Documenting 20th and 21st century glacier change and landscape evolution with maps and land, aerial, and space-based geospatial imagery in Alaska’s Kenai Mountains

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Abstract

Data fusion and analysis of maps and remote sensing data collected from different spatial perspectives (ground, air, and space) at different times from the early 20th century to the present using different sensors were used to answer questions about glacier behavior and rapidly changing landscapes of Alaska’s southern Kenai Mountains. Expeditions to three fiords of the southern Kenai Mountains were conducted during the summers of 2004, 2005, 2006, and 2021. Each expedition used repeat photography to document glacier behavior and change, and landscape evolution at six Kenai Mountains glaciers, most located within Kenai Fjords National Park. Bear Glacier, Aialik Glacier, Pedersen Glacier, Holgate Glacier, Little Holgate Glacier, and Northwestern Glacier were studied and at a minimum, their terminus positions were determined for the following dates: 1909, 1950, 1961, 1973, 1990, 2004-2006, and 2021. Each glacier displayed unique asynchronous behavior. Since 1909, all displayed long-term terminus retreat. However, the timing for each glacier was unique. In 2021, Holgate Glacier was advancing, while the other five glaciers were retreating.

Keywords: data fusion; geospatial imagery; glacier change; Kenai Mountains

Introduction

Study Location. The location of this investigation includes several of the fiords of Alaska’s southern Kenai Mountains. The Kenai Mountains, with maximum elevations approaching 2,000 m, are a ~195-km-long by ~45-km-wide mountain range which extends south-southwest from near Anchorage, Alaska, to the southern end of the Kenai Peninsula and the Gulf of Alaska. Two icefields, the Harding Icefield and the Grewingk-Yalik Glacier Complex, straddle the higher elevations of the Kenai Mountains. The icefields receive over 10 m of snow each year. According to Loso et al. (2014), the Kenai Fjords National Park area of the Kenai Mountains contains 287 glaciers. These glaciers cover approximately 48.5% of the park. They range from glaciers that cover less than 1 km² to the largest, Bear Glacier, with an area of nearly 200 km² (Molnia, 2008).
More than 35 glaciers, including all the glaciers studied in this investigation originate from the eastern Harding Icefield, which has an area of >2,500 km². Sixteen of these have lengths greater than 8 km. The Harding Icefield is the Kenai Mountain’s largest icefield and the largest icefield located entirely in Alaska. More than a dozen of these glaciers flow from the icefield and terminate in fiords that connect to the Gulf of Alaska, including all in this study (Figure 1).

Figure 1. Kenai Mountains - Inset map of Alaska (upper left) shows the location of the Kenai Mountains (red square). The larger map shows a more detailed view of the extent of the Kenai Mountains with its two large icefields, the Harding Icefield, and the Grewingk-Yalik Ice Complex. The locations of the three fiords that are the focus of this study (Resurrection Bay, Aialik Bay, and Harris Bay / Northwestern Fjord) are shown. The location of McCarty Fiord is also shown. Adverse weather conditions restricted data collection during the 2021 Expedition.

One or more glaciers was selected from each of the three fiords for analysis. At a minimum, their terminus positions were determined for the following dates: 1909, 1950, 1961, 1973, 1990, 2004-2006, and 2021. For several glaciers, crude 1849 terminus positions were discernible from the earliest known map that depicts the fiords (Figure 2 - Tebenkov, 1852). Each fiord hosts other small valley and mountain glaciers, several of which are named (Figure 3). Each of these fiords either terminates on the Gulf of Alaska Continental Shelf (Figure 4) or traverses the shelf and joins other fiords or sea valleys that were cut into the shelf during older glacial expansions (Molnia, 2008).
Figure 2. This 1849 Russian chart is the earliest map of the Kenai Mountains area that shows glacier positions. Shown in red are terminus locations for Holgate (H), an unnamed glacier (UN), McCarty (M), and Yalik (Y) Glaciers. Shown in blue are the locations of Resurrection Bay (R), Aialik Bay (A), Harris Bay (H), Two Arm Bay (TA), and Nuka Bay (N). McCarty Fiord is located at the head of Nuka Bay. The location of Northwestern Glacier at the head of Harris Bay is indicated (N), even though no terminus symbol is present. The map is part of Tebenkov’s Atlas, published in 1852.

Figure 3. Landsat image of the Kenai Mountain fiords area showing the location of Bear, Aialik, Pedersen, Holgate, Little Holgate, and Northwestern Glaciers. Also shown is the location of McCarty Glacier. The image base is part of a Landsat 8 image collected on August 4, 2021.
Figure 4. Bottom (outlined in red) - Shaded relief bathymetric chart of the central Gulf of Alaska continental margin, including the area of the Kenai Mountain fiords, depicts the locations of the many glacially eroded channels and sea valleys (yellow and orange) that are incised into the continental shelf. The area labelled C is Cook Inlet. The area labelled P is Prince William Sound. The large sea valleys and channels are the result of Pleistocene glacier erosion. The white rectangle corresponds to the larger upper image. Top - Enlarged view of the continental shelf area south of the Kenai Mountains. Notice that the three fiords that are the subject of this study (labelled N (Northwestern Fiord), A (Aialik Bay), and R (Resurrection Bay), all extend well beyond the areas currently occupied by active glaciers and well beyond the limits of Little Ice Age maximum extents. The same is true of McCarty Fiord (M), located to the west. Source: NOAA Alaska Fisheries Science Center (2021).

In addition to the imagery focused analysis of the selected glaciers, where possible, additional observations were made to document changes in ice thickness, presence and distribution of vegetation, and development of ice-marginal hydrological features. The investigated fiords are Resurrection Bay, the location
of Bear Glacier; Aialik Bay, the location of Aialik, Pedersen, and Holgate and Little Holgate Glaciers; Harris Bay/Northwestern Fiord, the location of Northwestern Glacier.

The research presented here is focused on how data fusion and the analysis of maps and remote sensing data collected at different times from the early 20th century to the present using several distinct types of sensors and from different spatial perspectives (ground, air, and space) can be used to answer questions about recent glacier behavior and the rapidly changing landscapes of Alaska’s southern Kenai Mountains.

To achieve the goal of documenting sub-decadal-, to decadal-, to century-scale glacier change, and landscape evolution with maps, land-, aerial-, and space-based geospatial imagery, this paper (1) Briefly summarizes the history of landscape photography in Alaska; (2) Documents how photographs and satellite images can be used to construct an extensive baseline upon which a ‘landscape change history’ can be constructed for the Kenai Mountain fiords; and (3) Shows how fusion of photographs and imagery from multiple sources is useful in understanding the complex dynamics of landscapes, ecosystems, and glaciers in Alaska’s Kenai Mountains, in particular, and Alaska, in general.

**Literature Review.** A detailed review of the scientific literature identified about a dozen articles that discussed various aspects of the glaciers of the greater Kenai Mountains area. Many deal with glacier mass balance and related changes in Kenai Mountain icefields and groups of glaciers. Several deal with identifying pre-20th century glacier behavior from analysis of glacier sediments or plant material deposited in glacier sediments. Much of this additional information is based on dendrochronology, analysis of vertical aerial mapping photography, space-based gravity measurements, and space-based laser altimetry. Some studies used remote sensing and Geographic Information Systems (GIS) to describe specific attributes of Kenai Mountain icefields or complexes of glaciers.

Only one study, Molnia et al. (2007) utilized repeat photography to document glacier change and landscape evolution at a number of Kenai Mountains glaciers, specifically glaciers located within or adjacent to Kenai Fjords National Park. This 2007 publication documents author Molnia’s initial efforts to use repeat photography to qualitatively and quantitatively document and describe near-century-scale glacier change in the southern Kenai Mountains.

During the summers of 2004, 2005, and 2006, more than 40 sites were revisited where historical photographs were made in 1908 and 1909 by Grant and Higgins (1913) and in the early 20th century (likely early 1920s) by unknown photographers. At each location, a new ‘repeat photograph’ was taken. Hundreds of additional photographs of the glaciers and associated landscapes of the fiords of the southern Kenai Mountains were also made. The fiords of the southern Kenai Mountains have glaciers that terminate in the ocean and sometimes calve icebergs (tidewater glaciers), glaciers that end on land (land-terminating glaciers), and glaciers that end in bodies of freshwater and sometimes calve icebergs (lake-terminating glaciers).

Of the other published studies, the earliest, by Rice (1987) examined changes in the Harding Icefield’s areal extent and surface features and made planimetric measurements of all the icefield’s glaciers, using 1950 and 1951, 1:63,360-scale, U.S. Geological Survey topographic maps. These are the same maps that serve as one data layer in this study. Rice compared them with 1984-85 aerial photography collected by the Alaska High Altitude Photography (AHAP) Program and found that the glacier covered area of the icefield had decreased by as much as 5%, with a net loss of ~123 km$^2$ of glacier during the intervening ~34 years. The greatest changes he observed were near sea level along the Gulf of Alaska coast and at the 300- to 600-m elevations on the northern and western sides of the Harding Icefield, the source area of all the glaciers studied. Many smaller glaciers located at elevations below 1,000 m had disappeared.

Adalgeirsdóttir et al. (1998) obtained airborne surface elevation profiles of thirteen Harding Icefield glaciers and the upper accumulation area of the icefield in 1994 and 1996, using a technique developed by Echelmeyer et al. (1996). These profiles were compared with the same 1:63,360-scale topographic maps used
by Rice, and the 1950-1952 aerial photographs used by the USGS in their preparation and revision. They concluded that the Harding Icefield has been thinning and shrinking since the 1950s and estimated that it has lost about 34 km$^3$ of ice in the ~44-year period between 1950-1952 and 1994-1996. They calculated that this corresponds to an icefield-wide lowering of about 21 m, the equivalent of an average mass balance of ~0.4 m/yr of water. They also concluded that the rate of change of surface elevation between 1994 and 1996 is significantly greater than the long-term average. Four of the thirteen glaciers that they profiled: Aialik, Bear, Holgate, and Northwestern Glaciers are included in this study.

Previously, Adalgeirsdóttir (1997), compared the location and aspect of Harding Icefield glaciers and found that glaciers on the icefield’s south side thinned more than those on the north side. Comparing area-averaged elevation change between tidewater-, lake-, and land-terminating glaciers, she found little difference. Tidewater glaciers thinned by an average of ~16 m, while the land-terminating glaciers thinned by ~17 m. She found no significant correlation between elevation change and glacier area, length, or surface slope.

Wiles et al. (1999) and Barclay et al. (1999), performed dendrochronological studies at a number of Kenai Mountain tidewater and former tidewater glaciers. Their work involved both living trees, some more than 680-years-old and a 1,119-year tree-ring-width chronology derived from more than 100 logs, recovered from about a dozen glaciers in the western Prince William Sound area, ~ 100-220 km east of the Kenai Mountains. Each of the logs had been sheared or uprooted by a past glacier advance. Collectively, their work showed that glacier fluctuations during the Little Ice Age were strongly synchronous on decadal time scales at many glaciers. Studies at eight locations indicated that advances occurred during the late-12$^{\text{th}}$ through 13$^{\text{th}}$ centuries and from the middle-17$^{\text{th}}$ to early-18$^{\text{th}}$ centuries. Nine glaciers showed evidence of a late-19$^{\text{th}}$ century advance.

Hall et al. (2005) used Landsat imagery collected in 1973, 1986, and 2002 to explore terminus position changes of about 20 Harding Icefield and Grewingk-Yalik Glacier Complex glaciers, including Aialik, Bear, Holgate, Northwestern, and Pedersen Glaciers. Using GIS software, they calculated: the extent of terminus position advance and retreat; the areas for the two ‘icefields’ for the periods of 1973 to 1986 and 1986 to 2002; and the area for each glacier for the periods of 1973 to 1986 and 1986 to 2002. They note that their measurements were made at the part of the terminus that showed the greatest amount of change. With respect to area change, their results indicated that between 1986 and 2002 the area of the Harding Icefield decreased from 1,753 km$^2$ to 1,679 km$^2$, a loss of ~78 km$^2$. This is an area loss of 3.62%. For the Grewingk-Yalik Glacier Complex, between 1986 and 2002 the area decreased from 403 km$^2$ to 399 km$^2$, a loss of ~4 km$^2$. This is an area loss of ~1%.

