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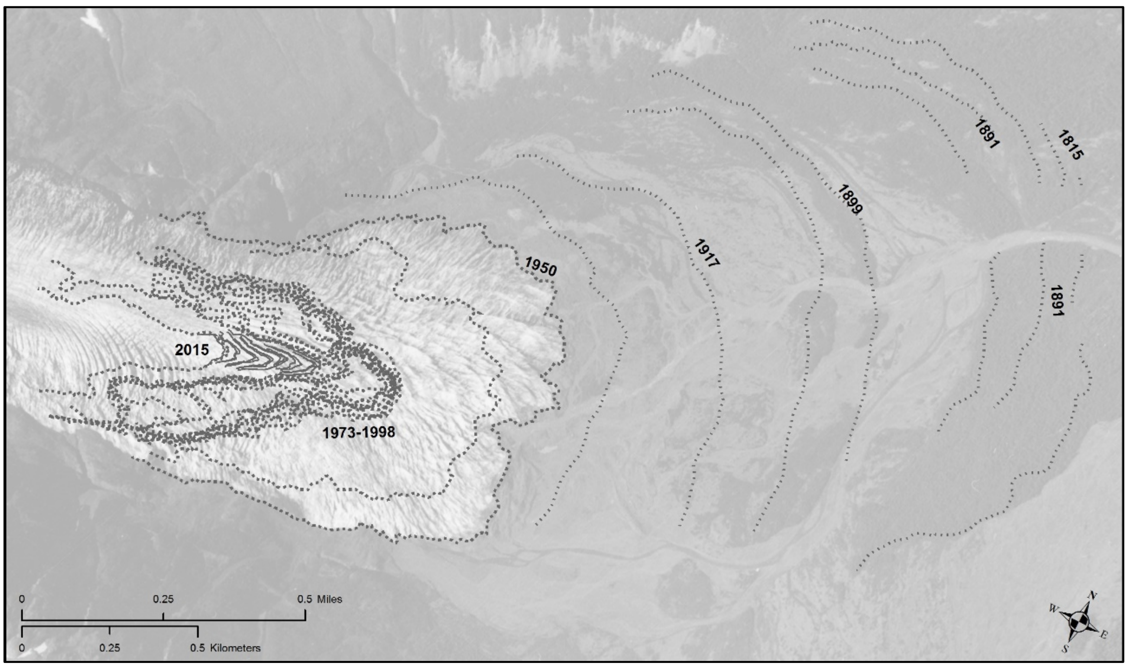
200 Years of Terminus Retreat at Exit Glacier

1815-2015

Natural Resource Report NPS/KEFJ/NRR—2016/1341



ON THE COVER
Map of Exit Glacier terminus positions, 1815-2015. Dotted lines represent pre-1950 positions based on moraine dated (Cusick 2001). Dashed lines represent positions digitized from aerial photos. Solid lines represent positions mapped with a hand-held GPS unit.

ON THIS PAGE
Photograph of Exit Glacier, as it flows outwards from the Harding Icefield on September 6, 2016.
Photograph courtesy of the National Park Service

200 Years of Terminus Retreat at Exit Glacier

1815-2015

Natural Resource Report NPS/KEFJ/NRR—2016/1341

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Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Abstract

In this paper we present dated historical terminus positions for Exit Glacier compiled from previously published moraine data, georeferenced historical aerial photos and direct measurements recorded with mapping-grade GPS. We test two methods for measuring the rate of retreat, a centerline method and a box method. Overall retreat is the same using both methods but some interannual differences are highlighted. We present the results and explain the differences of each method. For simplicity and consistency in future measurements, we recommend continuing measurements using the centerline method.

Results of the centerline method indicate that over the last 200 years, Exit Glacier retreated 2.5 km from its 1815 Little Ice Age maximum to its position in September 2015. As it retreated, the terminus also became narrower and transformed from a piedmont glacier to a wide valley glacier to a narrow valley glacier as it appears today. The terminus remained stable at its 1815 maximum position until approximately 1889; over that period only, a small retreat of 14 meters occurred. During the period of retreat from 1889 to 2015, the average rate was 19.7 m/yr. In the most recent 5-year period from 2011 to 2015, the average rate of retreat was 44.5 m/yr. Over the previous 5-year period from 2006-2010, the rate of retreat was slightly slower, 29.4 m/yr. Beginning in 2010, mapping of the terminus was performed in both fall and spring, allowing for separation of retreat occurring in summer and winter months. Retreat in summer months occurs a median of 6.7 times faster than during the winter.

Acknowledgements

We would like to acknowledge the contributions of numerous former staff at Kenai Fjords National Park and non-NPS partners who initiated this project through aerial photo acquisition and GPS mapping efforts. In particular, we would like to acknowledge former Kenai Fjords National Park Resource Managers, Mike Tetreau and Fritz Klasner, who initiated the park's glacier monitoring program including documenting changes at Exit Glacier's terminus during their respective tenures at the park. Last but not least, we would like to thank Mike Loso for his thoughtful review of this paper.

Introduction

Background

Kenai Fjords National Park was established in 1980 "*to maintain unimpaired the scenic and environmental integrity of the Harding Icefield, its outflowing glaciers, and coastal fjords and islands in their natural state*" (ANILCA sec.201(5)).

The Harding Icefield, the largest icefield wholly contained within the United States, consists of 1,800 km2 of ice (Adalgeirsdóttir et al. 1998) and dominates the landscape within the boundaries of Kenai Fjords National Park (KEFJ). Approximately 38 distributary glacier tongues flow from the icefield. Exit Glacier, located in the northeastern corner of the Harding Icefield (Figure 1), is the only road-accessible glacier in the park and, by walking less than one mile on a well-maintained trail, provides an up-close view of a glacier. This ease of accessibility allows Exit Glacier to be one of the most highly-visited glaciers in Alaska, with over 100,000 annual visitors, including President Obama on his 2015 trip to Alaska when he chose Exit Glacier to highlight the impacts of climate change.

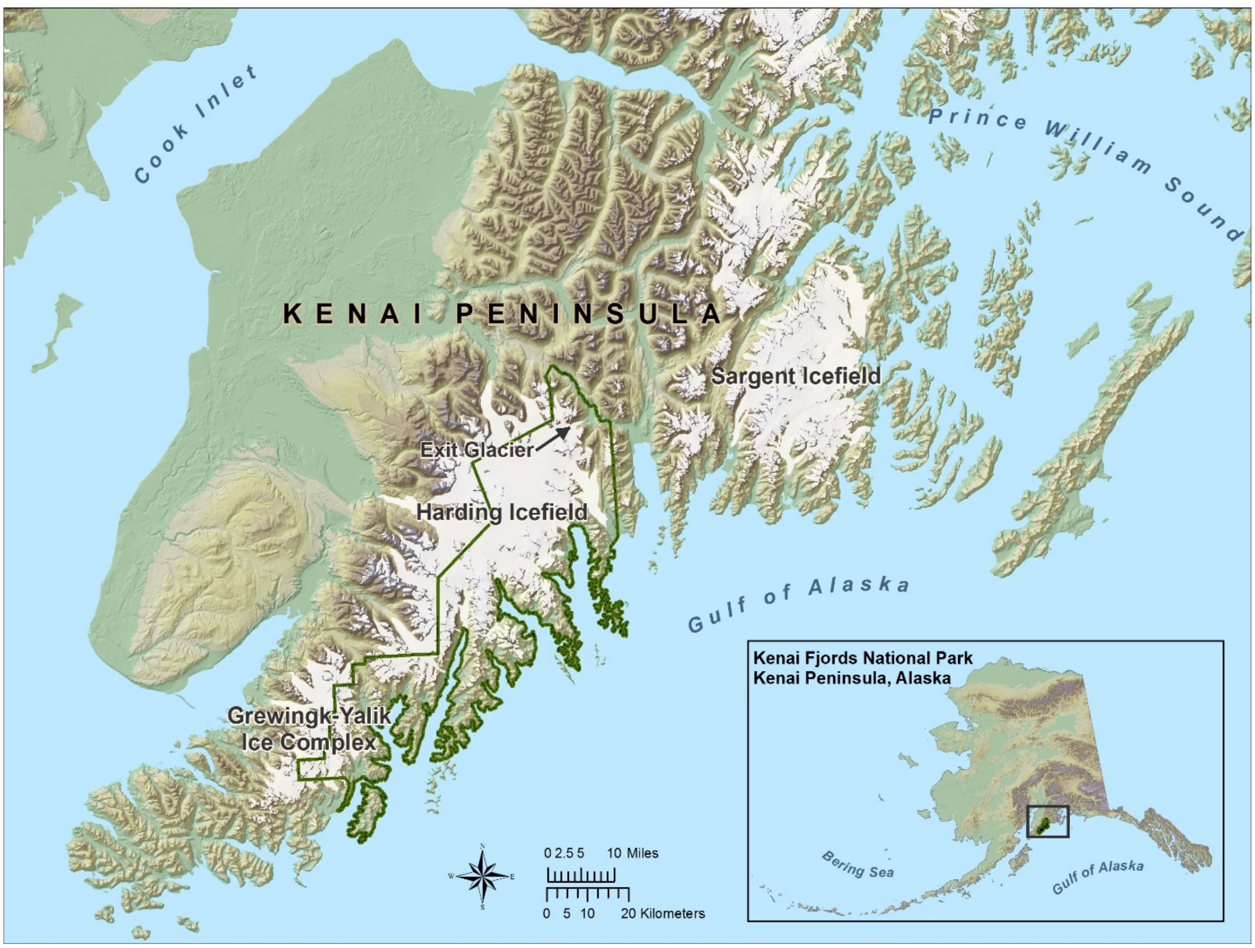

Figure 1. Kenai Fjords National Park is located on the southeastern side of the Kenai Peninsula in southcentral Alaska. Glaciers and snow cover 48.5% of the park (Loso et al 2014).

