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Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate

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Abstract

Alaska's climate is changing and one of the most significant indications of this change has been the late 19th to early 21st century behavior of Alaskan glaciers. Weather station temperature data document that air temperatures throughout Alaska have been increasing for many decades. Since the mid-20th century, the average change is an increase of ~ 2.0 °C. In order to determine the magnitude and pattern of response of glaciers to this regional climate change, a comprehensive analysis was made of the recent behavior of hundreds of glaciers located in the eleven Alaskan mountain ranges and three island areas that currently support glaciers. Data analyzed included maps, historical observations, thousands of ground-and-aerial photographs and satellite images, and vegetation proxy data. Results were synthesized to determine changes in length and area of individual glaciers. Alaskan ground photography dates from 1883, aerial photography dates from 1926, and satellite photography and imagery dates from the early 1960s. Unfortunately, very few Alaskan glaciers have any mass balance observations.

In most areas analyzed, every glacier that descends below an elevation of ~ 1500 m is currently thinning and/or retreating. Many glaciers have an uninterrupted history of continuous post-Little-Ice-Age retreat that spans more than 250 years. Others are characterized by multiple late 19th to early 21st century fluctuations. Today, retreating and/or thinning glaciers represent more than 98% of the glaciers examined. However, in the Coast Mountains, St. Elias Mountains, Chugach Mountains, and the Aleutian Range more than a dozen glaciers are currently advancing and thickening. Many currently advancing glaciers are or were formerly tidewater glaciers. Some of these glaciers have been expanding for more than two centuries. This presentation documents the post-Little-Ice-Age behavior and variability of the response of many Alaskan glaciers to changing regional climate.
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1. Introduction

1.1. Alaskan glaciers

Glaciers cover about 75,000 km^2 of Alaska (Fig. 1). Recent estimates range from 73,800 km^2 (Post and Mayo, 1971) to 74,700 km^2 (Post and Meier, 1980), to 75,110 km^2 (Molnia, 1982). This represents about 5% of Alaska's land area and includes glaciers on 11 mountain ranges (Coast Mountains, Saint Elias Mountains, Chugach Mountains, Kenai Mountains, Aleutian Range, Wrangell Mountains, Talkeetna Mountains, Alaska Range, Ahklun and Wood River Mountains, Kigluaik Mountains, and Brooks Range), one large island (Kodiak Island), one island archipelago (Alexander Archipelago), and one island chain (Aleutian Islands). Glaciers in Alaska extend from as far southeast

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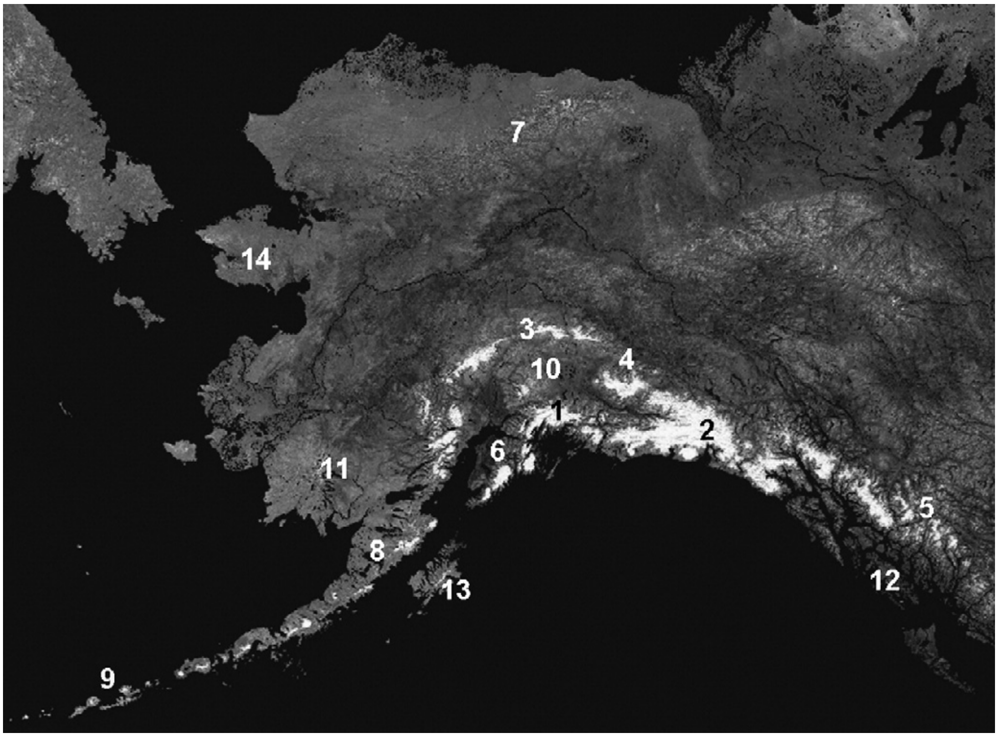


Fig. 1. AVHRR image map showing the location of the 14 glacierized areas of Alaska. Current glacier cover for each region, based on data presented in Molnia (in press), is: 1) Chugach Mountains — ~ 21,320 km^2; 2) Saint Elias Mountains — ~ 14,300 km^2; 3) Alaska Range — ~ 14,000 km^2; 4) Wrangell Mountains — ~ 5300 km^2; 5) Coast Mountains — ~ 7280 km^2; 6) Kenai Mountains — ~ 4810 km^2; 7) Brooks Range — <1000 km^2; 8) Aleutian Range — ~ 2000 km^2; 9) Aleutian Islands — ~ 2000 km^2; 10) Talkeetna Mountains — ~ 1000 km^2; 11) Ahklun–Wood River Mountains — ~ 60 km^2; 12) Alexander Archipelago — <100 km^2; 13) Kodiak Island — <50 km^2; and 14) Kigluaik Mountains — <1 km^2. AVHRR base figure by Michael Fleming is modified from Molnia, 2000.

as N55°19′ and W130°05′, about 100 km east of Ketchikan; to as far southwest as Kiska Island at N52°05′ and E177°35′ in the Aleutian Islands; to as far north as N69°20′ and W143°45′ in the Brooks Range. The number of glaciers is unknown, having never been systematically counted, but probably exceeds 100,000. Most are small, upland cirque glaciers. Approximately 2000 are valley glaciers. Of these valley glaciers, ~ 60 (<0.1% by number) are tidewater glaciers (Viens, 1995). Hence, by number, >99.9% of Alaska's glaciers are land-based or terrestrial. By area, tidewater glaciers occupy ~ 27,000 km^2, or ~ 1/3 of the glacier-covered area of Alaska.

Alaskan glaciers range in elevation from above 6000 m to below sea level. Most are unnamed. Fewer than 700 glaciers have been officially named by the U.S. Board on Geographic Names. Nearly all of these named glaciers and about 1000 additional unnamed glaciers descend below an elevation of ~ 1500 m.

During the Little Ice Age (LIA), the total glacier-covered area and the number of mountain ranges and islands with glacier cover were significantly larger than present (Molnia, in press). Since then, as has been the case in all of Earth's temperate glacier-covered areas, there has been a significant decrease in glacier length, area, and thickness. However, the timing, magnitude, and complexity of this "post-LIA" glacier change in each of Alaska's 14 glacier-bearing areas have been different. To understand these complexities, a detailed assessment of each of Alaska's glacier-bearing regions was prepared as part of the USGS' comprehensive *Satellite Image Atlas of the Glaciers of the World* series (Molnia, in press). Key findings from this *Atlas* assessment are synthesized and succinctly presented here specifically to define the late 19th to early 21st century behavior of Alaskan glaciers in response to a documented changing regional climate which is characterized by temperature increases at all monitoring stations throughout Alaska. As the details presented here show, although there is a significant thinning of lower-elevation glaciers and retreat of glacier termini, the current behavior of Alaska's glaciers varies significantly from area to area, varies significantly with elevation, and is extremely dynamic.

Although not the focus of this presentation, the many studies summarized by Molnia (in press), clearly show that Alaskan glacier behavior was also exceptionally dynamic during the LIA and the time period between the LIA and the late 19th century.

Today, not all Alaskan glaciers are retreating. Many glaciers at higher elevations are thickening or show no change. Several volcanoes, including Redoubt Volcano and Mt Katmai, had 20th century eruptions that melted summit glaciers. Since then, new glaciers have formed in their craters. At elevations below ~ 1500 m, more than a dozen large, non-surging glaciers, including Hubbard, Harvard, and Meares Glaciers (all currently tidewater glaciers), Lituya and North Crillon Glaciers (formerly tidewater glaciers), and South Crillon Glacier (a lake terminating glacier) are currently thickening and/or advancing. Others, such as Taku Glacier (formerly a tidewater glacier) and Johns Hopkins Glacier (a tidewater glacier) are fluctuating around their recent maximum advance margins.

During the post-LIA period, many Alaskan glaciers demonstrated behaviors that were not related to climate drivers. Some retreated because of tidewater glacier dynamics, while others advanced because of surge dynamics. Both of these behaviors are addressed below.

1.2. Alaskan climate — the last millennium

The term "Medieval Warm," is used to characterize 9th to mid-15th century temperatures that were warmer than those of the subsequent Little Ice Age (Bradley and Jones, 1993; Crowley and Lowery, 2000). According to Mann et al. (1999), Northern Hemisphere mean temperatures during the 11th to 14th centuries were about 0.2 °C higher than those during the 15th to 19th centuries, but lower than mid-20th century temperatures. The Arctic Climate Impact Assessment (ACIA, 2004) characterizes temperature trends during the last millennium as a modest and irregular cooling from 1000 A.D. to around 1850 A.D. to 1900 A.D., followed by an abrupt 20th-century warming.

According to Bradley (1990), the period from 1550 A.D. to 1900 A.D. may have been the coldest period in the entire Holocene. During this period, there is widespread evidence of glaciers reaching their maximum post-Pleistocene positions. Similarly, the lowest $\delta^{18}O$ values and melt percentages for at least 1000 years are recorded in ice cores for this interval (ACIA, 2004). During the LIA, existing glaciers advanced on all continents and in each of the 14 Alaska regions.

For Alaska, Calkin et al. (2001) report that widespread glacier advances were initiated at ~ 700 yr B.P. and continued through the 19th century. Specific examples are studies by Wiles et al. (1999) and Barclay et al. (1999), who performed dendrochronological investigations at a number of Kenai Mountain tidewater and former tidewater glacier sites. Their work involved both living trees, some more than 680-year-old, and a 1119-year tree-ring-width chronology derived from more than a 100 logs, recovered from glaciers in the western Prince William Sound area. Each of these logs had been sheared or uprooted by a past glacial advance. Their work showed that glacier fluctuations during the LIA were strongly synchronous on decadal time scales at many glaciers. Studies at eight locations indicated that advances occurred during the late 12th through 13 centuries and from the middle-17th to early 18th centuries. Nine glaciers showed evidence of a late 19th century advance. Glaciers studied include Tebenkof, Cotterell, Taylor, Wolverine, Langdon, Kings, Nellie Juan, Ultramarine, Princeton, Excelsior, and Ellsworth Glaciers in Prince William Sound and Billings Glacier in the southern Chugach Mountains. This pattern of LIA glacier advances in mountain ranges along the margin of the Gulf of Alaska is similar on decadal time scales to that of the well-dated glacier fluctuations throughout the rest of Alaska.

Alaskan glaciers exhibited dynamic behavior even prior to the LIA. A study of 17 coastal and near-coastal Alaskan and British Columbian glaciers (Reyes et al., 2006) documents a widespread glacier advance during the first millennium A.D. Glaciers at several sites began advancing about 200 A.D.–300 A.D., based on radiocarbon-dated overridden forests. They report that the advance was centered on 400 A.D.–700 A.D., when glaciers along a 2000 km transect of the Pacific North American cordillera overrode forests, impounded lakes, and deposited moraines.

1.3. Recent temperature trends

A compilation of mean annual and seasonal air temperatures for Alaska's 19 first-order observing stations with records spanning more than a half century (Anchorage, Annette, Barrow, Bethel, Bettles, Big Delta, Cold Bay, Fairbanks, Gulkana, Homer, Juneau, King Salmon, Kodiak, Kotzebue, McGrath, Nome, St. Paul, Talkeetna, Yakutat) was prepared by the University of Alaska Geophysical Institute's Alaska Climate Research Center (Alaska Climate Research Center, 2005). It confirms that during the period from 1949–2004 (Fig. 2), the average temperature change was an increase of ~ 1.9 °C. Interestingly, more than 75% of this warming occurred prior to 1977. On a seasonal basis, most of the warming

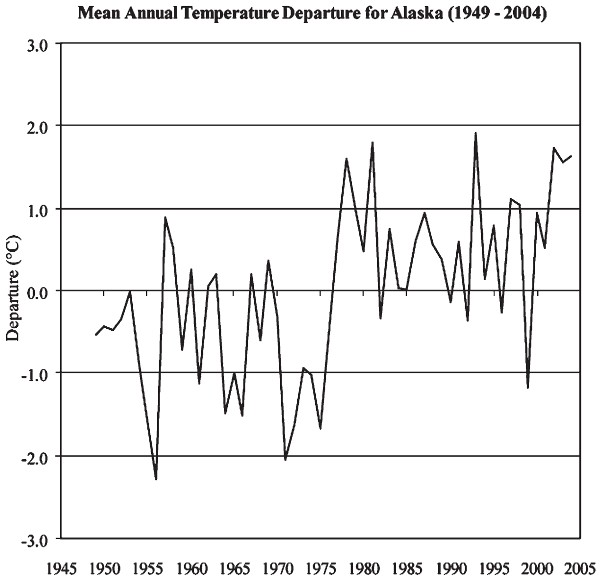


Fig. 2. Chart showing the aggregate mean annual temperature departure for Alaska for the period from 1949 to 2004). Figure is derived from data provided by Martha Shulski, Alaska Climate Research Center, Geophysical Institute, University of Alaska Fairbanks.

has occurred in winter and spring, with a smaller change in summer, and an even smaller change in autumn. Prior to 1949, air temperature data were far less abundant and far less reliable. The post-1949 trend is non-linear and is characterized by large annual variability. The 5-year moving average demonstrates cyclical behavior, with the period from 1949 to 1975 substantially colder than the period from 1977 to 2004. During the 1977 to 2004 period, very little additional warming occurred, with the exception of Barrow, the northernmost of the first order stations. In 1976, a stepwise shift appears in the temperature data, which corresponds to a phase shift of the Pacific Decadal Oscillation, characterized by increased southerly flow and warm air advection into Alaska during the winter, resulting in positive temperature anomalies (Alaska Climate Research Center, 2005).

For the 55-year period from 1949 to 2004, mean spring temperatures increased an average of ~ 2.2 °C; mean summer temperatures increased an average of ~ 1.3 °C; mean autumn temperatures increased an average of ~ 0.5 °C; and mean winter temperatures increased an average of ~ 3.5 °C. Talkeetna, the weather station closest to the Talkeetna Mountains, a mountain range where every glacier is thinning and retreating, reported a ~ 3.0 °C mean annual temperature increase, the highest of any of the 19 locations. It also reported the maximum mean annual winter temperature increase, ~ 5.1 °C. Every station reported increases in mean annual winter, spring, and summer temperatures. All except Fairbanks, which experienced no change, also reported increased mean autumn temperatures.

For the period 1977–2004, the average temperature change was an increase of ~ 0.2 °C. Mean spring temperatures increased an average of ~ 0.2 °C; mean summer temperatures increased an average of ~ 0.55 °C; mean autumn temperatures increased an average of ~ 0.4 °C; and mean winter temperatures increased an average of ~ 0.4 °C. Eight stations (Anchorage, Cold Bay, Fairbanks, Gulkana, Kodiak, Nome, St. Paul, and Yakutat) reported decreases in mean annual temperature. Talkeetna reported a ~ 1.8 °C mean annual temperature increase, the highest of any of the 19 locations. It also reported the maximum mean annual winter temperature increase, ~ 2.9 °C. Mean annual summer temperatures increased at 15 of the 19 stations (Alaska Climate Research Center, 2005).

All of Alaska's first-order observing stations are at elevations below 400 m, with 14 of the 19 located less than 40 m above sea level. Although there is unequivocal evidence of warming temperatures at lower elevations throughout Alaska, little data have been collected in direct proximity to glaciers or at higher elevations. Only two glacier-proximal meteorology stations have published records that span a quarter century or more. These stations are located at "Benchmark Glacier" sites (Fountain et al., 1997). Their climate, glacier geometry, glacier mass balance, glacier motion, and stream runoff are being monitored. Meteorological data collection began in 1968 (USGS, 2004). The Alaska stations are located at Gulkana and Wolverine Glaciers, at elevations of 1480 m and 990 m respectively. At these stations, no clear long-term temperature trend is apparent. For Gulkana Glacier, the average mean annual temperature since 1968 has been −4.1 °C. For 3 of the last 5 years of record (1999–2003), the mean annual temperature has been colder than the 30+ year average. Similarly, for 3 of the first 5 years (1968–1972), the mean annual temperature (sensor corrected data) was also colder. For Wolverine Glacier, the average mean annual temperature since 1968 has been −1.3 °C. For 3 of the last 5 years of record (1998–2002), the mean annual temperature has also been colder than the 30+ year average. Similarly, for 3 of the first 5 years (1968–1972), the mean annual temperature (sensor corrected data) was also colder. Clearly, more glacier-proximal stations and data are needed to better understand the relationship of temperature and precipitation change and the observed behavior of Alaska's glaciers.