VonLooy et al. (2006) used remote sensing and digital elevation models (DEMs) to examine the accelerating thinning and contribution to sea level rise of Harding Icefield and Grewingk-Yalik Glacier Complex glaciers. They compared a 1950s USGS Digital Elevation Model (DEM) produced from the same USGS topographic maps used in several other studies and a 2000 Shuttle Radar Topographic Mission (SRTM) DEM with more recent DEMs produced from airborne Lidar profiles collected along glacier center-lines. Their results indicate that thinning rates from the mid-1990s to 1999 (~0.72 ± 0.13 m/yr) accelerated by a factor of 1.5 as compared with the 1950 to 1994-1996 period (~0.47 ± 0.01 m/yr) for the same 13 glaciers on the Harding Icefield that were investigated by Adalgeirsdóttir et al. (1998). Comparison of the USGS and SRTM DEMs indicate the Harding Icefield and Grewingk-Yalik Glacier Complex thinned an average of ~0.61 ± 0.12 m/yr from 1950 to 1999. Between 1950 and 1999, the volume of the 13 glaciers decreased by 72.1 ± 15.0 km$^3$ and the surface elevation decreased, with a thinning rate of 0.61 ± 0.12 m/yr. This is equivalent to an annual loss of 1.19 ± 0.24 km$^3$/yr of melt water, approximately one percent of the estimated post-1950 mountain glacier contribution to sea level.

According to Arendt (2006), net balance is the total volumetric change of a glacier divided by the time interval between measurements. The average net balance rate is net balance divided by the average area of the glacier at the earlier and later times. Arendt computed net balance rates and average net balance rates for 10 Kenai Mountains glaciers including Aialik, Bear, and Holgate Glaciers. Rates were determined for two time-
intervals: 1950 to 1994-1996 and 1994-1996 to 2001. For the ‘early’ interval, data were computed by comparing 1950s USGS topographic map data with airborne laser altimetry data collected May 28 or 29, 1994 or May 19, 1996. For the ‘recent’ interval, data were computed by comparing airborne laser altimetry data collected May 28 or 29, 1994 or May 19, 1996 with airborne laser altimetry data collected May 18, 2001.

Arendt found that the subset of land-terminating glaciers had an average change in net balance rate of \(-0.070 \pm 0.30 \text{ m/yr}\), and \(0.060 \pm 0.40 \text{ m/yr}\) for all glaciers, indicating that there is no significant difference between the two groups. For the ‘early’ interval, Arendt found that Harding Icefield land-terminating glaciers had an average change rate of \(-0.070 \pm 0.30 \text{ m/yr}\), and \(0.060 \pm 0.40 \text{ m/yr}\) for all glaciers, indicating that there is little difference between the two groups.

For Aialik Glacier, the Net Balance ‘early’ was 0.002\(\pm\)0.03 km\(^3\)/yr water equivalent; the Net Balance ‘recent’ was -0.010\(\pm\)0.006 km\(^3\)/yr water equivalent; the Average Net Balance Rate ‘early’ was 0.02\(\pm\)0.35 m/yr water equivalent; and the Average Net Balance Rate ‘recent’ was -0.11\(\pm\)0.07 m/yr water equivalent. For Bear Glacier, the Net Balance ‘early’ was -0.18\(\pm\)0.04 km\(^3\)/yr water equivalent; the Net Balance ‘recent’ was -0.205\(\pm\)0.009 km\(^3\)/yr water equivalent; the Average Net Balance Rate ‘early’ was -0.85\(\pm\)0.19 m/yr water equivalent; and the Average Net Balance Rate ‘recent’ was -1.02\(\pm\)0.04 m/yr water equivalent. For Holgate Glacier, the Net Balance ‘early’ was -0.021\(\pm\)0.011 km\(^3\)/yr water equivalent; the Net Balance ‘recent’ was -0.007\(\pm\)0.002 km\(^3\)/yr water equivalent; the Average Net Balance Rate ‘early’ was -0.31\(\pm\)0.16 m/yr water equivalent; and the Average Net Balance Rate ‘recent’ was -0.10\(\pm\)0.04 m/yr water equivalent. For McCarty Glacier, the Net Balance ‘early’ was 0.007\(\pm\)0.020 km\(^3\)/yr water equivalent; the Net Balance ‘recent’ was 0.034\(\pm\)0.006 km\(^3\)/yr water equivalent; the Average Net Balance Rate ‘early’ was 0.06\(\pm\)0.16 m/yr water equivalent; and the Average Net Balance Rate ‘recent’ was -0.29\(\pm\)0.05 m/yr water equivalent.

Lanik et al. (2018), describes a suite of eight glacier management and monitoring activities that have been performed by the National Park Service (NPS) and affiliated researchers in Kenai Fjords National Park. Collectively, they include: (1) Mass balance; (2) Repeat photography; (3) Terminus mapping; (4) Surface elevation change; 5) Timelapse photography; (6) Thickness measuring; (7) Aerial extent measuring and; (8) Measuring glacier flow rates.

Arendt et al. (2013) investigated the mass balance behavior of Gulf of Alaska glaciers using two complementary satellite sensors, one measuring changes in gravity (GRACE) and the other changes in glacier surface elevation (ICESat). GRACE (Gravity Recovery and Climate Experiment), a NASA experiment, maps Earth’s gravity field by measuring the distance between two satellites, using GPS and a microwave ranging system. Observations of changes in gravity between data collections are related to changes in the mass of materials at the Earth’s surface below. Causes of observed gravity variations include exchanges between ice sheets or glaciers and the ocean, such as accumulation of new snow or glacier ice melting (NASA, 2014).

ICESat (Ice, Cloud, and land Elevation Satellite) was the NASA Earth Observing System mission that measured glacier ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics with space-based laser altimetry (NASA, 2017). A mass concentration (mascon) is a measure of the mass of glacier ice present in a predefined 3° x 3° gridded cell of the Earth’s surface.

The researchers collected, compared, and contrasted high-resolution GRACE mascon data for ‘Gulf of Alaska glaciers’ with other in-situ glaciological, climate, and remote-sensing observations, including ICESat results, to compute a regional glacier mass balance, a measure of the volume of water present in a glacier or glacier area during the period of observation. They determined that for the 7-year period from December 2003 to December 2010, the mascon cells that included the Kenai Fjords glaciers lost 65 \(\pm\) 11 Gt of ice per year. They concluded that summer mass balance was responsible for the maximum interannual variability. A Gt (gigaton) is equivalent to one cubic kilometer of water. Comparing GRACE and ICESat results, they found that in the ~6-year period between October/November 2003 and October 2009, GRACE data showed a mass balance loss of 61 \(\pm\) 11 Gt/yr, while ICESat glacier elevation change data showed a loss of 65 \(\pm\) 12 Gt/yr.
ICESat elevation changes show a strong elevation dependence, with 2–4 m/yr of thinning at low elevations tapering to near-zero changes at high elevations. Multiplying these elevation changes by the area distribution of ‘Gulf of Alaska glaciers’ they obtained an average of 0.79 ± 0.15 kg/m²/yr of water loss.

Giffen et al. (2014) used Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM) imagery collected in 1973, 1986, and 2000 to examine all the glaciers in Kenai Fjords National Park. Image-processing software was used to create GIS shape files of glacier extent. They found that Pedersen, McCarty, and Dinglestadt Glaciers all retreated between 1951 and 2005, with little terminus change between 1986 and 2000. McCarty and Dinglestadt Glaciers are not being investigated in this study.

Recession rates were slightly higher for tidewater terminating glaciers (Aialik, Bear, Holgate, McCarty, and Northwestern Glaciers) compared to land and lake terminating glaciers (Chernof, Exit, Indian, Kachemak, Killey, Lowell, Nuka, Pedersen, Petrof, Skilak, Tustumena, and Yakik Glaciers) that flow to the west and north. Pedersen Glacier is the only glacier in this category included in this study.

Northwestern Glacier advanced from 2000 to 2005. Between 1951 and 2005, Bear Glacier became buoyant resulting in an increase in its rate of terminus retreat. Interior northward and westward flowing glaciers had a recession rate of ~29 m/yr, while coastal southward and eastward flowing glaciers averaged ~32 m/yr, a reduction of ~21 km² in total ice cover during the period from 1986 to 2000.

Pelto (2017), summarized the behavior of Pedersen Glacier from 1951 to 2015. Citing Giffen et al. (2014) he stated that Pedersen Glacier slowly but steadily retreated 706 m between 1951 and 1986, averaging ~20 m/yr) and an additional 434 m (23 m/yr) from 1986 to 2005.

In 1994, part of the terminus was fronted by a small proglacial lake, with most of the terminus located on land. Eleven years later in 2005, the lake’s length had grown to 1.1 km along its center axis. Between 1994 and 2015 the glacier retreated 2,600 m, an average of 125 m/yr. A comparison of the 2013, 2015, and 2016 terminus positions indicated that the recession was continuing rapidly. In 2015, Pedersen’s northern tributary had a width of ~150 m and barely reached the main glacier. Pelto reported that the snowline rose dramatically between 1994 and 2016, from 550 m in 1994, to 800 m in 2005, to 850 m in 2015.

Jakob et al. (2021), used CryoSat-2 interferometric-swath-processed data collected between 2010 to 2019 to generate new and independent mass balance estimates for the Gulf of Alaska region and High Mountain Asia. CryoSat-2 (European Space Agency, 2021) was designed and launched in 2010 to measure the thickness of polar sea ice and monitor changes in glaciers and ice sheets, especially those that blanket Greenland and Antarctica. Its mission is to provide a precise picture of how the Polar Regions are responding to changing climate. After breaking each area into multiple subregions, they extracted elevation-dependent thinning rates which revealed ongoing mass loss across the sub-regions. They also extracted monthly time series of elevation change, exploiting CryoSat’s high temporal repeat capability to reveal seasonal and multiannual variation in rates of glaciers’ thinning.

They found that between 2010 and 2019, the Gulf of Alaska region, which includes the Kenai Mountains study area, lost mass at a rate of 76.3 ± 5.7 Gt/yr (0.89 ± 0.07 m water equivalent per year), for a sea level contribution of 0.078 ± 0.008 mm/yr.

Surprisingly, the High Mountain Asia region which is often referred to as the “Third-Pole”, only produced 37% of the Alaskan contribution, losing mass at a rate of 28.0 ± 3.0 Gt/yr (0.29 ± 0.03 m water equivalent per year). Both regions lost more than 4% of their respective ice volume during the 9-year study period.

Materials and Methods

Methodology

In August 2021, Molnia led a new photographic expedition to the southern Kenai Mountains. The expedition revisited many of the sites that had been previously occupied and photographed between 2004 and
2021 expedition was to: 1) photographically document summer 2021 glacier positions and behavior; and 2) to rephotograph as many of the previous photo locations as possible to produce new 2021 photographs for comparison with three groups of older photos, so that glacier change could be examined on sub-decadal, decadal, and century scales. The 2021 expedition attempted to observe and photograph all the large glaciers in each fiord and more than 50 other smaller alpine and valley glaciers, and their associated landscapes from locations where each had been previously photographed at various known times in the past. Resulting ‘pairs’ or ‘triplets’ were then qualitatively and quantitatively analysed to determine what changes had occurred during the period between photographs, especially whether the targeted glaciers were thickening or thinning, growing, or shrinking, advancing, or retreating, and moving or stationary. Ancillary information including maps, satellite imagery, and aerial photographic data were also analysed so that the magnitude of the changes observed could also be determined.