Why Melt Matters: Global, Regional and Local Implications

The worldwide retreat of glaciers is of great concern, as the increased rate of glacial melt is a bellwether of climate change (Leclerq et al. 2014). Mountain glaciers, such as those in KEFJ, provide approximately half of glacial meltwater contributions to sea-level rise (Meier 2007). From the mid-1950s to mid-1990s annual volume loss from Alaska's glaciers was nearly double the annual volume loss of the Greenland ice sheet (Arendt et al. 2002). From 2003-2009, Alaska's glaciers continued to be of the greatest contributors of glacial melt to sea level rise outside of the polar ice caps (Gardner et al. 2013). In addition to sea level rise, impacts from shrinking glaciers in Alaska and similar environments include changes to nutrient fluxes in near-glacier ecosystems (Hood and Berner 2009; Hood et al. 2009; Neal et al. 2010); decreasing freshwater storage leading to hydrological change (Bliss et al. 2014); change to timing of water runoff and water quality (O'Neel et al. 2014) threatening freshwater biodiversity (Jacobsen et al. 2012); and impacts to marine wildlife and seabirds (Lydersen et al. 2014; Robinson et al. 2001). O'Neel et al. (2015) summarize regional changes resulting from physical, chemical and biological impacts from loss of glacial ice in the Gulf of Alaska and Northern Pacific coast.

In addition to the environmental impacts identified above, glacier retreat also imposes socioeconomic impacts on local communities. Mountain communities in dry regions around the world are dependent on glacial meltwater and runoff for their water supply, such as in the Andes where glacial meltwater is necessary for irrigation and drinking water (Rhoades et al. 2008). In the temperate rainforest of coastal southcentral Alaska, glaciers are not a significant source of water for human use and consumption and changes related to this are not a foreseeable concern, but changes in tourism may be. People travel from around the world to visit KEFJ to see wildlife, to sportfish, or to see glaciers, all activities related to the presence of glaciers. The income from tourism supports many people in small communities such as Seward, Alaska, the gateway community for KEFJ. This prompts the question of how glacier loss will impact the economies of these communities.

In 2015 KEFJ visitors were surveyed to understand how visitor satisfaction at KEFJ will change as the distance from which they can observe Exit Glacier increases and the size of the glacier decreases (Moser et al. 2016). In other words, will they still be satisfied coming to the park as Exit Glacier retreats farther from the end of the trail? Results of the survey indicate that the condition of Exit Glacier in 2015 was only moderately acceptable and that visitors seem to be more tolerant of overall recession than they are of their ability to experience Exit Glacier at close range (Moser et al. 2016). This survey focused on Exit Glacier but may apply to all glacier margins in the park. Total glacier area in KEFJ decreased 11% between 1950 and 2005, with area of ice lost dominated by terminus retreat and larger areas disappearing at lower elevations (Loso et al. 2014).

Documenting the changes to a glacier is not only of interest to the general observer, but is important for researchers and scientists interested in landscape change including soil development (Ahlstrand 1983; Cusick 2001), stream development and colonization (Milner and York 2001; McDermott et al. 2010), vegetation succession (Helm and Allen 1995), and mycorrhizal chronosequences (Helm et al. 1996).

Measuring Glacial Melt

The retreat of glacier termini is the most visible and striking example of shrinking ice volume to the typical observer, but it is only one metric that is used to measure ice loss. Terminus retreat signifies a change in glacier length as the position of the farthest extent of the ice mass moves closer to the head of the glacier. However, glaciers are three-dimensional features and ice melts along all margins. At Exit Glacier, this has been measured as change in areal extent (Giffen et al. 2014; Rice 1987), surface elevation (Larsen et al. 2015; Adalgeirsdóttir et al. 1998; Sapiano et al. 1998; Echelmeyer et al. 1996; Van Looy et al. 2006) and ice thickness (Truffer and Haberman 2011, Truffer 2014). These metrics can be used together to calculate total ice volume. For a glacier that is part of a larger glacier complex, such as Exit Glacier and the Harding Icefield, the upper boundary that is contiguous to other glaciers does not change, but all external boundaries, where the ice meets land or water, do.

Global interest in mapping glacier boundaries is evident by the development of the Randolph Glacier Inventory (RGI), a global database of compiled glacier outlines including glaciers of the Harding Icefield (Raup et al. 2007). The boundary of an individual glacier confined by bedrock is more straightforward to delineate than a glacier flowing from a larger mass of ice made up of contiguous glaciers such as the Harding Icefield (Kienholz et al. 2013). Each new version of the GLIMS technical reports provide updates on additions and edits to the RGI by region, creating a detailed history of glacier boundary development. GLIMS version 5 technical report (Arendt et al. 2015) indicates that the current glacier boundaries of Alaska (RGI version 4) were modified to redefine glacier divides using Burgess et al. (2013) velocity fields and updated to include topographic and hypsometric attributes (Kienholz et al. 2014). The previous boundary, specific to the Harding Icefield, was developed using Landsat TM scenes acquired between 2005-2009 for the external boundaries and using the NED DEM for the upper drainage divides (Le Bris et al. 2011). The external extents of these two most recent versions of Exit Glacier appear identical with the only apparent changes being in the upper divide. The upper divide of Exit Glacier has consistently been the most challenging part of the boundary to define as it occurs on the relatively flat region of the central icefield plateau.

In 2015, researchers at the U.S. Geological Survey (USGS), Alaska Pacific University (APU) and KEFJ worked together to incorporate available in situ data to redefine the upper divide of Exit Glacier as part of a surface water boundary delineation for the Exit Creek drainage basin (Curran et al. in prep) . In situ flow vector measurements (collected as 1. part of an existing glacier mass balance study by KEFJ and 2. opportunistically when an existing APU equipment cache was relocated and mapped) were incorporated with modelled ice flow vectors (Burgess 2013) resulting in a new delineation of the upper divide of Exit Glacier's boundary. External non-ice areas were delineated along topographical divides established from a lidar-derived 2-meter digital elevation model acquired by Aerometric, Inc. in 2008. We then modified this new drainage area boundary by clipping the non-ice areas to the existing RGI boundary to create a new glacier boundary for Exit Glacier. A map of this final boundary is presented in Figure 2 and illustrates how small the current terminus is in relation to the entire glacier, a consideration that should be made when thinking about terminus retreat in relation to the health of a glacier as a whole. Based on this new boundary, Exit Glacier lies between 123 – 1,666.7 m in elevation and covers an area of 37.8 km^2. Exit Glacier is

9.97 km long (along the 2014 centerline from the RGI). It should be noted that a glacier boundary cannot simply be updated with a new terminus position; all glacier margins must be mapped at the same time. This boundary will be available for download as a shapefile from the NPS Integrated Resource Management Applications (IRMA) data portal located at www.IRMA.NPS.gov.

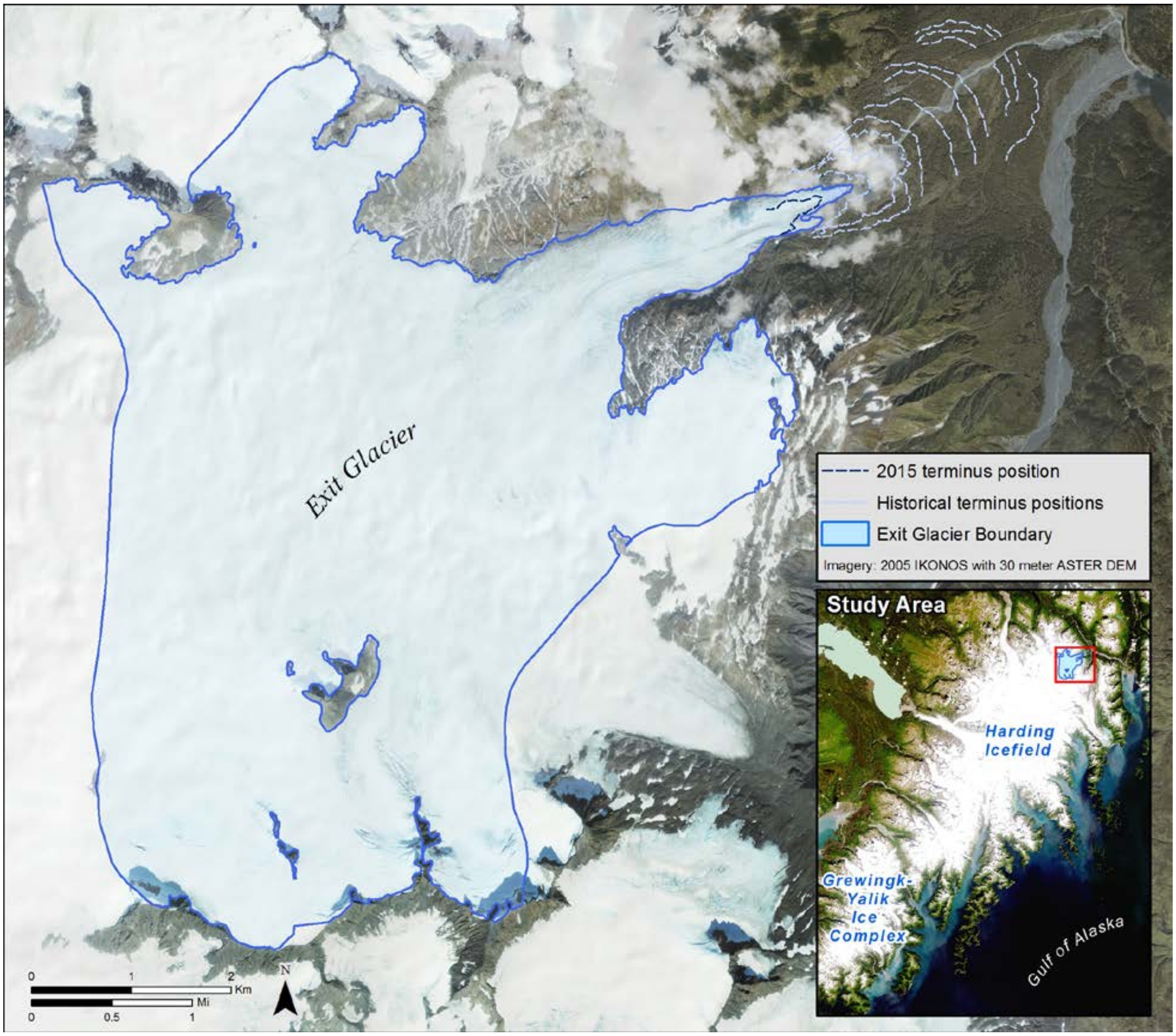

Figure 2. Map of Exit Glacier boundary. This figure provides perspective on the ratio of the terminus position to the whole areal extent of Exit Glacier and illustrates why the boundary cannot be simply edited to update the terminus positon but must be mapped as a whole. By including the historical terminus positions on this map we can see that nearly half of the distributary of Exit Glacier has melted in the last 200 years.