With respect to precipitation, Alaska has also grown substantially wetter during the 20th century. The sparse historical record since 1900 shows mixed precipitation trends, with increases of up to 30% in the south, southeast and interior, and smaller decreases in the northwest and over the Bering Sea. Between 1968 and 1990, precipitation has increased by an average of 30% for Alaska west of 141° W. longitude, all of Alaska except the southeastern panhandle (Grossman and Easterling, 1994). The growing season has lengthened by more than 14 days since the 1950s (Parson et al., 2000).

1.4. Tidewater glaciers

Tidewater glaciers occur in the Coast Mountains, Saint Elias Mountains, Chugach Mountains, and Kenai Mountains. What is unique about tidewater glaciers is that they originate in upland accumulation areas, traverse terrestrial areas of varying lengths as they descend towards sea level, and then extend into the marine environment where their beds extend below sea level. Not only are their termini subject to calving, but their entire lengths are subject to the same climatic conditions that affect all of their neighboring terrestrial glaciers. Hence, a tidewater glacier is a terrestrial glacier that has expanded beyond the limit of its terrestrial environment.

All current tidewater glaciers extend into or occur at the heads of fiords that are the product of Pleistocene and older erosion (Molnia and Carlson, 1975; Carlson et al., 1982). From an examination of Alaskan topographic maps and aerial photography, Viens (1995) determined that during the last quarter of the 20th century, there were 51 active tidewater glaciers and 9 former tidewater glaciers. All were located between McCarty Fiord (McCarty Glacier) of the Kenai Mountains, to the west, and LeConte Bay (LeConte Glacier) of the Coast Mountains to the east. Some of these glaciers, like the catastrophically retreating Columbia Glacier, produce vast quantities of icebergs. Some, like Muir Glacier, have retreated onto land and no longer make contact with the sea. These 60 tidewater glaciers have an area of ~ 26,834 km^2, ~ 1/3 of the glacier-covered area of Alaska. By number, they represent significantly less than 0.1% of Alaska's glaciers.

The term *tidewater glacier* was introduced by Russell (1897) and defined as *glaciers which enter the ocean and calve off to form bergs*. A similar definition, *A glacier that terminates in the sea, where it usually ends in an ice cliff from which icebergs are discharged*, is presented in the *Glossary of Geology* (Bates and Jackson, 1987, pg. 687).

Tidewater glaciers are part of the glacial-marine environment (Molnia, 1981), and usually are very dynamic. Tidewater glaciers exhibit three types of terminus behavior: advance, retreat, and stability. Except when surging, those that are advancing move forward at maximum rates of several tens of meters per year. With those that are retreating, retreat rates are typically higher by an order of magnitude or more. Generally, the advance and retreat cycle of each tidewater glacier is asynchronous, unique to the individual glacier. For example, Harvard, Yale, and Meares Glaciers are three adjacent, south-flowing tidewater glaciers in western Prince William Sound. Harvard is located to the west, Meares to the east, while Yale is in the middle. Since the early 20th century, Harvard Glacier has advanced nearly 2 km, Yale has retreated more than 6 km, and Meares has advanced ~ 1 km. The type of terminus behavior displayed is usually a function of the calving rate. However, parts of Yale Glacier's terminus that have retreated from its fiord to the terrestrial environment continue to retreat, although at a lower rate. Calving is defined as *The breaking away of a mass or block of ice from a glacier...* (Bates and Jackson, 1987, pg. 96). In tidewater glaciers, the rate of calving, much more so than climate controls the glacier's terminus behavior and length. Calving glaciers lose most of their mass by calving, rather than by surface melting.

An explanation for the observed dynamics of tidewater calving glaciers was presented by Post (1975), who suggested that the terminus of a tidewater glacier needed to be in shallow water to minimize its rate of calving and that the rate of calving increases in an exponential fashion with an increase in terminus water depth. He suggested that a stable tidewater glacier had its base grounded on the floor of a fiord with its terminus in relatively shallow water on a terminal moraine that the glacier had built. In front of the moraine, the water depth could be hundreds of meters. If the glacier terminus was advancing, it did so by pushing the moraine down-fiord. This involved erosion of the ice contact or up-fiord side of the moraine and deposition on the down-fiord side of the moraine. If the glacier lost contact with its moraine and retreated into deep water, its rate of calving would substantially increase. Some tidewater glaciers, such as Tyndall Glacier in Icy Bay of the St. Elias Mountains, have retreated to the head of their fiords where they make minimal contact with tidewater and have been stable for decades.

For example, Field (1975b) reported that the advancing Harvard Glacier was advancing at about 22 m/yr, while Molnia and Post (1995) reported that between 1967 and 1993, Bering Glacier had retreated as much as 10.7 km (an average of ~ 450 m/yr, with a maximum retreat of 2.6 km between 1977 and 1978. Even though some tidewater glaciers may have accumulation area ratios (AARs) of greater than 0.93, due to calving they still are retreating. Hence, while the advance of a tidewater glacier is climate dependant and is a function of a positive balance, the amount of retreat of a tidewater

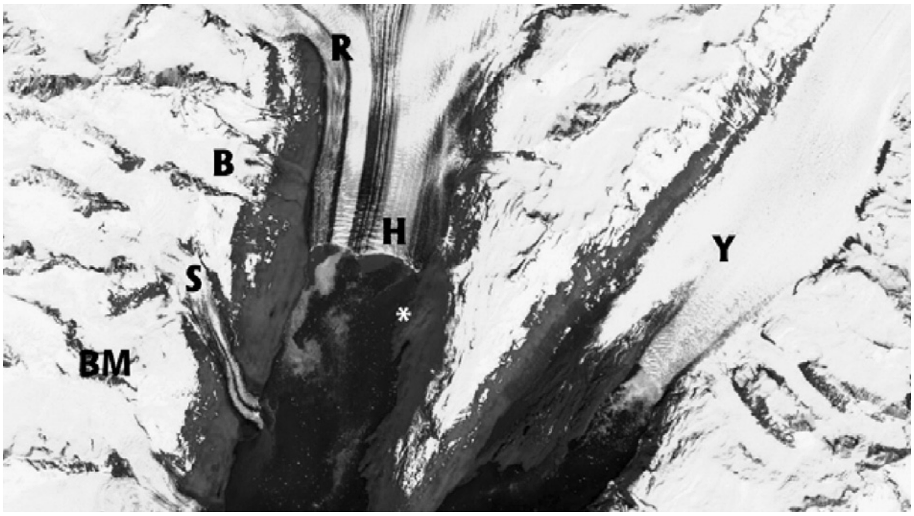


Fig. 3. A 10 km by 15 km portion of a June 24, 2000 ASTER Level 1B panchromatic mosaic (scenes AST_L1B_003_06242000213409_04272003194754 and AST_L1B_003_06242000213418_04272003194744) showing the head of College Fiord in Western Prince William Sound. Glaciers present include Yale (Y), Harvard (H), Radcliffe (R), Baltimore (B), Smith (S), and Bryn Mawr (BM). Of the annotated glaciers, Harvard and its tributary Radcliffe are advancing, while Baltimore, Smith, Yale, and Bryn Mawr Glaciers are retreating. The white star (*) marks the location from which the photographs in Fig. 4 were made.

glacier before stability is reached may be climate independent. Details about the behavior of a number of individual tidewater glaciers will be described in the geographic region sections which follow.

1.5. Surging glaciers

Most glaciers have nearly constant average annual flow rates. Some exhibit substantial variations with major flow irregularities. In the first case, any variations that occur, are generally predictable on a seasonal basis, with longer period changes occurring as the glacier responds to changes in mass balance. In the latter situation, some glaciers have dramatic annual velocity changes, often characterized by brief periods with velocity increases of 10 to 1000 times. These glaciers are said to "surge." Surges involve large amounts of ice displacement and often are characterized by rapid advances of the glacier terminus. The first observed surge widely reported by the media was the 1937 surge of Black Rapids Glacier in the eastern Alaska Range, where the terminus advanced more than 5 km in less than a year (Time Magazine, 1937). The terms "galloping glacier" and "runaway glacier" were widely used to report this occurrence.

Post (1969) offers the following definition for a surging glacier; *one which periodically (15–100+ years) discharges an ice reservoir by means of a sudden, brief, large-scale ice displacement, which moves 10 to 100 or more times faster than the glacier's normal flow rate between surges*. Post continues, *Glacier surges are not unique events which might result from exceptional conditions such as earthquakes, avalanches, or local increases in snow accumulation. These movements apparently are due to some remarkable instability which occurs at periodic intervals in certain glaciers*. The comment about earthquakes and avalanches is in response to a theory of earthquake-induced glacier advance proposed by Tarr and Martin (1910) to explain changes that they observed in glaciers of the Yakutat Bay Region following the 1899 Yakutat Earthquake. Post (1965) had previously published his observations that the 1964 Alaskan Earthquake had not produced snow and ice avalanches or short-lived glacier advances on glaciers in the Coast Mountains, St. Elias Mountains, Chugach, Mountains, Wrangell Mountains, and Alaska Range. Post (1965) coined the term *surge* because *the term "advance" is frequently technically incorrect as the affected glaciers do not always advance beyond their former limits. The term "surge" is here used to describe sudden, large-scale, short-lived glacier movements whether a terminal advance occurs or not.* Surging glaciers typically undergo alternating phases with short periods of active rapid flow, usually lasting from 1 to 3 years (surge) followed by much longer periods of slow flow lasting from 10 to 100 years (quiescence). The quiescent stage of a surging glacier may have seasonal velocity variations. Some glaciers called "pulsing glaciers" (Mayo, 1978) exhibit frequent weak surges.

Glacier surges have been observed in many parts of the world, but the greatest concentration of surging

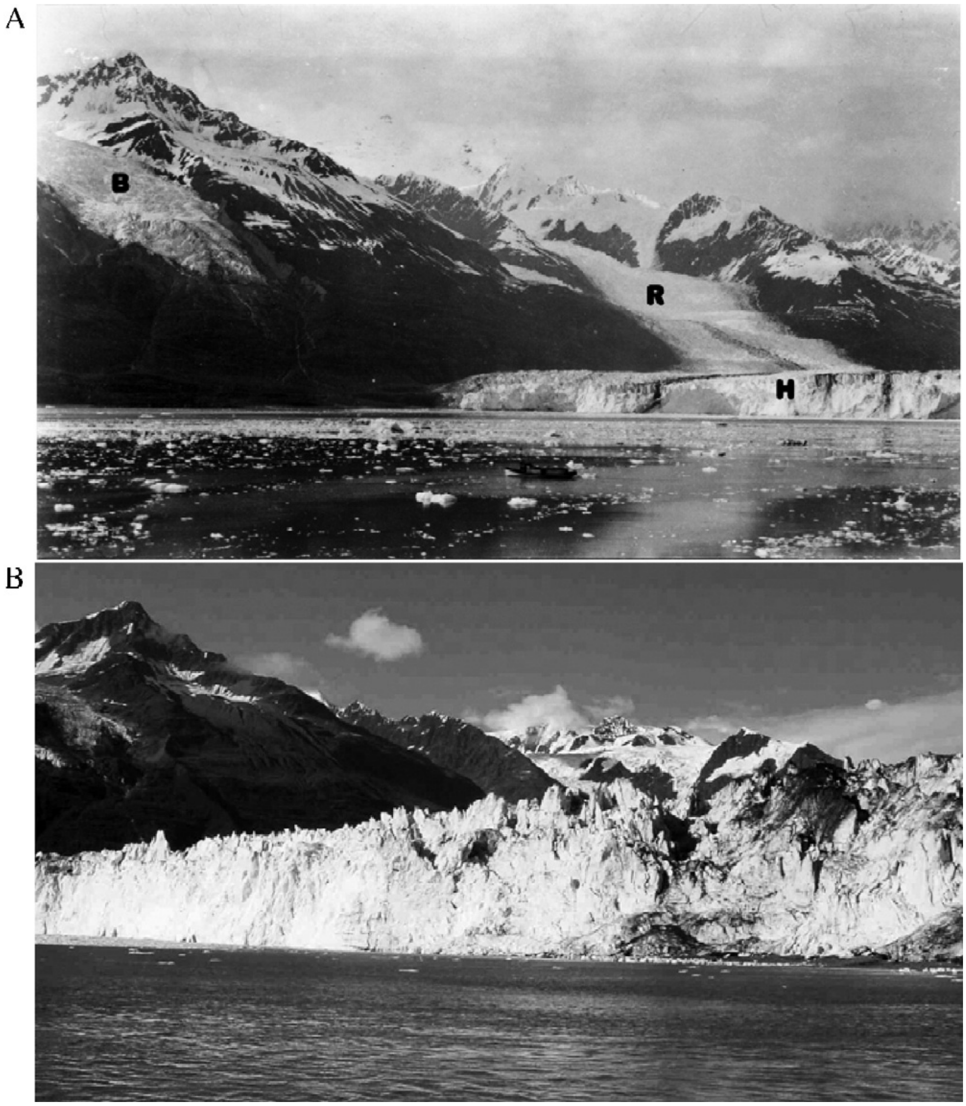


Fig. 4. A pair of north-looking photographs taken from near the head of Harvard Arm, College Fiord, Prince William Sound, (see Fig. 3). The pair documents changes that occurred during the 91 years between July 1, 1909 (A) and September 3, 2000 (B). The 1909 photograph by U.S. Grant shows Harvard Glacier (H) at the head of Harvard Arm with Radcliffe Glacier (R), its largest tributary flowing into it at the right of center, Baltimore Glacier (B), a retreating hanging glacier is at the left side of the photo. If any vegetation is present it is on the hill slopes above the fiord (1909 — USGS Photo Library Photograph by Grant # 208). The 2000 photograph documents the continuing advance of Harvard Glacier, which has completely obscured the view of Radcliffe Glacier. Baltimore Glacier has continued to retreat and thin. Vegetation, especially Alder, has become established on the hill slopes. Harvard Glacier has advanced more than 0.9 km since 1909 (photograph by Bruce F. Molnia).

glaciers is in western North America, especially in the St. Elias Mountains, eastern Chugach, Mountains, eastern Wrangell Mountains, parts of the Alaska Range, and in the Icefield Ranges adjacent to the U.S.–Canada border (Post, 1969). Most glaciers in the regions that support surging glaciers do not surge. Post (1969) noted only 205 surging glaciers out of several thousand western North American glaciers that he examined. About 75% of these were in Alaska. Clarke et al. (1986) noted that only 6.4% (151 of 2356) glaciers they examined in the St. Elias Mountains of Canada were surge type.

2. Methods

In 1978, the USGS began the preparation of an 11-chapter USGS Professional Paper (Professional Paper 1386, Chapters A–K), the *Satellite Image Atlas of Glaciers of the World*., edited by Richard Williams and

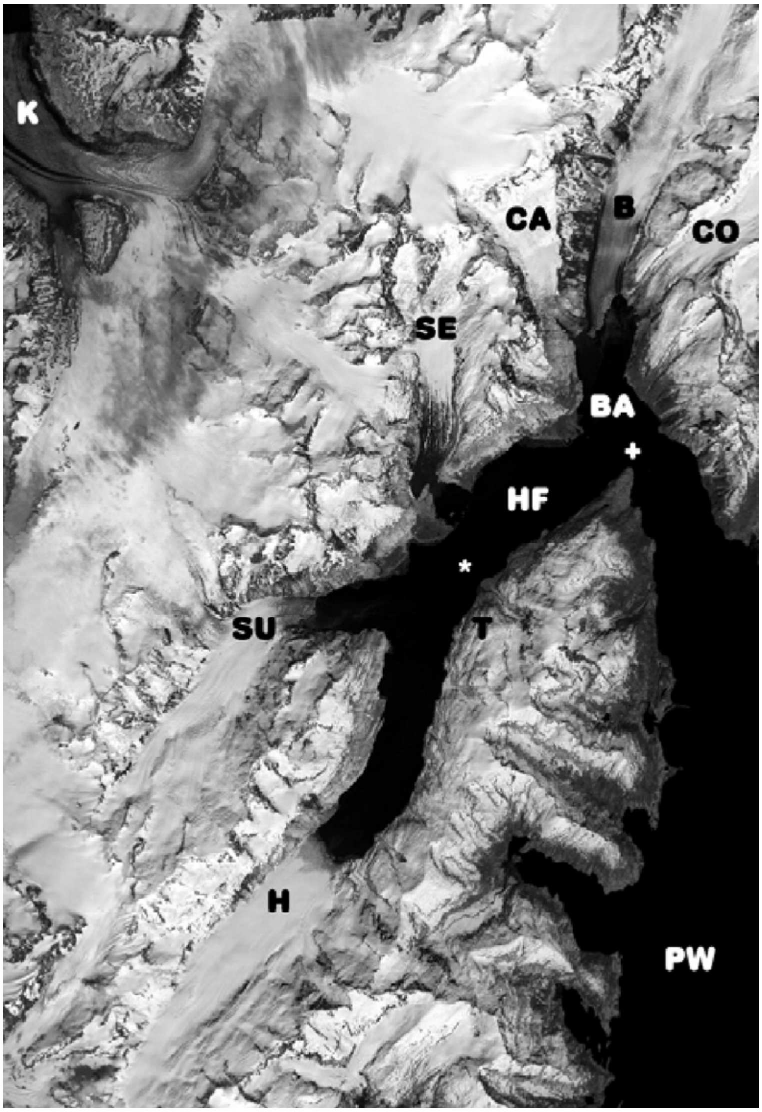


Fig. 5. A 30 km by 55 km portion of a June 24, 2000 ASTER Level 1B panchromatic scene (AST_L1B_003_06242000213418_04272003194744) showing Northwestern Prince William Sound. Among the glaciers present are Harriman Glacier (H), Surprise Glacier (SU), Serpentine Glacier (SE), Cascade Glacier (CA), Barry Glacier (B), Coxe Glacier (CO), and Toboggan Glacier (T). Of the annotated glaciers, all except Harriman Glacier are retreating. Harriman Glacier was advancing during the 1990s, but has changed little during the past decade. The white star (*) marks the location from which the photographs in Fig. 6 were made. The white plus (+) marks the 1899 location of the combined termini of Cascade, Barry, and Coxe Glaciers. Since 1900, they have retreated ∼ 7 km, most of which occurred prior to 1920.

