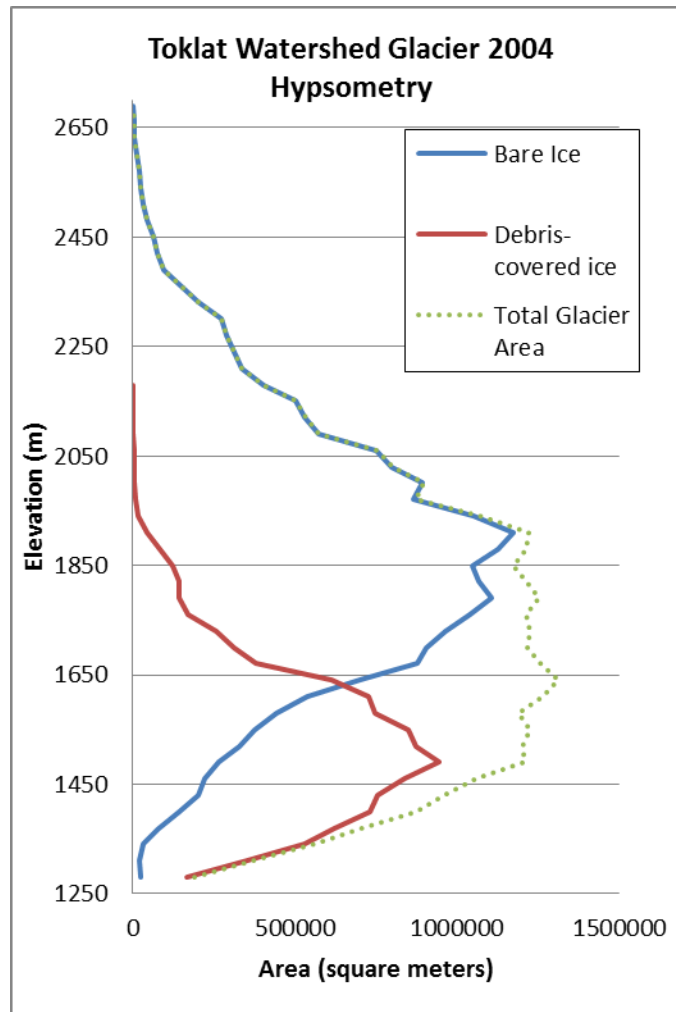


**Figure 21.** Area-Altitude distribution (hypsometry) of glaciers and subsets of bare ice and debris-covered ice for the upper west Toklat watershed.

### ***West Fork Teklanika Glacier***

As volunteer citizen scientists, Brian Schmidt and friends (all from California), collected terminus and surface elevation coordinates and elevations on a glacier in the headwaters of the West Fork Teklanika with a mapping grade GPS (Trimble GeoXT). Photographs (Figure 22) that this group took also helped inform terminus mapping from 2004 IKONOS imagery (Figure 23).

The group collected 7 GPS point measurements with one control point on a boulder (Figures 22 and 23). These 2011 heights were adjusted based on the difference between the GPS control point and the 2010 IFSAR DTM elevation at that point. Note that the GPS height was also corrected for the height of the boulder, since the boulder is an isolated enough feature that it would be smoothed over in the lower resolution DTM. Five of the points occurred on debris-covered ice with one on bare ice. Points 1-3 were at the terminus with varying thicknesses of debris cover on the ice there. Point 1 with a thin

veneer of debris appears to have the greatest melt rate, with the bare ice second (Table 4). There are not enough points to extrapolate to the entire glacier thus that is not reported.



**Figure 22.** Glacier at the head of the west fork of the Teklanika River on June 29, 2011. Photo by Brian Schmidt. The boulder in the foreground was surveyed as a natural benchmark to provide an ice free reference point for future surveys.

**Table 4.** Differences between 2010 DTM and 2011 GPS heights and debris thicknesses at the GPS points on west fork Teklanika glacier. Names correspond to the labeled points in Figure 23. All values in meters unless otherwise indicated.

| Name          | 2011 GPS height | Elevation Change (m/yr) | Cumulative Error | Debris Thickness (m) |
|---------------|-----------------|-------------------------|------------------|----------------------|
| Control Point | 1165            | 0                       | 1.3              | NA                   |
| 1             | 1206            | -2.3                    | 1.2              | veneer               |
| 2             | 1211            | -0.5                    | 1.2              | 0.06                 |
| 3             | 1213            | -0.7                    | 1.2              | 0.10                 |
| 4             | 1240            | -0.4                    | 1.1              | 0                    |
| 5             | 1278            | -1.3                    | 1.2              | 0.09                 |
| 6             | 1338            | -2.1                    | 1.1              | 0                    |

Unfortunately it is difficult to calculate changes in area or terminus retreat from previous data (1950s USGS topographic quadrangle maps) because differences in resolution of the imagery used and debris cover seem to make the extent difficult to resolve in the earlier imagery (black and white air photos) . A comparison of automated mapping from Landsat 7 in 2003 (30 meter resolution) (Arendt et al. 2012, GLIMS) with manual mapping from IKONOS in 2004 (1 m resolution) shows the drastically different interpretation of extent from these two methods (Figure 23).

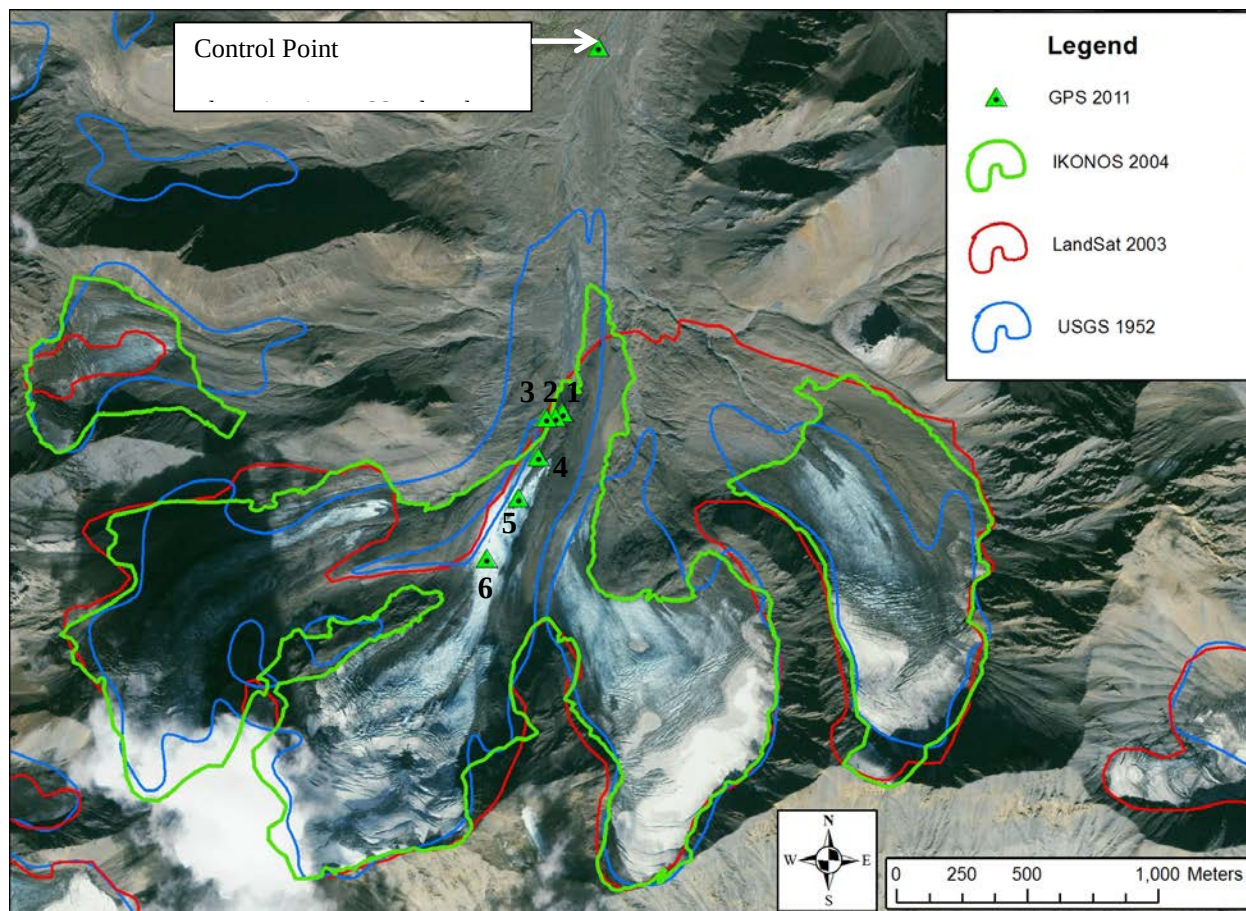


**Figure 23.** Comparison of extents between mapping dates (1950s, 2003, and 2004), methods, and resolution. On this small (~4 km<sup>2</sup>), debris-covered glacier, mapping extent is difficult and ambiguous without the ability to ground truth or a DTM that matches the terminus date. Numbers next to the green triangles correspond with point names in Table 3.

### ***West Fork Cantwell Glacier***

Sam Hooper, a seasonal backcountry ranger at DENA, collected points marking the bare-ice terminus of the West Fork Cantwell Glacier using a recreational grade GPS (Garmin GPSmap76CSx GPS, ~3 m horizontal accuracy). This glacier has a substantial amount of debris cover on either side of a bare-ice area in the middle of the lowermost glacier (Figure 24 and Appendix A). The bare-ice terminus is retreating more quickly than the insulated debris-covered areas and has been tracked for retreat rates since 1950 (Figure 24). The bare-terminus of West Fork Cantwell Glacier appears to have retreated at an average rate of 11 meters/year from 1950 to 2011. The retreat rate appears to have increased slightly since 1993 (see table in Figure 24).