Previous Exit Glacier Terminus Measurements

The retreat of Exit Glacier has been of interest to KEFJ resource managers since the park was established in 1980. Three independent studies mapped and dated Exit Glacier's moraines (Cusick 2001; Wiles 1992; Ahlstrand 1983) and provide the only physical evidence of pre-1950 terminus positions. In the early 1980s, in situ observations of terminus positions were attempted but there is no documentation of data until 1987 when survey points were established and measurements were taken using a compass bearing, clinometer and a measuring tape (Tetreau 1989). Tetreau noted that minor advances during the winter were typical at Exit Glacier but that in the winter of 1987-88 an advance of 15-18 m was observed, plowing over new trails and signs that had been recently constructed by the park. This advance was followed by a stable terminus position in the summer of 1988. These tape measurements were made weekly until 1991 when a new technique was implemented using a transit and stadia rod to map the terminus margin and plotted in AutoCad (Tetreau 2006). In 1999 park staff used a Trimble GPS unit to map the terminus position by walking the edge of the glacier for the first time, but the glacier front quickly became too steep and dangerous to continue this method again until 2008.

In 2005, KEFJ resource manager, Mike Tetreau, compiled unpublished park data into a fact sheet documenting recent Exit Glacier history (Tetreau 2005), notably:

- 1983/84 – 1991/1993: Exit Glacier advanced 150 m.
- 1994-1995 the terminus was stable and formed a moraine that was eroded away by Exit Creek within ten years.
- 1995-2005 the glacier retreated annually.
- 2002 the terminus retreated 105 m.

In 2003, 2004 and 2005 the park contracted AeroMap, Inc. to acquire aerial photographs of the glacier terminus that were geo-referenced and used to digitize the terminus position. Existing aerial photography that had been previously acquired by AeroMap, Inc. was also purchased to fill in some of the gaps of Exit Glacier's history (Tetreau 2006). KEFJ acquired new aerial photography for Exit Glacier terminus mapping again in September 2006 and 2007 (Klasner 2007). Subsequent remotely sensed image acquisitions include aerial photography and lidar-derived digital elevation products in 2008 (Aero-Metric, Inc. (formerly AeroMap, Inc.)) of the Harding Ice Field, Exit Glacier, and Bear Glacier; a 2012 WorldView orthoimage of a heavily shadowed Exit Glacier, and an orthophoto mosaic of Exit Glacier in 2015 (Quantum Spatial, Inc. (formerly Aero-metric, Inc.)). Satellite imagery from 1950(51), 1986, 2000, and 2005(6) were used to calculate terminus retreat rates for 27 glaciers of the Kenai Peninsula's Harding Icefield and Grewingk-Yalik Ice Complex, including Exit Glacier and nine other glaciers in KEFJ (Giffen et al. 2014). Klasner (2007) noted discrepancies in the various methods used to delineate the terminus positions as well as discrepancies in the measurement methods and recommended verifying and addressing these inconsistencies for future analyses.

In this report, we give a detailed account of our data processing and measurement techniques to provide consistent methods for measuring the retreat of Exit Glacier. We assess the consistency of the existing georeferencing of the available aerial photos and re-georeference each one as needed. We describe how we re-digitized all terminus positions at a higher resolution and we measured the change in terminus positions using two methods, the centerline and box methods, and compared the results. We selected the centerline method for this project and future measurements of Exit Glacier's retreat.

Methods

Exit Glacier's retreat from the Little Ice Age Maximum to present has been tracked using three types of data: moraines (dated with dendrochronology), georeferenced historical aerial photographs, and GPS mapping of the ice front.

Datasets

In this work, we compile multiple sources of data on the movement of Exit Glacier's terminus over time. Pre-1950 terminus positions are determined from ground-based mapping of Exit Glacier's moraines across the glacial forelands by Joel Cusick (2001), Gregory Wiles (1992), and Gary Ahlstrand (1983). Post-1950 terminus positions are mapped using available historical aerial photography and, beginning in 2008, annual or sub-annual GPS mapping of the terminus position by NPS staff, in addition to aerial photography, as available.

Moraine Mapping and Dating

Recessional moraines form when a stable or retreating glacier's terminus remains in a stable location long enough for sediment and debris to accumulate into a free-standing depositional feature. These features can be used as geomorphic evidence of a glacier's historic position and can be dated with dendrochronology, lichenometry, cosmogenic radionuclide dating, and other techniques. Moraines accurately demonstrate the physical position of a former glacier terminus, but moraine ages are subject to errors in dating techniques.

Moraines at Exit were dated using dendrochronology, a tree-dating method that uses the annual growth rings of trees to establish tree ages and minimum ages of stability for tree-covered soil surfaces. Dendrochronology is commonly used in determining chronologies of recently deglaciated landscapes (Harrison and Winchester 2000; Koch and Kilian 2005; Xu et al. 2012). As a glacier retreats from a stable position, the remaining moraine stabilizes, enabling plants to colonize in a process called vegetation succession. By counting the annual growth rings of the oldest trees on a moraine, the age of the trees can be determined, making it possible to establish the date when the moraine soil stabilized, and by extension, the date when the glacier retreated from that position.

An initial tree ring chronology of obvious moraines in the forelands of Exit Glacier was created by NPS scientist Gary Ahlstrand in 1983 shortly after the park was established. This work was later updated by two graduate students: Gregory Wiles (1992), who incorporated Exit Glacier in a regional study of glacial fluctuations and climate, and Joel Cusick (2001), who completed a detailed chronosequence and more extensive mapping of the glacier foreland in the Exit Glacier area. Cusick incorporated the earlier efforts into his work as appropriate, given existing records, documentation, and personal communications with the earlier authors.

In dendrochronology, the interval between soil stability (usually assumed to commence when glacier ice retreats away from the moraine) and the beginning of plant growth is known as ecesis. Defining the ecesis interval is key to accurately determining the age of a landform. Ecesis varies regionally, based on microclimate, precipitation, seed availability, and the tree species in question. Cusick determined the ecesis interval for spruce trees at Exit Glacier to be 25 years. This agrees well with a study of ecesis at Portage Glacier (Crossen 1997). Cusick assumed alders to colonize immediately, with an ecesis interval of 0 years. For dating of younger moraines, Cusick primarily used black cottonwood, as they are the dominant species on the outwash plain, with an ecesis period of five years. Spruce were used for older moraines, as they have a longer life span, and can thus capture the age of older features. Cusick determined the ecesis interval for spruce trees at Exit Glacier to be 25 years. When dates for a moraine differed between the studies, Cusick defaulted to using the oldest possible date across all studies. This captures the minimum age of the feature, and allowed him to utilize data from the early work, before some of the oldest trees on select moraines may have died.

Terminus positions prior to 1815 are unknown, but assumed to have been less advanced than the 1815 moraine and therefore any associated moraines would likely have been destroyed by subsequent advances of the glacier, or reworking of sediment by Exit Creek. A deposit of buried logs, just east of the 1926 moraine, was dated with radiocarbon to the 1600s (Wiles 1992). This suggests that an advance of ice buried living trees, and probably a moraine, at that time. Nonetheless, a soil pit near the confluence of Resurrection River and Exit Creek revealed a volcanic ash deposit from 4000 BP, indicating that no glacier has advanced over the area during intervening time (Cusick 2001). This supports the 1815 position as the likely Little Ice Age maximum (Cusick 2001) and, likely, the Holocene maximum (Wiles 1992).

Aerial Photos and High-Resolution Satellite Imagery
Cusick's study involved compiling available historical aerial photography of the Exit Glacier terminus and foreland areas. KEFJ later acquired other available aerial photos for subsequent dates and digitized them for initial work on Exit Glacier terminus positions. These photos allow for precise and spatially extensive mapping of the glacier edge. For this project we carefully checked all of the available imagery for georeferencing accuracy and updated where necessary. We then digitized the terminus position from each georeferenced image – both those with updated georeferencing, and those without. Although we used the moraine positions that Cusick mapped in the field for this project, none of Cusick's data digitized from the aerial photos were used. Imagery used is listed in Table 2 and is presented in Appendix C. Further details on sources of imagery are available in Cusick (2001). Cusick's moraine data and our resultant geospatial data will be available for download from the NPS IRMA data portal located at www.IRMA.NPS.gov.

Global Positioning System (GPS) Mapping
Beginning in 2008, NPS staff began annual mapping Exit Glacier's terminus using a Trimble GeoExplorer mapping grade handheld GPS unit with external antenna and walking the edge of the terminus. The accuracy of the units used varies from submeter (the earlier models) to decimeter (the Geo 7x and Zephyr 2 antenna used in 2015). The portion of the glacier that was mapped was limited by what was safely accessible based on terrain around the glacier. If the glacier towered above the mapper an offset was applied within the GPS unit so the mapper could maintain a safe distance from the glacier. Estimation of this offset could also introduce error of approximately 1.5 m. In years when the terminus was very thin and the edge of the glacier was below the mapper, it could be walked and mapped right at the glacier's edge. In 2008 and 2009, the terminus position was mapped annually in the fall to capture the beginning/end of the water year. (The water year is the period within which

glacier studies are conducted, based on the hydrological seasons, marking the transition from ablation season to accumulation season). Beginning in 2010, both spring and fall terminus locations were mapped, allowing for differentiation of winter and summer terminus change. Summer season is defined here as late May or early June to late September; winter encompasses the remainder of the year. Some variability exists in the timing of early summer measurements based on late winter snowpack (the edge of the terminus must be free of snow in order to accurately map its edge) and availability of staff. The fall measurement is made in late September.

