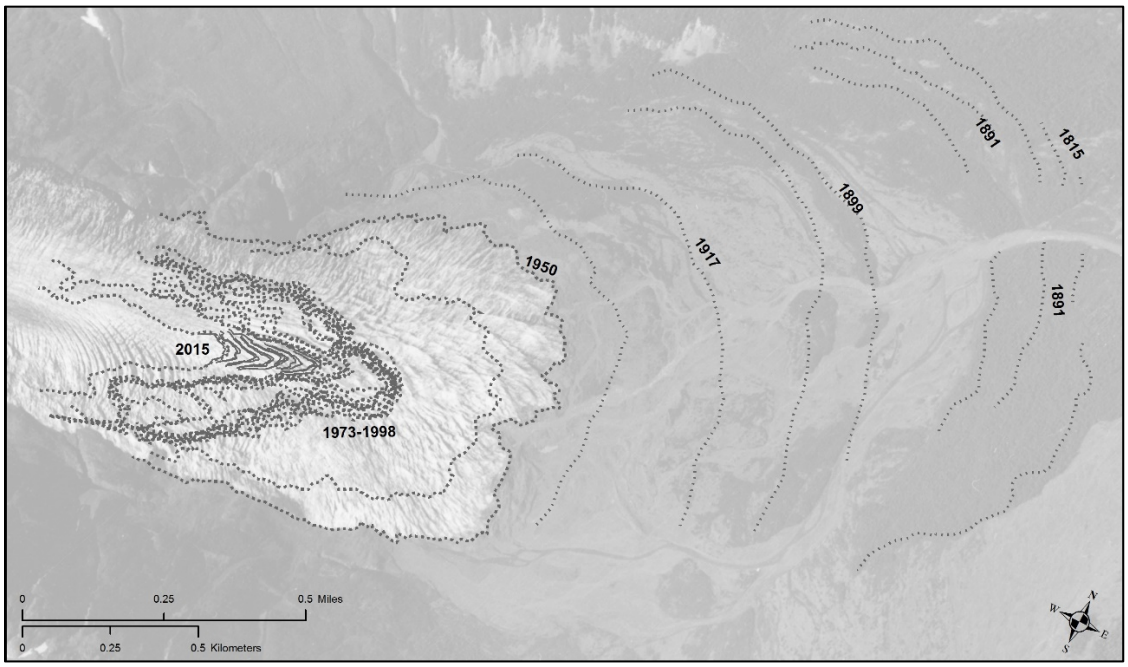
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

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

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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).

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

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

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.

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.