Jane Ferrigno. Chapter A contains a summary of *The Fate of the Earth's Cryosphere at the Beginning of the 21st Century: Glaciers, Snow Cover, Floating Ice, and Permafrost*. While chapters B–K are regional summaries of glacier behavior on a continental and subcontinental basis. In the *Satellite Image Atlas of the Glaciers of the World* series, the primary data set that is used to establish a global baseline for determination of glacier terminus positions and changes is digital imagery data collected by Landsat Multispectral Scanner (MSS) sensors on the Landsat 1, 2, and 3 satellites, during the first decade of operation of the Landsat Program between 1972 and 1981.

For the Alaska Chapter, Chapter K (Molnia, in press), this baseline is a set of 90 Landsat I and II color-composite images compiled by the author from the Landsat data holdings of the EROS Data Center, Sioux Falls, SD. The data set consists of an individual color-composite Landsat image for each path-row point centered in Alaska that has glaciers present.

A

B

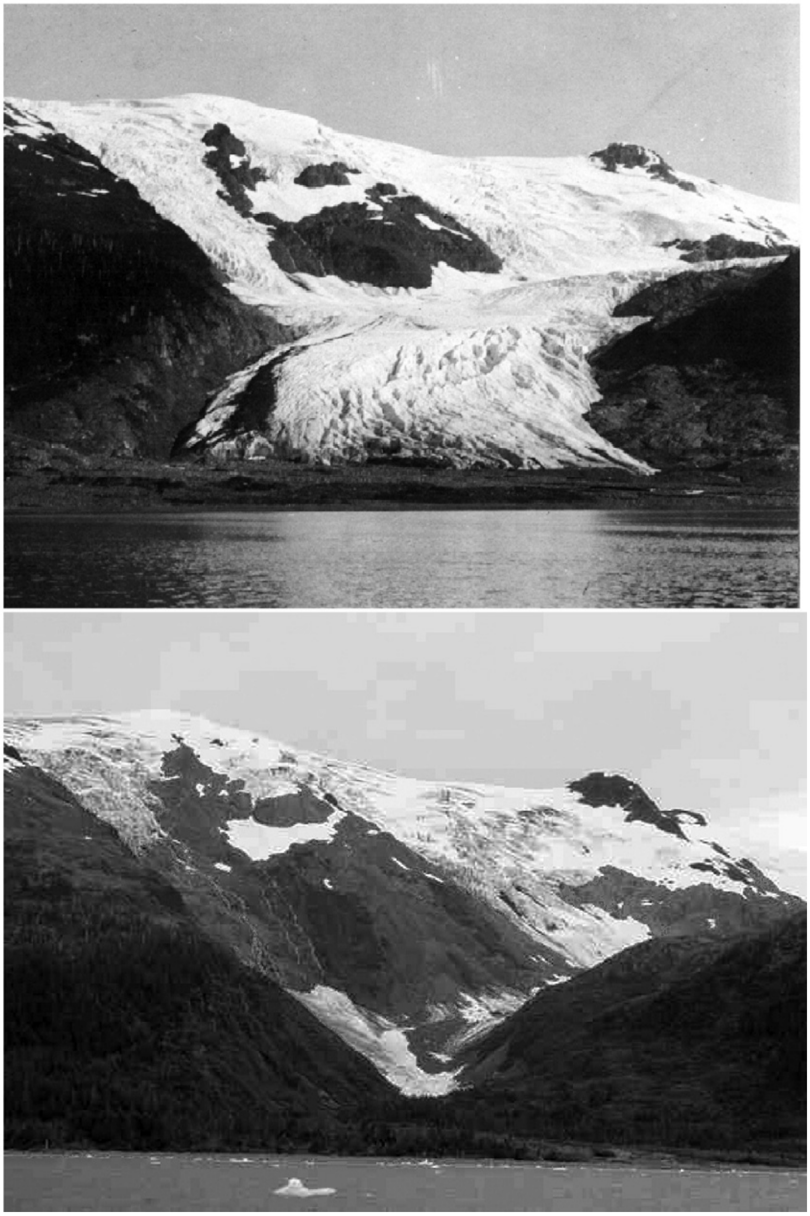


Fig. 6. A pair of north-looking photographs of Toboggan Glacier, both taken from about the same offshore location, Harriman Fiord, Prince William Sound. The pair documents significant changes that have occurred during the 91 years between June 29, 1909 and September 4, 2000. The 1909 photograph by Sidney Paige (A) shows that early in the 20th century, Toboggan Glacier was thinning and retreating and was surrounded by a large bedrock barren zone. Minimal vegetation existed on the fiord-facing hill slopes. By 1909, the terminus appears to have thinned to about 50% of its former thickness (1909 — USGS Photo Library Photograph — Page # 731). The 2000 photograph (B) documents the continuing thinning and retreat of Toboggan Glacier. The former tributary located on the north (left) side of the glacier has also thinned and retreated significantly. Note the extensive vegetation that has developed on the beach and at the glaciers margins (photograph by Bruce F. Molnia).

To produce the summary presented here, the author has supplemented this 1972–1981 Landsat data set with data and information about the extent and distribution of Alaska's glaciers derived from 18th- to 21st-century reports of exploration; published and unpublished 19th- to 21st-century field-based scientific investigations; information extracted from numerous journal articles; 19th-to 21st-century ground-based photography obtained from archives, museums and libraries around the world; and 20th- and 21st-century aerial and space photography, digital satellite imagery, and airborne- and space-borne-radar imagery.

The most easily and frequently measured glacier parameter is the geographic position of the terminus. Modern maps, charts, and satellite and airborne images and photographs all can be used to determine terminus positions. So can charts from early navigators and "traditional knowledge" from Alaska Native oral histories. Proxy methods, such as tree coring and dendrochronology can yield approximate dates for end, recessional, and lateral moraines. Together these resources were used to determine the location of glacier termini and to document rates of change and current behavior of Alaskan glaciers. All of these diverse types of data have been used by investigators to make determinations about the changing positions of Alaskan glaciers (Molnia, in press).

In addition to imagery and photography, another significant resource used to develop the baseline and for assessing change in Alaskan glaciers is USGS topographic maps. Alaska has two primary types: 1) 1:250,000-scale (1° × 3°) maps published by the USGS between 1949 and 1979 (glaciers appear on ~ 60 individual maps); and 2) more detailed 1:63,360-scale maps. The 1:63,360-scale topographic maps are the most detailed USGS topographic maps of Alaska. They were prepared during the same time period as the 1:250,000-scale maps. These 2920 maps have dimensions of 15 min in latitude and from 20 to 36 min of longitude. The area portrayed on each sheet ranges from 536 km^2 to 725 km^2, depending on the latitude. Glaciers appear on more than 500 of these maps. Based on aerial photography and field surveys, the quality of these maps varies significantly. In remote mountainous areas with poor geodetic control, errors of several hundred meters may exist.

The primary purpose of this presentation is to summarize the aerial extent, distribution, and late 19th to early 21st century behavior of Alaska's glaciers on a region by region basis. The summary presented here will focus on behavior during the 'Landsat Baseline Decade' and, where possible, extend the informational baseline both retrospectively and prospectively. Representative examples will be used to characterize the behavior of glaciers in each area.

Regional areas and glacier lengths and areas presented are compiled from numerous sources. Most regional areas are taken from Molnia (1982) or Post and Meier (1980). Most glacier length and area measurements are from Field (1975a). Where possible, other sources are referenced.

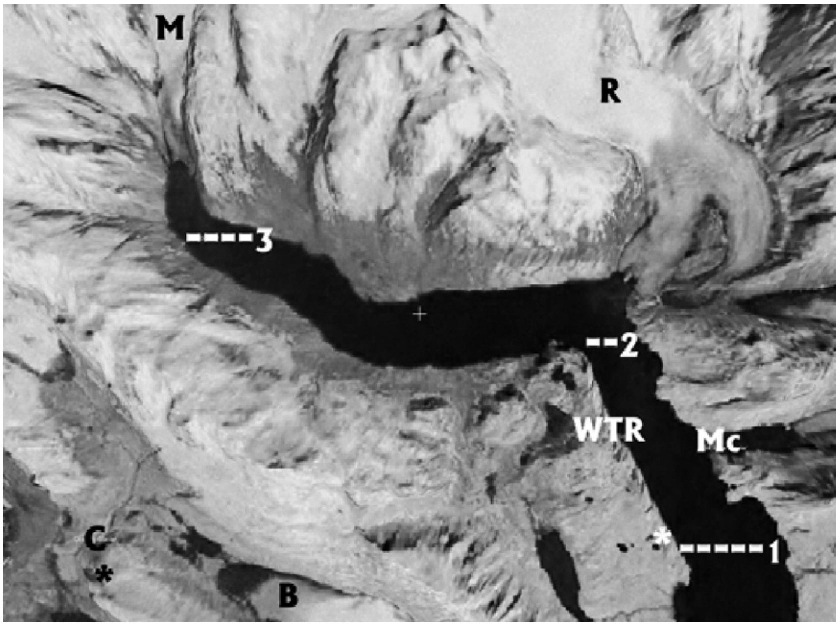


Fig. 7. Part of a Landsat image mosaic of Glacier Bay National Park and Preserve composed of Landsat 7 TM imagery collected between August 1, 1999 and August 10, 2000, produced by Jess Grunblatt and Jeff Bennett of the National Park Service Alaska Landcover Mapping Program, (Grunblatt and Bennett, 2004). Shown is a ~ 16 km by ~ 26 km area of Upper Muir Inlet. Labeled are Muir Glacier (M), Riggs Glacier (R), Burroughs Remnant (B), and Carroll Glacier (C). McBride Glacier is located at the head of McBride Inlet (Mc). McBride Inlet is the result of 2 km of post-1975 retreat. Muir Glacier's terminus is shown at its 2000 location at the head of Muir Inlet. It was located at the position of the white dotted line labeled 1 in about 1940, at the position of the white dotted line labeled 2 in about 1960, and at the position of the white dotted line labeled 3 in about 1980. Between about 1940 and about 1960, Muir Glacier retreated >8 km, the length of White Thunder Ridge (WTR). The white star (*) marks the location from which the photographs in Fig. 9 were made, while the black star (*) marks the location from which the photographs in Fig. 10 were made.

3. Results and analyses

3.1. Chugach Mountains

The Chugach Mountains are a 400-km-long by 95-km-wide mountain range. The eastern part of the Chugach Mountains is covered by a continuous series of connected glaciers and accumulation areas (Field, 1975b). Several studies have characterized this and adjacent regions as areas experiencing a significant 20th century retreat (Meier, 1984; Molnia and Post, 1995). A study by Sauber et al., 2000 computed the effect of this regional ice removal on crustal deformation in the eastern Chugach Mountains. Recognizing that the range of annual thinning of glaciers in this region ranges from 1–6 m/yr, they computed that uplift in ablation regions of these glaciers ranges from 1–12 mm/yr, with the greatest uplift being located just east of the Chugach Mountains, in the Icy Bay region, an area where the Guyot Glacier has retreated more than 50 km since 1904.

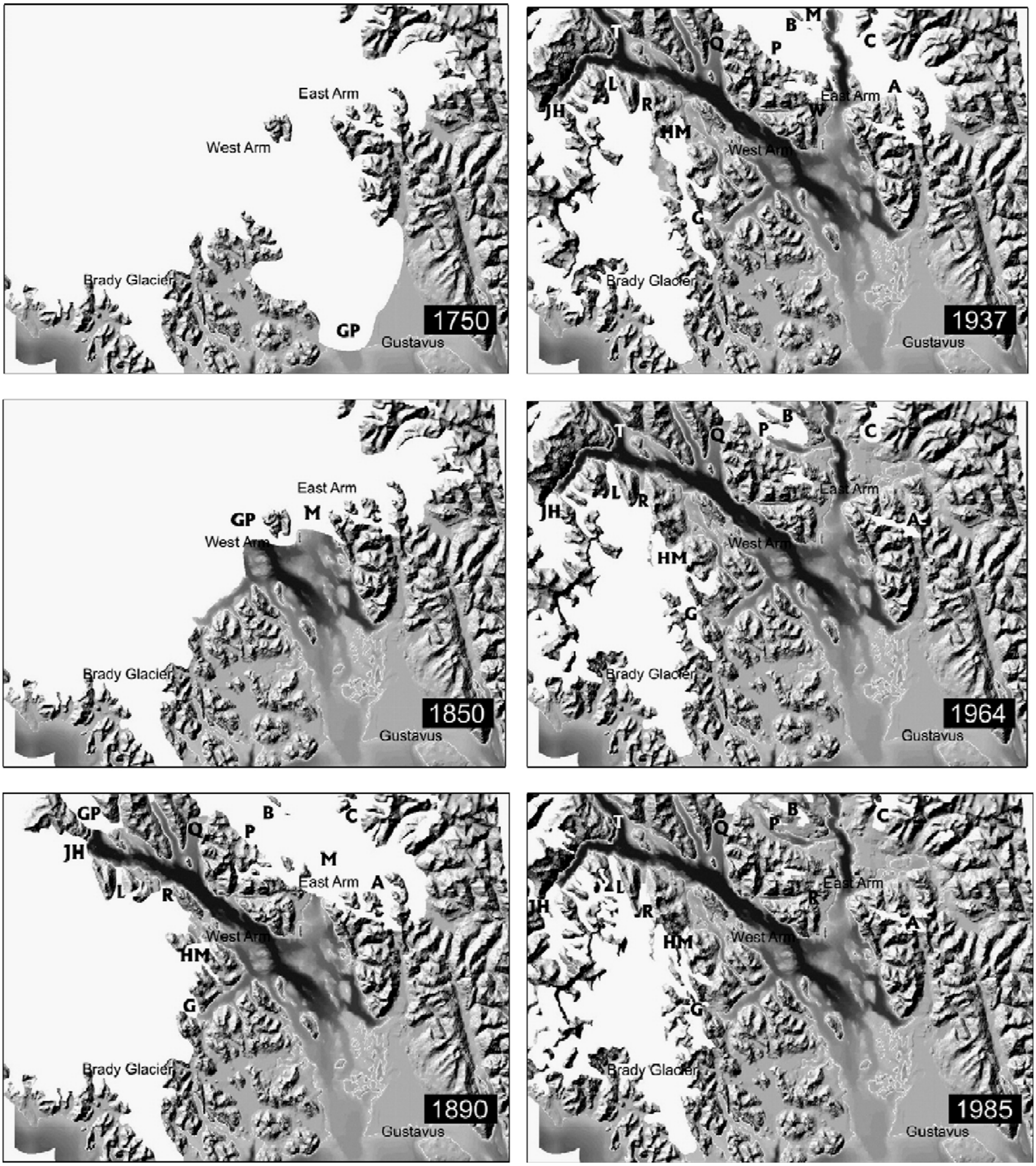
During the 'Landsat Baseline Decade,' the Chugach Mountains had a glacier-covered area of ~ 21,000 km^2. The only advancing glaciers were located in Western Prince William Sound (Fig. 3). During the baseline decade, Meares Glacier (~ 26 km long with an area of ~ 142 km^2), and Harvard Glacier (~ 40 km long with an area of ~ 525 km^2) were advancing, while Bryn Mawr Glacier (~ 8 km long with an area of ~ 26 km^2), Harriman Glacier (length of ~ 8 km and an area of ~ 26 km^2), and Columbia Glacier (~ 54 km and an area of ~ 1100 km^2) advanced during the early part of the decade. Smith Glacier (~ 10 km long with an area of ~ 20 km^2) was stable for most of the baseline, with the position of its termini fluctuating from year to year. Available evidence suggests that all other valley and outlet glaciers in the Chugach Mountains were thinning and retreating.

Through the early 21st century, Meares and Harvard Glaciers (Fig. 4) were still advancing, while Harriman Glacier (Fig. 5) was stable. All other valley and outlet glaciers in the Chugach Mountains, whether terrestrial or tidewater, were thinning and/or retreating. The 20th century behavior of Toboggan Glacier (Fig. 6) is typical of many Chugach Mountain valley glaciers.

