Photograph by Page Spencer

Visualizing Climate Change—Using Repeat Photography to Document the Impacts of Changing Climate on Glaciers and Landscapes

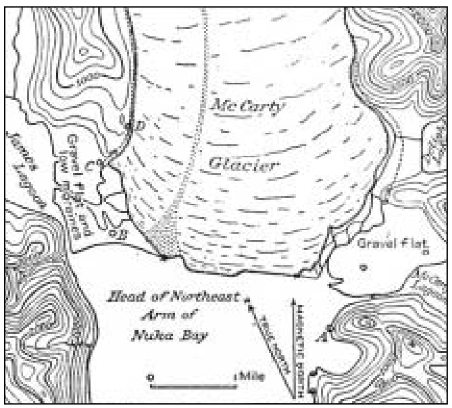


Figure 1. Sketch map of the terminus of McCarty Glacier and upper Nuka Bay made by Grant and Higgins *(1913)* in July 1909. The point labeled 'A' is the location from which the photographs in *Figure 4* were made. Maps like this one are very useful in relocating historical photograph locations. Unfortunately, they are associated with less than 10% of the historical photographs found.

By Bruce F. Molnia, Ronald D. Karpilo, Jr., Jim Pfeiffenberger, Doug Capra

Introduction

Repeat photography is a technique in which a historical photograph and a modern photograph, both having the same field of view, are compared and contrasted to quantitatively and qualitatively determine their similarities and differences. This technique is being used in both Kenai Fjords National Park (KEFJ) and Glacier Bay National Park and Preserve (GLBA) to document and understand changes to the landscapes of both parks as a result of changing climate. The use of repeat photography to document temporal change is not new. What is unique here is the systematic approach being used to obtain photographic documentation of landscape change for every fiord in KEFJ and GLBA. Through analysis and interpretation of these photographs, both quantitative and qualitative information is extracted to document the landscape evolution and glacier dynamics of both parks.

Initially, the emphasis of this study was on documenting the post-Little Ice Age (LIA) behavior of glaciers in both parks. However, the focus has expanded to a much broader documentation of landscape evolution and glacier change in response to post-LIA climate change. Repeat photography is being used to assess changes in sedimentation, sediment distribution, vegetation type and distribution, vegetative succession, wetland location and extent, hydrology, shoreline characteristics, and glacier extent, thickness, and terminus position. Glacier retreat, resulting in the exposure of new land surfaces, is the process that governs all of the other parameters being monitored.

A survey of recent Alaska glacier behavior *(Molnia 2006)*, confirmed that more than 99% of all of the valley glaciers in Alaska are currently retreating. Therefore, it is not surprising that all of the landscapes being observed in KEFJ are characterized by long-term glacier retreat. In GLBA the picture is more complicated. There, although all East Arm glaciers have experienced nearly continuous retreat, several West Arm glaciers have undergone significant periods of advance during parts of the twentieth and early twenty-first centuries. However, all these glaciers have experienced significant, post-LIA ice loss.

In all cases, the driver for landscape and glacier change appears to be an Alaska-wide increase in air temperature, which may also be accompanied by an increase in precipitation. Groisman and Easterling *(1994)* reported that between 1968 and

National Park Service and Dallas Museum of Natural History photograph

1990 precipitation increased an average of 30% over the region west of 141° W. longitude (i.e., all of Alaska except southeastern Alaska). Since 1949, Alaska weather station temperature data are characterized by a significant increase in mean annual air temperature. A compilation of mean annual and seasonal air temperatures for Alaska's 20 first-order observing stations, prepared by the University of Alaska Geophysical Institute's Alaska Climate Research Center, confirms the average temperature change over the last five decades was an increase of ~3.6°F (~2.0°C) *(Alaska Climate Research Center 2005)*. Interestingly, more than 75% of this warming occurred prior to 1977. Most of the warming occurred in winter and spring, with a smaller change in summer. Prior to 1949, air temperature data were far less abundant and less reliable. Stations with longer-term records do not indicate the significant warming trends seen post-1949.