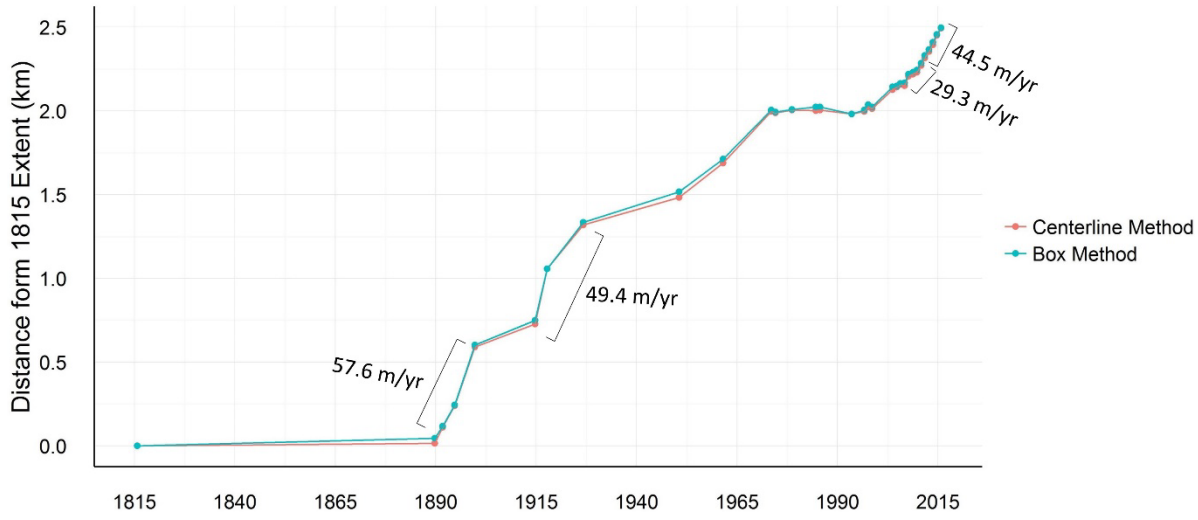


Figure 8: Retreat of Exit Glacier from 1815 Little Ice Age maximum to September 2015. The long-term rate of retreat from 1889 to 2015 was an average of 19.7 m/yr. Measurements made with the centerline method are shown in red, and box method in blue. A maximum of one measurement per year is shown, using 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.