Columbia Glacier, a tidewater calving glacier, and the largest glacier in Prince William Sound, is an excellent example of the dynamic natural variability of Chugach Mountain glaciers. Currently, it is in catastrophic retreat. During the later part of the 'Landsat Baseline Decade,' it had a pre-retreat length of ~ 66.5 km and ice speeds at its terminus of between 5 and 6 m/d. Part of its terminus was grounded on Heather Island and an adjacent submarine moraine that protected it from significant loss of ice through calving and retreat. But in January 1979, the glacier retreated from Heather Island and lost contact with its moraine. Thus began an 'irreversible, drastic retreat' (Meier et al., 1980) that has since resulted in ~15 km of retreat, and thinning of as much as 400 m. By 2001, the velocity at the terminus increased nearly five-fold to 25 m/d or more than 9 km/yr (Krimmel, 2001).

Columbia Glacier has been observed since the late 18th century. According to Tarr and Martin (1914), it showed minimal change between 1794 and 1900. Gilbert (1904) photographed and mapped the lower 15 km of the glacier in 1899. He documented a land-based advance that occurred in 1892 and a retreat underway in 1899. Grant visited the glacier in 1905, and again with Higgins in both 1908 and 1909 (Grant and Higgins, 1913). They concluded that the glacier's land-based terminus retreated between 1899 and 1905, advanced between 1905 and 1908, and advanced even more through June 1909. Tarr and Martin (1914) observed that the glacier continued to advance through their 1911 visit. Tarr and Martin quantified the changes that they and Gilbert observed for the 20-year period between 1892 and 1911: A) 1892–July 1899, retreat of 243 m, average retreat of ~ 35 m/yr; B) July 1899–June 24, 1909, advance of ~ 150 m, average advance of ~ 15 m/yr; C) August 23, 1909–July 5, 1910, advance of 213 m, average advance of ~ 245 m/yr; D) July 5, 1910–September 5, 1910, advance of 33 m, average advance of ~ 200 m/yr; and E) September 5, 1910–June 21, 1911, advance of <30 m, average advance of ~ 38 m/yr. Hence during the 19-year period from 1892 to 1911, Columbia Glacier advance ~ 290 m, an average advance of ~ 15 m/yr. Field (1932) reported an advance from 1917–1922, followed by a period of retreat. By 1931, 275 m of recession occurred at the west margin of the glacier, ~ 60 m of recession on Heather Island, and from 120–250 m of recession along the land-based eastern margin. This retreat was quickly followed by another advance. Field (1937) revisited Columbia Glacier in 1935 and measured 1045 m of advance at the west margin of the glacier, 72 m of advance on Heather Island, and 25 m of advance on the land-based eastern margin. In 1947, Miller (1948) observed that a recession of ~ 100 m had occurred since the 1935 advance. Field (1975b) reported that an advance of 100 m or more was underway between 1947 and 1949. Eight years later (1957), he observed the glacier was slowly retreating from the moraine formed by the late 1940s advance. Field (1975b) reported that between 1960 and 1971, annual observations of

Columbia Glacier were made by a variety of individuals, except for 1962. During this period, the glacier experienced a small advance between 1957 and 1961, recession or minimal change between 1961 and 1968, a slight advance of a few tens of meters on land between 1968 and 1969, and an advance on Heather Island and on the eastern land-based terminus between 1969 and 1971. Small scale fluctuations of the terminus continued through 1982. During the >80 yr period, since Gilbert's 1899 visit the tidewater portion of Columbia Glacier remained in an extended stable position. Catastrophic retreat of Columbia Glacier tidewater terminus began in 1982 as a result of the tidewater portion of the glacier's terminus losing contact with its end moraine. Between



1982 and 2000 Columbia Glacier retreated 12 km, reduced its thickness by as much as 400 m, increased its speed from about 5 to 30 m/d, and increased its calving rate from 3×10^6 to 18×10^6 m^3/d (Krimmel, 2001). Since then ~ 2 km of additional retreat has occurred.

3.2. Saint Elias Mountains

The Saint Elias Mountains are a 550-km-long by 180-km-wide mountain system, straddling the Alaskan–Canadian border, and paralleling the coastline of the northern Gulf of Alaska. About 2/3 of the Saint Elias Mountains are located within Alaska. The Alaskan Saint Elias Mountains extend northwest from Lynn Canal to the Chugach Mountains. The highest peak in the Alaskan Saint Elias Mountains is Mount Saint Elias. Its 5489 m-high summit, which is a United States–Canada border peak, is only located about 15 km from sea level. This closest point is the terminus of Tyndall Glacier, a tidewater glacier, now stabilized at the head of its fiord. Elsewhere in the Alaskan Saint Elias Mountains, Mount Bona (5005 m), Mount Vancouver (4785 m), Mount Fairweather (4663 m), and Mount Hubbard (4557 m) all exceed 4500 m. More than two dozen other peaks have elevations greater than 3300 m. The highest peak, Mt. Logan (6050 m), is located entirely within Canada.

Hundreds of glaciers cover more than 14,200 km^2 of the Alaskan part of the Saint Elias Mountains. Included are parts of the three largest temperate glaciers in North America, Bering Glacier (~ 200 km long with an area >5000 km^2), Malaspina Glacier (with the largest piedmont lobe of any Alaskan glacier and an area of ~ 5000 km^2) and Hubbard Glaciers. More than 50 Saint Elias Mountains glaciers have lengths greater than 8 km. Little Jarvis Glacier, with a length of 3.2 km, is one of the glaciers surveyed during the International Geophysical Year in 1957–1958 (American Geographical Society (AGS), 1960). It was resurveyed by a University of Alaska Fairbanks team in 1995. In the 38 years between surveys, the terminus retreated about 190 m, an average of about 5 m/yr. During the 38 yr interval, Little Jarvis Glacier experienced a small loss in area (1995 area of 2.45 km km^2 vs. 1958 area of 2.5 km^2), but no change in volume, due to a small thickening in its upper accumulation area (Sapiano et al., 1998).

About 250 years ago, there was no Glacier Bay (Fig. 7). Its basin was filled by a single, large tidewater glacier, an ancestral Grand Pacific Glacier that reached into Icy Strait. The terminus location, occupied in ~ 1750, marks the Little Ice Age maximum extent of the glacier. In terms of Post's tidewater glacier model, the 1750 Grand Pacific Glacier was in an advanced, extended position.

Soon after 1750, it began to retreat. By the end of the 19th-century, retreat exceeded 55 km, resulting in an average annual retreat rate of ~ 0.33 km/yr. As the ice continued to thin and retreat, individual inlets began to become exposed, each with its own unique retreating ice tongue. Each inlet has its own history and timing of ice movement. For instance, Muir Glacier, located in the eastern arm of the bay, separated from the main Glacier Bay ice mass in the early 1860s and has retreated continuously. This complex sequence of glacier retreat and fiord appearance has been documented by many investigators, beginning with Reid (1892 and 1896).

Fig. 8. The post-Little-Ice-Age evolution of Glacier Bay is depicted in a series of six maps that span the 235 yr period from 1750 to 1985. Ron Karpilo of the U.S. National Park Service produced the base map. Each map covers an area of ~ 75 km by ~ 100 km. The 1750 map (a) shows Grand Pacific Glacier (GP) extending to its Little-Ice-Age maximum position, and completely filling Glacier Bay with ice. The locations of what will become East and West Arms are shown. The upland accumulation area of Brady Glacier is also shown. Brady Glacier extends beyond the southern limit of the map. By 1850 (b), Grand Pacific Glacier has retreated ~ 50 km. Within two decades, Muir Glacier (M), its eastern tributary, will separate and begin retreating up East Arm. By 1890 (c), in West Arm, Grand Pacific Glacier has retreated an additional 50 km. It still fills all of Tarr Inlet. Hugh Miller Glacier (HM) and Geikie Glacier (G) both separated from Grand Pacific Glacier by ~ 1870 and each has a tidewater terminus in its own inlet. Reid Glacier (R), Lamplugh Glacier (L), and Johns Hopkins Glacier (JH), all former tributaries to Grand Pacific Glacier have separated from it and all sit at the mouths of their respective inlets. Carroll Glacier, located at the head of Queen Inlet (Q) and Rendu Glacier, located at the head of Rendu Inlet, the inlet between Queen and Tarr Inlets, have separated from Grand Pacific Glacier and retreated a significant distance up their respective fiords. In East Arm, Muir Glacier has retreated an additional 10–15 km. Its major tributaries Adams Glacier (A), Casement Glacier (C), Plateau Glacier (P), and Burroughs Glacier (B) are thinning, but still connected to Muir Glacier. By 1937 (d), in West Arm, Grand Pacific Glacier has retreated off the map to the north, crossing the Canadian Border and exposing Tarr Inlet (T). Since the late 1920s, Johns Hopkins Glacier has been advancing. Previously it retreated ~ 8 km, exposing Johns Hopkins Inlet. In East Arm, Muir Glacier has retreated to the north limit of the map, exposing ~ 15 km of Muir Inlet. By 1964 (e), with the exception of Johns Hopkins Glacier which has been advancing for more than 30 years and Lamplugh Glacier which is experiencing a small advance, all of the glaciers in West Arm continue to retreat. In East Arm, Casement and Adams Glaciers, have retreated from tidewater and continue to retreat on land. Grand Pacific Glacier is now advancing, but is still north of the mapped area. By 1985 (f), with the exception of Johns Hopkins Glacier which has been advancing for more than 50 years and Lamplugh Glacier which is fluctuating near the mouth of its inlet, all of the glaciers that are shown continue to retreat. About this time, the advancing Grand Pacific Glacier connects with Margerie Glacier, located at the head of Tarr Inlet. A 2006 map is not presented as no change would be seen when compared to the 1985 map. Base map courtesy of Ron Karpilo, U.S. National Park Service.

Every retreating tidewater glacier that transitioned on to land has continued to retreat. Many have completely disappeared (Fig. 8).

About 1890, as Grand Pacific Glacier continued to retreat in the western arm of the bay, Johns Hopkins Glacier separated from it. Each glacier independently continued to retreat for about the next 35 to 40 years. Then, both began to advance. While Grand Pacific Glacier has returned to a regime dominated by active thinning and retreat, Johns Hopkins Glacier continues to advance, advancing more than 1.5 km since the late 1920s.

Glacier Bay contains more than 50 named glaciers and one of the most spectacular fiords in Alaska. Many of its glaciers originate at elevations in excess of 2000 m. About a dozen have lengths exceeding 15 km, the longest and largest being Grand Pacific Glacier with a length of about 60 km and an area of about 650 km^2. This glacier originates in Alaska, flows through British Columbia, and terminates in Alaska. Both Brady Glacier and Carroll Glacier (Fig. 9) have areas in excess of 500 km^2. Glacier Bay extends for more than 100 km from its mouth at Icy Strait to the termini of Grand Pacific Glacier at the head of Tarr Inlet and Johns Hopkins Glacier at the head of Johns Hopkins Inlet.

Annual field observations by the author during much of the 'Landsat Baseline Decade' indicate that during the period from 1974 to 1982, 12 tidewater glaciers (McBride, Riggs, Muir, Grand Pacific, Margerie, Toyatte, Johns Hopkins, Gilman, Hoonah, Kashoto, Lamplugh, and Reid Glaciers) were actively calving icebergs into Glacier Bay. Since then, the termini of several, such as Muir Toyatte, Hoonah, and Kashoto Glaciers, have retreated above sea level. About 90 years earlier, when mapped by Reid in 1890 and 1892 (Reid, 1896), Glacier Bay had only ten tidewater calving termini (Muir, Carroll, Rendu, Grand Pacific, Johns Hopkins, Reid, Hugh Miller, Charpentier, Geikie, and Wood Glaciers), with many of today's glaciers still part of the much larger, late 19th century ice mass.

After 1860, Muir Glacier separated from Grand Pacific Glacier, and by the early 1880s, its continuing retreat began to expose Muir Inlet. By the end of the 20th century, retreat exceeded 40 km. From south to north, Muir's side inlets, Adams Inlet (~ 1905), Wachusett Inlet (~ 1927), McBride Inlet (~ 1946), and Riggs Inlet (~ 1966) began to appear. Field and Collins (1975) report that during the 84 yrs between 1886 and 1968, the average rate of retreat of the Muir Glacier was 400 m/yr. Between 1926 and 1982, retreat totaled 30 km and the ice thickness decreased more than 650 m at the location of the 1982 terminus (Krimmel and Meier, 1989). By the mid-1990s, Muir Glacier retreated above tidewater and its length had decreased to less than 30 km. Hall et al. (1995) used Landsat imagery to document changes in upper Muir Inlet between 1973 and 1986. In the 13 years between images, Muir Glacier retreated more than 7 km (Fig. 10).

Lituya Bay, a 15-km-long, 'I-shaped' fiord, contains three named glaciers: North Crillon Glacier, Cascade Glacier, and Lituya Glacier, all of which were tidewater at various times during the 20th century. A large end moraine at the mouth of the bay, a well-preserved lateral moraine (Solomon's Railroad) on the west side of the bay, and tree-covered stagnant glacier ice located on the west side of the bay are evidence that an expanded and combined Lituya–North Crillon Glacier filled Lituya Bay during the early LIA sometime prior to ~ 1700 A.D. Prior to the end of the 18th century, this glacier retreated nearly 20 km, probably through catastrophic calving retreat and separating into numerous tributaries. In 1786, when mapped by LaPerouse, the bay was 'T-shaped,' with five glaciers present at its head, a pair in each of the upper ends of the 'T' and a hanging glacier at the center of the 'T.' In the ~ 10 km-long top of the 'T,' each glacier terminated at or near tidewater. Lituya Glacier, the western-most of the five descended from the Fairweather Range into Desolation Valley and flowed in both directions, with the southeastward flowing lobe ending in Lituya Bay. Between the observations of LaPerouse in 1786 (LaPerouse, 1799), and USGS mapping in 1917, the tidewater termini of Lituya Glacier advanced about 5 km, while that of North Crillon Glacier advanced about 3 km. Each has advanced ~ 1 km since 1920, and each continues to advance. Since being mapped by the author in 1976 (Molnia and Wheeler, 1978), both have built outwash fan-deltas around their termini that separated them from tidewater, and ceased to calve icebergs.

Most adjacent glaciers are retreating. For example, Grand Plateau Glacier, with a length of 50 km and an area of about 455 km^2, has been retreating and thinning for more than a century. Its LIA maximum position, adjacent to the Gulf of Alaska coastline, was at least 2 km south of its 1906–1908 terminus position. By 1941, at least five ice-marginal lakes had developed, the largest being more than 2 km wide. By 1966, the entire southern margin of the glacier was surrounded by a single ice-marginal lake, formed by the enlargement of the original individual lakes. This lake, which was 7 km by 5 km in 1975, continued to enlarge through the early 21st century as the glacier calved icebergs, thinned, and retreated. Grand Plateau Glacier is a good example of a lacustrine calving glacier. Through the late 20th century, its terminus behavior has closely resembled the retreat dynamics of a tidewater glacier.

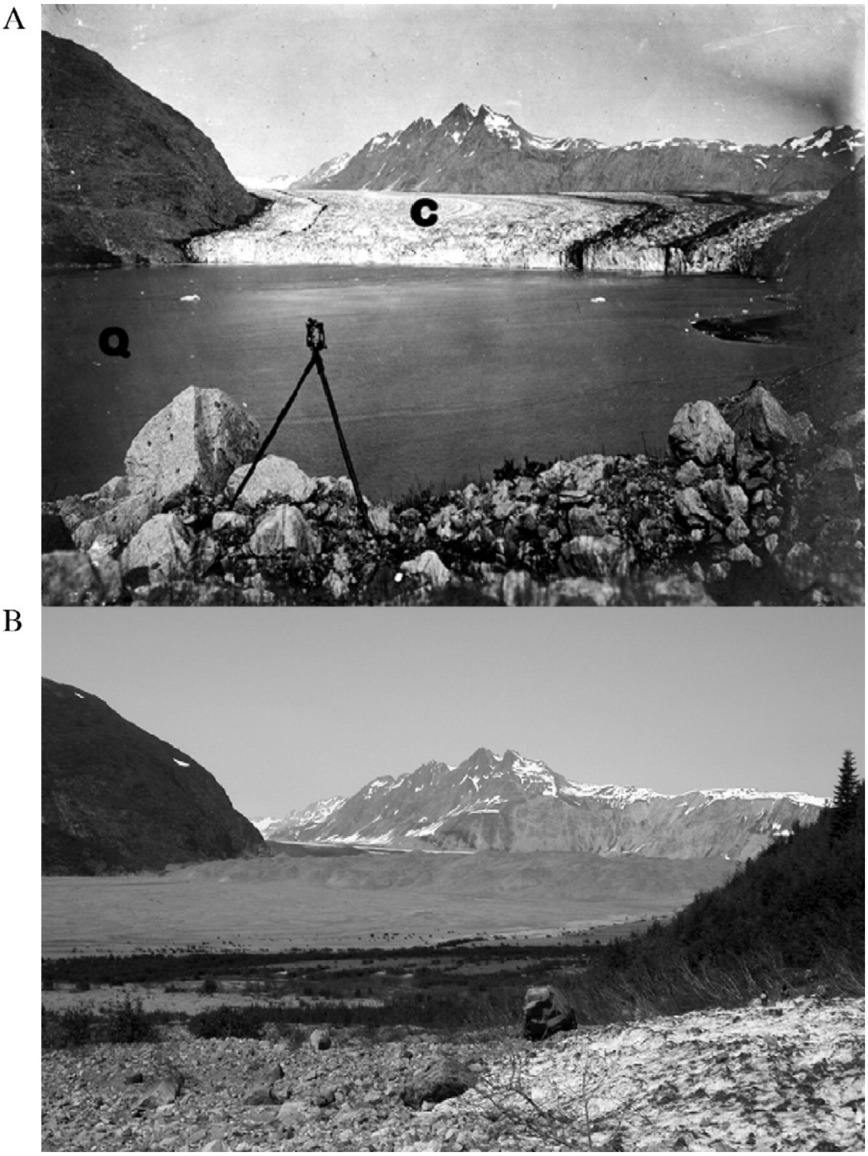


Fig. 9. A pair of northwest-looking photographs, both taken from the same location, several hundred meters up a steep alluvial fan located in a side valley on the east side of Queen Inlet, Glacier Bay National Park and Preserve, showing changes that have occurred to Carroll Glacier and upper Queen Inlet during the 98 years between August 1906 and June 21, 2004. The 1906 photograph by C.W. Wright (A), shows the tidewater calving terminus of Carroll Glacier (C) sitting at the head of Queen Inlet (Q) — (USGS Photo Library Photograph by Wright # 333). No vegetation is visible. The 2004 photograph (B) shows that the terminus of Carroll Glacier has become a stagnant, debris-covered terminus that has thinned by >50 m, and retreated from its 1906 position. The head of Queen Inlet has been filled by >125 m of sediment. Note the vegetation on the sediment fill and fiord wall (photograph by Bruce F. Molnia).