Georeferencing of Historical Aerial Imagery

Available historical aerial photography was checked for accuracy of georeferencing using terrain features manually identified from 2008 lidar imagery. Selected features were chosen to be stable in the landscape, easily identifiable, and near the position of the glacier terminus. These features are shown in purple in the left panel of Figure 3, shown on top of a shaded relief map derived from lidar. If features appeared to be aligned with ground features in the imagery, original georeferencing was retained. If a misalignment was apparent, as shown with green arrows in the middle panel of Figure 3, image georeferencing was updated using the terrain features visible in that specific image. Note that some features are covered by glacier ice in older imagery, and are thus not used. An illustration of updated georeferencing, with improved alignment between terrain features and imagery is shown in the right panel of Figure 3. It is important to note that georeferencing was optimized for the area immediately surrounding the glacier terminus for this project; areas of the image distant from this focus are likely to have unreliable georeferencing. Details of image georeferencing, including scale of heads-up digitization and image resolution, are given. All available imagery that were used for digitizing terminus positions are shown in Appendix C.

Digitizing Terminus Positions

After accurate georeferencing was ensured, the glacier terminus was manually traced using heads-up digitization. Scale of digitization was consistent within a single image but varied between images based upon resolution and photo illumination. Finest possible resolution for digitization of each image was chosen. All were digitized at a minimum scale of 1:5,000 with 89% at 1:2,500 or finer. Details are given in Table 1.

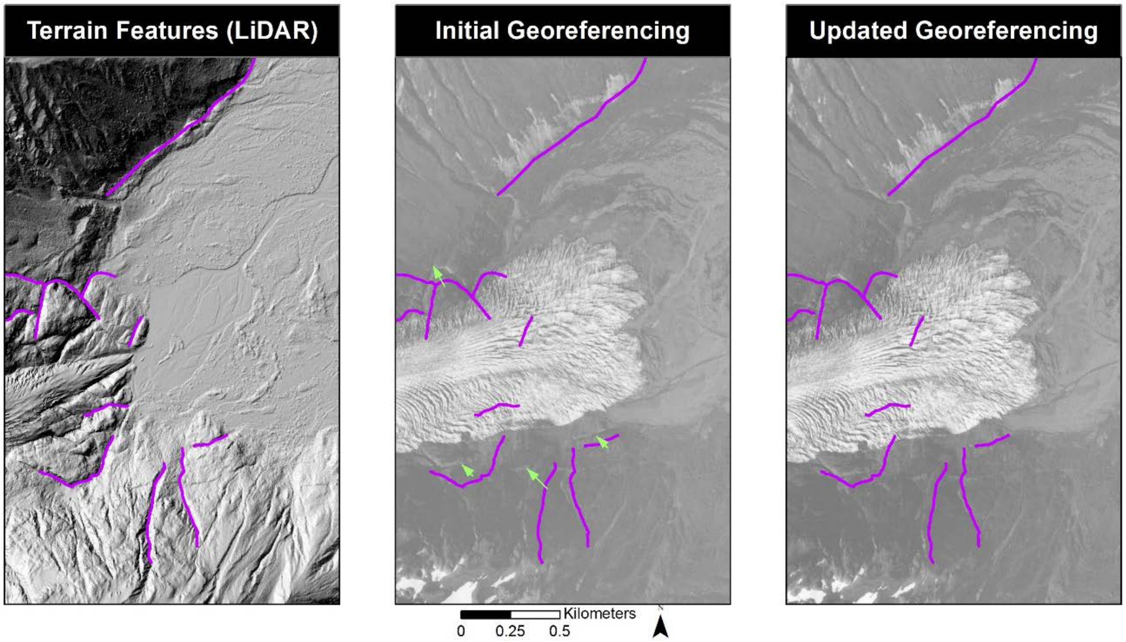

Figure 3: Georeferencing of historical aerial imagery at Exit Glacier terminus. Left panel shows a hillshade of the lidar dataset used to identify stable and identifiable terrain features, traced in purple. The middle panel shows a 1950 image, before update, with a slight misalignment between terrain features and image placement. Right panel shows update of georeferencing, with terrain features more closely aligned with imagery. As the glacier retreated, more ground features were exposed and utilized for georeferencing. Only features visible in each specific image were used.

Table 1: Details of Historical Aerial Photography of Exit Glacier and Terminus Digitization

Date	Updated Georeferencing?	Resolution (m)	Digitization Scale
8/8/1950	Y	1.020	1:2,500
7/1/1961	N	0.458	1:2,500
6/28/1973	Y	0.580	1:2,500
7/27/1974	N	0.763	1:2,500
8/24/1978	Y	1.390	1:5,000
8/14/1984	N	1.770	1:5,000
9/2/1985	Y	0.300	1:1,000
7/10/1993	N	1.550	1:2,500
6/16/1996	N	1.000	1:2,000
9/3/1996	Y	1.000	1:2,500
8/28/1997	N	0.305	1:1,000
8/14/1998	Y	0.944	1:2,500
9/11/2003	N	0.600	1:1,000
9/22/2004	Y	0.313	1:1,000
9/8/2005	N	0.213	1:1,000
9/11/2006	N	0.216	1:1,000
9/16/2007	Y	0.206	1:1,000
8/3/2015	N	0.300	1:1,000

Measuring Retreat

Measuring glacial retreat can be accomplished in several ways. This document details measurements of Exit Glacier's retreat using a classic centerline method, as used in many studies, including Giffen et. al (2014), among others, and the box method, introduced by Moon and Joughlin (2008).

Centerline Method

This method measures retreat along a central axis of a glacier. Direction of the central axis, and any turning points, is determined manually along the major axis of flow. The azimuth of line segments for the terminus are 44.3° for the northern (moraines) segment and 290.2° for the southern (GPS & photo) segment. Glacier extent is then measured using the maximum point of ice present in the given direction.

Centerline

Historically, Exit Glacier was a piedmont glacier, spilling out of a small constricting valley as it exited the Harding Icefield and spread into a wide arc across the valley floor. As the glacier has retreated to the west and south, its terminus has returned to a steep valley, no longer extending in a wide arc onto the flat forelands. This change was accompanied by a bend in the major axis of the glacier. Thus, measurements of retreat along a central axis must also have a bend. The line of measurement used for this work, along with past positions of the terminus front, is shown in black in Figure 4.

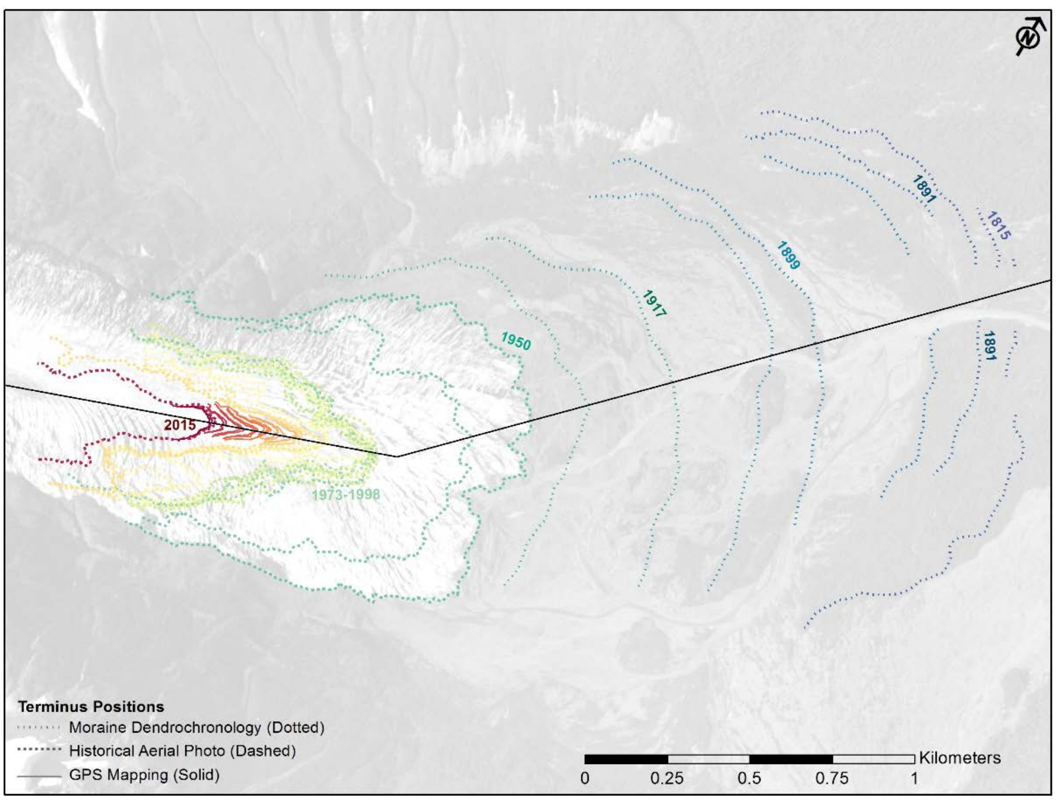

Figure 4: Exit Glacier terminus positions, depicting glacier extent from 1815 to fall 2015. Centerline used for measurements shown in black, terminus positions shown in color scale from purple to red, with cooler colors showing older positions, and hotter colors more recent. Background image is 1950 aerial photo.