2021 field activities consisted of: 1) finding the location from which a ‘historical’ baseline photograph had been made; 2) matching the field of view depicted in each photograph with its corresponding Kenai Mountains landscape; 3) rephotographing the original field of view from as close to the original site as possible; 4) recording the photo location’s geographic coordinates to permit plotting of the location and to facilitate future revisits; and 5) photographing the GPS receiver’s coordinates and the reproduced historical photograph to minimize future data confusion and to facilitate accurately identifying which collected data components correspond to each site when data processing begins weeks to months in the future. Cameras used also had internal GPS receivers and clocks to provide time and date, as well as latitude and longitude in the photograph’s metadata.

Prior to the August 2021 expedition, Molnia prepared a photo book consisting of more than 150 baseline reference photographs. The book consisted of three groups of photographs. Chronologically, the three groups of photographs, described below, are: (Group 1) the early 20th century ‘historical’ photographs; (Group 2) a group of photographs that are part of a ‘Kenai Fjords National Park Special Photo Collection’; and (Group 3) photographs made by Molnia during a 2001 visit to the fiords, and during the 2004, 2005, and 2006 expeditions. Included in this group are more than 30 photographs taken from original Grant and Higgins photo locations to produce repeat photography pairs. The technique where a sequential photograph is made from a previously occupied photo location is termed ‘repeat photography’ (Webb et al., 2010). Some of these resulting photo pairs, which are part of the National Snow and Ice Data Center (NSIDC) ‘Glacier Photo Collection’ (National Snow and Ice Data Center, 2015) can be downloaded from the NSIDC: https://nsidc.org/data/glacier_photo/search/.

Group 1, the ‘historical’ photographs consisting of approximately 50 photographs that were made more than 110 ten years ago in 1908 and 1909 by US Geological Survey geologists U.S. Grant III and D.F. Higgins. Many of these photographs are reproduced in USGS Bulletin 526 (Grant & Higgins, 1913). All can be downloaded from the USGS Photo Library site: https://library.usgs.gov/photo/#/. Four additional photographs, with little information about their provenance and little or no metadata, likely dating from the early 1920s are included in this first group. USGS Bulletin 526 also contains sketch maps of each fiord depicting 1908-1909 glacier positions and the locations from which the photographs were taken.

Group 2 includes more than 40 photographs taken more than 30 years ago in August 1990 by NPS Rangers Mike Tetreau and Bud Rice. These images are part of a larger ‘Kenai Fjords National Park Special Photo Collection’ that is housed both at the park and at the NSIDC. They can be downloaded from NSIDC at nsidc.org. A description of the collection is available at https://nsidc.org/the-drift/data-update/kenai-fjords-national-park-special-photo-collection-added-to-nsidc-glacier-photo-collection/.

Group 3 includes about 100 photographs taken by Molnia between July 2001 and August 2006, during four the earlier visits (2001, 2004, 2005, and 2006) to the Kenai Mountains fiords. More than 30 of these photographs were taken in 2004, 2005, or 2006 from original Grant and Higgins photo locations in order to produce repeat photography pairs. The technique where a sequential photograph is made from a previously occupied photo location is termed ‘repeat photography’ (Webb et al., 2010). Some of these resulting photo
pairs, which are part of the National Snow and Ice Data Center (NSIDC) ‘Glacier Photo Collection’ (National Snow and Ice Data Center, 2015) can be downloaded from the NSIDC: https://nsidc.org/data/glacier_photo/search/. Four additional photographs, with little information about their provenance and little or no metadata, likely dating from the early 1920s are included in this first group.

Together, the three groups of photographs serve as the baseline data set from which to assess the annual, to decadal, to century - scale glacier change and landscape evolution within the three fiords. The previous revisits had resulted in the production of more than 25 repeat photography pairs spanning 96-98 years. Some of these locations were again revisited in 2021 producing new image triplets. During the field survey, about ½ of the photo deck’s locations were successfully revisited and photographs taken of more than 60 sites of the previously pictured glaciers. Several examples of new repeat photo pairs or triplets are presented below for each of the fiords visited.

To augment interpretation and to provide a historical context documenting how the area has changed over time, sketch maps made by Grant and Higgins in 1908 and 1909, oblique aerial photographs taken by USGS hydrologist Austin Post in 1961, Landsat satellite imagery collected between 1973 and 2021, and oblique aerial photographs taken by the first author between 2000 and 2018 were used to provide additional views and perspectives and to document glacier terminus positions and changes.

**Historical Photography and Imagery**

Considering Alaska’s remote location, its early landscape photographic record is extensive. Historical photographs depicting the land surface of southern Alaska has existed for more than 150 years. The earliest known photographs date from the late 1860s, all postdating the 1867 purchase of Alaska from Russia. The earliest known systematic vertical aerial photographs of Alaska date from the late 1920s. For the southern Kenai Mountains, they date from 1950.

The earliest authenticated photographs of Alaska were taken by Eadweard Muybridge, the ‘father of motion pictures’ in August 1868 (Molnia, 2010). Although many of Muybridge’s photographs depict southeast Alaskan landscapes that were shaped by glacier erosion, they do not depict any glaciers. In fact, it would take an additional 15 years before the first documented photograph of an Alaskan glacier was taken.

In 1879, eleven years after Muybridge photographed the landscapes of the Fort Wrangel area, John Muir led an expedition to southeast Alaska to observe modern glacier behavior. Muir’s written description of his discoveries, especially the magnificent iceberg-calving glaciers of Glacier Bay quickly spread throughout the world, focusing significant attention on the glaciers of Alaska. Unfortunately, a camera was not part of the field equipment Muir carried. Instead, Muir made sketches of the glaciers that he observed.

Four years later, in 1883, a US Army expedition led by Lt. Frederick Schwatka (Schwatka, 1885) explored areas adjacent to Glacier Bay and produced the first published photograph depicting a glacier, ‘Saussure’ Glacier, a small retreating valley glacier, adjacent to what is now the Chilkoot Trail (Figure 5).

Also in 1883, the first photographs depicting large Alaskan tidewater glaciers and glacier-covered landscapes were taken in Glacier Bay by amateur and commercial photographers. In July 1883, Captain James Carroll piloted the steamship *Idaho* to within ~125 m of the terminus of Muir Glacier (Catton, 1995). Passengers, including journalist Eliza Skidmore (Skidmore, 1884 & 1886) obtained photographs of glaciers within the bay. Her photographs and written descriptions, combined with Muir’s writings, stimulated two decades of tourism resulting in hundreds of photographs depicting Glacier Bay’s massive glaciers (Figure 6).

These early photographs provided the public, and policy and decision makers with the first visual confirmation of why the glacier-covered areas of southern Alaska were unique areas worthy of scientific study, protection, and preservation. This was certainly a factor in establishing the Glacier Bay National Monument in 1925, and the Kenai Fiords National Park, 55 years later.
Figure 5. An 1883 lithograph produced from one of the first photographs taken of an Alaskan glacier. Although it is labelled “Finger of Saussure Glaciers,” this name was never adopted. The glacier, which is underfit in its valley, appears to have a retreating terminus. It is probably an unnamed glacier on the east side of Mount Hoffman, Coast Mountains. Lithograph from Schwatka (1885). Photograph by Charles A. Homan, U.S. Engineers.

Figure 6. 1893 photograph by commercial photographer Frank La Roche (right) of Muir Glacier terminus and Glacier Bay from an elevation of ~550 m ASL on the flanks of Mount Wright. The other person in the photograph is James Carroll, Captain of the steamship Idaho. Carroll and the Idaho transported tourists to Glacier Bay as early as 1883.

In 1909, every large glacier present in the fiords of the southern Kenai Mountains was photographed (Figure 7) within a 20-day period by U.S. Grant and D.F. Higgins. They were engaged in a study of the ore deposits and the general geology of Prince William Sound and the southern part of Kenai Peninsula for the U.S. Geological Survey (Grant & Higgins, 1913). The previous year, 1908, Higgins took four photographs of cirque glaciers located in the Thumb Cove area of Resurrection Bay, ~12 km south of Seward. In all, 48 1908
and 1909 Grant and Higgins photographs of southern Kenai Mountain’s glaciers digitized from the archive at the USGS Photo Library, located in Denver, Colorado ([https://library.usgs.gov/photo/#/](https://library.usgs.gov/photo/#/)) were used in this study.

![Figure 7](image)

**Figure 7.** Four 1909 Grant & Higgins photographs of glaciers in the Kenai Mountain fiords. A: July 24, 1909 photograph of Holgate (right) and Little Holgate Glaciers by U.S. Grant (Grant 132). B: July 23, 1909 photograph of Pedersen Glacier by U.S. Grant (Grant 130). C: July 26, 1909 photograph of Northwestern Glacier by U.S. Grant (Grant 137).

For a NPS Southwest Alaska Network photographic monitoring program, Jorgenson and Bennett (2006), compiled a list of Kenai Fjords National Park historical photographs. They identified 50 unique historic images taken prior to 1933. These included: 43 by Grant and Higgins taken in 1909; 3 by Grove Kael Gilbert taken in 1899; 1 by Ralph W. Stone in 1904; 1 by George C. Martin in 1906; and 2 by Stephen R. Capps in 1932.

Grant and Higgins comment (1913), that in the course of their work all the tidewater glaciers and many other glaciers located near tidewater “were seen and some notes, photographs, and maps were made.” They continue that “it is thought worthwhile to put on record the information thus obtained regarding the glaciers, for it will afford a basis for future study of the fluctuations of these ice streams” (pg. 1). They add that it “is not expected to make many additions to the large amount of scientific material concerning the problems of glaciers and glaciation that is already available, but it is intended to supply some definite information regarding the present positions of the fronts of the glaciers and the more evident facts of their fluctuations. Moreover, it is hoped that this publication may attract attention to some of the most magnificent American scenery that is now accessible to the tourist and nature lover.” It is these ~50 photographs that were the focus of the Molnia-led 2004, 2005, and 2006 expeditions. During the 2021 expedition, the locations of many of these photographs were visited and a new image of the field of view was collected to upgrade previously made pairs to triplets.

Systematic space-based imaging of Alaska’s remote landscapes, including the Kenai Mountains, began in 1972 with the launch of the first Landsat satellite, the Earth Resources Technology Satellite 1 (ERTS1), later renamed Landsat 1. Since 1972, when Landsat began collecting data, Alaska has been imaged thousands of times by Landsat and other space-based multispectral (MSS) instruments, as well as other types of sensors, such as space-based radar. An October 12, 2021 search of the USGS EarthExplorer website ([earthexplorer.usgs.gov](http://earthexplorer.usgs.gov)) for all Landsat scenes that included the three fiords, regardless of percentage of cloud cover, identified >900 individual Landsat images.
To assist in the understanding and interpretation of the glacier change and landscape evolution that has occurred in the fiords of the southern Kenai Mountains, a total of four Landsat images of the southern Kenai Mountains, one from 1973, 1991, 2006, and 2021, were downloaded from the USGS EarthExplorer website (Figure 8). Landsat has a footprint larger than most multispectral sensors, ~185 km by ~185 km. A time series of sequential images, or a combination of Landsat images with images from other types of sources can provide a long-term synoptic look at areas ranging from entire icefields to individual glaciers.

![Figure 8. Two Landsat images depicting the fiords and glaciers that are the subject of the study. The August 20, 1973 Landsat 1 image (1973-08-20) on the left was the first cloud-free Landsat image ever collected of the Kenai Mountains glaciers. The August 4, 2021 Landsat 8 image (2021-08-04) on the right was collected during the 2021 field expedition. A comparison of the two images shows significant retreat of Bear, Pedersen, Little Holgate, Northwestern, and McCarty Glaciers, little change of Aialik Glacier, and a small advance of Holgate Glacier in the nearly 48 years between image collections.](image)

**Repeat Photography** - Repeat photography is a technique in which a historical and a modern photograph, both having similar fields of view, are compared, and contrasted to determine their similarities and differences quantitatively and qualitatively. In precision repeat photography, both photographs have the identical field of view, ideally being photographed from the identical location. The use of repeat photography to document temporal change in glaciers and mountainous landscapes is not new. It originated as a glacier-monitoring technique in the European Alps more than a century ago.