Hubbard Glacier, the largest tidewater glacier in Alaska is >120 km long with an area of ~ 3875 km^2. It has a calving face that is more than 10 km long. Plafker and Miller (1958) report, based on a radiocarbon-dated sample, that 1130 +/− 160 yr BP, the Hubbard Glacier filled Yakutat Bay and extended into the Pacific Ocean. Arcuate ridges at Monti Bay and near the city of Yakutat are the terminal and recessional moraines that mark this maximum ice advance. Beginning in the 14th century, the Hubbard then underwent a significant retreat of more than 25 km. During the 18th century, it readvanced more than 10 km to Blizhni Point (Plafker and Miller, 1958). A submarine moraine at the lower end of Disenchantment Bay resulted from this advance which culminated after l700 AD. From the late 18th century through the early 19th century another period of retreat, amounting to

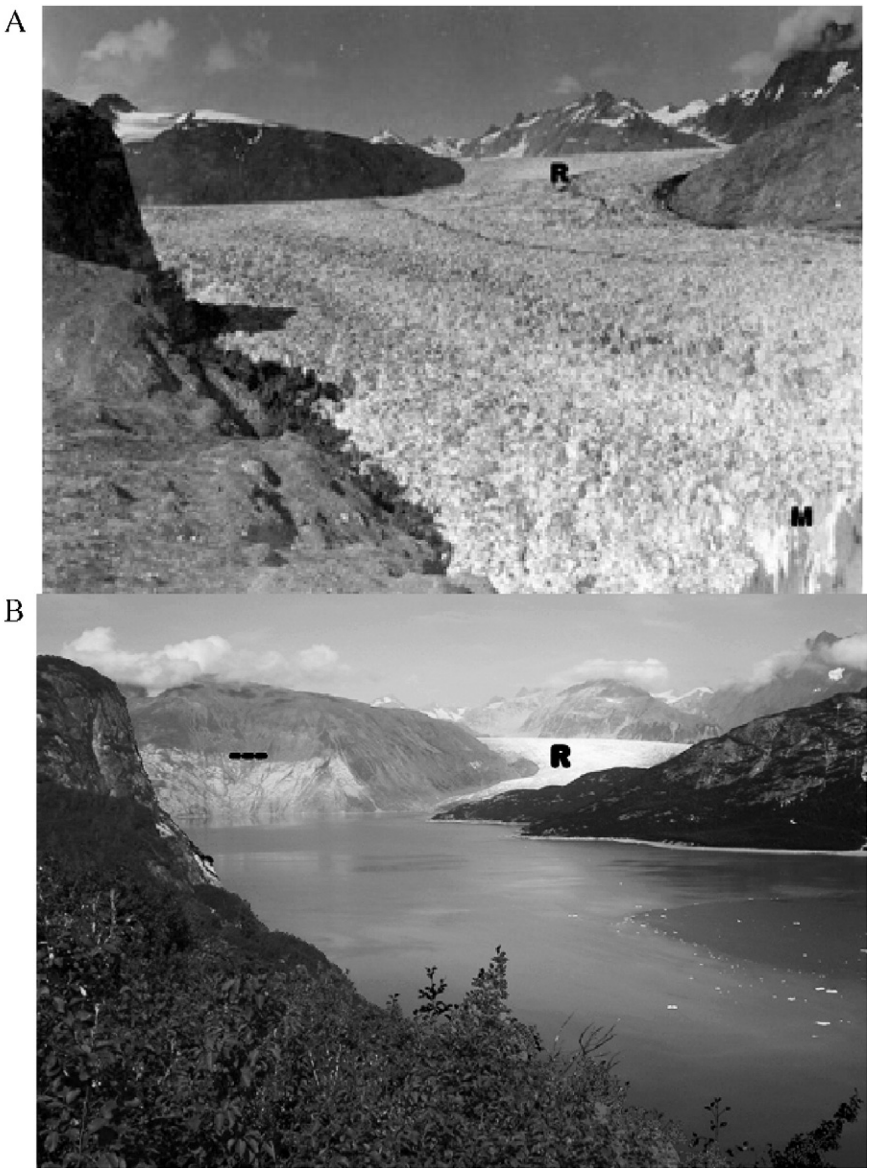


Fig. 10. A pair of northeast-looking photographs, both taken from Station 4 on White Thunder Ridge, Muir Inlet, Glacier Bay National Park and Preserve. The pair documents changes that have occurred during the 63 years between August 13, 1941 and August 31, 2004. The 1941 photograph (A) by William O. Field shows Muir Glacier (M) and Riggs Glacier (R) filling Muir Inlet and extended south beyond the right edge of the photograph. The maximum ice thickness is >800 m. Note the absence of any vegetation in the 1941 photograph (1941 National Snow and Ice Data Center — Field 41–64). The 2004 photograph (B) documents the retreat of Muir Glacier out of the field of view and the significant thinning and retreat of Riggs Glacier. Note the dense growth of alder and the correlation between Muir Glacier's 1941 thickness and the trimline (−) on the left side of the 2004 photograph (photograph by Bruce F. Molnia).

more than 5 km, occurred. A detailed history of the Hubbard Glacier's LIA behavior is presented by Barclay et al. (2001).

Prior to 1890, Hubbard Glacier again began to advance, an advance that continues into the 21st century. Trabant and Krimmel (2001) compared terminus changes between 1895 and 1998. They found that the average rate of advance has accelerated from about 16 m/yr between 1895 and 1948 to about 26 m/yr between 1948 and 1998. The 100-yr average advance rate is ~22 m/yr for most of the terminus. In 1986 and again in 2002, Hubbard Glacier's advancing terminus blocked the entrance to Russell Fiord with push moraines. In each case, the water level in Russell Lake rose more than

15 m. Following failure of the sediment and ice dams, catastrophic floods resulted. Each removed more than 500 m of the terminus.

During most of the 20th century, Tyndall Glacier (Fig. 11), a tidewater glacier located in Taan Fiord at the head of Icy Bay, was in retreat. Originally a tributary to Guyot Glacier, it became independent in 1960. By 1990, it retreated an additional ~ 17 km, before reaching a position of stability at the head of its fiord. At its 2005 terminus position, the glacier is ~ 700 m thinner than it was in 1959. The current terminus location is only about 12 km from the summit of Mt. St. Elias (at an elevation of 5489 m). This 46% gradient is one of the steepest on Earth.

3.3. Alaska Range

The Alaska Range consists of a number of adjacent and discrete mountain ranges that extend in an arc more than 750 km in length. From east to west, named ranges include: the Nutzotin, Mentasta, Amphitheater, Clearwater, Tokosha, Kichatna, Teocalli, Neacola Tordrillo, Terra Cotta, and Revelation Mountains. Many ranges support glaciers. The Alaska Range contains several thousand glaciers ranging in size from tiny unnamed cirque glaciers with areas of <1 km^2, to very large valley glaciers with lengths exceeding 75 km and areas of more than 500 km^2. Alaska Range glaciers extend in elevation from above 6000 m, near the summit of Mount McKinley, to a little more than 100 m above sea level at Capps and Triumvirate Glaciers. In all, the Alaska Range supports ~ 13,725 km^2 of glaciers.

Gulkana Glacier is one of two Benchmark Glaciers in Alaska. It was visited and photographed by Moffit in 1910 and again by Pewe in 1952. In the 42 years between photographs, Gulkana's terminus retreated more than 4 km. A comparison of the 1957 USGS topographic map

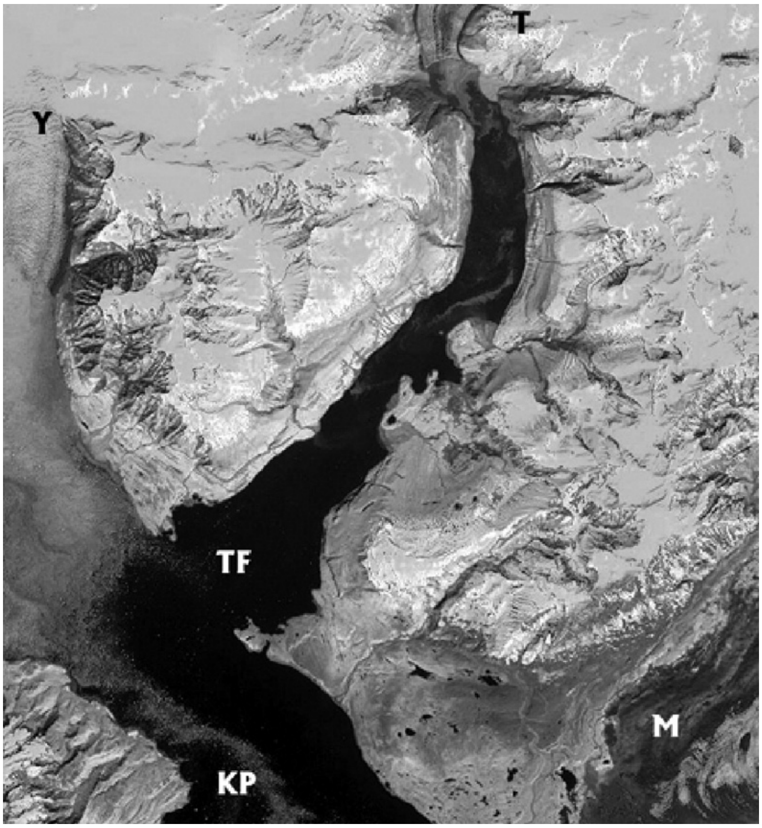


Fig. 11. A 20 km by 30 km portion of a June 06, 2001 ASTER Level 1B panchromatic scene (AST_L1B_003_2003276802) showing the northeastern part of Icy Bay. To the right is essentially iceberg-free Taan Fiord (TF) with Tyndall Glacier (T) at its head. To the center is the eastern part of upper Icy Bay with the actively iceberg-calving Yahtse Glacier (Y) at its head. Both Yahtse and Tyndall Glaciers are former tributaries to Guyot Glacier. Since the first decade of the 20th century, Guyot Glacier has retreated ~ 50 km, opening Icy Bay. For more than two decades (1939–1960) Guyot Glacier's terminus remained in the narrow neck of the bay between Kichyatt Point (KP) and the north side of Taan Fiord. Since 1960, four separate fiords have become exposed at the head of Icy Bay. A part of the stagnant, debris-covered terminus of the Malaspina Glacier (M) is present at the lower right edge of the image.

and data obtained during an airborne profiling survey conducted on 12 June 1993 (Echelmeyer et al., 1996) indicates that the glacier retreated ~ 1.75 km. During the 36 years between data sets, the glacier's area decreased 8%, from 18.5 km^2 to 17.0 km^2. The average annual retreat rate was 48.6 m/yr.

Rates of retreat and thinning at Gulkana Glacier increased at the end of the 20th century (personal communication, March 2001, K. A. Echelmeyer, University of Alaska Fairbanks). Between the 1950s and middle 1990s, the glacier thinned 0.434 m/yr and had its volume decrease by 0.00822 km^3/yr. Between the middle 1990s and 1999, the glacier thinned by 0.748 m/yr and had its volume decrease by 0.0136 km^3/yr.

Muldrow Glacier is typical of many Alaska Range debris-covered glaciers. It is also a surging glacier (Post, 1960, 1969). It flows to the northeast from high on the slopes of Mount McKinley. Two named tributary glaciers, Brooks and Traleika Glaciers, furnish much of Muldrow's ice. From May of 1956 through the summer of 1957, Muldrow Glacier surged a distance of ~ 6.5 km. The maximum observed velocity during the peak of movement was ~ 350 m/d or about 24 cm/min. Surface levels dropped up to 100 m in the upper glacier area and increased 200 m in the lower glacier. For almost a decade prior to the surge a wave of thickening ice moved down the upper part of the glacier at a rate of ~ 0.75 m/d. Post (1960), who described the 1956–1957 surge, reported that an analysis of moraine patterns on the glacier's surface suggests that at least four prior surges occurred within the past several hundred years, with the most recent pre-1956 surge occurring between 1906 A.D. and 1912. A large moraine, down-valley from the terminus was formed by a late 16th or early 17th century advance and represents the LIA maximum position of Muldrow Glacier. Ice stagnation and retreat followed, but about 150 years ago, this was interrupted by a new surge that deposited a second set of moraines, from ~ 1.5 to 4.5 km behind the 16th or 17th century moraines. The 1957 surge overrode much of the second set of moraines. Vegetation covers the ablating, stagnant ice-cored moraine of the glacier's terminus for a distance of two or more kilometers from the terminus. Since the last surge, the glacier has thinned by tens of meters with little change in terminus position.

At the start of the 'Landsat Baseline Decade,' all of the non-actively surging valley glaciers in the Alaska Range were stagnating, thinning, and/or retreating (Denton and Field, 1975). Several glaciers surged early during the baseline period, but no terminus advances were reported or subsequently documented. At the end of the 20th century and into the early 21st century, all of the valley and outlet glaciers in the Alaska Range continued to thin and/or retreat (Fig. 12). Some glaciers with debris-covered termini, such as Ruth Glacier, have vegetation growing on their near-stagnant termini.

3.4. Wrangell Mountains

The Wrangell Mountains are a large young volcanic massif with a maximum length of about 155 km and width of 85 km. Mount Blackburn (4996 m), Mount Sanford (4,949 m), Mount Wrangell (4317 m), Regal Mountain (4440 m), Mount Jarvis (4091 m), Mount Zanetti (3965 m), Rime Peak (3883 m) and Mount Drum (3661 m) are the highest peaks. Mount Drum and Mount Sanford are separate, nearby volcanic constructs that support a number of glaciers which radiate from their summits. In total, the Wrangell Mountains support about 50 outlet glaciers with lengths of 8 km or more and have an ice-covered area of ~ 5000 km^2. Many of the glaciers surge (Post, 1969).

At the center of the west-central Wrangell Mountains is a broad upland ice field, Wrangell Icefield, covering an area of ~ 750 km^2. It extends eastward from the crater of Mount Wrangell to the head of Nabesna Glacier, a distance of ~ 35 km. It is bounded on the north by Mount Sanford and Mount Jarvis.

Mount Wrangell is the youngest and only currently active volcano in the Wrangell Mountains. Glaciological investigations have been conducted at the its summit since 1961 (Benson, 1968). The 4 × 6 km summit caldera is topped by an ice cap with ice flowing outward in all directions (Benson et al., 1975). The summit caldera's depth approaches 1 km (Benson and Motyka, 1978; Clarke et al., 1989). A prominent feature on the caldera's rim is North Crater, one of the three rim craters. The mean annual temperature at the summit is ~`20 °C, consequently all melting at the summit caldera is by volcanic heat (Benson and Follett, 1986). Annual snow accumulation at the summit is ~ 130 cm of water equivalent (Benson et al., 1975). In 1966, Benson et al. measured a basal ice melt rate of 1.47 cm/d (Benson et al., 1975). Using a conduction-only heat transport model, they calculated that a heat flow of 900–1800 μcal/cm^2/s is necessary to account for the observed melting. They state that this heat flow is ~ 1000 times greater than Earth's average geothermal heat flux. Benson and Motyka (1975) show that the geothermal heat flux had increased significantly since the 27 March 1964 Alaskan Earthquake. They report a melting of $>22 \times 10^6$ m^3 of ice in the North Crater, an order of magnitude increase in the area of exposed rock, and a settling of the glacier surface of up to 160 m since 1964.