During the LIA (13th to 19th centuries), glacier ice covered most of KEFJ and GLBA. As recently as the mid-eighteenth century, fiords of both parks were filled by massive glaciers that in some instances, extended beyond today's southern park boundaries. In KEFJ, glacier retreat began during the second half of the nineteenth century, while in GLBA retreat began much earlier, perhaps ~1750 AD. For example, McCarty Glacier in KEFJ has retreated ~15 mi (25 km) from its LIA maximum position, while Northwestern Glacier has retreated ~9 mi (15 km). In GLBA, Muir Glacier has retreated more than ~68 mi (110 km), with ~25 mi (40 km) of retreat occurring after 1900.

Methods

The key to successful repeat photography is finding high quality historical photographs that become the baseline for comparison with modern images. For GLBA, more than 1,400 late nineteenth century and early twentieth century, ground- and sea surface-based photographs have been found. More than half of these depict glacier termini and related features. About 300 are from the nineteenth century, with the earliest predating 1885. Sources include the National Archives, the Alaska State Library, the National Snow and Ice Data Center (NSIDC), the GLBA archive, travel narratives, scientific publications, internet sites, antique dealers, and the U.S. Geological Survey Photographic Library located in Denver, Colorado. More than 800 of these photographs have been acquired by the lead author and compiled into a digital database. Analog photographs (paper prints) are scanned and converted to digital images.

Nearly all of the historical photographs lack important elements of metadata, most significantly location, camera specifics, lens information, and film and exposure data. In most cases, only the name of the photographer and the date of acquisition are known. No photographs have latitude and longitude of the collection site. For GLBA, historical photographs used were made by H.F. Reid (1890-1892), Frank LaRoche (~1890), the International Boundary Commission (~1895-1915), G.K. Gilbert (1899), C.W. Wright (1906 and 1931), J.B. Mertie (1916), A.H. Brooks (1924), W.O. Field (beginning in 1926), and Juneau-based commercial photographers Winter and Pond (~1895-1920), among others. Few of these photographs have been published.

During the summers of 2003-2005, ~125 GLBA locations depicted in historical photographs were revisited. Prior to field work, locations were determined by comparing historical photographs with topographic maps and aerial photographs. However, actual locations for most sites were only found through a trial and error field process in which features on the historical photograph were matched by comparing the spatial relationships between mountain peaks and foreground features. This revealed that a surprisingly large number of historical photographs were made from the decks of boats. Several were made from the surface of no longer existing glaciers. At approximately 25% of the land-based locations, cairns were found and reoccupied.

At each site, we recorded a standard set of data and information, including date and time of visit, latitude, longitude, and eleva-

Visualizing Climate Change – Using Repeat Photography to Document the Impacts of Changing Climate on Glaciers and Landscapes

Location of paired images photographed in Kenai Fjords National Park.

❷ Figure 2. A pair of northeast-looking photographs taken from about 5 mi (8 km) north of the mouth of McCarty Fjord, KEFJ. The photographic pair documents significant changes that have occurred during the 95 years between July 30, 1909 (Figure 2A) and August 11, 2004 (Figure 2B). Figure 2A shows the east side of the retreating tidewater terminus of McCarty Glacier. The gravel bar located in the upper center of the photograph is the same one shown on the Grant and Higgins sketch map in Figure 1. Figure 2B shows the terminus of McCarty Glacier has retreated out of the field of view. A small part of the glacier, located more than 10 mi (~16 km) up McCarty Fjord is visible above the left of center.

❸ Figure 3. A pair of west-looking photographs taken from the same shoreline location of Pedersen Glacier, Aialik Bay, KEFJ. Figure 3A, an early twentieth century postcard shows the terminus of Pedersen Glacier, fronted by an iceberg filled lagoon. Figure 3B, a 2005 photograph, documents the retreat of the glacier and the formation of a vegetated, outwash plain-wetland complex in the area exposed as the glacier retreated. The glacier has retreated about 1.1 mi (1.75 km).

❹ Figure 4. A pair of north-looking photographs taken from the same location on the backbeach south of Bear Glacier, KEFJ. Figure 4A shows the eastern terminus of Bear Glacier, fronted by a small outwash plain and a small lagoon in July 1909. In Figure 4B, the only part of Bear Glacier visible in August 2005 is a tributary descending from the mountains. Bear Glacier has thinned by more than 660 ft (200 m), and the eastern terminus has retreated more than ~ 2 mi (3 km). The lagoon has been filled with sediment and the outwash plain to the north is covered by grasses, wildflowers, shrubs, and trees.