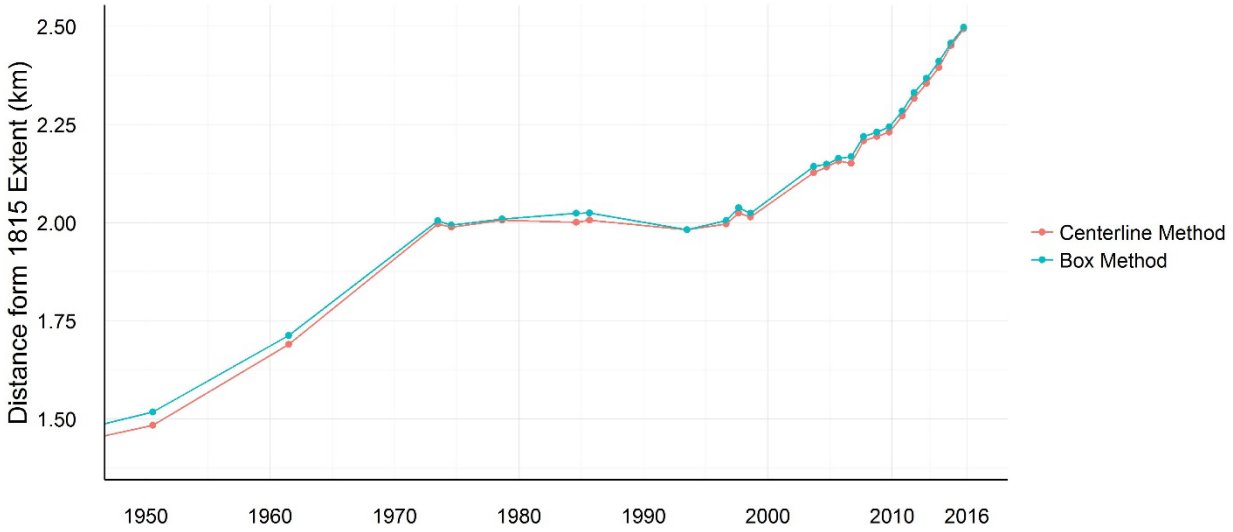


Figure 9: Retreat of Exit Glacier from 1950 to September 2015. Measurements made with the centerline method are shown in red, and box method in blue. A maximum of one measurement per year is shown. Note that some small advances are recorded, including 1974 (8 m), 1984 (5 m), 1993 (24 m), 1998 (10m), 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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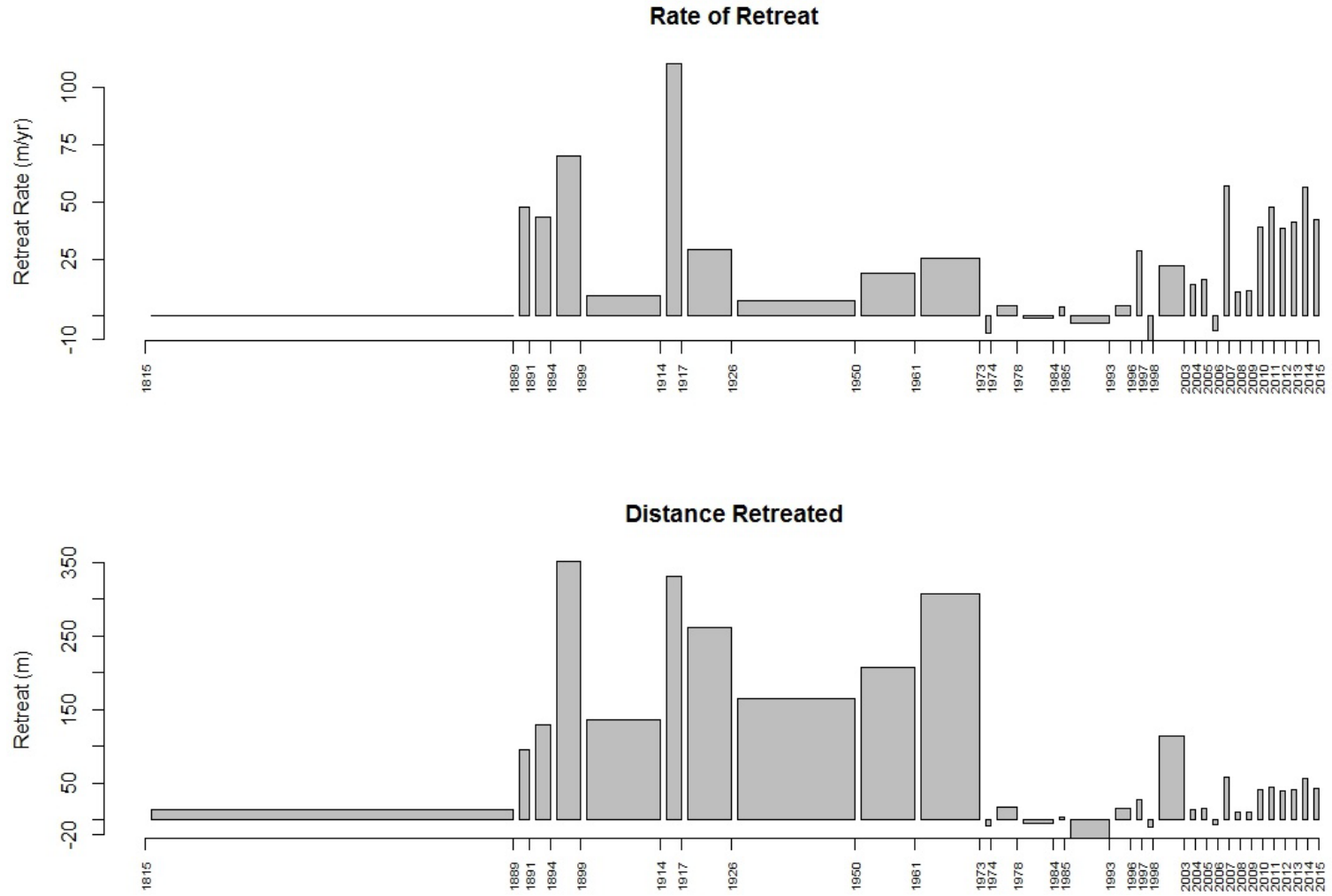
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Appendix A: Measurements of Exit Glacier's Retreat from 1815 to 2015