Perpendicular Measurements

Using the centerline method, the farthest point of each terminus position along the axis of the centerline is measured as the glacier's annual extent. To measure retreat for a given terminus position, a line perpendicular to the centerline is drawn at a point where it intersects the farthest reach of that terminus position. This line is then used to measure the distance of that terminus from the 1815 extent, which is close to the Little Ice Age maximum (Cusick 2001). Distance is measured along the centerline, rather than as a direct point-to-point distance. This allows us to capture maximum front of the glacier in both the piedmont and valley glacier modes. An example of this is shown in panel A of Figure 5, with the red line showing measurement of the 1950 terminus in the accompanying aerial photo. Position is measured as a distance along the centerline from the 1815 reference point of maximum extent.

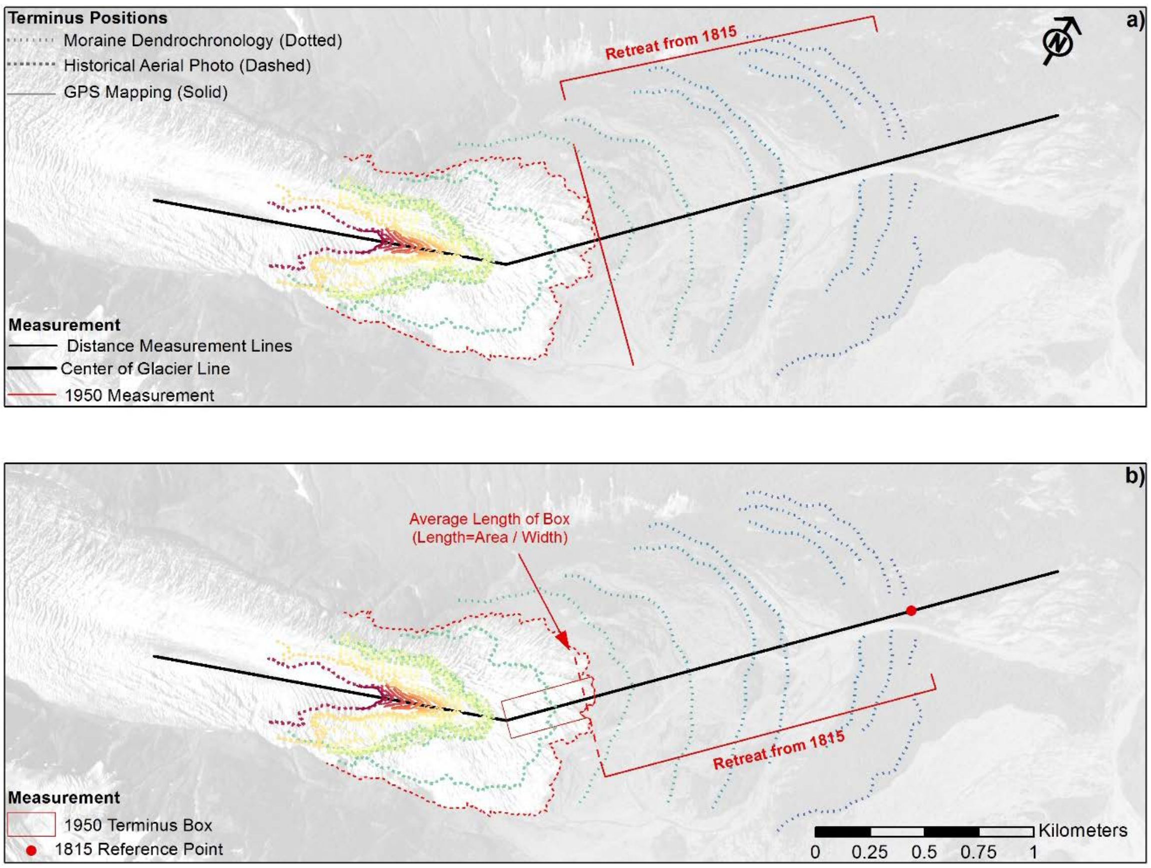

Figure 5: Methods for measuring terminus positions and retreat from 1815. Panel A shows the centerline method, and panel B shows the box method for measuring retreat from 1815 to the 1950 moraine. The centerline, denoting direction of major flow, is shown in black. Terminus positions are shown in a color ramp denoting age, with warm colors denoting recent years, and cool colors denoting older positions.

Box Method

While the centerline method captures the absolute maximum extent of the glacier at a given time, it is not necessarily representative of the majority of the glacier front. Retreat, or advance, can be asymmetric, and small tongues of ice can extend well beyond the main face of the ice. The box method allows measurement of average position of the glacier front, across the width of the box used for measurement. A polygon is created parallel to the centerline, or major axis of the glacier, with one rectangular end, and the other end truncated by the mapped terminus. An example of this for the 1950 terminus is shown as a red polygon in panel B Figure 5. Then, the average length of the polygon is determined simply by dividing area by width. This gives us the average position of the terminus front and is used to calculate distance of retreat from the 1815 maximum reference.

<u>Defining Boxes</u>

As Exit Glacier has retreated, the terminus front has narrowed significantly. Older moraines are over a kilometer wide, while the contemporary glacier snout is under 100 m. Measuring the retreat of the glacier front thus necessitates boxes of changing widths as well.

The orientation of the boxes follows that of the centerline retreat. The edges of the boxes, however, are oriented to capture the maximum extent of the glacier through the period of interest; (i.e. the box is not equally split on both sides of the centerline; it may be shifted north or south, although axis is parallel to centerline, to contain the glacier's toe during that period).

Here, we measure the retreat of Exit Glacier in three distinct periods: one for the piedmont glacier stage, with a wide measurement, one as it began to pull back from the valley floor, but remained laterally extensive in the lower bedrock-confined valley and a third, in the glacier's current mode of shaded and protected valley glacier, with substantial lateral retreat off neighboring rock walls (Figure 6). The periods are defined by substantial change in the width of the terminus, corresponding to the different glacial stages. Break years reflect both the changing width, and years of data available to us. In this research, we measure the terminus position from 1815-1961 with a wide box (175m) in the piedmont phase, a mid-size box (68m) in the wider valley glacier phase from 1973-1998, and a narrow box (32m) in the current steep valley glacier phase, beginning in 2003. Width was chosen manually, in order to capture glacier front over a longer interval of time.

Mapping of older moraines, prior to 1899, contains gaps due to erosion by the Resurrection River and Exit Creek. To trim the box and calculate an area and length for these discontinuous terminus positions, we connected the moraines as mapped by Cusick (2001) using a straight line, more technically known as piecewise linear interpolation.

This is not possible for the 1815 terminus position, where only one portion of moraine remained to be mapped in 1999, on the north side of Exit Creek (Cusick 2001). The location of the 1815 terminus reference point is the same for both the box and centerline method. This allows for easy comparison between the two measurement techniques.

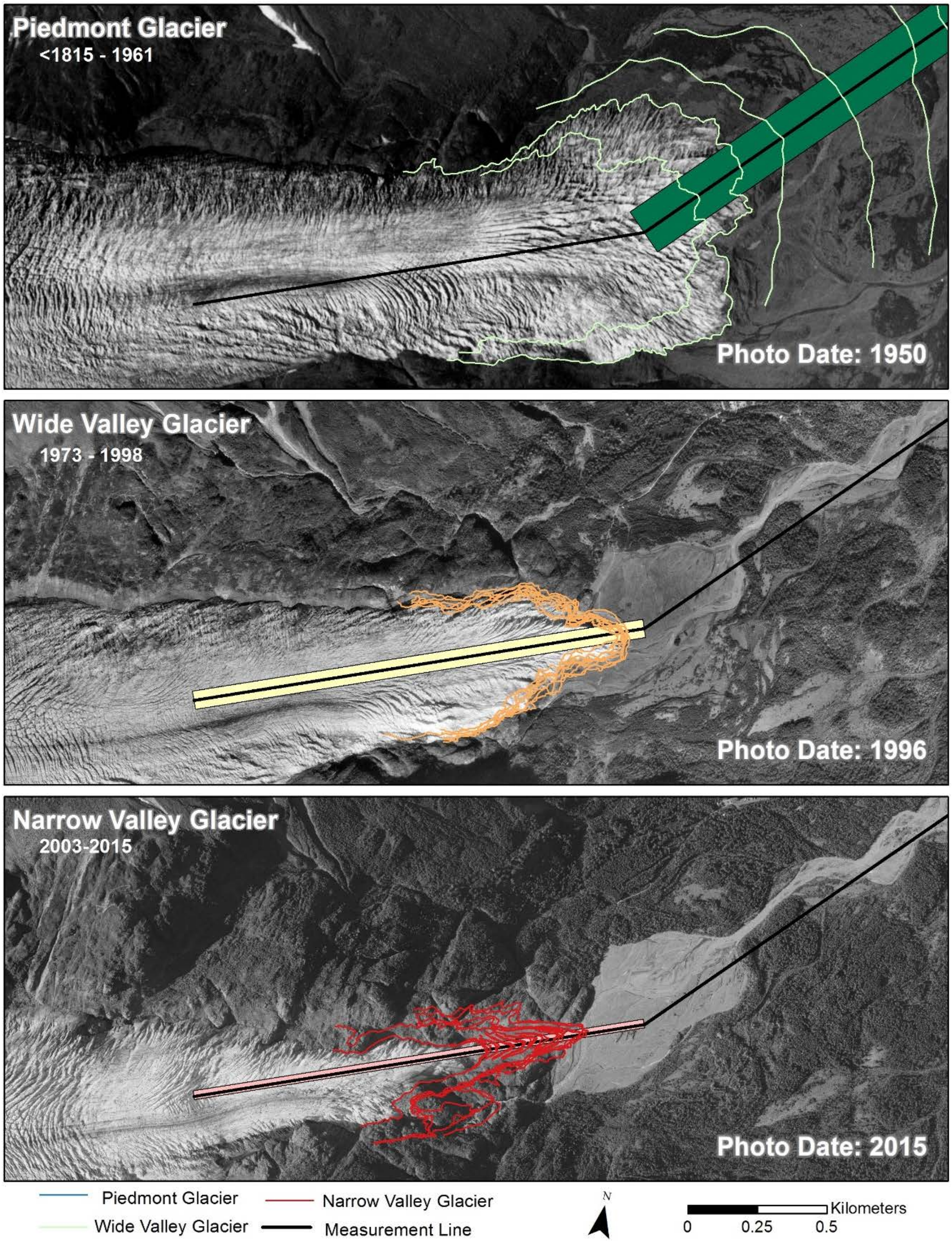

Figure 6: Aerial photos representing each of the three periods used for measuring the retreat of the Exit Glacier.