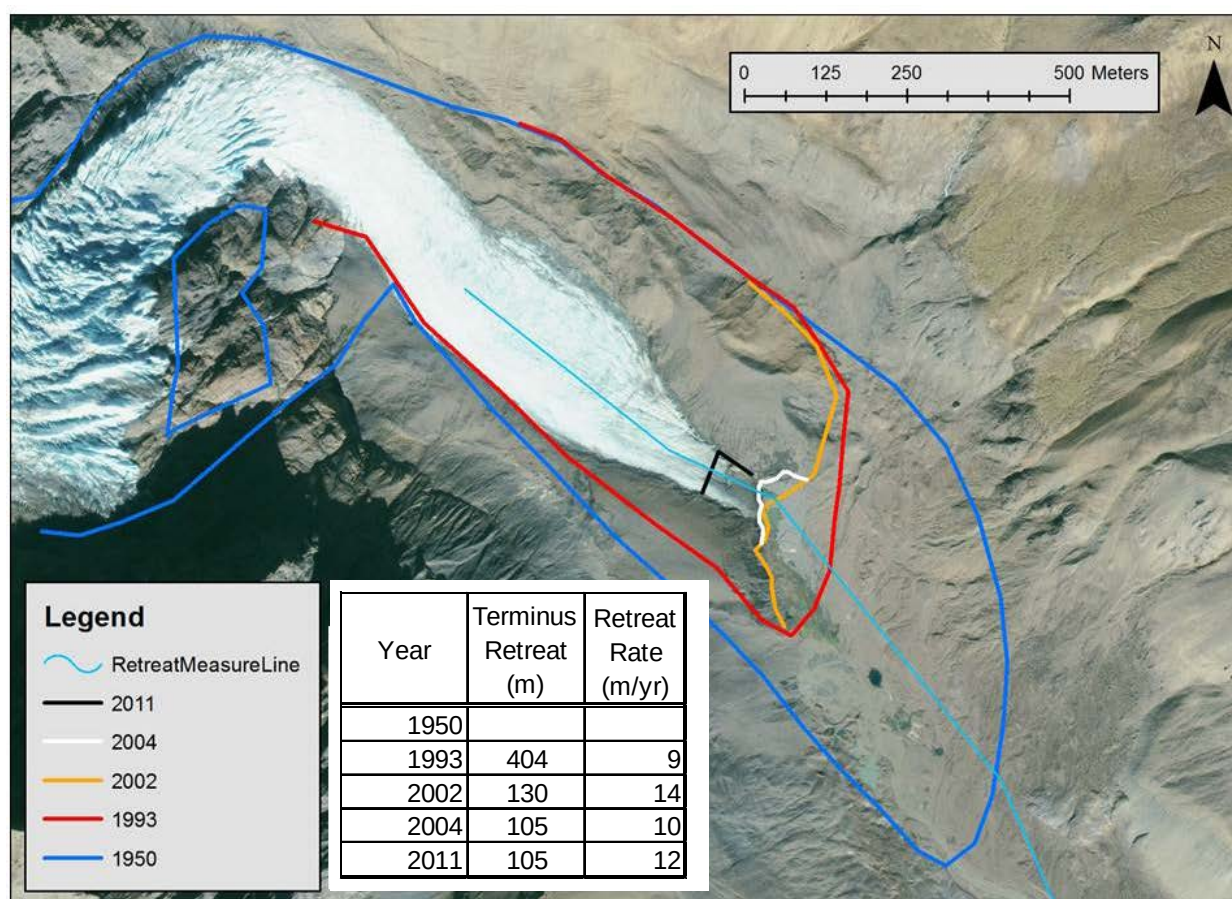


**Figure 24.** Terminus positions and retreat rates of the lower west fork Cantwell glacier. Retreat rates (meters/year) are measured along the light blue line between each successive terminus position. Base imagery is IKONOS 2004.

## Surging Glacier Observations

No glaciers were observed to be surging from 2011 to 2013.

## Index Stations Mass Balance Summary

### Index Station Measurements

Seasonal mass balance measurements at the index stakes on Kahiltna and Traleika glaciers continued in 2011-2013. Two stakes were tracked on each glacier through 2012, the older index stakes placed in 2007 (stakes labeled: 07-K17-9M and 07-T-9M) and the newer ones placed in 2010 (stakes labeled: 10-K17-6M and 10-T-7M). The 2007 Traleika stake (07-T-9M) was only used through 5/21/2011 because it became severely tilted after melting out by a supraglacial stream. However, both stakes on Kahiltna Glacier were accessible, vertical and useful for observation. Three new stakes were placed on each glacier in spring 2013 to provide more data about spatial variability and balance gradients (Figures 2 and 3) ((Traleika stakes labeled: 13-T1A-6M, 13-T1B-6M, 13-T1C-6M and Kahiltna stakes labeled: 13-K17A-6M, 13-K17B-6M, 13-K17C-6M). Balances at the stakes are shown in Table 5. Unfortunately the new stake data on Kahiltna was lost from the June 2013 visit so

no data for those stakes for 2013 is included in this report. Raw data are included in Appendix C. Balance years 2011-2013 continued on the negative annual balance trend of the last seven years for Traleika Glacier (but with a near neutral balance in 2012). On Kahiltna the negative trend in 2013 was broken with a strong positive balance.

In 2011 the index stakes at both glaciers showed significantly negative annual balances, Kahiltna's stakes were 63% of the most negative annual balance recorded to date while Traleika's was 81% (Table 5). The negative annual balances on both glaciers were driven by both below average snow accumulation and above average snow and ice ablation. Kahiltna's winter balance was 42% of average and Traleika's was 60%. Summer balance on Kahiltna was 111% of average and Traleika was 138% (Table 5). The annual balances at the long term equilibrium line altitudes are also negative with Kahiltna at 68% of the most negative balance recorded to date and Traleika at 72%. These annual balances were determined using the average balance gradients determined during the early years of the monitoring program (Mayo 2001).

In 2012 the index stakes at both glaciers showed slightly negative annual balances, Kahiltna's stakes were 10% of the most negative annual balance recorded to date while Traleika's was 6% (Table 5). Kahiltna's winter balance was 70% of average and Traleika's was 114%. Summer balance on Kahiltna was 87% of average and Traleika was 63% (Table 5). The annual balances at the long term equilibrium line altitudes are also negative at Kahiltna at 25% of the most negative balance recorded to date, but positive at Traleika at 55% of the most positive annual balance to date.

In 2013 Kahiltna's stakes were 63% of the most positive annual balance recorded to date while Traleika's annual balance was 34% of the most negative annual balance recorded (Table 5). Kahiltna's winter balance was 127% of average and Traleika's was 110%. Summer balance on Kahiltna was 60% of average and Traleika was 99% (Tables 5 and 6). The annual balances at the long-term equilibrium line altitudes are positive at Kahiltna at 66% of the most positive balance recorded to date, and 42% at Traleika.

**Table 5.** Summary tables for Kahiltna glacier index stakes. Balances are expressed in meters water equivalent (m w.e.) as well as percent of average (value in parentheses).

| Kahiltna Glacier<br>Stake Names                                  | Measure Date | Elevation (m)        | Winter Balance (m w.e.) (percent of average) | Summer Balance (m w.e.) (percent of average) | Annual Balance (m w.e.) (percent min or max) | Balance Gradient (m w.e./m elev) | ELA Estimate (meters) | Estimated Annual Balance at Equilibrium Line Altitude (m w.e.) |
|------------------------------------------------------------------|--------------|----------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------|-----------------------|----------------------------------------------------------------|
| 07-K17-6M<br>10-K17-6M                                           | 6/8/2011     | 1922<br>1944         | 0.43 ± 0.09 (42%)                            |                                              |                                              |                                  |                       |                                                                |
| 07-K17-6M<br>10-K17-6M                                           | 8/15/2011    | 1922<br>1942         |                                              | -1.03 ± 0.24 (111%)                          | -0.61 ± 0.26 (-63%)                          | 0.0031                           | 2116                  | -0.81                                                          |
| 07-K17-6M<br>10-K17-6M                                           | 4/25/2012    | 1919<br>1943         | 0.72 ± 0.56 (70%)                            |                                              |                                              |                                  |                       |                                                                |
| 07-K17-6M<br>10-K17-6M                                           | 8/13/2012    | 1915<br>1940         |                                              | -0.82 ± 0.63 (87%)                           | -0.10 ± 0.85 (-10%)                          | 0.0031                           | 1948                  | -0.30                                                          |
| 13-K17A-6M<br>13-K17B-6M<br>13-K17C-6M                           | 6/6/2013     | 1985<br>1960<br>1961 | 1.29 ± 0.14 (127%)                           |                                              |                                              |                                  |                       |                                                                |
| 07-K17-6M<br>10-K17-6M<br>13-K17A-6M<br>13-K17B-6M<br>13-K17C-6M | 8/1/2013     | 1984<br>1957<br>1966 |                                              | -0.56 ± 0.38 (60%)                           | 0.73 ± 0.35 (63%)                            | 0.0031                           | 1676                  | 0.53                                                           |

**Table 6.** Summary tables for Traleika glacier index stakes. Balances are expressed in meters water equivalent (m w.e.) as well as percent of average (value in parentheses).

| Traleika Glacier<br>Stake Names | Measure Date | Elevation (m) | Winter Balance (m w.e.) (percent of average) | Summer Balance (m w.e.) (percent of average) | Annual Balance (m w.e.) (percent min or max) | Balance Gradient (m w.e./m elev) | ELA Estimate (meters) | Estimated Annual Balance at Equilibrium Line Altitude (m w.e.) |
|---------------------------------|--------------|---------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------|-----------------------|----------------------------------------------------------------|
| 07-T-6M<br>10-T-7M              | 5/21/2011    | 2085          | 0.39 ± 0.36 (60%)                            |                                              |                                              |                                  |                       |                                                                |
| 07-T-6M<br>10-T-7M              | 9/6/2011     | 2085          |                                              | -1.89 ± 0.31 (138%)                          | -1.49 ± 0.31 (-81%)                          | 0.0046                           | 2410                  | -0.88                                                          |
| 10-T-7M                         | 4/26/2012    | 2090          | 0.75 ± 0.75 (114%)                           |                                              |                                              |                                  |                       |                                                                |
| 10-T-7M                         | 9/1/2012     | 2085          |                                              | -0.86 ± 0.57 (63%)                           | -0.11 ± 0.27 (-6%)                           | 0.0046                           | 2108                  | 0.51                                                           |
| 10-T-7M                         | 5/28/2013    | 2085          | 0.75 ± 0.75 (114%)                           |                                              |                                              |                                  |                       |                                                                |
| 13-T1A-6M                       | 5/28/2013    | 1703          | 0.24 ± 0.26                                  |                                              |                                              |                                  |                       |                                                                |