Since 2000, Molnia has systematically used ground-based, precision repeat photography at more than 75 glaciers from about 225 locations to document glacier and landscape change in Alaska’s Coast Mountains, St. Elias Mountains, Chugach Mountains, Kenai Mountains, Prince William Sound, and Copper River Basin on time scales that range from inter-annual to multiple-decadal. More than 150 ground-based image pairs have been produced (Figure 9).

Through analysis and interpretation of these photo pairs and time series, both quantitative and qualitative information is extracted to document glacier dynamics and landscape evolution, especially landscape response to retreating glacier ice on time scales that range from inter-annual to multiple-decadal on local and regional scales.
An example of repeat photography – This pair of northeast-looking photographs taken from ~8 km north of the mouth of McCarty Fiord documents significant changes that have occurred during the ~95 years between July 30, 1909 and August 11, 2004. The 1909 photograph by U.S. Grant shows the east side of the terminus of the then retreating McCarty Glacier, a tidewater glacier. Little, if any vegetation can be seen on the upper slopes of adjacent mountains, but beach grass is present in the foreground and several types of trees are present on the back beach in this 1909 photo (Grant 143). The left side of the 2004 photograph by Molnia shows a triangle of McCarty Glacier, which has retreated >15 km up McCarty Fiord. Dense, diverse vegetation, featuring alder, willow, and spruce, has become established on the hill slopes and back beach areas. Note the continued presence of beach grass in the foreground.

Airborne-platform-based repeat photography is also being used to augment the ground-based assessments and to monitor change at geographic scales ranging from individual glaciers to entire mountain ranges. Combining modern satellite data and historical and modern photographic imagery with historical reports, maps, and traditional knowledge provides significant information about Alaskan glacier behavior and history. It also provides unequivocal visual documentation of how Alaskan glaciers are changing. Combining and ‘fusing’ data from different sensors often enhances the information that can be extracted.

In addition to the activities described above, Kenai Fjords National Park has established its own glacier photography monitoring activity. In 2012, Kenai Fjords National Park Physical Scientist, Deb Kurtz compiled a ‘Kenai Fjords National Park Glacier Photographs Collection’ (National Park Service, 2021) to support an ongoing repeat photography project documenting coastal glacier change in Kenai Fjords National Park. The collection which is supported with metadata, has two parts: 1) the Grant/Higgins-Molnia dataset of repeat photography pairs (1909 ‘historical’ photographs and 2004-2005-2006 ‘recent’ photographs); and (2) a catalog of 43 glacier photographs with metadata taken between August 13 and August 15, 1990, by Park natural resources staff members, Mike Tetreau and Bud Rice. Most of these photos were taken from boat-based photo point locations. The original slides from this dataset are archived in the Park’s collections in Seward, Alaska. Digital copies are available from NSIDC. Details about the collection are available at: https://www.nps.gov/kefj/learn/nature/glacier-repeat-photography.htm. The website presents the following description: “There are many challenges in accurately replicating and aligning photos taken from boats due to variable positioning influenced by currents, winds, tides, and the height of the boat itself. Despite the challenges, the resulting photo sets effectively document the changing landscape. Several glaciers exhibited remarkable change in the recent past, which inspired an effort to annually photo-document the more accessible glaciers, and to repeat all photos every few years when possible. As of 2020, most of the park’s glaciers continue to shrink, and the repeat photo collection continues to grow. The collection currently consists of 77 sets of photos, including 265 photos of 40 individual glaciers or glacier groups.”
Results and Discussion

Although the focus of this study is documenting the behaviour of individual glaciers in the three fiords, the study also summarizes the findings of a number of papers that focused on regional glacier behavior in the Kenai Mountains, the Harding Icefield, Kenai Fjords National Park, adjacent areas, or some combination of these individual geographic features.

Fiord Specific Glacier Studies

This section examines the behaviour of one or more glaciers in each of the three fiords studied in 2021. This is done in two ways. First, using glacier-specific published scientific journal data and the several types of imagery obtained for each glacier (described below), a summary describing glacier behavior and changes in glacier geometry is derived. Second, individual photographs or repeat photography pairs or triplets are presented for each of the studied glaciers. Each pair or triplet is accompanied by a narrative describing the changes observed.

‘Imagery’ assessed by the authors and used for determining the behaviour for each glacier examined consists of:

1. 1909 ground- or boat-based photographs taken by Grant and Higgins, and obtained from the USGS Photo Library.
2. 1909 sketch maps made by Grant and Higgins, and published in USGS Bulletin 526.
3. Several 1920s ground-based photographs of Kenai fiord’s glaciers, each lacking information about either the photographer, the location from which they were collected, the date they were collected, or some combination of data components.
4. USGS 1:63,360 or 1:250,000 scale topographic maps published in the early 1950s, based on aerial photography collected between 1941 and 1950.
5. Oblique aerial photography of each glacier made by Post on August 12, 1961.
6. Landsat images of the glaciers in each fiord dating from August 16, 1973, June 22, 1991, August 27, 2006, and August 4, 2021. These dates were selected from hundreds of available Landsat images depicting the three fiords and their glaciers collected between 1972 and 2021 for the following reasons: The August 16, 1973, image is the first ‘cloud-free’ Landsat image collected following the initial launch of Landsat that shows all the southern Kenai Mountains fiords that are the subject of this study. The June 22, 1991 Landsat image, collected nearly 18-years after the 1973 image, is the first ‘cloud-free’ Landsat image obtained following the August 1990 NPS systematic photographic survey of Park glaciers conducted by Tetreau and Rice. The August 27, 2006 Landsat image, collected more than 15-years after the 1991 image, is a ‘cloud-free’ Landsat image obtained a little more than two weeks after Molnia’s 2006 field survey. The August 4, 2021 Landsat image, collected a little less than 15-years after the 2006 image, is a ‘cloud-free’ Landsat image obtained during the Molnia-led 2021 field survey.
7. Ground- and boat-based photographs from the Kenai Fjords National Park Glacier Photographs Collection.
9. Unique images collected by various sensors, such as a 1984 vertical aerial photograph of Bear Glacier, produced by the Alaska High Altitude Photography (AHAP) Program.
10. One-of-a-kind maps, such as a historic Russian 19th century navigational atlas.

With respect to the last item, Figure 2 is a piece of an 1849 Russian chart of Cook Inlet and parts of the adjacent Kenai Peninsula (Tebenkov, 1852), that depicts the positions of the termini of several glaciers (Holgate, Northwestern, McCarty, and Yalik Glaciers), located at the heads of Kenai Mountains fiords. It is the earliest known map that shows glacier termini locations.
Resurrection Bay

Resurrection Bay is an ~40-km long fiord that extends from the city of Seward and the delta of the Resurrection River at the northern head of the fiord to the Harding Gateway, the ~10-km long passage located at the mouth of the fiord. The maximum water depth in the fiord is ~293 m. Bear Glacier, the largest glacier in the fiord, occupies a side valley that joins the fiord from the northwest, ~20 km south of Seward (Figure 10).

![Figure 10](https://www.nps.gov/kefj/index.htm)

Bear Glacier

When mapped by Grant and Higgins (1913) on July 20 and 21 July 1909, Bear Glacier was ~26 km long and it ended on an outwash plain-sand flat, a maximum of about 400 m from the shore of Resurrection Bay, with the central part of the terminus much closer to the Bay. Its terminus consisted of a small piedmont lobe that was as much as 4.6 km wide (Figure 11 - left).

Grant and Higgins (1913) state that "Along the center of the ice front high tides reach the glacier". They depict the glacier’s terminus region as having two significant medial moraines that divide the terminus region into three nearly equal segments (northern, central, and southern). The southern moraine is the largest, being about two to three times the width of the northern moraine.

Using dendrochronology, Viereck (1967), determined that a trimline located seaward of the 1909 terminus position formed between 1835 and 1845. Tree-ring-counts performed on trees located beyond the trimline determined that these trees were as much as 350 years old, dating from the earliest 16th century. No evidence of a more extensive earlier Little Ice Age (LIA) terminus position was found.
Figure 11. Left - 1909 – Grant and Higgins sketch map of the terminus of Bear Glacier made on July 20 and 21, 1909. Points ‘A,’ ‘B,’ & ‘C,’ from which photographs were taken, are labelled in red. This map is Figure 11 of USGS Bulletin 526: [https://pubs.usgs.gov/bul/0526/report.pdf](https://pubs.usgs.gov/bul/0526/report.pdf). Elevations are from United States Coast and Geodetic Survey Chart No. 8538 with a contour interval of 200 feet. Right - 1950 - Part of the 1950, 1:63,360 scale, Blying Sound D-7 Topographic Map Quadrangle (USGS, 1950a), with a contour interval of 200 feet. The map, made by the USGS using photogrammetric methods from aerial photographs taken in 1950, depicts the terminus of Bear Glacier. Notice the ice-marginal lake that developed on the southeast side of the terminus during the 41 years following the release of the 1909 map.

As depicted on the Blying Sound D-7 USGS Topographic Map Quadrangle, Scale: 1:63,360 (Figure 11 - right) compiled from 1950 aerial photography (USGS, 1950a), the northeastern part of Bear Glacier’s terminus retreated ~400 m from its 1909 position and a small ice-marginal lake developed along the northeastern part of the margin. Little change occurred on the southern – southwestern third of the terminus during that 41-year period.

On an August 12, 1961 oblique aerial photograph of the glacier, taken by Austin Post, the lake is visible and about the same size as in 1950 (Figure 12 - left). A color-infrared vertical aerial photograph taken by the Alaska High Altitude Photography Program (AHAP) shows that by August 1984, the length of the ice-marginal lake had nearly doubled (Figure 12 - right). However, much of the southwestern terminus still remained in contact with the fluvial plain that it has continuously occupied since at least 1909.

In the 71 years between the terminus position shown on the 1950 topographic map and on the August 6, 2021 Landsat 8 image, Bear Glacier retreated a maximum of ~6.75 km, with most of the retreat of the southern and southwestern sections of the terminus occurring post-2000. In the 11 years between the 1950 topographic map and Post’s August 12, 1961 photograph, Bear Glacier showed little change. Similarly, in the 12 years between Post’s August 12, 1961 photograph and the August 16, 1973 collection of a Landsat 1 image, Bear Glacier’s terminus again showed little change. However, due to the 80-m-resolution of the 1973 Landsat 1 image, small changes would be difficult to determine.
Figure 12. Left - 1961 - Northwest looking August 12, 1961 oblique aerial photograph of Bear Glacier made by Austin Post. The irregularly-shaped ice-marginal lake on the southeast side of the terminus which formed prior to 1950, expanded to a maximum length of ~1.5 km by 1961. Right - 1984 - August 14, 1984 AHAP false-color vertical aerial photograph (L120F0313) of much of Bear Glacier. By 1984, continued retreat of the southeastern side of the glacier resulted in the formation of the crescent-shaped ice-marginal lake. In the 23 years between photographs, the lake grew to a length of ~4.5 km. On the southwestern side of Bear Glacier, little changed. Although two small irregularly-shaped ice-marginal lakes developed, there are at least two locations where no retreat occurred as parts of the glacier terminus were still in contact with the outwash plain that separates the glacier from Resurrection Bay.

In the ~18 years between August 1973 and August 1991, the north side of Bear Glacier’s terminus retreated a maximum of ~4.6 km, while the southern and southwestern sections showed little change. Between 1990 and 2006, there was little change on the north side of the glacier while the southern and southwestern parts of the terminus began to retreat rapidly, each as much as a kilometer. Between 2001 and 2005, the southern and southwestern sections of the terminus retreated a maximum of ~3.0 km.