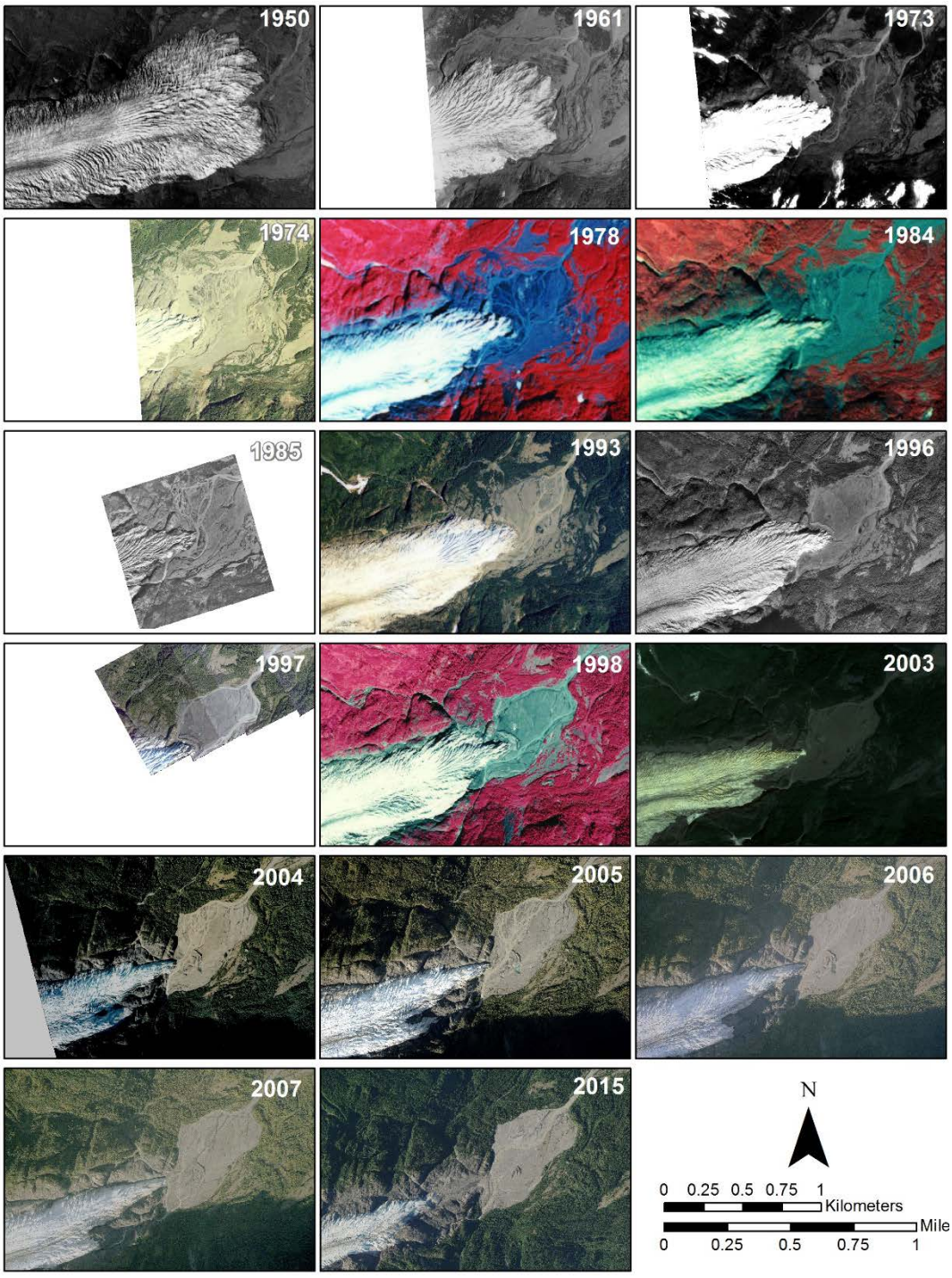
Year	Month	Day	Decimal Date	Retreat: Centerline Method (km)	Retreat: Box Method (km)	Interval Between Measurements (yrs)	Retreat Rate: Centerline Method (m/yr)	Retreat Rate: Box Method (m/yr)
1815			1815	0.0000	0.0000	0.00	0.0	0.0
1889			1889	0.0140	0.0448	74.00	0.2	0.6
1891			1891	0.1093	0.1159	2.00	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.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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