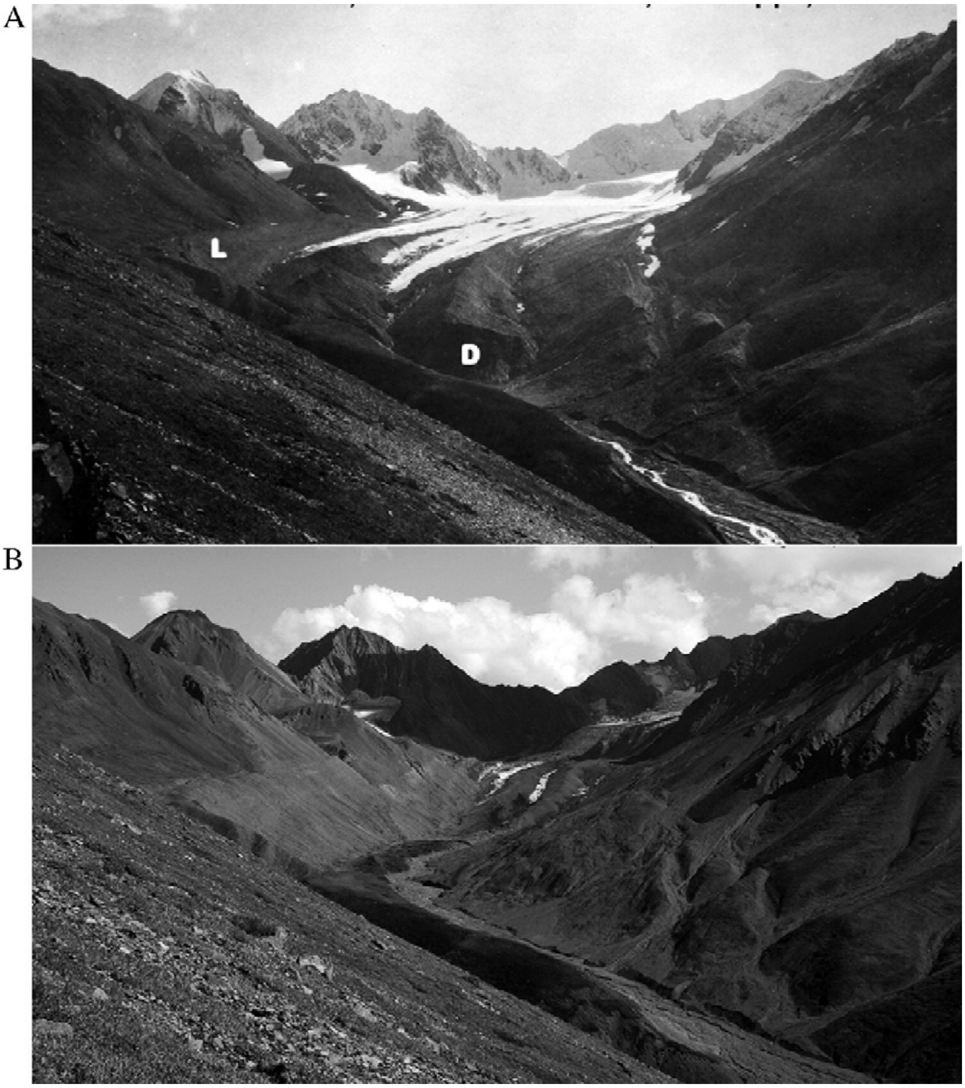


Fig. 12. A pair of north-looking photographs, both taken from the same location near the retreating unnamed valley glacier that heads the East Fork of the Teklanika River, Denali National Park and Preserve. The pair documents changes that have occurred during the 85 years between June 1919 and early August 2004. The 1919 photograph by Stephen Capps (A) shows the then retreating, near-vertical, debris-covered terminus (D) of the glacier having an elevated lateral moraine (L) on its west (left) side. Small tundra plants are the only identifiable vegetation (USGS Photo Library Photograph by Capps). The 2004 photograph (B) by Ron Karpilo, U.S. National Park Service documents the continued thinning and retreat of the unnamed glacier. The glacier has retreated >300 m since 1919, retreating at an average rate of ~ 4 m/yr.

They also report that the average heat flux over the past decade had exceeded 1000 μcal/cm^2/s.

Between 1965 and 1984, Benson and Follett (1986) report that the crater's ice continued to thin, with its surface elevation decreasing by nearly 200 m. They state that between 1965 and 1976, about 3.2×10^7 m^3 of ice was lost to melting and evaporation. In the 20 years between 1965 and 1984, ~ 85% of the crater's ice disappeared. To account for this ice loss, they state that an average volcanic heat flux of 62 W/m^2 is required. This is ~ 1400 times Earth's average heat flux. Elsewhere in the summit caldera, little change has been noted in the surface elevation of the ice cover.

Seasonal studies (Sturm, 1995) and photogrammetric investigations (Sturm et al., 1991) show that the 30-km-long Athna Glacier and the smaller South and Center Mackeith Glaciers have been advancing from 5–18 m/yr since the onset of increased heat flux following the 1964 earthquake. All of Mount Wrangell's other outlet glaciers have remained stationary or retreated. Sturm states that the advancing glaciers display little seasonal variation in surface velocity while other glaciers, such as East and West Chetaslina Glaciers experience a 50% increase in surface velocity in spring and summer. These glaciers have a common accumulation zone located around the North Crater.

Nabesna Glacier, with a length of 87 km with an area of ~ 815 km^2, is the largest of the outlet glaciers and is also the largest inland glacier in North America, with as many as 40 tributaries. Capps (1910) first visited Nabesna's terminus in 1908. At that time the first 3 km of the glacier were covered by thick debris. He states that "The extent of the terminal moraine shows that the glacier is at present retreating. It has been deposited so recently that over most of it no vegetation has as yet obtained a foothold... ." Retreat continues.

During the 'Landsat Baseline Decade,' three glaciers, Athna Glacier and South and Center Mackeith Glaciers, were advancing, apparently in response to non-climatic drivers (Sturm, 1995). All of the other valley and outlet glacier in the Wrangell Mountains were retreating, thinning, or stagnating. At the end of the 20th century and into the early 21st century, no additional information was available about Athna Glacier and South and Center Mackeith Glaciers. All other valley and outlet glaciers in the Wrangell Mountains continued to thin and/or retreat.

3.5. Coast Mountains

The Coast Mountains form the mainland portion of southeastern Alaska, extending for about 690 km from Portland Canal to the south, to Skagway to the north. From east to west, the glacier-covered area of the Coast Mountains is as much as 130 km wide. Included in the Coast Mountains are a number of individual ranges: Peabody Mountains, Rousseau Range, Halleck Range, Seward Mountains, Lincoln Mountains, Buddington Range, Kakuhan Range, Chilkoot Range, Sawtooth Range, and Takshanuk Mountains, all of which support glaciers. To the south, the glaciers are small and sparsely distributed. They increase in size and number to the north. The greatest concentrations of Coast Mountain glaciers are in two icefields, the Stikine and the Juneau Icefields. When mapped in the 1950s, the Coast Mountains had a glacier-covered area of ~ 7250 km^2.

The two best known and studied glaciers of the Coast Mountains are the Mendenhall and Taku Glaciers. Mendenhall Glacier, a terrestrial glacier with a length of ~ 20 km and an area of ~ 100 km^2, has retreated more than 5 km from its LIA maximum position. Its post-LIA behavior is similar to more than 2 dozen other Juneau Icefield outlet glaciers. Lawrence (1950) determined that Mendenhall's retreat began between 1767 and 1769 and that by 1910, the terminus had retreated about 1500 m, an average retreat rate of about 10 m/yr. This period of retreat included a readvance that tilted trees in the mid-1800s. Between 1910 and 1949, the last year of Lawrence's field investigation, the glacier had retreated another 1.5 km, at an average rate of nearly 40 m/yr. Near the beginning of the 20th century, the continuing retreat began to expose a bedrock basin which became the location of an ice-marginal lake that fronted the central portion of the glacier's terminus. Through about 1940, ongoing retreat exposed more of the basin and enlarged the lake. One reason for the significant difference in pre-1910 versus post-1910 retreat rates is the addition of calving as a means of ice loss. Previously, with a land-based terminus, ignoring sublimation, only melting was responsible for ice loss. With the development of the ice-marginal lake, a single calving event could remove a volume of ice from the glacier's terminus equal to what otherwise would take weeks or months to loose by melting. Mendenhall Glacier continues to retreat. Calving is the most significant cause of retreat of the lacustrine portion of the glacier, while melting is responsible for the continuing thinning and retreat of the land-based part of the glacier.

Taku Glacier is 60-km-long, with an area of about 860 km^2. It was advancing during the Landsat baseline period, then stable for about a decade, and then began to readvance at the start of the 21st century. The terminus of Taku Glacier advanced 7 km between 1890 and 1990. It also was overriding moraines and outwash of Norris Glacier, located to its southwest. At the end of the 19th century, when the recent advance of Taku began, it was a tidewater calving glacier with depths in its fiord exceeding 100 m. When photographed by the Alaska Aerial Survey Expedition in the late 1920s, the terminus was still tidewater. Sediment produced and transported by the advancing glacier began filling upper Taku Inlet, so that by the mid-1930s, ships that previously had access to the terminus of the glacier could not enter the Inlet. About 1937, Taku Glacier's advancing terminus began forming a push moraine that protected the terminus and restricted calving. This phase of advance continued until about 1988.

Following more than a decade of stability, the terminus began to advance. Motyka et al. (2001) report that between late 2000 and the summer of 2001, Taku Glacier began to readvance at a rate of 30 cm/d. The advance caused a striking deformation of adjacent proglacial sediments. Compression by the advancing ice has caused the outward propagation of at least two prominent bulges: the more distal (width 35 m, height 3 m) at a rate of about

10 cm/d; and the more proximal (width 80 m, height 4.5 m) at a rate of 15 cm/d. There are no visible thrust faults in the sediments, but shear must be occurring as part of bulge propagation. While stationary during the 1990s, the terminal region continued to thicken, with surface elevation rising at an average rate of 1.4 m/yr. Previous work showed that this glacier is actively excavating soft sediments and entrenching itself into these sediments as its terminus continues to grow and advance. When observed by the author between 2004 and 2006, the central part of Taku Glacier's terminus was continuing to advance, while its lateral margins were experiencing a small amount of retreat (Fig. 13).

Nolan et al. (1995) used radio-echo sounding and seismic reflection techniques to measure Taku Glacier's ice thickness and bed morphology. The maximum ice thickness they measured was about 1477 m and the minimum bed elevation was about 600 m below sea level. They determined that the sub-sea level basin that underlies the glacier extends about 50 km up-glacier. Future retreat of the glacier would expose a deep fiord basin extending well into the Coast Mountains. They also compared the surface elevation in 1989, the date of their survey with the 1948 surface elevation determined from photogrammetry. They state that the glacier had thickened by "10–25 m over the past 40 years," but

A

B

Fig. 13. Two June 19, 2004 photographs of the terminus of Taku Glacier. (A) shows the advancing central part of Taku's terminus, where the glacier is in contact with a vegetated bar, while (B) shows Taku Glacier's eastern margin where the glacier appears to be thinning and has a conspicuous trimline. Photographs by Bruce F. Molnia.

measurement of differences of 1948 versus 1989 surface elevations from their Fig. 4 shows thickening of more than 100 m on the northeast side of the transect. Regardless of the actual amount of thickening, the positive mass balance, so close to the glacier's terminus is significant.

Herbert and Eagle Glaciers, located immediately north of the Mendenhall Glacier have similar retreat histories to that of the Mendenhall Glacier. Both developed ice-marginal lakes during late 20th century retreat. As was the case of the Mendenhall Glacier, retreat rates increased due to calving. The development of an ice-marginal lake during retreat, due to exposure of a previously deepened part of the glacier's bed that fills with water, is not uncommon in the retreat of other terrestrial Alaskan glaciers.

During the first 2/3 of the 20th century (1902–1964), Chickamin Glacier (25 km long with an area of ~ 140 km^2), retreated more than 2.7 km by melting, an average retreat rate of ~ 44 m/yr (Field, 1975d). Sometime after it was mapped (USGS, 1955) and August 1979, when it was photographed by the Alaska High-Altitude Aerial Photography Project (AHAP), it retreated about a kilometer and formed an ice-marginal lake. During the last two decades of the 20th century, it retreated > 1.5 km. Retreat continues and it is currently forming a new ice-marginal lake. Since 1902, Chickamin Glacier has retreated ~ 5.2 km, with an average retreat rate of > 50 m/yr.

LeConte Glacier, the southernmost tidewater glacier in the Northern Hemisphere, has a length of about 35 km, an area of 487 km^2, and ice speeds near its terminus of up to 23 m/d (Post and Motyka, 1995; Echelmeyer and Motyka, 1997). At the end of the 20th century, LeConte Glacier had an extremely active calving terminus, producing large quantities of icebergs from a 50 m high face. Between 1887, when it was first charted, and 1963, LeConte

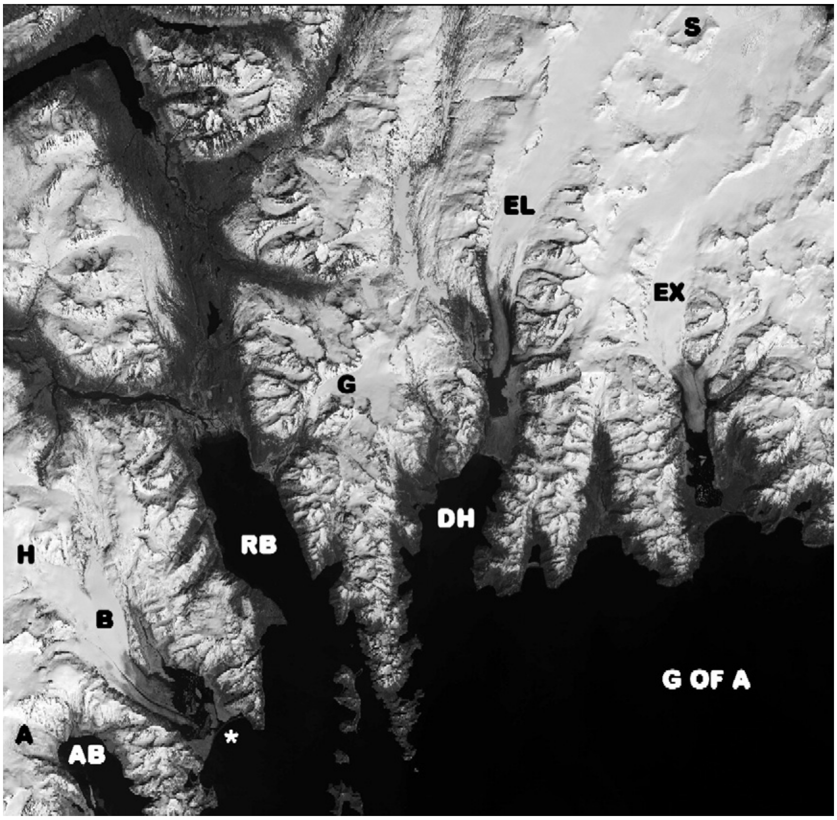


Fig. 14. A June 9, 2001 ASTER Level 1B panchromatic scene (AST_L1B_003_06092001214033_06182001095021) showing part of the southeastern Kenai Mountains, including parts of the Sargent (S) and Harding (H) Icefields. Among the larger glaciers present are Excelsior Glacier (EX), Ellsworth Glacier (EL), Godwin Glacier (G), Bear Glacier (B), and Aialik Glacier (A). Of the annotated glaciers, all except Aialik Glacier are rapidly retreating. Aialik Glacier is retreating very slowly and currently is within 200 m of its 1909 position. Excelsior and Ellsworth Glaciers are the two largest outlet glaciers of the southern Sargent Icefield. Resurrection Bay (RB) and Day Harbor (DH) are fiords that have been glacier-free since the Pleistocene. At that time, greatly expanded glaciers covered much of the Gulf of Alaska (G OF A) continental shelf. Godwin Glacier extended to near the east shore of Resurrection Bay during the 18th century (Davidson, 1904). Aialik Glacier expanded into Aialik Bay (AB) during the Little Ice Age. The white star (*) marks the location from which the photograph in Fig. 16 was made.

Glacier retreated 3.7 km (Post and Motyka, 1995). This was followed by a period of terminus stability from 1963 to 1994. Between 1994 and 1998, the glacier retreated an additional 2 km, much of it by submarine calving (Echelmeyer and Motyka, 1997; Hunter et al., 2001). When observed by the author in 2003, it was continuing to calve and retreat.