Hall et al. (2005), found that with respect to terminus position change, between 1973, and 2002, Bear Glacier’s length experienced ‘extensive recession’ but the actual amount or retreat was ‘difficult to measure’.

Arendt (2006), calculated that Bear Glacier’s net balance for the ~45- year period 1950 to 1994-1996 was 0.18±0.04 km³/yr water equivalent, and the net balance for the ~6-year period from 1994-1996 to 2001 was -0.205±0.009 km³/yr water equivalent. The average net balance rate for the period 1950 to 1994-1996 was 0.85±0.19 m/yr water equivalent, and the average net balance rate for the ~6-year period 1994-1996 to 2001 was -1.02±0.04 m/yr water equivalent. Error bars on the measured changes are large due to major differences in snowfall amounts during the two measurement periods.

Much of this rapid retreat was due to disarticulation (Molnia, 2012). Due to its buoyancy, parts of the terminus, which had rapidly thinned, decreased in thickness to the point of floatation. Rapid retreat through passive calving became the dominant retreat mechanism. This is characterized by the loss of large numbers of tabular icebergs, some up to 1 km in maximum dimension.

Figure 13 displays six oblique aerial photographs that show changes in the terminus for the 54-year period from 1961 to 2015. The most striking changes occur in the three-year period 2002 to 2005.
Figure 13. Six oblique aerial photographs, all from offshore Resurrection Bay looking to the northwest, illustrate changes in the piedmont lobe of Bear Glacier during the 54-year period from 1961 to 2015. The 1961 photograph was taken by Austin Post. The other five are by Bruce Molnia. During the early 21st century, especially between 2002 and 2005, the southwestern part of the glacier retreated >3 km, much as the result of rapid passive calving (disarticulation). The photos were taken on August 12, 1961, September 3, 2002, August 6, 2005, August 29, 2007, August 12, 2010, and July 15, 2015.

Figure 14 closely corresponds to the oblique aerial photos in Figure 13. It displays six Landsat images that span the 42-year period from 1973 to 2015. Five of the six are from the same years as the Molnia aerial photographs shown in Figure 13 (2002, 2005, 2007, 2010, and 2015). The sixth is from 1973, the earliest Landsat image that shows a cloud-free Bear Glacier. During the 29-year period between 1973 and 2002, nearly all the changes in Bear Glacier’s terminus occur in the northeastern part of the margin. As was previously seen, the most striking changes occur in the three-year period 2002 to 2005.
Figure 15 consists of eight Landsat images that focus on the early 21st century period of maximum terminus change. Spanning the 7-year period from 2000 to 2007, the eight Landsat images show little change in the extent of the southwestern extension of the terminus between 2000 and 2003, then rapid retreat from 2003 through 2006. Maximum retreat between 2000 and 2007 was ~4.1 km. The Landsat images date from August 9, 2000; June 2, 2001; October 27, 2002; May 7, 2003; September 14, 2004; June 28, 2005; September 12, 2006; and June 19, 2007.

Nearly every image from 2000 onward shows tabular icebergs that have calved from Bear Glacier’s retreating terminus. This is due to continued thinning of the glacier resulting in changes in the way Bear Glacier retreats. Bear Glacier’s piedmont lobe lies completely within the ablation zone. Initially, terminus retreat was dominated by melting. By the early 1950s, part of the glacier began to actively calve into the eastern ice-marginal lake. As this part of the glacier retreated into deeper water, the calving rate increased, partly due to the absence of a protective end moraine. Near the end of the 20th century, thinning of the glacier margin accelerated and the thickness of the lower piedmont lobe thinned to a point where its buoyancy began to cause parts of the terminus to float, resulting in an increase in active calving. In the 2000–2010 decade, with continued thinning, more of the terminus floated and disarticulated, resulting in more than 4 km of terminus retreat.

Bear Glacier’s piedmont lobe occupies a deeply scoured basin, often referred to as Bear Glacier Lake or Bear Glacier Lagoon. Immediately offshore of Bear Glacier, seafloor depths approach 200 m. With respect to ice thickness and depths in Bear Glacier Lake, Truffer (2014) describes a radar system that could be deployed as both a ski-team ground-based survey instrument and as an airborne survey instrument. The ground-based survey proved more reliable for narrow valleys, while the airborne survey allowed for large area coverage that worked particularly well over open ice. The maximum Bear Glacier ice thickness measured exceeded 650 m indicating that the glacier’s bed is grounded well below sea level. Ice thickness on the Harding icefield was up to 450 m.

Maximum water depths in Bear Glacier Lake are unknown. However, a preliminary survey conducted in 2006 by the Molnia revealed a number of locations where the depth to the floor of the basin exceeded 75 m, the limit of the depth sounder used. Hence, as Bear Glacier’s piedmont lobe thinned, its terminus area could
quickly change from grounded to floating as its thickness decreased below the neutral buoyancy thickness, or as it retreated into more deeply eroded parts of its basin. Between 2002 and 2007, a period of intense disarticulation, part of the terminus retreated nearly 3 km. Several times, 0.6-1.0 km-size icebergs separated from Bear Glacier’s terminus.

Figures 16 & 17 present two examples of how the retreat of Bear Glacier is portrayed with repeat photography. Both examples document changes that occurred in the nearly 15-year period between August 8, 2006 and August 3, 2021.

Figure 16. West-looking repeat photography pair showing part of the terminus of Bear Glacier on August 8, 2006 (left) and the open waters of Bear Glacier Lake with drifting icebergs on August 3, 2021. In the 2006 image the part of the glacier’s terminus in the foreground is grounded onshore. Subsequent melting of in-situ stagnant ice and terminus retreat resulted in the transition of the foreground area back to open water. Between 2006 and 2021, the northeastern part of the glacier shown in the 2006 image retreated more than 3 km.

Figure 17. Northwest-looking repeat photography pair taken from near the middle of Bear Glacier Lake showing part of the terminus of Bear Glacier on August 8, 2006 (left) and the open waters of Bear Glacier Lake on August 3, 2021. In the 2006 image several large icebergs, calved from the rapidly retreating terminus of Bear Glacier are drifting in front of the glacier’s terminus. Subsequent melting and retreat resulted in a significant increase in the area of the lake and a subsequent reduction of calving and iceberg production. Between 2006 and 2021, the central part of the glacier’s terminus shown in the 2006 image retreated more than 3 km.

Figure 18 displays Landsat images that document the changes in the position of Bear Glacier’s terminus in the 48-year period between 1973 and 2021. Between 2006 and 2021, the terminus retreated a maximum of 2.5 km.
Figure 18. Figure 18. Figure 18. Figure 18. Bear Glacier - Four Landsat images depict changes in the terminus of Bear Glacier in the nearly 48 years between August 16, 1973 (Landsat 1) and August 4, 2021 (Landsat 8). During that period, the southwestern part of the terminus retreated more than 6.5 km with most of the retreat occurring after 2000, while the northwestern part of the terminus retreated about 4.5 km with most of the retreat occurring between 1950 and the early 1980s. Both the June 22, 1991 and August 27, 2006 images were collected by Landsat 5.

In other studies, Adalgeirsdóttir et al. (1998) found that between the 1950’s and the middle 1990’s, Bear Glacier with a 1950’s area of 228.5 km², had its terminus retreat a maximum of 1.55 km and had its area decrease by 8.75 km². Its volume decreased by 9.7 km³, and its average elevation decreased by 38.4 m. They also found that its mean annual mass balance was -0.7 m. For the same period, on an annual basis, Bear Glacier thinned by 0.872 m, had its volume decrease by 0.195 km³, and shortened by 36 m/yr. Giffen et al. (2014) found that between 1951 and 2005, Bear Glacier became buoyant resulting in an increase in its terminus retreat.

Summarizing all the available information about Bear Glacier shows that during the early 16th century, Bear Glacier extended several hundred meters beyond its 1909 terminus position. A trimline located seaward of the 1909 terminus position formed between 1835 and 1845. No evidence of a more extensive early LIA terminus position was found. In 1909, Bear Glacier was ~26 km long and it ended on an outwash plain-sand flat, ~400 m from the shore of Resurrection Bay, with the central part of the terminus much closer to the Bay. Its terminus consisted of a small piedmont lobe that was a maximum of 4.6 km wide.

By 1950, the northeastern part of Bear Glacier’s terminus retreated ~400 m from its 1909 position and a small ice-marginal lake developed along the northern part of the margin. Little change occurred on the southern third of the terminus during this 41-year period. In 1961, the lake was about the same size as in 1950. By 1961, Bear Glacier’s southern – southwestern terminus area showed little change.

By 1984, the length of the ice-marginal lake had nearly doubled, growing to ~4.5 km. However, much of the southwestern terminus still remained in contact with the fluvial plain that it had continuously occupied since prior to 1909. Between 1973 and 1991, the north side of Bear Glacier’s terminus retreated a maximum of ~4.6 km, while the central and southern parts showed little change.

Between 1990 and 2002, there was little change on the north side of the glacier while the central and southern parts of the terminus began to retreat rapidly, each losing up to a kilometer. By 2005, the central and southern parts of the terminus retreated a maximum of ~3.0 km. By 2007, maximum retreat was ~4.1 km. Through 2021, the terminus retreated up to an additional 2.5 km. In summary, from 1900 through 2021, Bear Glacier retreated a maximum of ~6.75 km, with most of the retreat of the northeastern part of the glacier occurring before 1984 and the retreat of the central and southern part of the terminus occurring after 2000.

Aialik Bay

Aialik Bay (Figure 19) is an ~40 km long fiord with maximum water depths of ~192 m. It extends from the terminus of Aialik Glacier at its head to the Chiswell Islands, located at its mouth. Pedersen Glacier (spelled ‘Pederson’ on many early maps and charts) is in a side valley on the west side of the fiord ~7 km south of Aialik Glacier. Immediately adjacent to Pedersen Glacier, Aialik Bay shoals to water depths as shallow as 5-9 m. This is the location of the submarine end moraine that marks Aialik Glacier’s LIA Maximum position. The east and
west margins of the moraine are exposed at low water. Holgate Glacier is located at the head of Holgate Arm, an 8 km long fiord that enters Aialik Bay from the west, ~15 km south of Aialik Glacier. Maximum water depths in Holgate arm are ~157 m. The arm shoals at the southeastern end, likely delineating the LIA maximum extent of Holgate Glacier.

![1973-08-16](image1.png) ![2021-08-04](image2.png)

**Figure 19.** Two Landsat images of Upper Aialik Bay depict the northeast part of the Harding Icefield with its major outlet glaciers - Aialik, Pedersen, and Holgate Glaciers. In the nearly 48 years between August 16, 1973 (Landsat 1) and August 4, 2021 (Landsat 8), Aialik Glacier has retreated less than 1 km, Pedersen Glacier has experienced a major recent rapid retreat, and Holgate Glacier experienced a small recent advance. At this scale, the behavior of Little Holgate Glacier is difficult to discern.

**Aialik Glacier**

When mapped by Grant and Higgins (1913) between July 22 and 24, 1909, Aialik Glacier was an ~11 km long tidewater glacier located at the head of Aialik Bay (Figure 20). They observed the glacier from the top of Squab Island, a glacially-sculpted bedrock knob located in the bay, ~2 km southeast of the glacier’s terminus. They write that: “On each side of the glacier is a marked bare zone, and in the bare zone on the south side is a lateral moraine. When the ice extended over this bare zone, possibly 10 years ago, the front was about a quarter of a mile (~400 m) in advance of its present position”. They also note that: “Much more advanced positions of Aialik Glacier, occupied several centuries ago, are indicated by shoals, caused by morainic accumulations, stretching across the head of Aialik Bay opposite and a mile (1.6 km) north of the front of the Pederson Glacier” (Grant and Higgins, 1913).
Figure 20. Two maps of Aialik Bay - Left – Grant and Higgins sketch map of upper Aialik Bay made July 22-24, 1909. Points ‘A,’ ‘B,’ ‘C,’ & ‘D’ from which they took photographs, are labelled in red. This map is Plate XXXIII of USGS Bulletin 526: https://pubs.usgs.gov/bul/0526/report.pdf. Elevations are from United States Coast and Geodetic Survey Chart No. 8538 with a contour interval of 200 feet. Right – September 8, 2014 - Part of the National Park Service (2020) Map of Kenai Fjords National Park, depicting Aialik Bay. At this scale, little change is discernible in the positions of Aialik, Pedersen, or Holgate Glaciers.