Seasonality of Retreat

Since 2010, terminus positions have been mapped in both the spring and the fall, allowing us to calculate retreat occurring over both summer and winter seasons separately. The summer season spans late May or early June to late September, with winter covering the rest of the year. There is some variability in the timing of the early summer mapping, depending on the melt date of the seasonal snowpack at the glacier toe. Retreat over these shorter seasons was measured by both the centerline and box methods, as described above.

Results

Comparison of Box and Centerline Methods

Across all positions measured, the mean difference between the box and centerline measurement techniques was 10 m, with a standard deviation of 7 m. Total distance of retreat for the centerline method was 2.49 km, only 3 m less than that measured by the box method, which is less than the width of a typical moraine, and close to the precision of mapping from aerial photography. Both methods give nearly identical estimates for rate of retreat, differing by centimeters.

While the centerline method measures the absolute maximum position of the glacier toe, the box method measures the average position of the glacier front across an area of interest. This accounts for uneven changes along the ice front and avoids situations where a single point of ice protruding far from the main face of the glacier gives the annual measurement. In such a situation, a year with a point of ice would show little retreat, though much ice has melted around the point. Subsequent years would show a jump, as the next measurement captures the melting of ice around the point, and the following year's retreat.

An example of how the two methods of measurement differ is shown in Figure 7. Glacier extent in 2005 is shown in green and 2006 in pink. The box method measurements are shown as a solid line, while centerline methods are shown with a dashed line. In 2005, the upper left panel, the glacier has a fairly square front; the two measurements are close together. In 2006, the glacier has narrowed, pulling back significantly on the sides, but has also pushed a narrow point of ice beyond the 2005 position. Is this considered an advance or retreat? The answer depends upon the method of measurement and highlights the difference between the two.

In the bottom panel of Figure 7, the green polygon visible is ice in 2005 that melted before the 2006 photo. The box method records a retreat, capturing the smaller area of ice, which can indeed be quantified accurately as retreat across the glacier front. The centerline method records a small advance, giving higher import to a small ice protrusion 4 m across, extending 6 m beyond the 2005 extent for an area of 65 m^2, than to the narrowing of ice on the north and south sides of the glacier front, which have a combined area of 190 m^2. Both measurements are arguably accurate, measuring slightly different quantities: maximum extent of ice, as compared to aggregate behavior of the entire glacier front. The 2005-2006 example shown here is the only case at Exit Glacier where the two methods diverged on a retreat or advance; rather, it is more commonly a difference of precise distance measured.

The centerline method is based on the farthest extent of the glacier, regardless of any other changes along the terminus and so it identifies this change as an advance. The box method considers the change in ice across the width of the terminus and, because of lateral thinning, it quantifies the change as an overall ice loss and, therefore a retreat. The strength of the centerline method is that it is a consistent measurement of the change in position measured from the farthest extent of the terminus each year. The strength of the box method is that it is based on ice loss along the width of the terminus and excludes any anomalous protrusions.

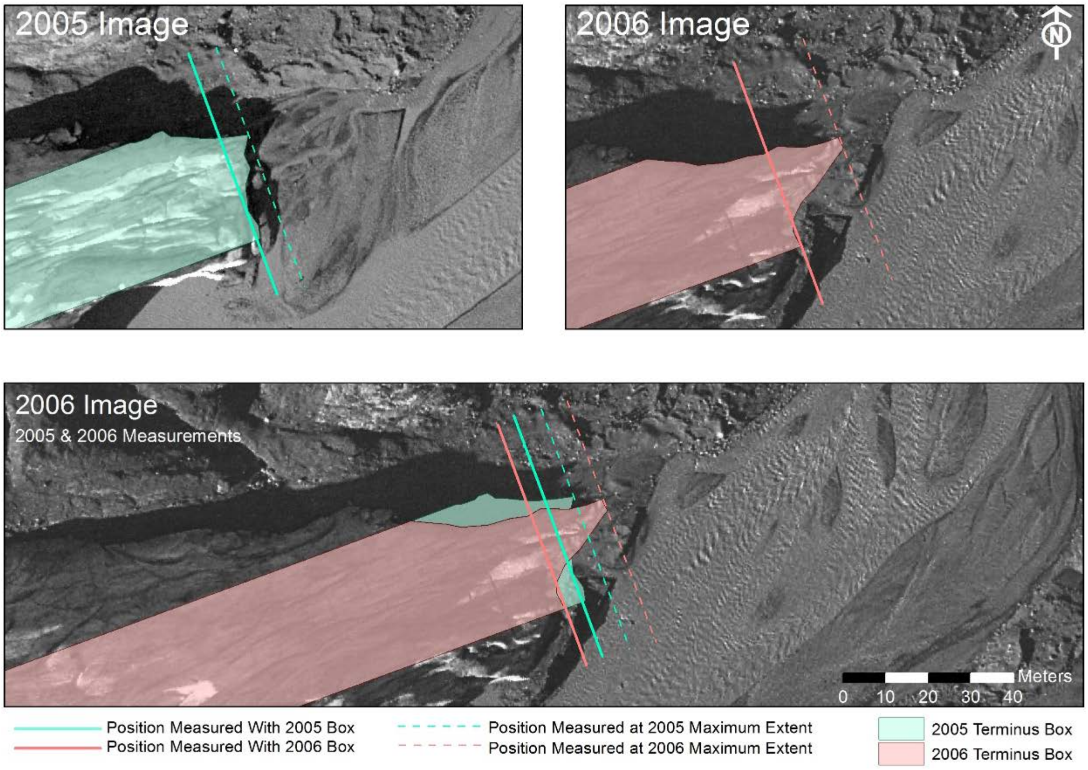

Figure 7: Comparison of box and centerline measurements of terminus position in 2005 (green) and 2006 (pink). The box method measures average position of glacier front across width of box, shown with a solid line, while the centerline method measures the tip of the foremost piece of ice, as shown with a dotted line. The centerline measures an advance of 6 meters, while the box measures a retreat of 4m. In the lower panel, the green polygon visible is ice in 2005 that melted before the 2006 photo. The box method captures the thinning and retreat, while the centerline records the furthest extent of the glacier front.

Although we think the box method handles irregularity of the terminus shape better and is more representative of ice loss, we chose the centerline method for its simplicity and transparency in measuring glacial retreat. It is important to note that the centerline captures absolute farthest piece of ice and will always record an absolute retreat from 1815 slightly less than the box method, by definition, as the box method measures average length across the glacier front. For simplicity and transparency, we recommend continued use of the centerline method going forward in measuring Exit Glacier retreat.

Centerline Retreat Results

Over the last 200 years, Exit Glacier retreated 2.5 km from its 1815 Little Ice Age maximum to its position in September 2015, based on the centerline method. The terminus remained stable at its 1815 maximum position until approximately 1889, when a first small retreat of 14 meters was marked with deposition of a moraine. During the period of retreat from 1889 to 2015, the average rate was 19.7 m/yr. If the period of stability from 1815 to 1889 is included, the rate of retreat falls to 12.5 m/yr. In the most recent 5-year period from 2011 to 2015, the average rate of retreat was 44.5 m/yr. Over the previous 5-year period from 2006-2010, the average retreat rate was 19.7 m/yr. These values were calculated using the centerline method; box method values for distance of retreat do not differ significantly (t-test; p=0.95). The glacier has retreated 0.5 km since the mid-1990s, and 1 km since 1950.

All measurements of Exit Glacier's terminus position, retreat, and linear-piecewise retreat rate (easily conceptualized as the slope of each individual line segment between two dates), are available in Appendix A. A bar plot of retreat distances and rates is given in Appendix B for ease of visual comparison across different time periods. For enhanced detail in recent years, graphs showing the retreat from 1815 to present and 1950 to present are shown in Figure 8 and Figure 9.

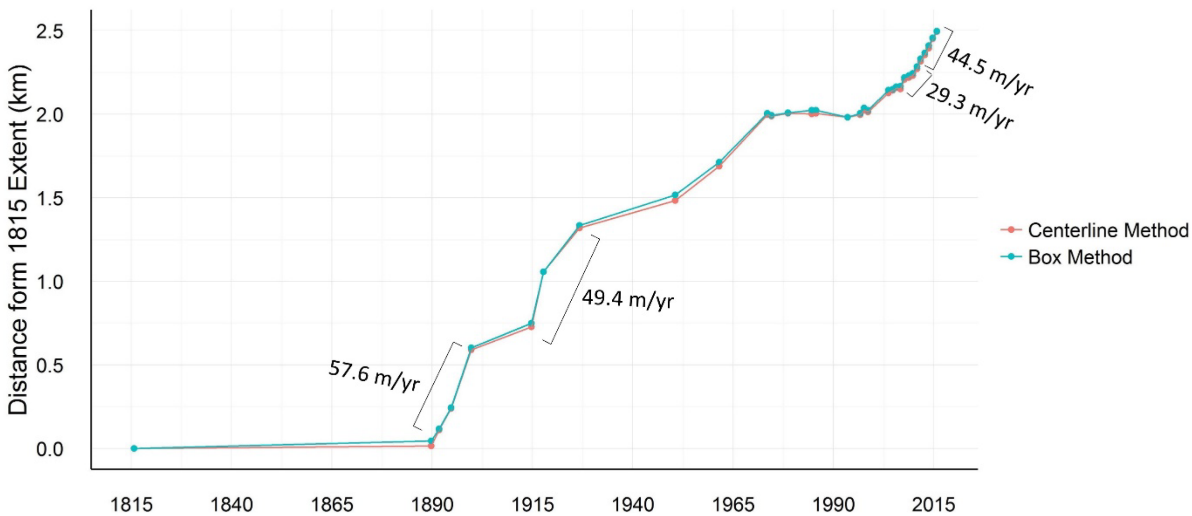

Figure 8: Retreat of Exit Glacier from 1815 Little Ice Age maximum to September 2015. The long-term rate of retreat from 1889 to 2015 was an average of 19.7 m/yr. Measurements made with the centerline method are shown in red, and box method in blue. A maximum of one measurement per year is shown, using fall measurements near the end of the water year, and omitting those made in spring and mid-summer. Labeled retreat rates are average rate for select periods of rapid retreat. The most rapid period of retreat during the period of record occurred from 1889 to 1899, at 57.6 m/yr. The second fastest rate of retreat occurred from 1914 to 1926, at 49.4 m/yr. The current rate of retreat, at 44.5 m/yr from 2010 to 2015, is the third fastest recorded in the last 200 years, and is the fastest retreat seen in non-moraine evidence data.