**Table 6 (continued).** Summary tables for Traleika glacier index stakes. Balances are expressed in meters water equivalent (m w.e.) as well as percent of average (value in parentheses).

|           |           |             |                 |                           |                            |        |      |      |
|-----------|-----------|-------------|-----------------|---------------------------|----------------------------|--------|------|------|
| 13-T1B-6M | 5/28/2013 | 1711        | $0.11 \pm 0.23$ |                           |                            |        |      |      |
| 13-T1C-6M | 5/28/2013 | 1715        | $0.09 \pm 0.19$ |                           |                            |        |      |      |
| 10-T-7M   | 8/28/2013 | not visited |                 | $-1.35 \pm 0.33$<br>(99%) | $-0.63 \pm 0.28$<br>(-34%) | 0.0077 | 2168 | 0.39 |
| 13-T1A-6M | 8/28/2013 | 1700        |                 |                           | $-2.91 \pm 0.26$           | 0.0077 |      |      |
| 13-T1B-6M | 8/28/2013 | 1709        |                 |                           | $-3.09 \pm 0.11$           | 0.0077 |      |      |
| 13-T1C-6M | 8/28/2013 | 1713        |                 |                           | $-3.01 \pm 0.12$           | 0.0077 |      |      |

### ***Index Station Data Discussion***

The greatest strength in maintaining a program of seasonal glacier mass balance measurements and calculations is in tracking seasonal and interannual variability. Such knowledge puts long term trends into context of the minima and maxima that occur from year to year as well as the ability to discern patterns and/or noise that are contributing to the long term trends (Figure 25).

The average summer and winter balances are markedly different between the two sites where the average winter balance at Kahiltna (1.02 m w.e.) is 35% greater on average than that at Traleika 0.66 m w.e.), likewise the maximum at Kahiltna (2.00 m w.e.) for the 22 year period whereas the maximum at Traleika is (1.15 m w.e). These differences may be accounted for by two circumstances: 1) proximity of stake to long term ELA/whether the stake is in the long term accumulation or ablation area; 2) location of the stake in relation to the precipitation shadow gradient caused by the Alaska Range. Although it is at a lower elevation than the Traleika site (2085 m) the Kahiltna stakes (1985-1910 m) receive greater snowfall. The south side of the Alaska Range is known to receive more precipitation than the north side and this is in evidence from the greater size and length of glaciers there.

For summer balance values, Traleika on average (-1.37 m w.e.) has 30% greater amounts of snow/firn/ice loss than Kahiltna (-0.94 m w.e.). Again this difference may in part be due to the relative positions of the stakes to the ELAs. Traleika receives less snow, thus a larger portion of the summer balance is ice melt (with a significantly higher density/water equivalent than large portion of snowmelt at the Kahiltna stakes.

A correlation analysis comparing winter and summer balance at each glacier can show the strength of the contribution of winter and summer balance to the annual balance. At the Kahiltna index stakes both winter and summer balances appear to correlate with annual balance, with summer balance being slightly stronger (Table 7). At Traleika Glacier only the summer and annual balances correlate strongly (Table 7).

While the index stations were situated in an attempt for them to represent the balance of the entire glacier, the terrain dictated that they could not be located directly at the long-term ELAs. In addition the long-term ELA may shift through time and leave the stake above or below. At Kahiltna Glacier, the index station was thought to have been located above the long-term ELA (Mayo 2001), and indeed from the 22-year record it appears to be (average annual balance = 0.14 m w.e.). However,

from the last 10 years of mass balance data the average annual balance is very close to zero and hence at the ELA of the glacier.

**Table 7.** Results of a correlation analysis between the seasonal balances and annual balance from the period of 1991 to 2013 for the Kahiltna and Traleika index stakes.

|       | Kahiltna<br>$b_a$ | Traleika<br>$b_a$ |
|-------|-------------------|-------------------|
| $b_w$ | 0.67              | 0.25              |
| $b_s$ | 0.83              | 0.93              |
|       | $b_w$             | $b_w$             |
| $b_s$ | 0.15              | -0.14             |

At Traleika, the index station is located below the long-term ELA because at that location is the confluence of two major tributaries (Figure 4). It was thought that it would be better to capture the behavior of the main trunk glacier rather than just one tributary (Mayo 2001). Here the 22-year average annual balance is substantially negative (-0.69 m w.e.).

### Balances Calculated at Long-term ELA

Note that the annual balance values are NOT necessarily indicative of the balance of the entire glacier for the year, but they do give an indication of the relative magnitude of the glacier's balance. Based on data collected from two stakes on each glacier in the early to mid-1990s and the new stakes on Traleika in 2013, an average balance gradient was calculated for each glacier (for annual balance). Use of this balance gradient allows an estimate of the annual balance for each balance year at the long-term ELA (Figure 26). This is tentatively used to represent the annual balance of the entire glacier. However, such an interpretation should be viewed with caution because there were only two stakes used per glacier for 6 years and the gradients determined from these stakes have substantial variability (Mayo, 2001).

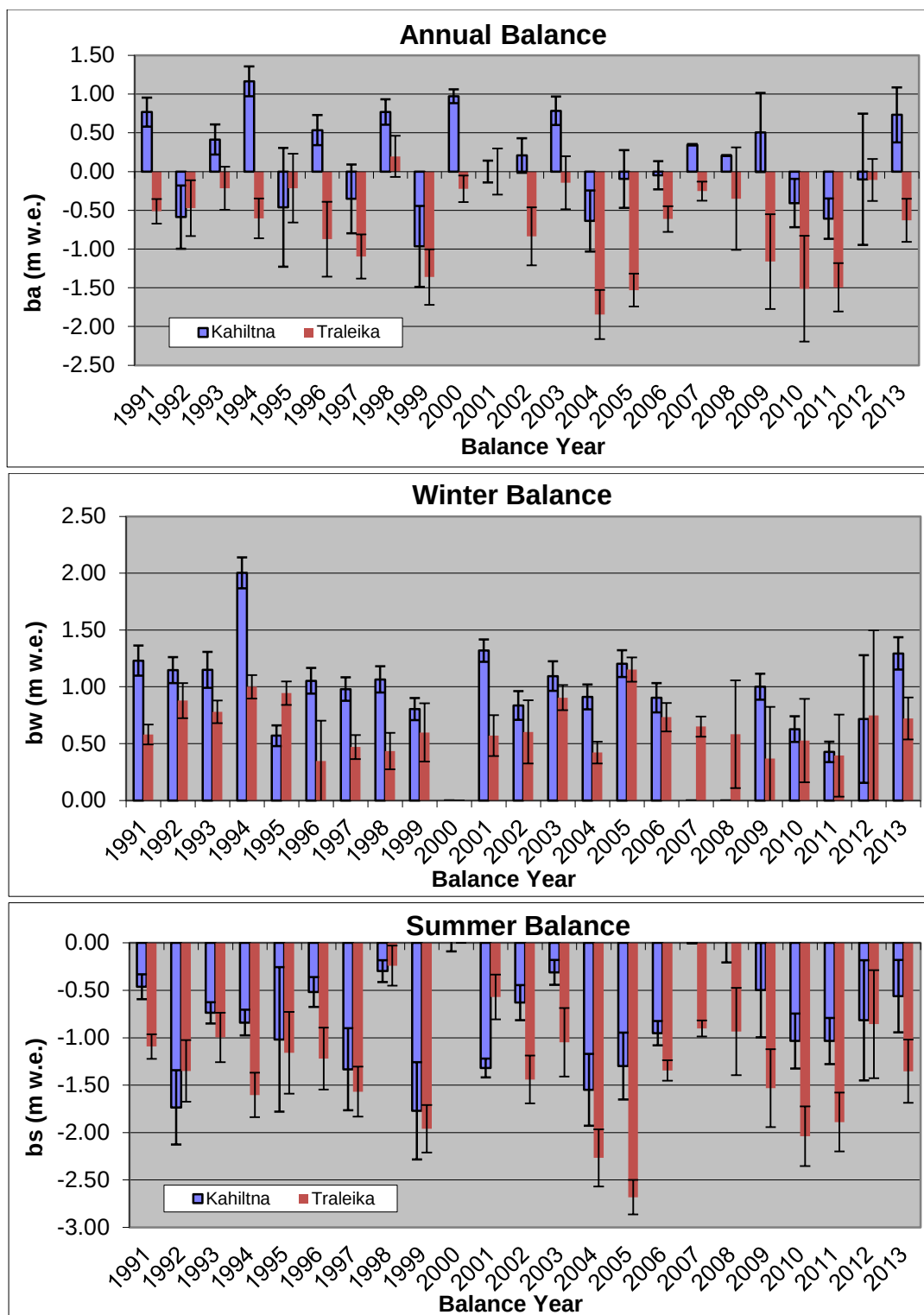


**Figure 25.** Annual, winter, and summer balances at the index stakes of Kahiltna and Traleika Glaciers. Error bars are shown for measurement errors as calculated through calculations (see Methods section for more detail).