Between 1909 and 2021, Aialik Glacier’s terminus position fluctuated, but never more than ~0.75 km. Field, 1975, commented that “On the whole, this terminus has been remarkably stable over the last six decades” (1909 to 1975).

The 2021 position of the southwestern edge of the glacier is ~500 m to 600 m behind the 1909 location. In 1909, Aialik was actively calving and showed a large area of exposed bedrock at sea level along its southwest margin.

As depicted on the Blying Sound D-8 USGS Topographic Map Quadrangle, Scale: 1:63,360 (Figure 21) compiled from 1950 aerial photography (USGS, 1950b), the northern part of Aialik Glacier’s terminus retreated ~400 m from its 1909 position. Over the next 112 years, the glaciers terminus position fluctuated with a net result of less than a kilometer of retreat and a thinning of less than 30 m.
Figure 21. **Top** - 1909 – Grant and Higgins sketch map of the terminus of Aialik Glacier made on July 23, 1909. Point ‘A’ on Squab Island, the location from which most photographs were taken, is labelled in red. This map is part of Plate XXXIII of USGS Bulletin 526: https://pubs.usgs.gov/bul/0526/report.pdf. Elevations are from United States Coast and Geodetic Survey Chart No. 8538 with a contour interval of 200 feet. **Bottom** - 1950 - Part of the 1950, 1:63,360 scale, Blying Sound D-8 Topographic Map Quadrangle (USGS, 1950b), with a contour interval of 200 feet. The map, made by the USGS using photogrammetric methods from aerial photographs taken in 1950, depicts the terminus of Aialik Glacier. Note the large embayment in the center of the terminus.

Figure 22 presents three oblique aerial images of the terminus of Aialik Glacier. An Austin Post August 12, 1961 oblique aerial photograph of the glacier shows that calving has produced a large, semi-circular alcove that extends several hundred meters into the face of the glacier’s terminus. Large ‘arms’ of ice extend beyond the embayment along both walls of the glacier’s valley, with the arm on the southwest (left) side extending three or more times further than the arm of the northeast (right) margin. A 2007 photograph by Molnia shows that
the northeast margin of the terminus has advanced several hundred meters, while the southwest arm has retreated. Much of the central part of the terminus is at about the same location. The embayment is much smaller and the face much straighter.

![Figure 22](image)

Figure 22. Three oblique aerial photographs showing the terminus of Aialik Glacier with Squab Island in the foreground, approximately 2 km south of the terminus. The 1961 photograph by Austin Post shows a large embayment in the glacier’s terminus. The 2007 and 2015 photographs by Bruce Molnia show the continuing thinning and minor retreat of the glacier.

A 2015 photograph by Bruce Molnia shows that the terminus has retreated up to 400 m and a wall of ice has been stranded that marks a former post-2007 terminus location. A large mass of glacial-fluvial sediment, part of which is vegetated, now sits up to a kilometer forward of the glacier’s southwest margin. All three images depict Squab Island, the location of the photo point for the repeat photography triplet displayed in Figure 23. Aialik Glacier has a width at its face of 0.16 km, and an accumulation area ratio (AAR) of 0.88.

Adalgeirsdóttir et al. (1998), report that between the 1950’s and mid-1990’s, Aialik Glacier, with a 1950 area of 118 km², had its terminus advance 540 m, but experienced no change in area. Between 1950 and the mid-1990s, its ice volume decreased by 2.6 km³, its average elevation decreased by 11 m, and its mean annual mass balance was -0.2 m. On an annual basis, Aialik Glacier thinned by 0.25 m, had its volume decrease by 0.03 km³, and lengthened by ~13 m/yr.

Hall et al. (2005), found that with respect to terminus position change, between 1973 and 1986, Aialik Glacier’s length decreased ~85 m, an average of ~7 m/yr, and between 1986 and 2002, its length decreased ~339 m, an average of ~7 m/yr. In the 19 years since 2002, the central part of the terminus retreated as much as 300-400 m, while the southwestern margin has retreated more than 500 m, exposing a large triangular shaped fluvial outwash plain.
Figure 23. Aialik Glacier Repeat Photography Triplet – These three photographs, spanning more than 112 years, were taken from the same location on top of Squab Island in Aialik Bay. The first was taken by U.S. Grant on July 23, 1909. The other two were taken by Bruce Molnia, one on July 13, 2004 and the other on August 5, 2021. Together, they document the continuing thinning and retreat of the terminus of Aialik Glacier. Note the thinning of the glacier, the retreating southwest (left) margin, and the increase in the amount of bedrock exposed at the base and center of the glacier’s face.

Arendt (2006), calculated that Aialik Glacier’s net balance for the ~45- year period from 1950 to 1994-1996 was 0.002±0.03 km$^3$/yr water equivalent, and the net balance for the ~6-year period from 1994-1996 to 2001 was -0.010±0.006 km$^3$/yr water equivalent. The average net balance rate for the ~45- year period from 1950 to 1994-1996 was 0.02±0.35 m/yr water equivalent, and the average net balance rate for the ~6-year period from 1994-1996 to 2001 was -0.11±0.07 m/yr water equivalent. Error bars on the measured changes are large due to significant differences in snowfall amounts during the two measurement periods.
Figure 24 displays four Landsat images that document changes in the position of Aialik Glacier’s terminus in the 48-year period between 1973 and 2021.

Figure 24. Aialik Glacier - Four Landsat images depict changes in the terminus area of Aialik Glacier in the nearly 48 years between August 16, 1973 (Landsat 1) and August 4, 2021 (Landsat 8). During that period, the terminus position fluctuated, but generally thinned and retreated. Comparison of the four Landsat images shows continuing retreat of the glacier’s southern margin and lesser retreat along the entire width of the terminus. The June 22, 1991 and August 27, 2006 images were both collected by Landsat 5.

Summarizing all the available information about Aialik Glacier shows that sometime during the LIA, Aialik Glacier extended at least 8 km beyond its present position, filling the northern fifth of Aialik Bay and depositing an end or recessional moraine adjacent to Pedersen Glacier. In 1909, when first mapped, it was an ~11 km long tidewater glacier located at the head of Aialik Bay with a recently exposed bare zone at its base. A decade earlier, Aialik Glacier’s terminus was ~400 m in advance of its 1909 position. Since 1909, Aialik Glacier’s terminus position has fluctuated, but never more than a kilometer. By 1950, the northern part of Aialik Glacier’s terminus had retreated ~400 m from its 1909 position. Between 1950 and the mid-1990’s, Aialik Glacier’s terminus advance 540 m, despite about 300 m of retreat that occurred between 1950 and 1964. Between 1973 and 1986, Aialik Glacier retreated ~85 m. Since 2002, the central part of the terminus retreated as much as 300-400 m, while the southwestern margin has retreated more than 500 m, exposing a large triangular shaped fluvial outwash plain. The 2021 position of the southwestern edge of the glacier is ~500 m to 600 m behind the 1909 position.
Pedersen Glacier

Pedersen Glacier is located ~7 km south of Aialik Glacier (Figure 20). Tebenkov’s 1852 Atlas depicts the presence of a glacier terminus ~ 800 m from the shoreline of Aialik Bay at Pedersen Glacier’s general location. Unfortunately, the portion of Tebenkov’s Kenai Peninsula chart shown in Figure 2, does not extend far enough south to accurately depict the location of Pederson Glacier.

Pedersen Glacier was retreating prior to first being mapped on July 22-24, 1909 by Grant and Higgins (1913). Its 1909 terminus position (Figure 25) was from 400 to 500 m behind its most recent post-Little Ice Age maximum position. Even then, part of the terminus was reached by high tide. Grant and Higgins speculated that the glacier may have been at its maximum position as recently as the early 1890s.

Figure 25. Top Left - 1909 – Grant and Higgins sketch map of the lower 4 km and terminus of Pedersen Glacier made on July 22-24, 1909. This map is part of Plate XXXIII of USGS Bulletin 526: https://pubs.usgs.gov/bul/0526/report.pdf. Elevations are from United States Coast and Geodetic Survey Chart No. 8538 with a contour interval of 200 feet. Bottom Left - 1950 - Part of the 1950, 1:63,360 scale, Blying Sound D-8 Topographic Map Quadrangle (USGS, 1950b), with a contour interval of 200 feet. The map, made by the USGS using photogrammetric methods from aerial photographs taken in 1950, depicts the terminus of Pedersen Glacier. The gravel bar adjacent to the glacier terminus is the LIA end moraine deposited by Aialik Glacier. Right – August 12, 1961 oblique aerial photograph of Pedersen Glacier taken by Austin Post. Note the small ice-marginal lakes and the parts of the terminus in contact with its fronting outwash plain.

Grant and Higgins (1913) describe the northern part of the terminus being "a perpendicular cliff of ice perhaps 100 feet (30 m) high", with a "well-marked bare zone on each side of the front", suggesting a recent greater extent. They write: "Along much of the front, a quarter to a third of a mile (~240 m to ~310 m) from the ice, are remnants of a low moraine, which has now been nearly cut away by the waves. On this moraine are herbaceous plants and some alders about 2 feet high. The moraine was probably deposited at the time when the glacier advanced to the edge of the bare zone mentioned above. This advance may have been made 15 years ago and apparently was the maximum advance of the glacier since the advent of the present forest...".

By 1950 (Figure 25), the glacier retreated an additional 400 m to 1,200 m (Field, 1975; Molnia, 2008). Then, a 600 m to 800 m-wide tidal embayment fronted much of the glacier. By 1964, another ~250 m of retreat occurred. As much as 1.5 km of retreat and the development of a large ice-marginal lake occurred between 1965 and 2000. Field (1975) commented that from 1950 to 1964, ice velocities in the lower 2 km of the glacier were ‘about 70 m/yr."
At least six studies (Grant and Higgins, 1913; Field, 1975; Hall et al., 2005; Molnia, 2008; Giffen et al., 2014; and Pelto, 2017) have described the behaviour of Pedersen Glacier since it was first observed. Pelto (2017) reported that Pedersen Glacier retreated 706 m between 1951 and 1986, averaging ~20 m/yr. Hall et al. (2005) found that between 1973 and 1986, the glacier’s length decreased ~511 m, an average of ~39 m/yr. This would mean that between 1951 and 1973, the terminus retreated ~195 m, at a much slower average retreat rate of 8.86 m/yr. Post’s 1961 oblique aerial photograph (Figure 27), shows several small ice-marginal lakes developing along the glacier’s southern margin as well as parts of the terminus still connected to its southern outwash plain.

Hall et al. (2005), report that between 1986 and 2002, the glacier’s length decreased ~108 m, an average of ~7 m/yr. Giffen et al. (2014) found that Pedersen Glacier retreated between 1951 and 2005, with little terminus change between 1986 and 2000. Pelto (2017) found that Pedersen Glacier retreated 434 m (23 m/yr) from 1986 to 2005. This would suggest that the retreat rate exponentially increased during the final few years of the interval. Pelto states that for the period from 1994 to 2015 the glacier retreated 2.6 km, an average rate of 125 m/yr. He further describes the growth of the ice-marginal lake that fronts Pedersen Glacier: “In 1994 part of the terminus was fronted by a small proglacial lake, with most of the terminus terminating on land. Eleven years later in 2005, the lake’s length had grown to 1.1 km long on its center axis”. He further states that “A comparison of the 2013, 2015 and 2016 terminus indicated that the recession was continuing rapidly” (Figure 26).