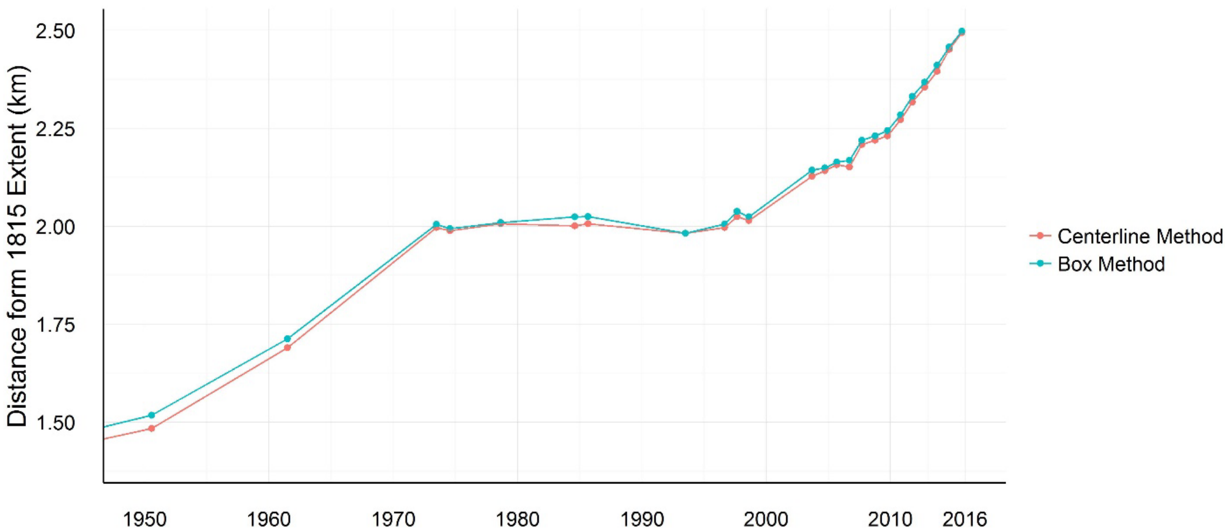

Figure 9: Retreat of Exit Glacier from 1950 to September 2015. Measurements made with the centerline method are shown in red, and box method in blue. A maximum of one measurement per year is shown. Note that some small advances are recorded, including 1974 (8 m), 1984 (5 m), 1993 (24 m), 1998 (10m), and 2006 (6 m) but the advances are dwarfed by distance retreated.

Seasonality of Retreat

A graph of seasonal retreat for the period 2008-2015 is illustrated in Figure 10. The period from 2010 to 2015 (five years and ten measurements) shows Exit Glacier retreated a median of 9.1 m over a winter season and a median of 33.3 m over a summer season. With the short summer season at Exit Glacier, this corresponds to a median rate of retreat of 14.3 m/yr (3.9 cm/ day) over the winter, and 93.5 m/yr (25.6 cm/ day) during the summer months, indicating that retreat in summer is 6.6 times faster than that during the winter. This is shown graphically in Figure 11, with red bars showing summer retreat, and blue showing winter.

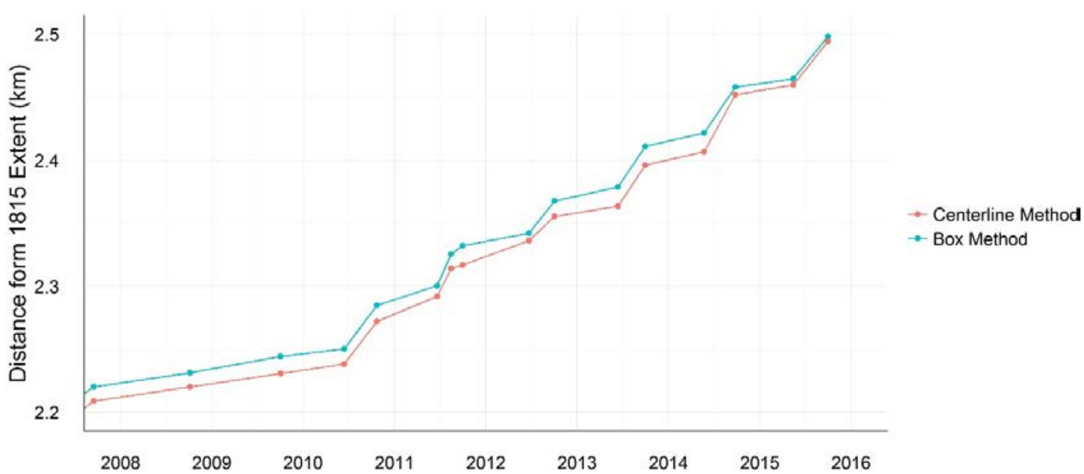

Figure 10: Retreat of Exit Glacier from 2008 to Fall 2015, showing fall and spring measurements. Multiple measurements per year began in 2010, and show both a greater distance and faster rate of retreat of ice in summer months.

Figure 11: Seasonal rate of retreat and distance retreated of the Exit Glacier terminus for years in which seasonal measurements are available. For 2010-2015, the median rate of retreat was 6.7 times faster in summer than winter.

KEFJ staff recall that, prior to 2006, there were some years that Exit Glacier advanced during cold winter months when the forward flow of the ice was greater than mid-winter melting of the ice front. This is no longer the case, as confirmed by park measurements documenting winter retreat. Though this may be surprising, the low elevation at Exit Glacier's terminus experiences substantial amount of warm weather and liquid precipitation in winter months. In the eight months from October to May, average air temperature was above 0° C on 51% of days from 2011 to 2016, as recorded by the Exit Glacier SNOTEL station. This results in substantial melting in winter months. Retreat or advance of the toe is dictated by the balance between ice melt and flow.

Summary and Future Work

This report documents changes in the position of Exit Glacier's terminus. It does not make inferences as to cause or mechanism. Retreat and advances of Exit Glacier are related to a combination of climatic factors which influence mass balance and a progression of glacial geometries which can influence flow rates, all on multiple timescales. This record of 200 years of retreat, interspersed with a few small advances, is ripe for future work, relating position of the glacier front to a variety of climate variables in addition to changes in glacier position, geometry, and associated geophysics. Future work may tease out the complexities of this system, specific to Exit Glacier. Specifically, we suggest future work relate this detailed record of terminus positions to summer temperature and insolation, the Pacific Decadal Oscillation, El Niño Southern Oscillation, and changes in glacial geometry.

KEFJ researchers will continue to document Exit Glacier terminus positions using GPS in the spring and fall, continue to digitize positions from aerial photography as it becomes available for continuity of this long-term data record, and continue to measure the retreat using the centerline method. The areal extent measurement of Exit Glacier and all ice on the Harding Icefield are scheduled to continue on a decadal timescale by the NPS Southwest Alaska Network of the Inventory and Monitoring program (Giffen et al. 2014).

This terminus dataset and subsequent measurements will be submitted to the Glacier Fluctuations Database (WGMS 2016).