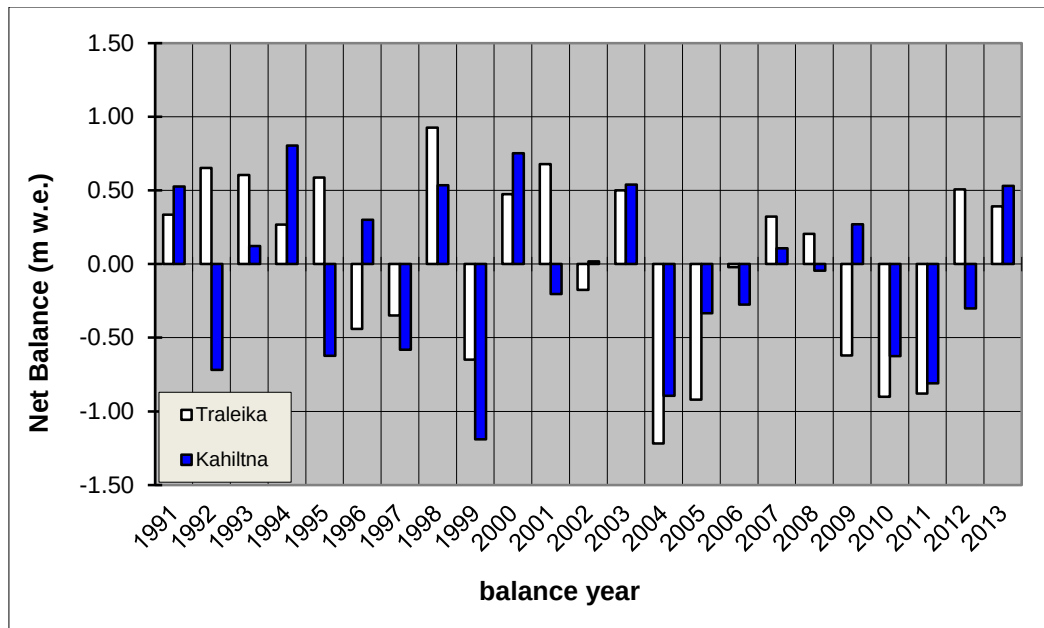


**Figure 26.** The calculated ELAs at the long-term ELA at each glacier. These values serve as an index of the entire glacier annual balance for each balance year.

Cumulative balances for each glacier are calculated by cumulatively adding the annual balance each year. Inspection of a cumulative balance curve (Figure 26) provides insight into trends that influence growth or shrinkage of glacier volume. Figure 26 shows that from 1991 to 2003 the Kahiltna generally had a neutral balance, but a negative trend has been maintained overall since 2004. At Traleika, there was an increasing trend to a maximum of 3.0 m w.e. in 2003, but like Kahiltna there has been a predominantly negative trend since 2004 so that the cumulative balance once again dropped below zero in 2011.

Recent results from repeat surface elevation surveys using aircraft borne laser altimetry equipment shows substantially different cumulative balances on both glaciers (Arendt et al 2014, Young 2013). Surface elevation surveys along the centerline of Kahiltna Glacier from 1994 to 2008 show a rate of ice loss at -0.75 m w.e./year, whereas the estimate from stake measurements (adjusted with the balance gradient as described above) is much lower at -0.11 m w.e./year. Likewise surface elevation changes show a rate of -1.07 m w.e./year versus stake measurements at -0.15 m w.e./year.

Traleika shows an increase in surface elevation from 2008 to 2010 of +1.41 m w.e./year (Arendt et al 2014), whereas the stake-based estimate show a loss of -0.75 m w.e./year (this study).

It is important to realize that the cumulative balance estimates based on stake data do not take into account the dynamics of glacier flow which is likely a primary factor accounting for changes in surface elevation. Ice surface elevation can change based on ice surface melt/lowering or gain due to snow accumulation and it can also change due to changes in the flow of ice from up glacier. In addition mass balance programs that use multiple stake measurements distributed across the glacier to estimate glacier wide mass balance often have systematically different cumulative results when compared to a geodetic balance determination (geodetic balance is usually accomplished by

differencing DEMs from two or more years) (e.g. Riedel and Larrabee 2011; Rolstad et. al 2009). In any case Denali's stake data gives a very limited window into conditions across the entire glacier and thus is best used for understanding seasonal and annual variability.

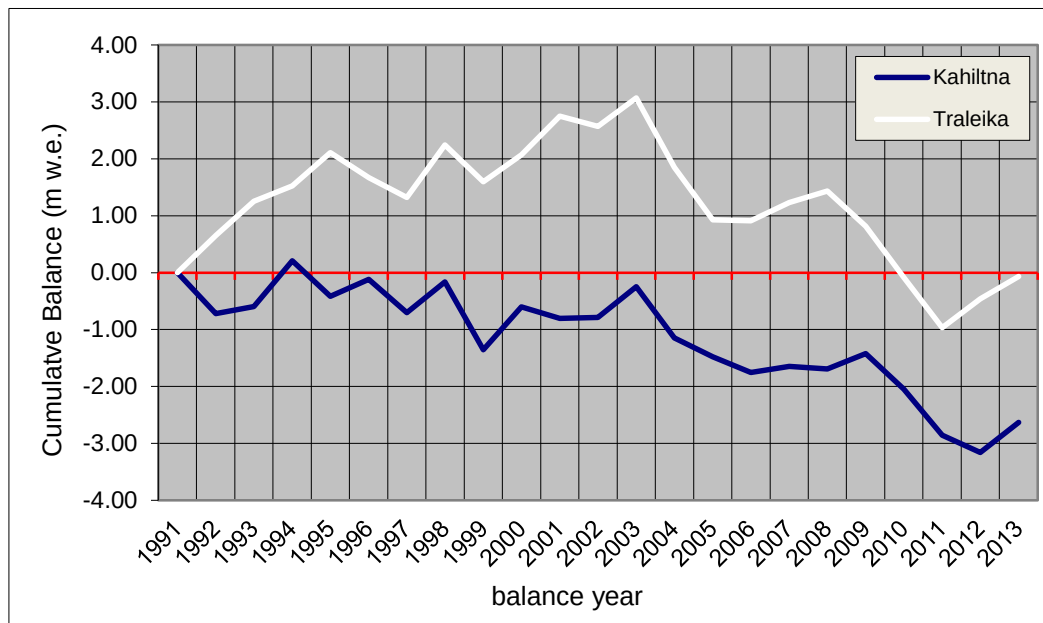


**Figure 27.** Cumulative balance graphs from the annual balances calculated at the long-term ELA for Kahiltna and Traleika glaciers. Cumulative balances for each glacier are calculated by cumulatively adding the annual balance each year.

### Glacier Stake velocities

During the 2011 to 2013 balance years, the index stakes on Kahiltna Glacier moved slightly faster than average with a range of 185 to 224 meters per year (long term average is 205 m/yr) (Figure 28). The Traleika Glacier index stakes moved faster than average with a range of 93 to 109 m/yr (the long term average is 71 m/yr) (Figure 28). Figure 29 illustrates some of the spatial variation of the index glaciers from 2013 stake measurements.

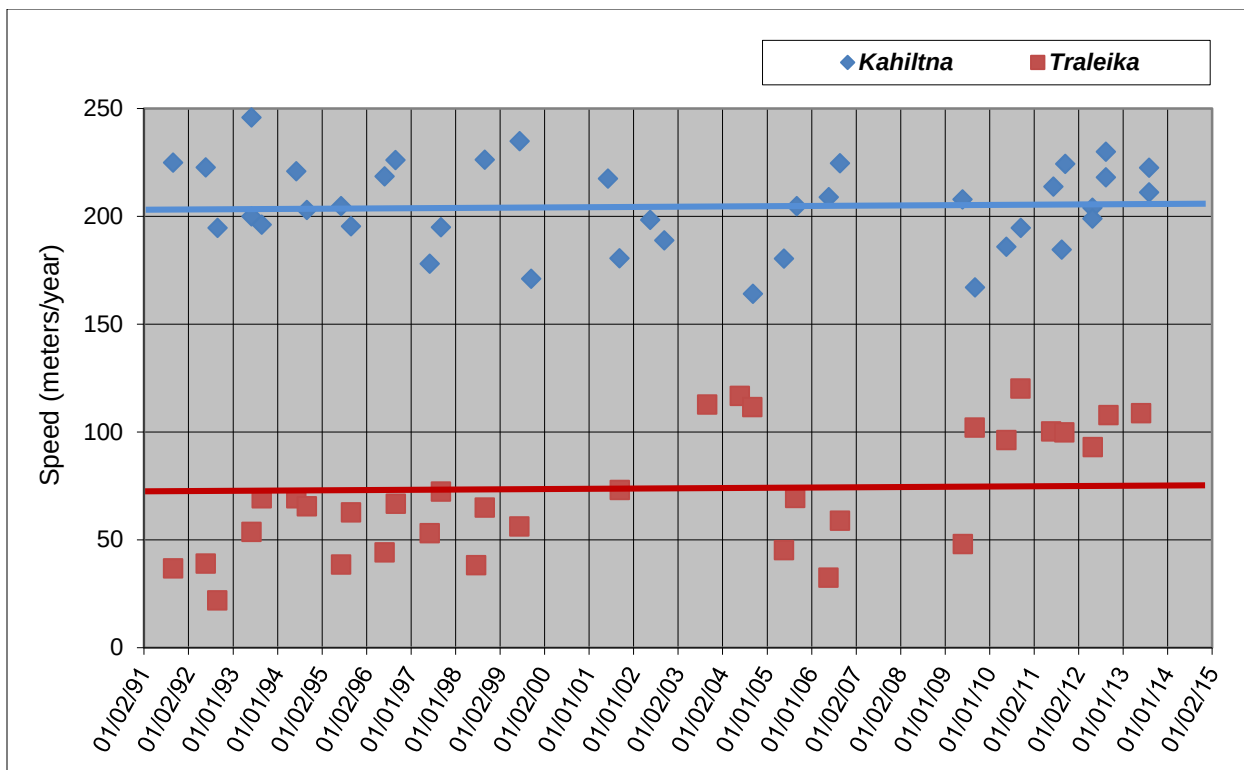


**Figure 28.** Surface speeds of Kahiltna and Traleika Glaciers from 1991 to 2013 as calculated from the long term index stake positions. The blue and red lines are the mean values for each glacier's surface speed.