During the 'Landsat Baseline Decade,' Baird Glacier (50-km-long with an area of about 785 km^2), Taku Glacier (60-km-long with an area of about 700 km^2), Hole-in-the-Wall Glacier (a distributary lobe of Taku Glacier), and Mead Glacier (37-km-long with an area of about 400 km^2) were advancing. Available evidence suggests that all other valley and outlet glaciers in the Coast Mountains were thinning and retreating. At the end of the 20th century, Taku Glacier was advancing and Hole-in-the-Wall Glacier was stable. Since 1979, Mead Glacier retreated ~ 2 km and formed an ice-marginal

A

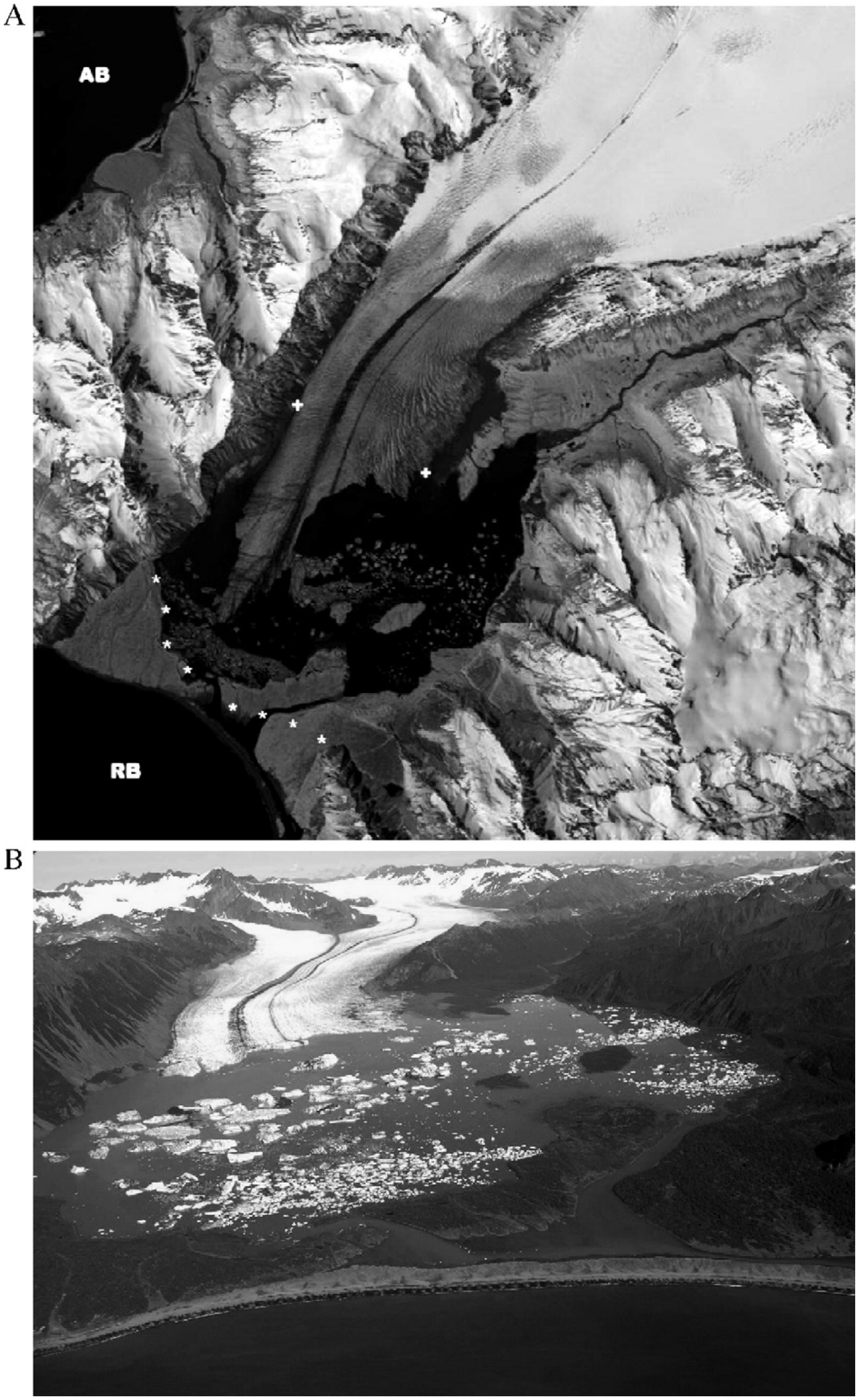
B

Fig. 15. A pair of northeast-looking photographs taken from about 8 km north of the mouth of McCarty Fjord, Kenai Fjords National Park. The pair documents changes that have occurred during the 95 years between July 30, 1909 and August 11, 2004. The 1909 photograph (A) by U.S. Grant shows the east side of the terminus of the then retreating McCarty Glacier, a tidewater glacier. Little, if any vegetation is present on the upper slopes, but beach grass is present in the foreground and trees are present on the back beach to the right (USGS Photo Library Photograph by Grant #143). The 2004 photograph (B) shows part of the retreated McCarty Glacier, more than 16 km up bay. Much of the retreat occurred prior to 1970. Dense, diverse vegetation, featuring alder, willow, and spruce, have become established on the hill slopes and back beach areas (photograph by Bruce F. Molnia).

lake. All other valley and outlet glaciers in the Coast Mountains were thinning and retreating. When observed between 2004 and 2006, Taku Glacier showed evidence of continuing retreat in its central terminus region.

3.6. Kenai Mountains

The Kenai Mountains (Fig. 14), with maximum elevations approaching 2000 m, are a 195-km-long by 35-



km-wide mountain range. Most of the Kenai Mountain glaciers descend from two large icefields, the Sargent and the Harding Icefields, and two smaller icefields, the Blackstone-Spencer and the Grewingk-Yalik Icefields. A number of other, generally smaller, glaciers descend from other isolated accumulation areas along the crests of many ridges and mountains. Combined, the Sargent and the Harding Icefields cover more than 4000 km^2 and have glaciers that descend into Prince William Sound, Cook Inlet, and Gulf of Alaska drainages. Many glaciers reach to near sea level, and more than a dozen have calving termini, eleven directly into tidewater. This region contains several hundred glaciers with nearly all of the larger glaciers having names. Seven have lengths of about 20 km, while two exceed 30 km.

During the 'Landsat Baseline Decade,' the Kenai Mountains had a glacier-covered area of ~ 4750 km^2. With the exception of Aialik Glacier (~ 18 km long with an area of ~ 120 km^2) and McCarty Glacier (~ 13 km long with an area of ~ 110 km^2), all of the valley and tidewater glaciers in the Kenai Mountains were stagnating, thinning, and/or retreating. Aialik and McCarty Glaciers each advanced more than 500 m during the second half of the 20th century. However, when observed between 2004 and 2006, both were retreating. By the end of the 20th century, all of the valley and outlet glaciers in the Kenai Mountains were thinning, stagnating, and/or retreating. When observed in 2000, Tiger Glacier was at about the same location as it was in 1908. Having been in retreat since about 1960 (Field, 1975c), Tiger Glacier must have experienced a late 20th century advance to regain its former position. McCarty Glacier (Fig. 15), a tidewater glacier located at the head of McCarty Fiord, was first mapped in 1909 by Grant and Higgins (1913). It retreated about 3.2 km between 1909 and 1927, retreated another 19 km between 1927 and 1950, and another 1.4 km through 1978. Between 1978 and the middle 1990s the terminus advanced ~ 700 m. Adalgeirsdottir et al. (1998) report that between the 1950s and middle 1990s, McCarty Glacier ice volume increased by 1.5 km^3 and its average elevation increased by 6.2 m. Since the mid-1990s it has retreated >250 m.

Anchor and Ogive Glaciers are two very small reconstituted glaciers in Northwestern Fiord. Each, a former tributary to Northwestern Glacier reaches tidewater. Both advanced a few meters between 2004 and 2005. Bear (Fig. 16), Ellsworth, and Excelsior Glacier are three large, lake terminating valley glaciers that are located adjacent to Resurrection Bay. Early in the 20th century, each had a terrestrial terminus. Subsequent retreat exposed deeply eroded segments of their beds which became ice-marginal lakes at each glacier. Rapid retreat has followed.

3.7. Brooks Range

The Brooks Range, the northernmost mountain group in Alaska, extends for nearly 1000 km in an east–west direction from the Yukon Territory, Canada–Alaska border, on the east to the Chukchi Sea on the west. The Brooks Range forms the drainage divide between the Arctic Slope to the north, and the Kobuk and Yukon Rivers to the south. The Brooks Range contains about a dozen named, generally east–west-trending, contiguous, mountain ranges. Glaciers exist within the eastern and central Brooks Range, spanning a distance of about 650 km. They are found in the Romanzof Mountains, the Franklin Mountains, the Philip Smith Mountains, the Endicott Mountains, and the Schwatka Mountains.

The largest glaciers and the greatest concentration of ice are located in the eastern ranges. Because the Brooks Range lies wholly north of the Arctic Circle, glaciers are generally classified as sub-polar. Most glaciers are in steep cirques with a northern exposure. Two of the three highest peaks in the Brooks Range, Mount Isto (2761 m), and Mount Michelson (2699 m) are in the Romanzof Mountains, Mount Chamberlin (2750 m), the second highest peak, is in the Franklin Mountains. A recent inventory of Brooks Range glaciers by the USGS (Suzanne Brown, personal communication, 1992) identified 1001 glaciers, with a total area of 723 km^2.

The 105-km-long Romanzof Mountains have a glacier-covered area of about 260 km^2, contain at least 188 glaciers (Evans, 1977); at least four of which have lengths of 5 km or more. Wendler (1969) determined that no glacier ice existed below an elevations of 1500 m, and that at least 66% of the glaciers are on north-facing slopes. Two, 8.3-km-long Okpilak Glacier and 7.6-km-long McCall Glacier, provide significant information about 20th century glacier fluctuations and related changes.

Fig. 16. A pair of images showing recent changes in the terminus of Bear Glacier. (A) is a ~ 10 km by 20 km portion of a June 9, 2001 ASTER Level 1B panchromatic scene (AST_L1B_003_06092001214033_06182001095021), showing the lower part of Bear Glacier and adjacent Resurrection Bay (RB). The line of stars (*) marks the glacier's early 20th century terminus position. During the 1990s, Bear Glacier began to retreat rapidly through the loss of large tabular pieces of ice from its terminus and lateral margin, a process known as disarticulation. Aialik Bay (AB) is in the upper left part of the image. A line drawn between the two white plus signs (+) marks the approximate location of Bear Glacier's terminus as shown in (B). (B) is an August 6, 2005 oblique aerial photograph by Bruce F. Molnia of the lower part of Bear Glacier. Between June 2001 and August 2005, the glacier retreated nearly 3 km. Much of the retreat was through the loss of large tabular pieces of ice, such as seen here. The largest pieces are >300 m in maximum dimension.

Okpilak Glacier, photographed by Leffingwell in 1907 (Hamilton, 1965), descends from an unnamed 2435-m-high mountain, about 18 km south of Mount Michelson. In 1958, Sable (1960) examined a number of glaciers in the Romanzof Mountains and revisited several photographic sites occupied by Leffingwell at Okpilak Glacier. Comparative photographs document that the glacier retreated more than 300 m in the intervening 51 years. Sable (1960) reports that, in 1956–1958, Okpilak Glacier's lateral moraines were 45 m to 63.5 m above the edges of the glacier. In 1907, they ranged from being level to 6 m above the ice. Sable found that the average thinning in the lower 2.3 km of the glacier was ~ 45 m and the mean rate was ~ 0.9 m/yr. Hence, Okpilak Glacier had thinned from 33 m to 69.5 m (0.65–1.35 m/yr) between 1907 and 1958. Sable also found that the ratio of ice lost to thinning versus the ice lost by recession of the terminus was roughly at least 25:1. Sable (1960) further states that, "All the smaller glaciers in the vicinity of Okpilak Glacier, for which photographic information from 1907 and 1958 can be compared, show evidence of marked recent recession and thinning." Significant retreat has continued to the present (Matt Nolan, December 2004, University of Alaska Fairbanks, personal communication).

During the 'Landsat Baseline Decade,' all Brooks Range glaciers were thinning and retreating. These conclusions are based on published field descriptions and a comparison by the author of the size and number of glaciers shown on pre-'Landsat Baseline Decade' USGS topographic maps and 1982 AHAP photography from the end of the baseline period. Limited information is available about behavior at the end of the 20th century and into the early 21st century. However, every glacier described showed significant evidence of thinning and retreat.

3.8. Aleutian Range

The Aleutian Range extends northeast–southwest along the spine and southeast side of the Alaska Peninsula for nearly 1000 km. The range contains more than 30 glaciers with lengths of 8 km or more; one, Blockade Glacier is 44 km long. Glaciers cover an area that exceeds 2600 km^2 (Molnia, 1982). During the 'Landsat Baseline Decade,' all of the larger valley glaciers in the Aleutian Range were stagnating, thinning, and/or retreating. Brabets et al. (2004) examined a number of smaller glaciers in the Tlikakila River Basin of Lake Clark National Park and Preserve and found a complex pattern of advance and retreat in adjacent glaciers. They analyzed 86 small unnamed glaciers, of which 64 were mapped in 1957, photographed in 1978, and imaged by Landsat 7 in 1999. Of the 64, between 1957 and 1978, 21 advanced (33)%, 8 were stable (12%), and 35 retreated (55%). Between 1978 and 1999, 7 advanced (11)%, 3 were stable (5%), and 54 retreated (84%). The average terminus advance/retreat rate increased from a retreat of 4 m/yr in the 1957–1978 period to a retreat of 14 m/yr between 1978 and 1999. Nearby, the three largest glaciers in the area retreated during the period between 1957 and 2001. Tanaina Glacier retreated 1210 m (31 m/yr), Glacier Fork Glacier (Fig. 17) retreated 587 m (13.3 m/yr), and North Fork Glacier retreated 454 m (10.3 m/yr).

At the end of the 20th century and into the early 21st century, all of the larger valley and outlet glaciers in the Aleutian Range continued to thin and/or retreat, while several of the smaller Tlikakila River Basin glaciers may have continued to advance (Brabets et al., 2004). When observed by the author in 2000, Tuxedni Glacier showed some evidence of a recent terminus advance. However, trimlines and abandoned moraines documented a long-term history of retreat and thinning.

The 1912 eruption of Mount Katmai melted and beheaded a number of summit and flank glaciers (Griggs, 1992). Following the eruption, two small glaciers formed within the crater on the talus beneath the crater rim. They continued to exist throughout the baseline period and into the early 21st century. Similarly, following the 1989–1990 eruption of Mount Redoubt, snow and glacier ice have reformed in its crater, replacing snow and ice melted during the eruption.

3.9. Aleutian Islands

The Aleutian Island chain, the 1900-km-long island arc which separates the Pacific Ocean from the Bering Sea, extends westward from False Pass at the western end of the Alaska Peninsula to longitude ~ 172° E., north of eastern Russia. The islands support 57 volcanoes of which 27 are active. At least 10 islands in the eastern and central part of the arc (Unimak, Akutan, Unalaska, Umnak, Yunaska, Atka, Great Sitkin, Tanaga, Gareloi, and Kiska Islands) had glaciers when topographically mapped. All of the mapped glaciers descended from the summits of active or dormant volcanoes, extending into calderas or flowing down their flanks. All headed at elevations > 1200 m.

During the 'Landsat Baseline Decade,' the Aleutian Islands had a glacier-covered area of < 3000 km^2. Limited information exists about the behavior of these glaciers during the "Baseline" or at the end of the 20th century and into the early 21st century. However, based on their small size, low elevation, and generally southerly location in an area with significant late 20th

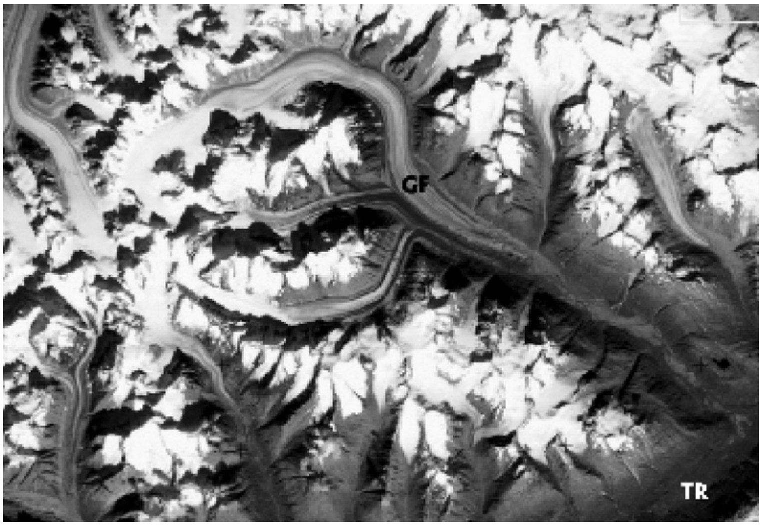


Fig. 17. A 24 km by 33 km portion of the Lake Clark National Park, 25-m resolution, 1:250,000-scale Satellite Image Map, produced by Michael D. Fleming from Landsat 7 imagery collected on September 6, 1999 (Fleming, 2000). Shown is part of the Tlikakila River (TR) Basin, an area where a number of small glaciers have recently been advancing. Between 1978 and 1999, Glacier Fork Glacier (GF), the large glacier in the center of the image retreated 587 m, retreating at an average rate of 13.3 m/yr.

century temperature increases, it is likely that they have continued to thin and retreat. Some may have melted away.