Pelto noted that Pedersens’s snowline rose dramatically between 1994 and 2016, from 550 m in 1994, to 800 m in 2005, to 850 m in 2015; and that Pedersen’s northern tributary had a width of ~150 m and barely reached the main glacier.

To try to both clarify and simplify the details of Pedersen’s behaviour, we measured the position of Pedersen’s terminus on several types of ‘imagery’ data (maps, photographs, and satellite images) that are being used to describe and quantify the behavior of the Glacier. The results (Table 1 and Figure 27), show that Pedersen Glacier retreated 4.86 km during the 121-years from the maximum advanced position (~1900) identified by Grant and Higgins. Therefore, the average retreat rate was 40.17 m/yr. Rates fluctuated over time,
with peak rates of > 350 m/yr between 2006 and 2010, and minimum rates of <20 m/yr for much of the pre-1980s period. Figure 28 presents a five-image repeat photography montage showing the rapid retreat and thinning of the glacier from offshore in Aialik Bay during the nearly 31-year period from August 13, 1990 to April 5, 2021.

Accurately determining the amount of terminus change is exceedingly difficult. Although many images are available, most were not useful due to image resolution, cloud cover, or shadows. There were also several long intervals where no data were available. Two other issues encountered were that the shape of the terminus is unique each time that it is imaged; and with each terminus, the rate and amount of change is different for various parts of the terminus. As a result, measuring change from one terminus position to the next is subjective. The most accurate method would be to draw the entire perimeter of every terminus on a single map, not just the most advanced point, to correctly determine and show the varying amounts of change.

Table 1. Pedersen glacier retreat during the 121-year period from 1900 to 2021

<table>
<thead>
<tr>
<th>Date</th>
<th>Distance (km)</th>
<th>Interval # of yr</th>
<th>Difference (in m)</th>
<th>Rate (m/yr)</th>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>121 yr</td>
<td>4.86 km</td>
<td>40.17 m/yr</td>
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</table>

Figure 27. Google Earth view of Pedersen Glacier with fourteen terminus positions plotted. Table 1 presents data describing the incremental retreat rates associated with each pair of positions.
Figure 28. A five-image repeat photography montage depicting the rapid retreat and thinning of Pedersen Glacier from offshore in Aialik Bay during the nearly 31-year period from August 13, 1990 to August 5, 2021. The four right side images are from Figure 12 in Lanik et al. (2018). The four left-side NPS repeat photographs of Pedersen Glacier were taken by Mike Tetreau in 1990 and by Deb Kurtz in 2013, 2015, and 2016. The August 5, 2021 photograph is by Bruce Molnia.

Figure 29 displays four Landsat images that document the changes in the position of Pedersen Glacier’s terminus in the 48-year period between 1973 and 2021. They date from August 16, 1973, June 22, 1991, August 27, 2006, and August 4, 2021.

Figure 29. Pedersen Glacier - Four Landsat images depict changes in Pedersen Glacier in the nearly 48 years between August 16, 1973 (Landsat 1) and August 4, 2021 (Landsat 8). During that period, the glacier thinned significantly and retreated continuously, retreating ~3.8 km. Both the June 22, 1991 and August 27, 2006 images were collected by Landsat 5.
Summarizing all the available information about Pedersen Glacier shows that in the mid-19th century, the terminus of Pedersen Glacier was ~ 800 m from the shoreline of Aialik Bay. It may have advanced for the next half century and it may have been at its maximum position as recently as the early 1890s. In 1909, its terminus position was from 400 to 500 m behind that recent maximum position. Even then, part of the terminus was reached by high tide. By 1950, the glacier retreated an additional 400 m to 1,200 m, resulting in a 600 m to 800 m-wide tidal embayment fronting much of the glacier. By 1964, another ~250 m of retreat occurred. Between 1965 and 2000, as much as 1.5 km of retreat occurred with the development of a large ice-marginal tidally-influenced lake. Specifically, the glacier retreated ~195 m between 1951 and 1973, ~511 m between 1973 and 1986, ~108 m between 1986 and 2002, ~326 m between 1986 and 2005, ~1,500 m between 2005 and 2015, and ~680 m between 2015 and 2021. In the 121-years from ~1900 to 2021, Pedersen Glacier retreated 4.86 km.

Holgate Glacier

Holgate Glacier is a tidewater glacier located at the head of Holgate Arm, the westernmost branch of Aialik Bay. Davidson (1904) describes Holgate as nearly reaching the beach, suggesting that in the 19th century, its terminus position was 10s to 100s of meters up valley from where it sat when photographed and mapped by Grant and Higgins in 1909. It was shown as being present on the 1849 Tebenkov map (Tebenkov, 1852 – Figure 2). Grant and Higgins’ photographs of the terminus (Figure 7A) show that "Holgate Glacier reaches tidewater in two streams separated by a small mass of rock, which not many years ago was a nunatak in this glacier. The northern and larger stream (Holgate Glacier) is discharging rapidly, but the discharge from the southern stream (Little Holgate Glacier) is small. Near the south side of the larger stream is a small medial moraine, but the glacier as a whole is free from medial moraines" (p. 59).

Grant and Higgins continue: “There are no trees on the sides of Holgate Arm within 1 mile (1.6 km) of its head, and beyond this the forest is sparse. There are no bushes and very few herbaceous plants close to sea level from the glacier to a point a quarter of a mile (~400 m) east” ... “The rock mass between the two parts of the glacial front has bushes only on its upper half on the front and on its upper fourth on the sides. In very recent years, possibly within the twentieth century, the front of the Holgate Glacier was about a mile in advance of its position in 1909.”

Grant and Higgins (1913), 1909 sketch map (Figure 30) and photograph (Figure 7A) of upper Holgate Arm and Holgate Glacier show both glaciers terminating in Holgate Arm. The Little Holgate Glacier is the name commonly applied to the smaller south-eastern arm.

The 1950 Blying Sound D-8 topographic map shows that the south side of Holgate Glacier’s terminus had retreated ~400 m from its 1909 position, while the north side remained unchanged (Field, 1975). Comparing the 1950 topographic map to the 1961 oblique aerial photograph shows that significant retreat of the southern part of the glacier continued, exposing bedrock along about a third of the base of the terminus. Field (1975, p. 519) quantifies this as “a further recession of around 500 m”.

Hall et al. (2005), reported that between 1973 and 1986, the terminus retreated ~234 m, an average of ~18 m/yr. From 1986 to 2002, “no change was detected”.

Arendt (2006), calculated that Holgate Glacier’s net balance for the ~45- year period from 1950 to 1994-1996 was -0.021±0.011 km$^3$/yr water equivalent, and the net balance for the ~6-year period from 1994-1996 to 2001 was -0.007±0.002 km$^3$/yr water equivalent. The average net balance rate for the ~45-year period from 1950 to 1994-1996 was 0.31±0.16 m/yr water equivalent. This equals the loss of a nearly 14 m vertical column of water, or a thinning of nearly 16 m. The average net balance rate for the ~6-year period 1994-1996 to 2001 was -0.10±0.04 m/yr water equivalent. This equals the loss of a nearly 60 cm vertical column of water, or a thinning of nearly 65 cm.
Repeat photography of Holgate Glacier from the north side of Holgate Arm (Figure 31), shows that from 2004 to 2016, although much of the terminus of Holgate Glacier was not visible, part of the south margin of the glacier could be seen. It decreased in size from 2004 to 2011 to 2016. Sometime after 2016, it began to advance. By 2021, it had readvanced to a position where it spanned the full width of the channel visible from the photo point. During that same period, the tributary that joined the terminus from the south, on the left side, melted away. (Figure 31).

The north side of Holgate Glacier’s terminus extends onto the beach located at the foot of the bedrock knob at the head of its fiord. On August 5th, 2021, the terrestrial terminus was advancing and developing a 2-4 m-high push moraine along its entire margin (Figure 32).

Repeat photography of Little Holgate Glacier’s terminus from the north side of Holgate Arm (Figure 31), shows that after 2004 and before 2016, when it was close to sea level, but about 100 m from the shoreline, the terminus of Little Holgate Glacier retreated completely out of the field of view. By 2021, it no longer existed at or near sea level, having retreated off the valley floor to an elevation approaching 100 m ASL. (Figure 31). Figure 33, a pair of images taken 15-years apart, depicts the rapid loss of the lower elevation area of Little Holgate glacier.
Figure 31. A five-image repeat photography montage showing the retreat of both Holgate (right) and Little Holgate (left) Glaciers during the period from 1909 to 2016; then, the readvance of Holgate Glacier and the disappearance of Little Holgate Glacier during the period from 2016 to 2021. The photos span 112 years. The four right side images are from Figure 11 of a NPS report by Lanik et al. (2018). The photographs of Holgate Glacier in the NPS panel were taken by U.S. Grant in 1909, by Bruce Molnia in 2004, and by Deb Kurtz in 2011 and 2016. The August 4, 2021 photograph is also by Molnia. Note the several hundred meters of advance that Holgate Glacier experienced after 2016. Repeat photography of the terminus of Little Holgate Glacier from the north side of Holgate Arm shows that after 2004 when it barely reached tidewater, and before 2011, Little Holgate Glacier retreated completely out of the field of view. By 2021, it no longer existed at or near sea level. Note the several hundred meters of advance that Holgate Glacier experienced after 2016.

Figure 32. August 5, 2021 photograph taken by Shawn Dilles showing the northern terrestrial terminus of the advancing Holgate Glacier. The push moraine, located in the middle ground of the image is 2-4 m high and is composed of poorly- sorted sediment ranging in size from silt to small boulders. The area in the foreground behind Bruce Molnia has been water worked and partially winnowed.
Figure 33. Southwest-looking repeat photography pair taken from near the mouth of Little Holgate Glacier’s valley. In the foreground of this August 8, 2005 (left) image by Michael Molnia, Bruce Molnia is pointing to the terminus of the retreating Little Holgate Glacier with the tunnel of a large englacial stream channel at its margin. The image on the right, taken by Shawn Dilles on August 4, 2021, nearly sixteen years later, shows that the glacier has retreated more than 300 m and no longer reaches its former outwash plain. The large granitic erratic located on the left edge of both images appears not to have moved in the interval between photographs.


Figure 34. Holgate Glacier - Six Landsat images depict changes in Holgate and Little Holgate Glaciers in the nearly 48 years between August 16, 1973 (Landsat 1) and August 4, 2021 (Landsat 8). From the 1970s until about 2006, Holgate Glacier’s terminus fluctuated within 500 m of its 1973 position. It then retreated about 500 m before it began advancing sometime after 2011. When visited on August 4, 2021, a newly formed push moraine (Figure 32) was present along the glacier’s north terrestrial margin.
Summarizing all the available information about Holgate Glacier shows that while currently a tidewater glacier located at the head of Holgate Arm, its 19th century location may have been 10s to 100s of meters retracted from where it sat when photographed and mapped in 1909. Then, two separate arms of Holgate Glacier (Holgate and Little Holgate Glaciers), approximately 750 m apart, reached tidewater. By 1950, the south side of Holgate Glacier’s terminus retreated ~400 m from its 1909 position, while the north side remained unchanged. By 1961, as much as 500 m of retreat of the southern margin occurred, exposing bedrock along ~1/3 of the base of the terminus. Between 1973 and 1986, the terminus retreated about 230 m. Between 1986 and 2002, little change was observed, but analysis of Landsat images showed slow continuing retreat, especially on the southern side. From 2004 to 2011, the southern margin of the glacier decreased in size, retreating ~300 m. Sometime after August 2016, Holgate Glacier began to advance, and by 2021, advance totalled ~700 m.

**Harris Bay and Northwestern Fiord**

Harris Bay (Figure 35) is an ~20 km long fiord with maximum water depths of ~221 m. It extends from the LIA recessional/end moraine deposited by Northwestern Glacier at the head of the bay, south to its mouth adjacent to Granite Island, where it joins the Gulf of Alaska. The recessional/end moraine is the boundary between Harris Bay and Northwestern Lagoon.