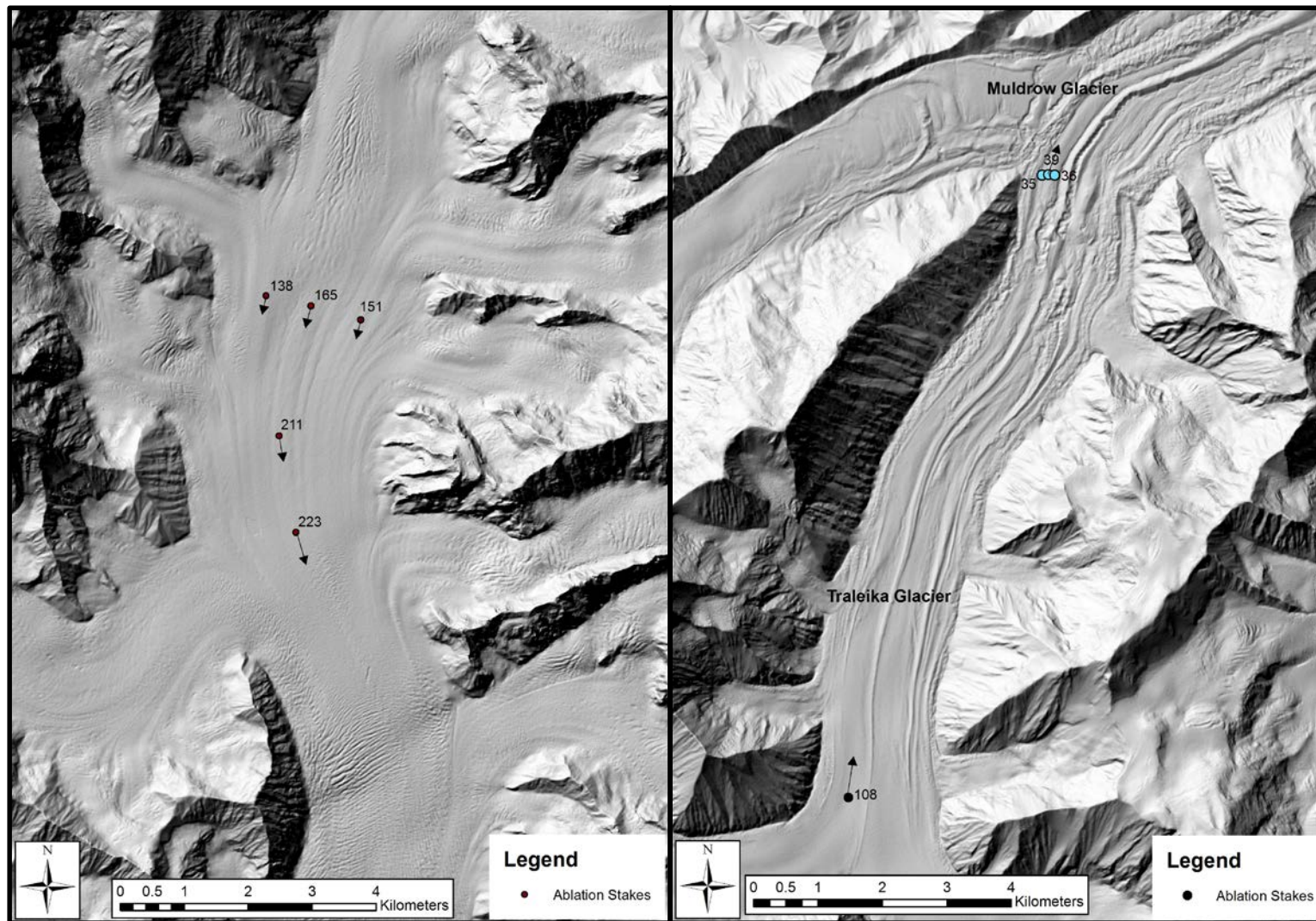


**Figure 29.** Stake velocities on Kahiltna and Traleika Glaciers during the 2013 summer season (except the upper Traleika stake which was the previous summer's velocity). The base map is the hillshade of the IFSAR DTM (Intermap Technologies Inc. 2011).



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## Appendix A –Panoramas and Comparative Photography



**Figure A-1.** A 360 degree panorama near the index station on Kahiltna Glacier, 06/08/2011. Camera location: 62.94121 degrees N, 151.24586 degrees W, 1933 m (6339 ft)



**Figure A-2.** A 360 degree panorama near the index station on Kahiltna Glacier, 08/15/2011. Camera location: 62.9415 degrees N, 151.24605 degrees W, 1937 m (6354 ft)



**Figure A-3.** A 360 degree panorama on the lower glacier near Joanna Young's KT5 stake. 08/15/2011 Camera location: 62.6442 degrees N, 151.3553 degrees W, 779 m (2556 ft).



**Figure A-4.** The lowermost glacier and terminus area of Kahiltna Glacier, 09/14/2011. This is a repeat photograph Capps, 1928 and Karpilo 2004. Camera location: 62.577 degrees N, 151.19 degrees W, 868 m (2846 ft).

50



**Figure A-5.** The lowermost glacier and terminus area of Kahiltna Glacier, 09/14/2011. This photo was taken approximately 50 m west of Figure A-4. Camera location: 62.577 degrees N, 151.19 degrees W, 868 m (2846 ft).



**Figure A-6.** The Kahiltna Glacier Index site, 08/13/2012. Camera location: 62.9415 degrees N, 151.24605 degrees W, 1937 m (6354 ft)



**Figure A-7.** A 360 degree panorama on the medial moraine near the index station on Traleika Glacier, spring 2011. Camera location: 63.12665 degrees N, 150.78655 degrees W, 2102 m (6896 ft).



**Figure A-8.** A 360-degree panorama on the Muldrow Glacier at the new “two-mile moraine” marker. Camera location: 63.43509 degrees N, 149.36333 degrees W, 1162 m (3812 ft).



**Figure A-9.** Comparison of photography of Polychrome glaciers originally taken by Stephen R. Capps on July 18, 1916 (top ) and June 26, 2011 by Ron Karpilo (bottom).



**Figure A-10.** Comparison of photography of East Fork Toklat Glacier originally taken by Stephen R. Capps on August 22, 1919 (top) and June 30, 2011 by Ron Karpilo (bottom).



**Figure A-11.** Comparison of photography of a glacier in Windy Creek originally taken by Stephen R. Capps in 1919 (top ) and July 30, 2011 by Ron Karpilo (bottom).



**Figure A-12.** Comparison of the lower section of West Fork Cantwell Glacier between 1928 (top by S. R. Capps) and 2011 (bottom photo by Sam Hooper).



**Figure A-13.** Comparison of the lower section of West Fork Cantwell Glacier between 1928 (top by S. R. Capps) and 2011 (bottom photo by Sam Hooper).



**Figure A-14.** Comparison of the terminus of Kahiltna Glacier and small glaciers in the surrounding mountains between summer 1916, summer 2004, and September 14, 2011.



**Figure A-15.** Comparison of panoramic photography of middle fork Toklat glacier originally taken by Stephen R. Capps in summer 1919 (top) and July 7, 2012 (bottom by Rob Burrows).



## Appendix B – Index Data

**Table B-1.** Balance Data from the worksheet used to calculate the balances from the data collected in the field. Blue highlighted text are fall measurements and red highlighted text are measurements suspect to have error and not used.

| <-----OBSERVATIONS-----> |              |            |                           |             |          |                                    |             |               |          |    |                  |                   |           |
|--------------------------|--------------|------------|---------------------------|-------------|----------|------------------------------------|-------------|---------------|----------|----|------------------|-------------------|-----------|
| Glacier                  | Stake Name   | Date m/d/y | <-----Stake Reading-----> |             |          | <-----Snow or New Firn Depth-----> |             |               |          |    |                  | Summer Surface    |           |
|                          |              |            | Tape b' (m)               | b error (m) | Strata   | Pit d (m)                          | Probe d (m) | Average d (m) | s.e. (m) | n  | s.d. d error (m) | Observed b'ss (m) | error (m) |
| Kahiltna                 | 07-K17-9M    | 6/8/2011   | 6.6                       | 0.04        | Snow     | 1.20                               | 0           | 0             |          | 0  | 0.00             | 5.40              | 0.04      |
|                          | K17-10-6M    | 6/8/2011   | 4.39                      | 0.04        | Snow     | 1.15                               | 1.06        | 1.07          |          | 12 | 0.17             | 3.24              | 0.41      |
|                          | 07-K17-9M    | 8/15/2011  | 4.47                      | 0.04        | Old firn | 0.00                               | 0.00        | 0.00          |          | 0  | 0.00             | 4.47              | 0.04      |
|                          | K17-10-6M    | 8/15/2011  | 4.38                      | 0.04        | Old firn | 0.00                               | 0.00        | 0.00          |          | 0  | 0.00             | 4.38              | 0.04      |
|                          | 07-K17-9M    | 9/14/2011  | 4.65                      | 0.04        | Old firn | 0.00                               | 0.00        | 0.00          |          | 0  | 0.00             | 4.65              | 0.04      |
|                          | K17-10-6M    | 9/14/2011  | 4.24                      | 0.04        | Old firn | 0.00                               | 0.00        | 0.00          |          | 0  | 0.00             | 4.24              | 0.04      |
|                          | 07-K17-9M    | 4/25/2012  | 7.03                      | 0.04        | Snow     | 2.25                               |             | 2.18          |          | 10 | 0.15             | 4.78              | 0.40      |
|                          | 10-K17-6M    | 4/25/2012  | 4.84                      | 0.04        | Snow     | 2.01                               |             | 1.77          |          |    | 0.40             | 2.83              | 0.40      |
|                          | 07-K17-9M    | 8/13/2012  | 4.75                      | 0.04        | Old firn | 0.90                               |             | 0.89          |          | 3  | 0.14             | 4.75              | 0.04      |
|                          | 10-K17-6M    | 08/13/12   | 2.48                      | 0.04        | Old firn | 1.0                                |             | 0.913         |          | 10 | 0.29             | 2.48              | 0.04      |
|                          | 13-K17-A30ft | 06/06/13   | missing                   | 0.04        | Snow     | 2.8                                |             |               |          |    |                  |                   |           |
|                          | 13-K17-B30ft | 06/06/13   | missing                   | 0.04        | Snow     | 3.3                                |             | 3.23          |          |    | 0.40             | unknown           |           |
|                          | 13-K17-C30ft | 06/06/13   | missing                   | 0.04        | Snow     | 3.6                                |             |               |          |    |                  |                   |           |
|                          | 07-K17-9M    | 8/1/2013   | 6.17                      | 0.04        | NFirn    | 1.4                                |             |               |          |    |                  | 6.17              |           |
|                          | 10-K17-6M    | 8/1/2013   | 4.17                      | 0.04        | NFirn    | 1.6                                |             | 1.48          |          | 10 | 0.21             | 4.17              | 0.21      |
|                          | 13-K17-A30ft | 8/1/2013   | 5.77                      | 0.04        | NFirn    | 1.55                               |             |               |          |    | 0.04             | 5.77              | 0.06      |
|                          | 13-K17-B30ft | 8/1/2013   | 5.52                      | 0.04        | NFirn    | 1.25                               |             |               |          |    | 0.04             | 5.52              | 0.06      |
|                          | 13-K17-C30ft | 8/1/2013   | 5.39                      | 0.04        | NFirn    | 1.32                               |             |               |          |    | 0.04             | 5.39              | 0.06      |
| Traleika                 | 07-T-6M      | 5/18/2010  | 6.17                      | 0.04        | Snow     | 1.35                               | 0.00        | 1.28          |          | 10 | 0.12             | 4.82              | 0.04      |
|                          | 07-T-6M      | 9/12/2010  | 3.42                      | 0.04        | Ice      | 0.00                               | 0.00        | 0.00          |          | 0  | 0.00             | 3.42              | 0.04      |