❺ Figure 5. A pair of northwest-looking photographs, both taken from the same offshore location in Harris Bay showing the changes that have occurred to Northwestern Glacier, KEFJ. Figure 5A shows the retreating terminus of Northwestern Glacier, in July 1909, extending to within ~1,500 ft (450 m) of its late-LIA maximum position. Figure 5B, taken in August 2004, shows that Northwestern Glacier has retreated out of the field of view. Ice-free Harris Bay and Northwestern Lagoon make up the foreground of the image.

Figure 2a: USGS Photographic Library photograph by U.S. Grant

Figure 2b: USGS photograph by Bruce F. Molnia

Figure 3b: USGS photograph by Bruce F. Molnia

Figure 4a: USGS Photographic Library photograph by U.S. Grant

Figure 4b: USGS photograph by Bruce F. Molnia

Figure 5a: USGS Photographic Library photograph by U.S. Grant

Figure 5b: USGS photograph by Bruce F. Molnia

tion of the site, and bearing to the center of each photographic target. Details were determined with GPS receiver and compass. At each location a suite of digital images and/or color film photographs were made of the same geographic features displayed in the field of view of the historical photograph, often using lenses of different focal lengths. Where possible, larger fields of view were imaged so resulting images could be cropped to match the historic image. Many historical photographs were made with rotating lens, panoramic, or mapping cameras, typically with fields of view that exceed those of most modern normal or wide-angle lenses. Consequently, for some locations, overlapping, sequential photographs were obtained that could be digitally stitched together.

In Glacier Bay's upper East Arm, where glacier retreat has been continuous for more than two centuries, several locations from which the lead author photographed McBride, Riggs, and Muir Glaciers between 1976 and 1980 were revisited. Nearly all of these locations were under glacier ice prior to the 1970s. Hence, these photographs are the 'historical' photographs in this area.

For KEFJ, very few pre-1950 photographs exist. Less than 50, early twentieth century, ground and sea surface-based photographs have been located that show identifiable landscape features. Almost all depict glacier termini and related features. Except for a few postcards, all date from 1909 and were made by U.S. Grant and D.F. Higgins, university professors who worked as contract geologists for the USGS. Their photographs were found at the USGS Photographic Library. Several dozen were published with sketch maps that identified photograph sites and glacier termini *(Grant and Higgins 1911, 1913)*.

During the summers of 2004-2006, ~40 KEFJ locations were identified and revisited, using the same methodologies as in GLBA. Grant and Higgins' text and sketch maps were useful in narrowing down about 25% of the locations. At many KEFJ sites, twentieth century glacier retreat exceeded ~9-12 mi (15-20 km). Consequently, many glaciers in the 1909 photographs were no longer visible from the original photo locations. No cairns were found at any location.

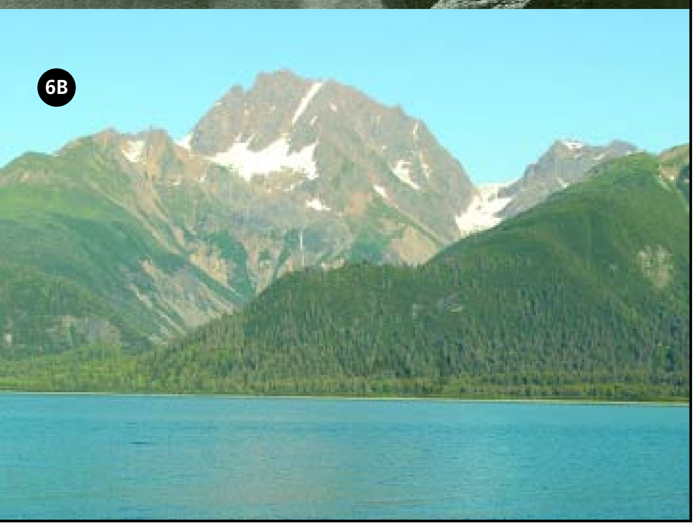
Following field work in both parks, new images and photographs were compared and contrasted with corresponding historical photographs to determine types and amounts of change, and to understand rates, timing, and mechanics of landscape evolution. Particular emphasis was placed on documenting the response of glaciers to changing climate and environment. In addition to the extracted information, the resulting photographic pairs provide striking visual documentation of the dynamic landscape evolution occurring in both parks.