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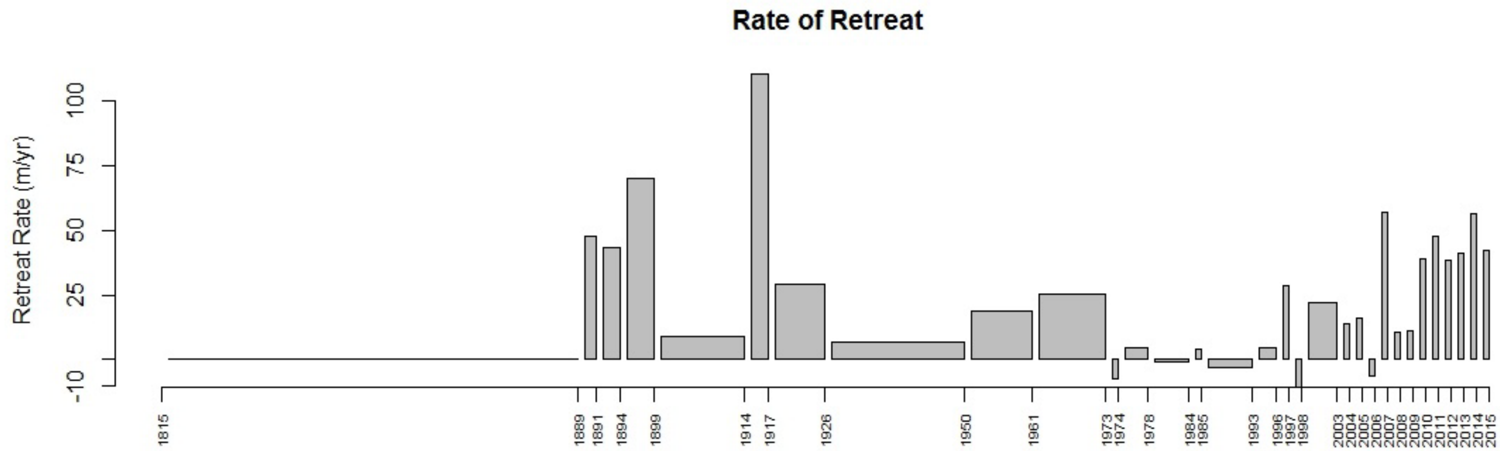
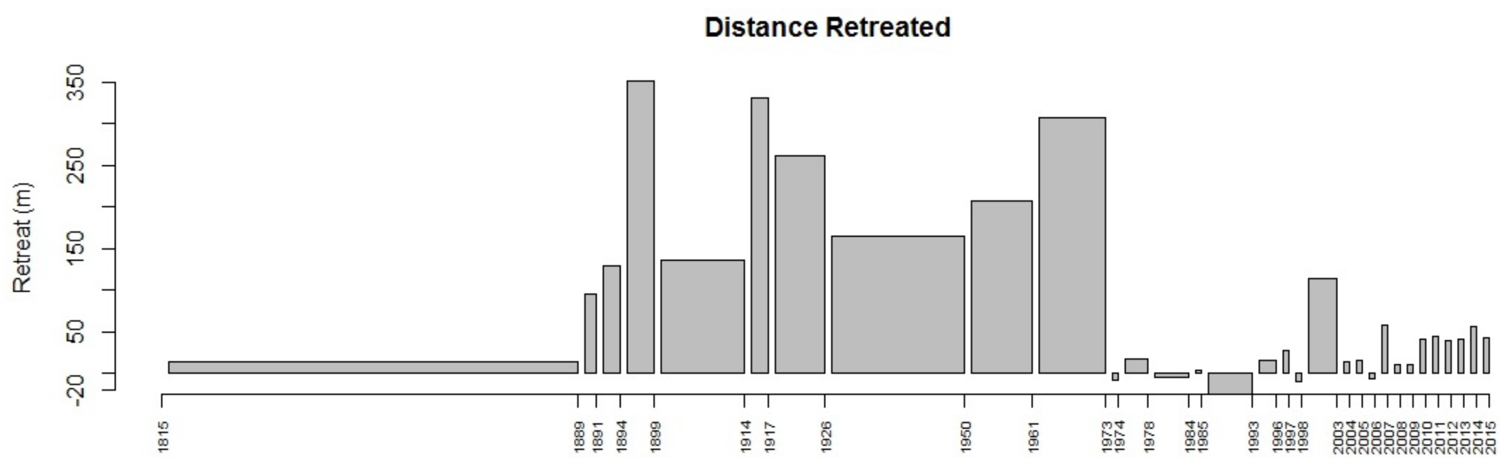
Appendix A: Measurements of Exit Glacier’s Retreat from 1815 to 2015

Year	Month	Day	Decimal Date	Retreat: Centerline Method (km)	Retreat: Box Method (km)	Interval Between Measurements (yrs)	Retreat Rate: Centerline Method (m/yr)	Retreat Rate: Box Method (m/yr)
1815			1815	0.0000	0.0000	0.00	0.0	0.0
1889			1889	0.0140	0.0448	74.00	0.2	0.6
1891			1891	0.1093	0.1159	2.00	47.7	35.5
1894			1894	0.2388	0.2444	3.00	43.2	42.8
1899			1899	0.5903	0.6025	5.00	70.3	71.6
1914			1914	0.7265	0.7483	15.00	9.1	9.7
1917			1917.745	1.0575	1.0568	3.00	110.3	102.8
1926			1926.745	1.3195	1.3339	9.00	29.1	30.8
1950	8	1	1950.580	1.4834	1.5178	23.84	6.9	7.7
1961	7	1	1961.495	1.6897	1.7125	10.92	18.9	17.8
1973	6	28	1973.487	1.9965	2.0052	11.99	25.6	24.4
1974	7	27	1974.567	1.9886	1.9940	1.08	-7.3	-10.4
1978	8	24	1978.643	2.0063	2.0092	4.08	4.3	3.7
1984	8	14	1984.617	2.0016	2.0243	5.97	-0.8	2.5
1985	9	2	1985.668	2.0060	2.0245	1.05	4.3	0.1
1993	7	10	1993.520	1.9817	1.9821	7.85	-3.1	-5.4
1996	9	3	1996.672	1.9968	2.0054	3.15	4.8	7.4
1997	8	28	1997.654	2.0248	2.0381	0.98	28.5	33.3
1998	8	14	1998.616	2.0144	2.0238	0.96	-10.7	-14.8
2003	9	11	2003.693	2.1276	2.1436	5.08	22.3	23.6
2004	9	22	2004.724	2.1420	2.1492	1.03	13.9	5.4
2005	9	8	2005.684	2.1575	2.1641	0.96	16.2	15.5
2006	9	11	2006.693	2.1512	2.1683	1.01	-6.3	4.1
2007	9	16	2007.706	2.2087	2.2199	1.01	56.8	51.0
2008	10	6	2008.762	2.2200	2.2312	1.06	10.7	10.7
2009	10	2	2009.750	2.2307	2.2441	0.99	10.9	13.0
2010	10	22	2010.805	2.2720	2.2847	1.05	39.1	38.5
2011	9	30	2011.745	2.3168	2.3321	0.94	47.6	50.4
2012	10	2	2012.751	2.3554	2.3676	1.01	38.4	35.4
2013	9	30	2013.745	2.3962	2.4109	0.99	41.0	43.6
2014	9	25	2014.731	2.4518	2.4578	0.99	56.5	47.6
2015	9	30	2015.745	2.4946	2.4983	1.01	42.2	39.9

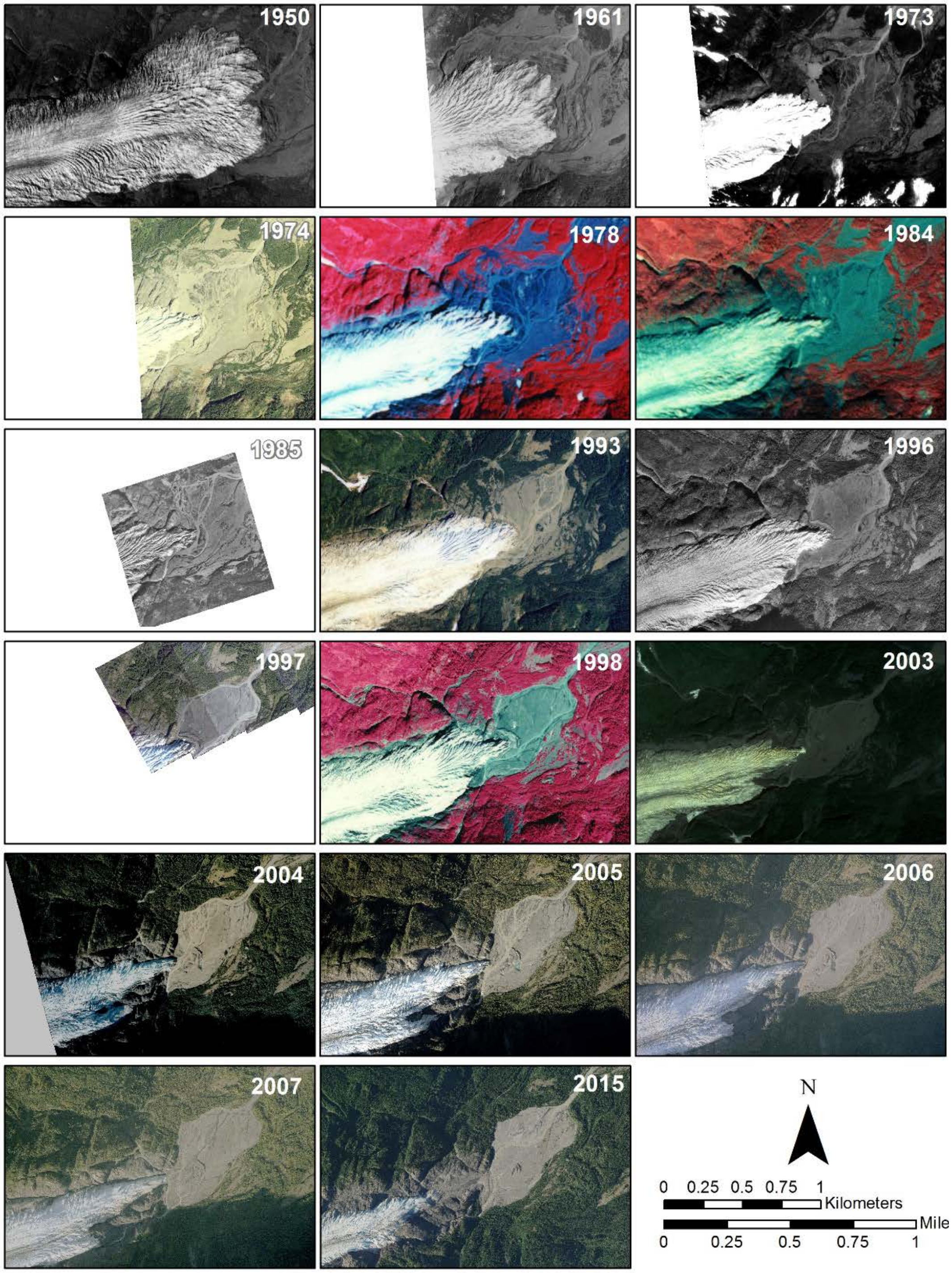
Appendix B: Bar Graph of Retreat and Retreat Rate





Barplot showing distance and linear-piecewise rate of retreat of the Exit Glacier terminus. Annual changes, from fall to fall measurement, are shown where sub-annual data is available, for consistency with other measurements, as labeled on the axis below. Box width corresponds with the length of time between measurements. Box height displays either speed or distance of retreat, as labeled. This graph allows for easy comparison of different time periods.

Appendix C: Historical aerial imagery of Exit Glacier used for digitizing terminus positions



Available aerial imagery used for digitizing Exit Glacier's historical terminus positions.

NPS 186/135205, November 2016

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