|          | <-----SURFACE MASS BALANCES-----> |               |                                 |       |       |       |                    |                                         |       |       |         |       |           |                    |       |                   |             |             |             |                    |             |       |
|----------|-----------------------------------|---------------|---------------------------------|-------|-------|-------|--------------------|-----------------------------------------|-------|-------|---------|-------|-----------|--------------------|-------|-------------------|-------------|-------------|-------------|--------------------|-------------|-------|
| Glacier  | Stake Name                        | Date<br>m/d/y | <---Old Firn and Ice Losses---> |       |       |       |                    | <-----NFirn, Sice or Snow Amounts-----> |       |       |         |       |           |                    |       | Seasonal Balances |             |             |             | Cumulative Balance |             |       |
|          |                                   |               | Density                         |       | b'(l) |       | Ice                | b <sub>a</sub> (l)                      | Depth |       | Density |       | Estimated | Snow               |       | bw & bs           |             | error       | ba          | error              | bc          | error |
|          |                                   |               | r                               | error | b'(l) | error | b <sub>a</sub> (l) | err                                     | d     | error | r       | error | or        | b <sub>a</sub> (f) | error |                   |             |             |             |                    |             |       |
|          |                                   |               | kg/L                            | error | m(w)  |       | m(w)               |                                         | m     |       | kg/L    |       | Measured  | m(w)               |       | m(w.e.)           | m<br>(w.e.) | m<br>(w.e.) | m<br>(w.e.) | m<br>(w.e.)        | m<br>(w.e.) |       |
| Kahiltna | 07-K17-9M                         | 6/8/2011      | 0.00                            | 0.05  | 0.00  |       | 0.00               | 0.00                                    | 0.00  | 0.06  | 0.00    | 0.05  | 0.00      | 0.00               |       |                   |             |             |             |                    |             |       |
|          | K17-10-6M                         | 6/8/2011      | 0.00                            | 0.05  | 0.00  |       | 0.00               | 0.00                                    | 1.07  | 0.06  | 0.40    | 0.05  | Estimated | 0.43               | 0.09  | 0.43              | 0.09        |             |             |                    |             |       |
|          | 07-K17-9M                         | 8/15/2011     | 0.80                            | 0.05  | 3.58  | 0.23  | -0.68              | 0.23                                    | 0.00  | 0.06  | 0.00    | 0.05  | 0.00      | 0.00               |       | -1.03             | 0.24        | -0.61       | 0.26        | 2.51               | 1.50        |       |
|          | K17-10-6M                         | 8/15/2011     | 0.80                            | 0.05  | 3.50  | 0.22  | 3.50               | 0.32                                    | 0.00  | 0.06  | 0.00    | 0.05  | 0.00      | 0.00               |       |                   |             |             |             |                    |             |       |
|          | 07-K17-9M                         | 9/14/2011     | 0.80                            | 0.05  | 3.72  | 0.23  | -0.54              | 0.36                                    | 0.00  | 0.06  | 0.00    | 0.05  | 0.00      | 0.00               |       |                   |             |             |             |                    |             |       |
|          | K17-10-6M                         | 9/14/2011     | 0.80                            | 0.05  | 3.39  | 0.21  | 3.39               | 0.32                                    | 0.00  | 0.06  | 0.00    | 0.05  | 0.00      | 0.00               |       |                   |             |             |             |                    |             |       |
|          | 07-K17-9M                         | 4/25/2012     | 0.80                            | 0.05  | 3.82  | 0.40  | 0.00               | 0.00                                    | 2.18  | 0.06  | 0.38    | 0.23  | Measured  | 0.83               | 0.55  | 0.83              | 0.55        |             |             |                    |             |       |
|          | 10-K17-6M                         | 4/25/2012     | 0.80                            | 0.05  | 2.26  | 0.35  |                    |                                         | 1.77  | 0.06  | 0.34    | 0.25  | Measured  | 0.60               | 0.57  | 0.60              | 0.57        |             |             |                    |             |       |
|          | 07-K17-9M                         | 8/13/2012     | 0.80                            | 0.05  | 3.80  | 0.24  | 0.08               | 0.34                                    |       |       |         |       |           |                    |       | -0.75             | 0.65        | 0.08        | 0.85        |                    |             |       |
|          | 10-K17-6M                         | 8/13/2012     | 0.80                            | 0.05  | 1.98  | 0.13  | -0.28              | 0.25                                    |       |       |         |       |           |                    |       | -0.88             | 0.62        | -0.28       | 0.85        | 2.41               | 1.73        |       |
|          | 13-K17-A30ft                      | 6/6/2013      | 0.8                             | 0.05  |       |       |                    |                                         |       |       |         |       |           |                    |       |                   |             |             |             |                    |             |       |
|          | 13-K17-B30ft                      | 6/6/2013      | 0.8                             | 0.05  |       |       |                    |                                         | 3.23  | 0.40  | 0.4     |       | Estimated | 1.29               | 0.14  | 1.29              | 0.14        |             |             |                    |             |       |
|          | 13-K17-C30ft                      | 6/6/2013      | 0.8                             | 0.05  |       |       |                    |                                         |       |       |         |       |           |                    |       |                   |             |             |             |                    |             |       |
|          | 07-K17-9M                         | 8/1/2013      | 0.8                             | 0.05  |       | 0.00  | 0.00               | 0.13                                    |       |       |         |       |           |                    |       |                   |             |             |             |                    |             |       |
|          | 10-K17-6M                         | 8/1/2013      | 0.8                             | 0.05  | 3.34  | 0.27  | 1.35               | 0.30                                    | 1.48  | 0.21  | 0.49    | 0.19  | Measured  | 0.73               | 0.35  | -0.56             | 0.38        | 0.73        | 0.35        | 3.14               | 1.76        |       |
|          | 13-K17-A30ft                      | 8/1/2013      | 0.8                             | 0.05  | 4.61  | 0.29  | 4.61               |                                         | 1.55  | 0.04  | 0.49    | 0.19  | Estimated | 0.77               | 0.34  |                   |             | 0.77        | 0.34        |                    |             |       |
|          | 13-K17-B30ft                      | 8/1/2013      | 0.8                             | 0.05  | 4.41  | 0.28  | 4.41               |                                         | 1.25  | 0.04  | 0.49    | 0.19  | Estimated | 0.62               | 0.31  |                   |             | 0.62        | 0.31        |                    |             |       |
|          | 13-K17-C30ft                      | 8/1/2013      | 0.8                             | 0.05  | 4.31  | 0.27  | 4.31               |                                         | 1.32  | 0.04  | 0.49    | 0.19  | Estimated | 0.65               | 0.32  |                   |             | 0.65        | 0.32        |                    |             |       |
|          |                                   |               |                                 |       |       |       |                    |                                         |       |       |         |       |           |                    |       |                   |             |             |             |                    |             |       |
| Traleika | 07-T-6M                           | 5/18/2010     | 0.90                            | 0.05  | 4.34  | 0.24  | -0.25              | 0.35                                    | 1.28  | 0.06  | 0.41    | 0.05  | Measured  | 0.53               | 0.09  | 0.53              | 0.37        |             |             |                    |             |       |
|          | 07-T-6M                           | 9/12/2010     | 0.90                            | 0.05  | 3.08  | 0.18  | -1.26              | 0.30                                    | 0.00  | 0.06  | 0.00    | 0.05  | 0.00      | 0.00               | 0.09  | -2.04             | 0.31        | -1.51       | 0.68        | -13.62             | 1.69        |       |
|          | T-10-7M                           | 9/15/2010     | 0.90                            | 0.05  | 4.43  | 0.25  | 0.00               | 0.30                                    | 0.00  | 0.06  | 0.00    | 0.05  | 0.00      | 0.00               |       | 0.00              |             |             |             |                    |             |       |

[illegible]