3.10. Talkeetna Mountains

The 160-km-long by 130-km-wide Talkeetna Mountains have their long axis oriented in a north–south direction. Many peaks have summit elevations >2000 m; the highest, an unnamed peak, reaches an elevation of 2550 m. Photographs of glaciers in the Talkeetna Mountains taken by Stephen Capps between 1913 and 1917 show many retreating glaciers. This is a trend that has continued through the early 21st century. Comparing aerial photographs taken by the author with Capps' photographs, it can be seen that an unnamed glacier at the head of Iron Creek, informally named Iron Creek Glacier, retreated ~ 4 km between August 1917 and August 2000. Collins (1971) states that, "It can reasonably be deduced that general recession has been the rule here in recent decades, and that climatic changes have caused a significant rise in the lower limit at which accumulation can take place. At present this lower limit of accumulation seems to be generally higher than 1850 m."

When mapped between 1951 and 1954, more than 100 glaciers were located on the southwestern flank of the mountains, generally heading at elevations above 1800 m. Seven had lengths of more than 8 km. The longest, an unnamed glacier, informally named South Sheep River Glacier (17.5 km long with an area of ~ 75 km^2) has been retreating since first mapped. Chickaloon Glacier (14.5 km long with an area of 32 km^2), and Talkeetna Glacier (11.6 km long with an area of 33 km^2), both have retreating termini that were covered with thick ablation moraines. Observations by the author suggest that these glaciers have lost as much as 5 km of their lengths since 1951–1954.

McCauley (1958) made planimetric measurements of all of the glaciers in the Talkeetna Mountains, using USGS 1:63,360-scale topographic maps prepared between 1948 and 1958. He calculated that the total glacier-covered area was about 300 km^2. The seven largest glaciers had a cumulative area of 212 km^2, accounting for ~ 2/3 of the total area. These seven glaciers had termini elevations at between 1460 m and 885 m. Recent observations by the author show that every one of these glaciers has retreated, some more than 3 km, and suggest that the Talkeetna mountains have lost as much as 20% of its glacier coverage since 1948–1958.

Limited revisions made in 1983 by the USGS to the 1954 Talkeetna Mountains 1:250,000-scale topographic map, based on aerial photography obtained in 1978, 1980, and 1981, show that at least 50 glaciers east of the Talkeetna and Chickaloon Rivers either decreased significantly in area or completely melted away. Similarly, almost all of the large glaciers west of the two rivers show retreat and shrinkage. An aerial survey by the author on 31 August 2000 of the entire glacier-covered Talkeetna Mountains documented that all of its valley glaciers were conspicuously thinning and retreating.

During the 'Landsat Baseline Decade,' the Talkeetna Mountains had a glacier-covered area of <300 km^2. All evidence available suggests that the glaciers of the Talkeetna Mountains were thinning, retreating, and/or stagnating. These conclusions are based on a comparison of the size and number of glaciers shown on topographic maps made from 1948–1952 data and AHAP photography from the middle of the baseline period (1977) and just after the "Baseline" interval (1983). When observed at the end of the twentieth century (31 August 2000), every glacier examined showed significant evidence of thinning and retreat. Many smaller glaciers had completely disappeared.

3.11. Ahklun and Wood River Mountains

The Ahklun and Wood River Mountains of southwestern Alaska have maximum elevations of ~ 1500 m. They are a northeast- to southwest-trending mountain range with a length of ~ 160 km and a width of ~ 50 km; extending from Bristol Bay to Chikuminuk Lake. Manley (William Manley, University of Colorado, personal communication, December 2000) examined all 106 glaciers that exist in the area and quantified 32 different parameters for these glaciers. He found that the total glacier-covered area was ~ 60 km^2 and that individual glaciers ranged in area from 0.05 km^2 to 6.4 km^2 with a median area of 0.26 km^2. They ranged in average elevation from 581 m to 1176 m with a median elevation of 937 m; ranged in length from 0.25 km to 4.38 km, with a median length of 0.61 km; ranged in width from 0.17 km to 2.97 km, with a median width of 0.72 km; and ranged in perimeter from 1.0 km to 23.8 km, with a median perimeter of 2.6 km. The equilibrium line altitudes (ELAs) ranged from 545 m to 1,155 m, averaging 929 m and displayed high local variability.

Chikuminuk Glacier, the longest glacier in the Wood River Mountains was mapped during the International Geophysical Year (American Geographical Society (AGS), 1960). At that time, it was 5.5-km long, 1.0-km wide, had an area of 5.77 km^2, and was retreating. More than 75% of the glacier was located at elevations above ~ 1000 m. When photographed in 1957, the terminus region exhibited much evidence of rapid retreat. The entire surface of the glacier was bare ice, with only a very small accumulation area. Elevated trimline positions indicated that Chikuminuk Glacier was thinning. On 11 May 1996, Chikuminuk Glacier was resurveyed with a geodetic airborne laser altimeter system (Sapiano et al., 1998). Interpretation of altimeter profiles show that the terminus had retreated by 830 m during the 39 years between surveys, an average annual retreat rate of 21.2 m/yr, the glacier's area had decreased by ~ 9% (from 5.77 km^2 in 1957 to 5.33 km^2 in 1996). Of the 9 glaciers mapped during the IGY, the retreat rate of the terminus of Chikuminuk Glacier was the greatest. At an elevation of ~ 480 m, during the 39 yr period between surveys, the glacier thinned as much as ~ 42 m. Above an elevation of ~ 1075 m, the glacier thickened by an average of ~ 10 m. Sapiano et al. (1998) state that a comparison of 1957 and 1996 volumes suggests the total volume of the glacier increased by 8×10^6 m^3; however, because of differences in methods, there is a large uncertainty in this number.

With the exception of Chikuminuk Glacier, lack of recent information makes it difficult to accurately determine the recent health of other Wood River Mountains glaciers. However, based on 1984 photography, the glaciers near Mount Waskey have actively thinned and retreated during the 'Landsat Baseline Decade.'

3.12. Alexander Archipelago

Glaciers are shown in mountainous areas on mid-20th century, USGS 1:250,000-scale topographic maps on six of the islands of the Archipelago: Revillagigedo Island, Prince of Wales Island, Kupreanof Island, Baranof Island, Chichagof Island, and Admiralty Island. Many of these glaciers were photographed from the air during the late 1920s. During the 'Landsat Baseline Decade,' the Alexander Archipelago had a glacier-covered area of <150 km^2. Most glaciers were located on Baranof Island. Most glaciers were very small, with areas less than 1 km^2. All of the glaciers in the Alexander Archipelago were thinning and retreating. Aerial observations by the author between 1999 and 2001 document that by the end of the 20th century, many of these smaller glaciers may have melted away.

3.13. Kodiak Island

Kodiak Island is located in the western Gulf of Alaska, south of Cook Inlet and east of Shelikof Strait. It has a length of about 160 km, and a maximum width of nearly 100 km. Kodiak Island is the largest island in Alaska. The USGS Kodiak, Alaska, 1:250,000-scale Topographic Map (USGS, 1952), based on 1948–1952 observations and photography, shows more than 40 cirque glaciers, mostly in a narrow upland region located on the mountainous backbone of the island between Koniag Peak (1362 m) to the south and Mount Glottof (1343 m) to the north and in adjacent drainages. When mapped, the largest glacier, Koniag Glacier, the only named glacier on the island, was about 2.5 km in length. It descended to elevations <500 m. One cluster of five glaciers occurred ~ 12 km southwest of Koniag Peak at the head of an unnamed tributary to Uyak Bay. An isolated, unnamed 1 km-long-glacier, the southernmost and westernmost glacier on the island, was located on the west side of an unnamed 1040 m-high peak, ~ 32 km southwest of Koniag Peak and 6 km north of Deadman Bay.

During the 'Landsat Baseline Decade,' Kodiak Island had a glacier-covered area of <100 km^2. All of the glaciers of Kodiak Island were thinning and retreating. This is based on a comparison of the size and number of glaciers shown on Kodiak's USGS topographic maps made from 1948–1952 data and AHAP photography from the middle of the baseline period (1977–1978). No information exists about the behavior of these glaciers at the end of the 20th century and into the early 21st century. However, based on their small size, low elevation, and location on an island experiencing a significant temperature increase, surrounded by temperate ocean water, it is likely that they have continued to thin and retreat. Some may have melted away.

3.14. Kigluaik Mountains

The only glaciers on the Seward Peninsula are located in the 65 km-long, east–west trending Kigluaik Mountains. There, as recently as 1986, 3 glaciers existed on 1437-m-high Mount Osborn and adjacent peaks, about 50 km north of Nome. Glaciers of the Kigluaik Mountains were investigated by Brooks in 1900 (Brooks, 1901), Henshaw and Parker in 1909 (Henshaw and Parker, 1913), and Kaufman and his students in the late 1980s (Kaufman et al., 1989; Calkin et al., 1998). These investigations document that glaciers existed in the Kigluaik Mountains through the late 1980s and that during the 20th century several glaciers completely disappeared. When last observed, the three remaining glaciers, Grand Central Glacier, Thrush Glacier, and Phalarope Glacier had a collective area of significantly less than 3 km^2 and were decreasing in area and length.

4. Discussion

As is described above, the general thinning and retreat of lower-elevation temperate glaciers is one of the most visible manifestations of the Post-LIA response of Alaskan glaciers to changing regional climate. As the regional summaries of Alaskan glacier behavior presented here document, most Alaskan mountain glaciers at lower elevations are thinning and/or retreating in response to a significant Post-LIA regional warming. In fact, of the glaciers described in the *Alaska* chapter of the *Satellite Image Atlas of the Glaciers of the World* (Molnia, in press), more than 98% are currently thinning and/or retreating.

Of those lower-elevation glaciers that are currently advancing, with the exception of South Crillon Glacier, an advancing lake-terminating glacier, and the small-advancing glaciers in the Aleutian Range reported by Brabets et al. (2004), all are marine tidewater or former tidewater glaciers. If fact, in 2005, 10 tidewater or former-tidewater glaciers were advancing. From west to east, they are Anchor, Ogive, Harvard, Meares, Hubbard, Lituya, North Crillon, Lamplugh, Johns Hopkins, and Taku Glaciers. However, since the late 19th century more than 50 glaciers have retreated from tidewater to the terrestrial environment. Some have disappeared.

As has also been shown, every Alaskan glacier has its own complex history and behavior. There is both local and regional variability. For example, many southeast Alaskan glaciers, such as most of the glaciers of the Glacier Bay and the Lynn Canal areas began to retreat as early as the mid-18th century, some more than a century before the advent of measurable air temperature change, while others in the same location advanced during that entire period.

Essentially all Alaskan mountain glaciers are temperate, meaning that meltwater exists in, on, or under the glacier for part, if not all of the year. Globally, temperate mountain glaciers are excellent indicators of climate change and are shrinking on all continents which host them. Hence, small changes in temperature and precipitation do have a significant impact on the health of these glaciers. Ongoing glacier melting is, and will continue to substantially reduce the length, area, thickness, and volume of Earth's temperate mountain glaciers. As Alaskan glaciers melt, their meltwaters flow into the Gulf of Alaska, and the Bering, Chukchi, and Beaufort Seas, contributing to sea level rise.

Many investigations have examined the role that temperate glaciers play in present and future sea-level change, with most of the attention on the last five decades of the twentieth century (NRC, 1977, 1983; Meier, 1984; NRC, 1985, 1990; Meier, 1990; Dyurgerov and Meier, 1997a,b; Meier, 1998; Dyurgerov and Meier, 1999, 2000; Bahr and Meier, 2000; Dyurgerov and Dwyer, 2000; Arendt et al., 2002; Meier and Dyurgerov, 2002; Meier and Wahr, 2002). Nearly all of these reports state that if all the remaining non-polar (temperate) glacier ice were to melt, a sea-level rise of < 1 m would result. Of the ~ 4% of Earth's land ice that is made up of mountain glaciers, Alaskan glaciers cover <1 / 10th, or <0.4%.

Meier (1984) documented that the glaciers of the Alaskan coastal region may contribute >1 / 3 of the total meltwater entering the global ocean. As current climate models predict future temperature increases, these glaciers may make even larger contributions to future rising sea level. To quantify the role of Alaskan glaciers to global sea-level change, Arendt et al. (2002) synthesized the results of laser altimeter thickness change studies of 67 glaciers in Alaska and adjacent Canada. The glaciers they investigated have an area of ~ 18×10^3 km^2 and represent ~ 20% of the glacier-covered area of Alaska and adjacent Canada. Their sample included a dozen tidewater calving glaciers, nearly a half-dozen lacustrine terminating glaciers, and ~ 50 land-terminating glaciers. Six were surging glaciers. Glaciers they investigated are located in nine of the fourteen regions described in this paper. None of the glaciers they investigated were located in the Talkeetna Mountains, Kigluaik Mountains, Alexander Archipelago, Kodiak Island, or Aleutian Islands. They extrapolated their measured thickness changes within each geographic region of Alaska and Canada investigated to all unmeasured glaciers in that region to quantify estimates of the contribution of 'Alaskan' glaciers to rising sea level. As they define it, 'glaciers in Alaska and neighboring Canada' cover an area of ~ 90,000 km^2 or ~ 13% of Earth's mountain glacier area. They estimate the total annual volume change of Alaska glaciers, expressed as water equivalent, to be -52 ± 15 km^3/yr for the period from ~ 1950 to 1993, and -96 ± 35 km^3/yr for the post-1993 period. These volumes are equivalent to a rise in sea level of 0.14 ± 0.04 mm/yr during the early period and 0.27 ± 1 mm/yr during the later period. With respect to thickness change, they report that during both periods, most glaciers had negative thickness changes, indicating significant surface lowering. During the recent period glacier thinning was more than twice as much (−1.8 m/yr) as that measured for the same glaciers during the early period (−0.7 m/yr).

The significance of the reported yield of Alaskan glaciers to global sea level can be seen in a comparison with similar data from Greenland. Krabill et al. (2000) report that analysis of aircraft laser altimeter surveys over northern Greenland, conducted in 1994 and 1999, indicates a net loss of ~ 51 km^3/yr of ice per year from the entire Greenland ice sheet. They state that this is sufficient to raise sea level by 0.13 mm/yr, a quantity that is ~ 7% of the observed rise. The estimated annual volume loss during the recent period from Alaska, 96 ± 5 km^3/yr (Arendt et al., 2002) is nearly twice that estimated for the entire Greenland Ice Sheet during the same period.

On a different note, the global baseline of Landsat 1, 2, and 3 glacier information that is presented in the *Satellite Image Atlas of the Glaciers of the World* series represents one of the most significant compilations of cryospheric information in existence. However, as Kargel et al. (2005) show, technological advancements permit the updating and expansion of this Landsat baseline with higher resolution, more sophisticated methodologies, such as those employed by the Global Land Ice Measurements from Space (GLIMS) international consortium. Unlike the retrospective approach applied by the *Satellite Image Atlas of the Glaciers of the World*, the GLIMS consortium actively acquires satellite images of the world's glaciers, analyzes them for glacier extent and changes, and assess change data for causes and implications for people and the environment. As Kargel et al. (2005) point out, although GLIMS is making use of multiple remote-sensing systems, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is optimized for a variety of necessary observations, including mapping of glacier boundaries and surficial materials, tracking of surface dynamics such as flow vector fields, and monitoring the development of supraglacial lakes. Software developed by the GLIMS consortium is designed to map clean-ice and debris-covered glaciers; classify terrain, emphasizing snow, ice, water, and admixtures of ice with rock debris; perform multi-temporal change analysis; visualize images and derived data; and interpret and archive derived data. A global glacier database has been designed at the National Snow and Ice Data Center (NSIDC, Boulder, Colorado), with parameters that are compatible with and expanded from those of the World Glacier Inventory (WGI) of the World Glacier Monitoring Service (WGMS, Zurich, Switzerland).

5. Conclusions

This presentation has summarized the aerial extent and distribution of Alaska's glaciers during the 'Landsat Baseline Decade,' and where possible, both retrospectively and prospectively as well. This informational baseline can be used by present- and future-researchers to document change in the number, length, and area of Alaskan glaciers. The abundant and diverse data presented here clearly document that the glaciers of Alaska are dynamic and that many are rapidly changing, with most at lower elevations thinning and/or retreating. Examples of the dynamic behavior of many Alaskan glaciers are presented, ranging from calving glaciers that have receded a kilometer or more in just a few years, to surging glaciers that have advanced several kilometers during a surge. Through the use of retrospective and prospective data, this presentation has also shown many examples of the dynamic natural behavior displayed by glaciers throughout Alaska.

Key findings include:

Every mountain range and island group investigated is characterized by significant glacier retreat, thinning, and/or stagnation, especially at lower elevations.

All but a few glaciers that descend below an elevation of ~ 1500 m are thinning and/or retreating.

Nearly all of the larger currently advancing glaciers are tidewater or former tidewater glaciers.

At some locations, glaciers have completely disappeared during the 20th century. In some areas, retreat that started as early as the early 18th century is continuing into the 21st century.

At some locations, retreat is resulting in the number of glaciers actually increasing, but the volume and area of ice decreasing.

Glaciers at higher elevations show little or no change.

Of the nearly 700 named Alaskan glaciers, approximately a dozen are currently advancing.

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