**Figure 35.** Three maps of Northwestern Glacier and Harris Bay – Northwestern Fjord - **Left** – Grant and Higgins (1913), sketch map of upper Harris Bay with the terminus of Northwestern Glacier sitting on its late Little Ice Age recessional/end moraine. The map was made on July 23, 1909. Point ‘A’ from which photographs were taken, is labelled in red. This map is Figure 12 of USGS Bulletin 526: [https://pubs.usgs.gov/bul/0526/report.pdf](https://pubs.usgs.gov/bul/0526/report.pdf). Elevations are from United States Coast and Geodetic Survey Chart No. 8538 with a contour interval of 200 feet. **Middle** - 1951 - Part of the 1951, 1:63,360 scale, Seldovia D-1 Topographic Map Quadrangle (USGS, 1951), with a contour interval of 200 feet. The map, made by the USGS using photogrammetric methods from aerial photographs taken in 1950, depicts the terminus area of Northwestern Glacier straddling Striation Island (S). The terminus as shown on the west side of the island is ~6 km from the 2021 terminus location. The approximate 2021 position of the glacier is marked by a dotted line and labelled ‘NW’. Anchor (A), Ogive (O), Northeastern (NE) Glaciers, and an unnamed glacier (U) are indicated by red letters. **Right** – September 8, 2014 - Part of the NPS (2020) Map of Kenai Fjords National Park, depicting Harris Bay and Northwestern Fjord. Note the 1900 position of the glacier. The full map, made from Landsat imagery is part of the online digital brochure, that is available at the NPS website: [https://www.nps.gov/kefj/index.htm](https://www.nps.gov/kefj/index.htm).
Northwestern Glacier

Fifteen-kilometer-long Northwestern Glacier extends from the southeastern side of the Harding Icefield to tidewater at the head of Northwestern Fiord. It was named by U. S. Grant for Northwestern University. The glacier’s terminus position was mapped on 23 July 1909 (Figure 35) by Grant and Higgins. It retreated more than 15 km since it reached its LIA maximum position in the latter half of the 19th century. When first mapped, the glacier was one of the largest ice streams on the Kenai Peninsula. On Tebenkov’s 1849 chart, the glacier is shown as almost reaching the Gulf of Alaska.

Comparing Grant and Higgins 1909 sketch map of Northwestern Glacier’s terminus position with the terminus position displayed on the USGS (1951) Seldovia D-1, 1:63,360 scale topographic map, Field (1975) reports that ~10 km of retreat occurred in the ensuing 42-year period. This results in an average retreat rate of 238 m/yr. Based on oblique aerial photography taken by Austin Post (Figure 36), between 1950 and 1964, Field (1975) documented that the glacier retreated another 3.5 km. This results in an average retreat rate of 233 m/yr.

Figure 36. Three oblique aerial photographs showing the retreating terminus of Northwestern Glacier and the rapidly expanding separation of the terminus into two lobes. The August 12, 1961 photograph was taken by Austin Post. The two 2015 photographs were taken by Bruce Molnia.

Hall et al. (2005), reported that between 1973 and 1986, Northwestern’s length decreased ~67 m, an average of ~5 m/yr, and between 1986 and 2002, its length decreased ~2,184 m, an average of ~137 m/yr. Adalgeirsdóttir et al. (1998), reported that between the 1950’s and middle 1990’s, Northwestern Glacier, with a 1950’s area of 66.25 km², had its terminus retreat 4.2 km and had its area decrease by 8.0 km². Its ice volume decreased by 5.0 km³, its average elevation decreased by 80.2 m, and its mean annual mass balance was -1.5 m. Between the 1950’s and middle 1990’s, on an annual basis, Northwestern Glacier thinned by 1.746 m, had its volume decrease by 0.109 km³, and shortened 92 m.

When photographed by Bruce Molnia in July 2000, a bedrock ridge separated the retreating terminus of Northwestern Glacier into two adjacent ice tongues. Much of the margin of the eastern tongue was located above tidewater. Since then, both tongues have been slowly retreating. When observed in August 2021, each ended above tidewater and contributed ice to the fiord by avalanching, rather than calving (Figure 37). Barren zones along the lateral margins of both tongues documented recent thinning and narrowing of the glacier. Northwestern Glacier has an accumulation area of ~54 km² and an ablation area of about 4.5 km², a width at its face of 0.9 km, and an AAR of 0.89. Giffen et al. (2014) found that Northwestern Glacier advanced from 2000 to 2005.
Figure 37. August 6, 2021 photograph of the retreating terminus of Northwestern Glacier, located at the northern head of Northwestern Fiord. Note that the left lobe and the right lobe are now completely separated and are two unique glaciers. While the left lobe barely reaches tidewater, the right lobe terminates meters above sea level. Note the absence of icebergs in the fiord. The photograph was taken by Bruce Molnia.

Figure 38 displays four Landsat images that document the changes in the position of Northwestern Glacier’s terminus in the 48-year period between 1973 and 2021. They date from August 16, 1973, June 22, 1991, August 27, 2006, and March 13, 2021. Between 1973 and 1990 Northwestern Glacier retreated nearly 800 m. Since 1990, the terminus position has fluctuated at the head of the fiord. In 2021, the distance between the two lobes continued to lengthen.
Summarizing all available information about Northwestern Glacier shows that the recessional/end moraine that separates Harris Bay from Northwestern Lagoon and Fjord, located nearly 16 km from the present terminus of Northwestern Glacier, marks the position of Northwestern’s terminus at the start of the 20th century. In the previous century, it may have reached into the Gulf of Alaska. In 1909, the glacier terminated just north of this moraine. From 1909 to 1950, ~10 km of retreat occurred. Between 1950 and 1964, the glacier retreated another 3.5 km. In the nine years between 1964 and 1973, a maximum retreat of ~1 km occurred. Between 1973 and 1986, the retreat rate decreased and Northwestern retreated ~67 m. Between 1973 and 1990, Northwestern Glacier retreated ~800 m. Between 1986 and 2002, it retreated ~2.2 km. By 2000, a ridge of bedrock separated the terminus of Northwestern Glacier into two adjacent ice tongues. Since then, aside from a small advance through 2005, both tongues have been slowly retreating. In 2021, each ended above tidewater and contributed ice to the fiord by avalanching, rather than calving. Barren zones along the lateral margins of both tongues documented recent thinning and narrowing of the glacier.

Glacier retreat and shoreline change

One of the most significant impacts of glacier retreat and thinning is the exposure of land areas that previously were located under the ice. In the southern Kenai Mountains, most of these areas are at or near sea level. The change from ice-filled fiord to newly exposed marine basin, with newly exposed coastline is apparent in each of the three fiords that were studied.

Concurrent with ice loss is the onset of vegetation, usually driven by the growth of plants growing from wind-transported seeds that were deposited on glacier till and related sediments. The resulting plants and trees attract pollinators, which in turn attract avian predators. As the vegetation expands, this newly established habitat attracts small mammals, which in turn attracts larger predators. A similar ecosystem development scenario occurs in the newly exposed aquatic environment.

Many tools are used to address landscape evolution and change in newly deglacierized areas. The NPS has invested significant resources to understand the rapidly changing coastal resources in Kenai Fjords National Park. Pendleton et al. (2004) developed a change-potential index (CPI) to map the relative coastal change-potential of the shoreline of the park to future sea-level changes. All or parts of the three fiords that are the focus of this study (the Bear Glacier and Bear Glacier Lake section of Resurrection Bay, Aialik Bay, and Harris Bay / Northwestern Fiord) are located within the park.

The CPI evaluates and ranks six parameters in terms of their physical contribution to coastal change. The parameters are: 1) geomorphology, 2) regional coastal slope, 3) rate of relative sea-level change, 4) historical shoreline change rates, 5) mean tidal range, and 6) mean significant wave height. Pendleton et al. (2004) state that “The CPI was developed from a Coastal Vulnerability Index (CVI) typically applied to coastlines undergoing long-term sea-level rise. The CPI is modified from the CVI and applied to the emergent coast of Kenai Fjords National Park to understand the limits of applying this type of assessment method in a variety of sea-level settings.”

Kenai Fjords National Park’s shorelines are described as consisting of sand and gravel beaches, rock cliffs, calving tidewater glaciers, mudflats, and alluvial fans. The areas within the park that are likely to be most susceptible to coastal change due to sea-level change are tidewater glaciers and outer coast shorelines of unconsolidated sediment where both shoreline erosion potential and wave energy are high.

Figure 39 depicts the Relative Coastal Change-Potential for Kenai Fjords National Park. Note that the coastline area adjacent to Bear, Aialik, Pedersen, and Holgate Glaciers, all correspond to the highest change category – the ‘very high’ ranking. The location of Northwestern Glacier falls into the ‘low’ category. This is due to the area being part of a large granitic pluton, a rock type and material that is very resistant to erosion.
Figure 39. Relative coastal change-potential (CPI) for Kenai Fjords National Park — Shoreline color corresponds to the intensity of potential change determined from the six variables of the CPI index. The very high change-potential shoreline is located along sandy pocket beaches where shoreline change-potential and significant wave heights are highest. The low change-potential shoreline is located along rock cliffs which are usually within sheltered locations in the fiords. Image is Figure 13 from Pendleton et al. (2004).

Conclusions

This study fused data from the analysis of maps and remotely-sensed imagery, collected from different spatial perspectives (ground, air, and space), at different times from the early 20th century to the present, using different sensors to determine the behavior of six temperate glaciers located in Alaska’s southern Kenai Mountains. The data about these glaciers (Bear Glacier, Aialik Glacier, Pedersen Glacier, Holgate Glacier, Little Holgate Glacier, and Northwestern Glacier) were studied and analysed, and at a minimum, their
Terminus positions were determined for the following dates: 1909, 1950, 1961, 1973, 1990, 2004-2006, and 2021. The results showed that each glacier displayed unique asynchronous behavior. Compared to their 1909 terminus positions, all displayed long-term terminus retreat. However, the timing of retreat for each glacier was unique. Several glaciers experience short-lived intervals of advance. In 2021, Holgate Glacier was advancing, while the other five glaciers were retreating.

Using repeat photography, image compilations consisting of multiple sequential images were produced to provide visual documentation of how each glacier was changing. Image pairs, image triplets, and even image quintuplets were made. Paired with the terminus position data, both qualitative and quantitative documentation was produced to enhance our understanding of the complex behavior of the six glaciers.

**Authors’ Contributions**

The contributions of authors to the manuscript are as follows: Conceptualization: BFM, CMK, SJD, KMA; Data curation: BFM, SJD; Formal analysis: BFM; Funding acquisition: BFM, SJD, KMA; Investigation: BFM, SJD, KMA; Methodology: BFM; Project administration: BFM, CMK; Resources: BFM; Software: BFM; Supervision: BFM; Validation: BFM, CMK, SJD, KMA; Visualization: BFM, SJD, KMA; Writing - original draft: BFM, CMK; Writing - review and editing: BFM, CMK, SJD, KMA.

All authors read and approved the final manuscript.

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**Conflict of Interests**

The authors declare that there are no conflicts of interest related to this article.

**References**


Davidson G (1904). The glaciers of Alaska that are shown on Russian charts or mentioned in older narratives: Transactions and Proceedings, Geographic Society of the Pacific, 2d series, Vol 3, 33 p.


Field WO (1975). Mountain Glaciers of the Northern Hemisphere, Vols. 1 and 2. Cold Regions Research and Engineering Laboratory, Hanover, NH.


Skidmore ER (1896). Discovery of Glacier Bay: National Geographic Magazine 7:140-146.


USGS (1951). Seldovia D-1 Topographic Map Quadrangle, Scale: 1:63,360, Topography by photogrammetric methods from trimetrogon aerial photographs taken in 1941-1946. https://ngmdb.usgs.gov/hr-bin/rv_browse.pl?id=d451448863a85d1b1703d8aa3b8378d4


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