**Table B-2.** Ice motion and glacier surface height data from the long-term observation sites on Kahiltna Glacier from index stakes. Text in red are unresolved errors.

| Date<br>(mm/dd/yy) | Period<br>(year) | Coordinates |           |          | Speed       | Direction            |                    | Surface         | Snow         | SSurf.          | Stake     | Emergence |                          |
|--------------------|------------------|-------------|-----------|----------|-------------|----------------------|--------------------|-----------------|--------------|-----------------|-----------|-----------|--------------------------|
|                    |                  | X<br>(m)    | Y<br>(m)  | Z<br>(m) | V<br>(m/yr) | Horizontal<br>(grad) | Vertical<br>(grad) | Altitude<br>(m) | Depth<br>(m) | Altitude<br>(m) | b'<br>(m) | e<br>(m)  | V <sub>e</sub><br>(m/yr) |
| STAKE 03-K17-9     |                  |             |           |          |             |                      |                    |                 |              |                 |           |           |                          |
| 4/30/2003          |                  | 588975.1    | 6980219.6 | 1946.7   |             |                      |                    | 1946.7          | 2.7          |                 | 7.1       |           |                          |
| 8/22/2003          | 0.3121           | 589176.8    | 6979520.5 | 1932.9   | 2331.6      | -82.1                | -1.21              | 1932.9          | 1.5          |                 | 5.7       | -12.4     | -39.7                    |
| 5/21/2004          | 0.7474           | 588982.9    | 6979999.1 | 1942.4   | 690.9       | 124.5                | 1.17               | 1942.4          | 2.0          |                 | 7.6       | 7.5       | 10.1                     |
| 9/7/2004           | 0.2984           | 588985.5    | 6979949.5 | 1937.5   | 167.2       | -96.6                | -6.17              | 1937.5          | 0.0          |                 | 4.6       | -1.7      | -5.8                     |
| 5/18/2005          | 0.6927           | 588993.8    | 6979826.8 | 1936.4   | 177.5       | -95.7                | -0.57              | 1936.4          | 2.5          |                 | 7.3       | -3.8      | -5.5                     |
| 9/2/2005           | 0.2930           | 588999.8    | 6979765.7 | 1931.3   | 210.3       | -93.8                | -5.27              | 1931.3          | 0.0          |                 | 4.6       | -2.4      | -8.2                     |
| 5/22/2006          | 0.7173           | 589012.7    | 6979616.8 | 1929.8   | 208.4       | -94.5                | -0.67              | 1929.8          | 2.4          |                 | 7.1       | -4.1      | -5.6                     |
| 8/21/2006          | 0.2491           | 589018.2    | 6979561.9 | 1927.4   | 221.4       | -93.5                | -2.75              | 1927.4          | 0.1          |                 | 4.6       | 0.1       | 0.4                      |
|                    |                  |             |           |          |             |                      |                    |                 |              |                 |           |           |                          |
| STAKE 07-K17-9M    |                  |             |           |          |             |                      |                    |                 |              |                 |           |           |                          |
| 8/20/2007          |                  |             |           |          |             |                      |                    |                 |              |                 | 6.5       |           |                          |
| 9/1/2008           | 1.035            | 588999.9    | 6980040.3 | 1935.2   |             |                      |                    | 1935.2          | 0.0          | 1935.2          | 0.0       |           |                          |
| 5/24/2009          | 0.726            | 589008.7    | 6979889.8 | 1933.7   | 207.8       | -96.3                | -0.64              | 1933.7          | 2.2          | 1931.5          | 0.0       | -1.5      | -2.1                     |
| 9/3/2009           | 0.279            | 589011.8    | 6979843.4 | 1930.0   | 167.1       | -95.8                | -5.09              | 1930.0          | 0.0          | 1930.0          | 0.0       | -3.7      | -13.3                    |
| 5/19/2010          | 0.706            | 589022.5    | 6979712.5 | 1928.1   | 185.9       | -94.8                | -0.88              | 1928.1          | 1.7          | 1926.4          | 0.0       | -1.8      | -2.6                     |
| 9/14/2010          | 0.323            | 589011.0    | 6979650.8 | 1924.4   | 194.6       | -111.8               | -3.80              | 1924.4          | 0.0          | 1924.4          | 0.0       | -3.8      | -11.6                    |
| 6/8/2011           | 0.731            | 589042.568  | 6979497.8 | 1921.7   | 213.9       | -87.0                | -1.08              | 1921.7          | 1.2          | 1920.5          | 6.6       | -9.3      | -12.7                    |
| 8/15/2011          | 0.186            | 589048.9    | 6979464.1 | 1919.5   | 184.6       | -88.1                | -4.06              | 1919.5          | 0.0          | 1919.5          | 4.5       | -0.1      | -0.3                     |
| 4/25/2012          | 0.695            | 589066.8    | 6979323.3 | 1918.8   | 204.1       | -91.9                | -0.31              | 1918.8          | 2.3          | 1916.6          | 7.0       | -3.3      | -4.7                     |
| 8/13/2012          | 0.301            | 589077.4    | 6979254.9 | 1915.5   | 229.9       | -90.3                | -3.13              | 1915.5          | 0.9          | 1914.6          | 4.8       | -1.1      | -3.7                     |
| 8/1/2013           | 0.966            | 589119.2    | 6979044.0 | 1912.3   | 222.5       | -87.5                | -0.92              | 1912.3          | 1.4          | 1910.9          | 6.2       | -4.5      | -4.7                     |
|                    |                  |             |           |          |             |                      |                    |                 |              |                 |           |           |                          |
| STAKE 10-K17-6M    |                  |             |           |          |             |                      |                    |                 |              |                 |           |           |                          |
| 6/8/2011           |                  | 588896.2    | 6980979.5 | 1943.9   |             |                      |                    | 1943.9          | 1.2          | 1942.7          | 4.4       |           |                          |

| Date<br>(mm/dd/yy) | Period<br>(year) | Coordinates |           |          | Speed<br>V<br>(m/yr) | Direction            |                    | Surface         | Snow         | SSurf.          | Stake     | Emergence |                          |
|--------------------|------------------|-------------|-----------|----------|----------------------|----------------------|--------------------|-----------------|--------------|-----------------|-----------|-----------|--------------------------|
|                    |                  | X<br>(m)    | Y<br>(m)  | Z<br>(m) |                      | Horizontal<br>(grad) | Vertical<br>(grad) | Altitude<br>(m) | Depth<br>(m) | Altitude<br>(m) | b'<br>(m) | e<br>(m)  | V <sub>e</sub><br>(m/yr) |
| 9/14/2011          | 0.268            | 588892.0    | 6980936.8 | 1941.7   | 224.4                | -106.2               | -3.31              | 1941.7          | 0.0          | 1941.7          | 4.2       | -2.1      | -7.8                     |
| 4/25/2012          | 0.613            | 588883.4    | 6980815.1 | 1942.5   | 198.9                | -104.5               | 0.44               | 1942.5          | 2.0          | 1940.5          | 7.0       | -1.9      | -3.2                     |
| 8/13/2012          | 0.301            | 588879.433  | 6980749.6 | 1939.6   | 218.2                | -103.8               | -2.84              | 1939.6          | 1.0          | 1938.6          | 2.5       | 1.6       | 5.4                      |
| 8/1/2013           | 0.966            | 588872.5    | 6980545.6 | 1938.9   | 211.1                | -102.2               | -0.21              | 1938.9          | 1.6          | 1937.3          | 4.2       | -2.4      | -2.4                     |
|                    |                  |             |           |          |                      |                      |                    |                 |              |                 |           |           |                          |
| STAKE K17A-13-6-6  |                  |             |           |          |                      |                      |                    |                 |              |                 |           |           |                          |
| 6/6/2013           |                  | 588706.9    | 6982751.6 | 1984.8   |                      |                      |                    | 1984.8          |              |                 |           |           |                          |
| 8/1/2013           | 0.153            | 588703.0    | 6982730.8 | 1984.4   | 138.3                | -111.7               | -0.99              | 1984.4          |              |                 |           |           |                          |
|                    |                  |             |           |          |                      |                      |                    |                 |              |                 |           |           |                          |
| STAKE K17B-13-6-6  |                  |             |           |          |                      |                      |                    |                 |              |                 |           |           |                          |
| 6/6/2013           |                  | 589411.6    | 6982585.6 | 1960.0   |                      |                      |                    | 1960.0          |              |                 |           |           |                          |
| 8/1/2013           | 0.153            | 589404.1    | 6982561.6 | 1956.7   | 165.1                | -119.4               | -8.33              | 1956.7          |              |                 |           |           |                          |
|                    |                  |             |           |          |                      |                      |                    |                 |              |                 |           |           |                          |
| STAKE K17C-13-6-6  |                  |             |           |          |                      |                      |                    |                 |              |                 |           |           |                          |
| 6/6/2013           |                  | 590187.2    | 6982360.4 | 1960.7   |                      |                      |                    | 1960.7          |              |                 |           |           |                          |
| 8/1/2013           | 0.153            | 590178.6    | 6982339.6 | 1965.9   | 151.1                | -124.8               | 14.35              | 1965.9          |              |                 |           |           |                          |

**Table B-3.** Ice motion and glacier surface height data from the long-term observation sites on Traleika Glacier from index stakes.