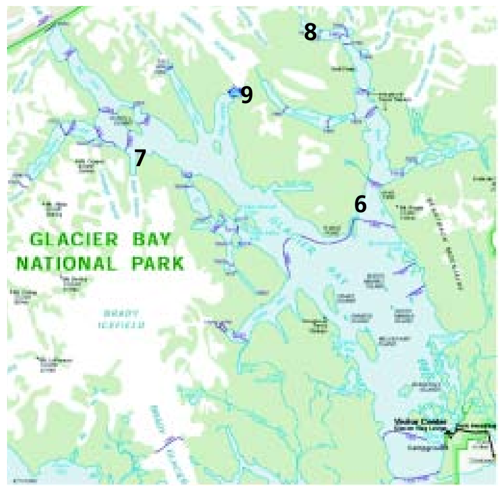
Results

Repeat photography provides significant insights into the post-LIA evolution of the landscapes of KEFJ and GLBA. For KEFJ, photographic evidence documents more than 80% of the post-LIA period. Information derived from the before and after pairs has been useful in documenting:

1) rapid influx of vegetation and the transformation from glacier till and bare bedrock to forest;
2) the post-1909 magnitude of retreat and thinning of Bear Glacier *(Figure 4);*
3) a similar thinning and retreat of Holgate Glacier and its former tributary, informally named Little Holgate Glacier;
4) the substantial retreat of Pedersen Glacier and the subsequent development of an extensive wetland *(Figure 3);*
5) the relatively small amount of change at Aialik Glacier;
6) the substantial post-1909 retreat of Northwestern Glacier resulting in the opening of Harris Bay and Northwestern Lagoon *(Figure 5);*
7) a similar substantial post-1909 retreat of McCarty Glacier resulting in the opening of McCarty Fiord *(Figures 1 and 2);* and
8) the transition from tidewater termini to land-based, stagnant or retreating, glacier termini at several locations including Yalik and Petrof Glaciers.

Visualizing Climate Change – Using Repeat Photography to Document the Impacts of Changing Climate on Glaciers and Landscapes





Location of paired images photographed in Glacier Bay National Park.

Figure 6. A pair of east-looking photographs, both taken from the same shoreline location on the west side of Muir Inlet, opposite Muir Point in GLBA. Figure 6A, taken in the late1890s, shows the terminus of Muir Glacier extending almost to the photo point and the absence of any identifiable vegetation. The August 2005 photograph (Figure 6B) documents the disappearance of Muir Glacier from the field of view. During the period between photographs, Muir Glacier has retreated ~15 mi (~25 km). Note the extensive vegetation.

Figure 7. A pair of south-looking photographs, both taken from the same hillside location near the mouth of Reid Inlet on the west side of the West Arm of Glacier Bay. Figure 7A shows the calving terminus of Reid Glacier extending almost to the mouth of Reid Inlet and the absence of any identifiable vegetation in June 1899. Figure 7B documents the retreat of Reid Glacier, almost out of the field of view, in September 2003. During the period between photographs, Reid Glacier retreated ~1.2 mi (~2 km). The spit of land that projects into Reid Inlet is part of an early twentieth century recessional moraine.

Figure 8. A pair of north-looking photographs, both taken from the same location in upper Muir Inlet showing changes that have occurred to the terminus of Muir Glacier, GLBA. Figure 8A shows the tidewater calving terminus of Muir Glacier extending across the entire field of view in July 1978. The height of the terminus above the fiord is ~165 ft (~50 m). Figure 8B, taken in September 2003, shows that the terminus of Muir Glacier has retreated from tidewater and is now terrestrial. Ice-cored recessional moraine and sediment deposits sit between the shoreline and the glacier terminus.