| Date<br>(mm/dd/yy) | Period<br>(year) | Coordinates |               |           | Speed       | Direction            |                    | Surface         | Snow         | SSurf.          | Stake     | Emergence |                          |
|--------------------|------------------|-------------|---------------|-----------|-------------|----------------------|--------------------|-----------------|--------------|-----------------|-----------|-----------|--------------------------|
|                    |                  | X<br>(m)    | Y<br>(m)      | Z<br>(m)  | V<br>(m/yr) | Horizontal<br>(grad) | Vertical<br>(grad) | Altitude<br>(m) | Depth<br>(m) | Altitude<br>(m) | b'<br>(m) | e<br>(m)  | V <sub>e</sub><br>(m/yr) |
| STAKE 03-T-9M      |                  |             |               |           |             |                      |                    |                 |              |                 |           |           |                          |
| 5/31/2003          |                  | 611,372.882 | 7,001,571.074 | 2,088.719 |             |                      |                    | 2088.7          | 2.0          | 2086.7          | 6.7       |           |                          |
| 8/28/2003          | 0.244            | 611,376.294 | 7,001,598.435 | 2,086.282 | 113.6       | 92.1                 | -5.61              | 2086.3          | NA           | 2086.3          | NA        |           |                          |
| 5/21/2004          | 0.731            | 611,385.721 | 7,001,683.465 | 2,085.069 | 117.0       | 93.0                 | -0.90              | 2085.1          | 1.2          | 2083.9          | 6.0       | -2.9      | -4.0                     |
| 9/2/2004           | 0.285            | 611,390.115 | 7,001,714.973 | 2,079.321 | 113.5       | 91.2                 | -11.38             | 2079.3          | 0.0          | 2079.3          | 2.8       | -2.5      | -8.9                     |

[illegible]

| Date<br>(mm/dd/yy) | Period<br>(year) | Coordinates |              |          | Speed       | Direction            |                    | Surface         | Snow         | SSurf.          | Stake     | Emergence |                          |
|--------------------|------------------|-------------|--------------|----------|-------------|----------------------|--------------------|-----------------|--------------|-----------------|-----------|-----------|--------------------------|
|                    |                  | X<br>(m)    | Y<br>(m)     | Z<br>(m) | V<br>(m/yr) | Horizontal<br>(grad) | Vertical<br>(grad) | Altitude<br>(m) | Depth<br>(m) | Altitude<br>(m) | b'<br>(m) | e<br>(m)  | V <sub>e</sub><br>(m/yr) |
| STAKE 13-T1B-6M    |                  |             |              |          |             |                      |                    |                 |              |                 |           |           |                          |
| 5/28/2013          |                  | 614,587.68  | 7,011,392.84 | 1,711.29 |             |                      |                    | 1711.3          | 0.2          | 1711.1          | 5.2       |           |                          |
| 8/28/2013          | 0.252            | 614,589.46  | 7,011,402.22 | 1,709.28 | 38.7        | 88.1                 | -13.26             | 1709.3          | 0.0          | 1709.3          | 1.5       | 1.7       | 6.6                      |
|                    |                  |             |              |          |             |                      |                    |                 |              |                 |           |           |                          |
| STAKE 13-T1C-6M    |                  |             |              |          |             |                      |                    |                 |              |                 |           |           |                          |
| 5/28/2013          |                  | 614,680.25  | 7,011,389.70 | 1,715.06 |             |                      |                    | 1715.1          | 0.2          | 1714.8          | 5.2       |           |                          |
| 8/28/2013          | 0.252            | 614,682.45  | 7,011,398.26 | 1,713.01 | 36.0        | 84.0                 | -14.47             | 1713.0          | 0.0          | 1713.0          | 1.7       | 1.5       | 6.1                      |

## Appendix C – Short report for DENA Current Resource Projects

### Glacier Monitoring

By Rob Burrows

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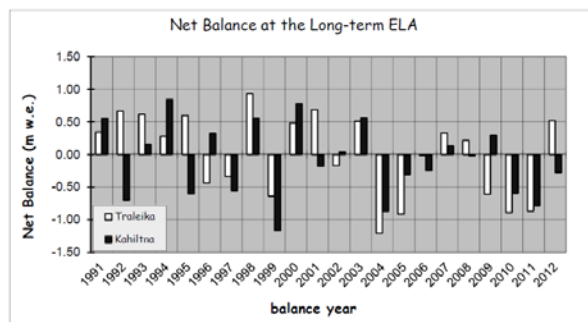
Glaciers are the enigmatic sculptors of the mountains. They are a sensitive indicator and powerful symbol of climate change. Almost all glaciers across the globe are thinning and retreating in unison from the warming climate. Denali's glaciers are no exception, however the highest elevation glaciers that sit on the roof of North America are robust and not seeing as dramatic loss as many other glaciers in Alaska and the world. Denali is a stronghold for glaciers because the high mountains provide a cold and snowy refuge, the best habitat for glaciers.



Glaciers are integral components of the region's ecosystem. Glacier behavior affects other components of the ecosystem, such as rivers, microclimate, and the creation and destruction of terrestrial habitat. Glaciers have been a feature of scientific interest since the first explorations of geologists in the early 1900s. The NPS has been conducting long term monitoring since 1991, below are recent updates on those efforts, as well as work by outside researchers.

- In 2013 the Kahiltna and Traleika glaciers were monitored for mass balance at index sites for the 22<sup>nd</sup> year.

- Thanks to the assistance of Denali backcountry rangers in fall 2012 and 2013, the Traleika index stake was accessed on foot for the second year in a row of the monitoring program.



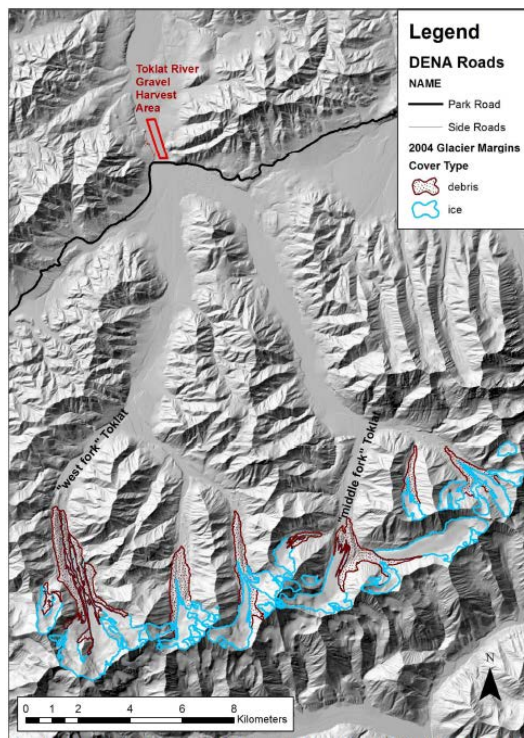
- The Traleika glacier as a whole had a neutral to slightly positive balance year in 2012. This year represents a hiatus from the negative trend the glacier has experienced since 2004.
  - Snowfall/winter balance was 115% of average.
  - Melt/summer balance was 63% of average.
- The Kahiltna Glacier as a whole had a neutral to slightly negative balance year. This adds to the negative trend on this glacier since 2004.
  - Snowfall/winter balance was 71% of average.
  - Melt/summer balance was 85% of average.

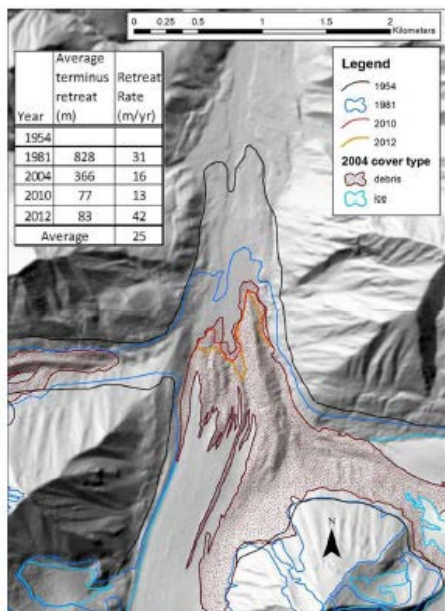


- The West Fork Toklat glacier was surveyed with a citizen science seminar in conjunction with the MSLC in August 2013. Six participants helped complete a GPS survey of the terminus last done in 2002 and of surface elevation of the lower glacier last done in 2002. The expedition will strike out once again August 7-11, 2014. See:  
<http://www.alaskageographic.org/static/1174/glaciology-backcountry-citizen-science>
- For virtual exploration of some of Denali's glaciers check out these 360 degree panoramas:  
<http://www.nps.gov/dena/photosmultimedia/vr-panos.htm>
- There is the **Fact Sheet** available for Denali Glaciers, see here for the digital version:  
<http://www.nps.gov/dena/naturescience/upload/GlacierMonitoring2012.pdf>
- There is a **NEW Fact Sheet** for Kids about glaciers, see here for the digital version:  
[http://www.nps.gov/dena/naturescience/upload/Glaciers\\_Kids\\_2014.pdf](http://www.nps.gov/dena/naturescience/upload/Glaciers_Kids_2014.pdf)

With funding from the NPS, researchers from University of Alaska Fairbanks and Alaska Pacific University have completed an inventory of all glaciers in Denali from 2010 satellite imagery. In addition they have compiled surface elevation change data from select glaciers. The changes in ice volume calculated from repeat airplane borne laser altimetry surveys reveal the following results:

- The area of Denali glaciers decreased by 8 percent between 1952 and 2010, with most of this loss occurring on small to medium size glaciers at mid elevations (1400-1800 meters elevation). A few glaciers increased in area, but this was due to surging, most notably Muldrow and Peters glaciers.
- 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). This is attributed to thickening of the upper elevations of this surging glacier system after the last surge of Muldrow in 1956/57. Lower elevations of the glacier system was 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. The lowest measured balance rate was on Middle Fork Toklat Glacier from 2008-2010. Kahiltna and middle fork Toklat thinning rates appear to have increased during the 2008 to 2010 period. Results from GPS surveys conducted during the citizen science courses indicate continued ice loss in middle fork and west fork Toklat Glaciers between 2010 and 2013.





This year Researchers from several universities will continue their large project to better understand the climate of the last 1,000 years in the Alaska Range. Last year they successfully drilled two ice cores that are just over 200 meters long (deep) on the Mt. Hunter summit plateau and installed a weather station there. This year they will maintain the weather station and date moraines of some of the large glaciers to the south of the Alaska Range crest such as Kahiltna.

For a teacher's eye view of part of the 2013 expedition see this PolarTrec blog:  
<http://www.polar trec.com/expeditions/reconstructing-the-past-climate-of-central-alaska>



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