Figure 9. A pair of northwest-looking photographs, both taken from the same location, several hundred meters up a steep alluvial fan located in a side valley on the east side of Queen Inlet, showing the changes that have occurred to Carroll Glacier and upper Queen Inlet. Figure 9A, taken in August 1906, shows the calving terminus of Carroll Glacier sitting at the head of Queen Inlet. Small shrubs in the foreground are the only vegetation that is visible. Figure 9B, taken 98 years later on June 21, 2004, shows that the terminus of Carroll Glacier has changed to a stagnant, debris-covered glacier that has significantly thinned and retreated. The head of Queen Inlet has been filled by sediment. An examination of early twentieth century nautical charts suggests that the sediment fill exceeds ~400 ft (125 m). Note the trees on the hillside and the vegetation that is developing on the sediment fill.

Figure 6a: Glacier Bay National Park archive
Figure 6b: USGS photograph by Bruce F. Molnia
Figure 7a: USGS Photographic Library photograph by G.K. Gilbert
Figure 7b: USGS photograph by Bruce F. Molnia
Figure 8a: USGS photograph by Bruce F. Molnia
Figure 8b: USGS photograph by Bruce F. Molnia
Figure 9a: USGS Photo Library photograph by C.W. Wright
Figure 9b: USGS photograph by Bruce F. Molnia

For GLBA, photographic evidence documents approximately half of the 250 years of the post-LIA period. Information derived from the before and after pairs has been useful in documenting:

1) the rapid influx of vegetation and the transformation from glacier till and bare bedrock to forest;
2) the post-late-1880s timing and magnitude of glacier retreat in East Arm, a trend continuing to the present *(Figure 6);*
3) a similar continuous retreat of the glaciers in the Geikie and Hugh Miller Inlet areas of West Arm;
4) early-twentieth century retreat and subsequent variability of Reid and Lamplugh Glaciers *(Figure 7);*
5) early-twentieth century advances of Johns Hopkins and Grand Pacific Glaciers, followed by the continued advance of Johns Hopkins Glacier and the retreat and thinning of Grand Pacific Glacier;
6) decadal-scale fluctuations of smaller glaciers, such as hanging glaciers in Johns Hopkins Inlet, including Hoonah and Toyatte Glaciers;
7) transitions from tidewater termini to land-based, stagnant or retreating, debris-covered, glacier termini in a number of locations including Muir, Carroll, and Rendu Glaciers *(Figure 8);*
8) the filling of upper Queen Inlet with more than 400 ft (~125 m) of sediment *(Figure 9);*
9) the rapid erosion of fiord-wall moraine following ice retreat; and
10) the development of outwash and talus features at many locations.

Our goal has been to locate and acquire historical photographs that document this dynamic landscape evolution, to interpret these historical photographs to quantify and visualize the appearance of the landscape at the time they were made, to revisit locations from which historical photographs were made and duplicate the photographs, and to document changes at each location and provide written and visual products that depict the mechanics and magnitude of the changes that occurred during the intervening period of time. We believe that the images presented here document our success.

To download before and after photograph pairs:
http://nsidc.org/data/glacier_photo/special_collection.html

To view animated pairs that simulate time-lapse photography of landscape change:
http://www2.nature.nps.gov/geology/GLBA/glaciers.htm and http://www.oceanalaska.org/research/rptglacier.htm

REFERENCES

Alaska Climate Research Center. 2005.
Temperature change in Alaska, 1949-2004.
http://climate.gi.alaska.edu/ClimTrends/Change/4903Change.html.

Grant, U.S., and Higgins, D.F. 1911.
Glaciers of Prince William Sound and the southern shore of the Kenai Peninsula, Alaska.
Bulletin of the American Geographical Society vol. XLIII. Pages 401-417.

Grant, U.S., and Higgins, D.F. 1913.
Coastal Glaciers of Prince William Sound and the Kenai Peninsula, Alaska.
U.S. Geographical Society Bulletin 526.

Groisman, P.Y., and Easterling, D.A. 1994.
Variability and trends of precipitation and snowfall over the United States and Canada.
Journal of Climate 7:184-205.

Molnia, B.F. 2006.
Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate.
Global and Planetary Change: doi:10/1016/j.gloplacha.2006.07.011.