Chapter 12: Alaska: Glaciers of Kenai Fjords National Park and Katmai National Park and Preserve

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Popular Summary

Much recent research points to the shrinkage of the Earth's small glaciers, however, few studies have been performed to quantify the amount of change over time. We measured glacier-extent changes in two national parks in southeastern Alaska. There are hundreds of glaciers in Kenai Fjords National Park (KEFJ) and Katmai National Park and Preserve (KATM) covering over 2373 sq km of parkland. There are two primary areas of glaciation in KEFJ – the Harding Icefield and the Grewingk-Yalik Glacier Complex, and three primary areas of glaciation in KATM - the Mt. Douglas area, the Kukak Volcano to Mt. Katmai area and the Mt. Martin area. We performed glacier mapping using satellite imagery, from the 1970s, 1980s, and from 2000. Results of the analysis show that there has been a reduction in the amount of glacier ice cover in the two parks over the study period, of approximately 22 sq km of ice, approximately -1.6% from 1986 to 2000 (for KEFJ), and of approximately 76 sq km of glacier ice, or about -7.7% from 1986/87 to 2000 (for KATM). In the future, measurements of surface elevation changes of these ice masses should be acquired; together with our extent-change measurements, the volume change of the ice masses can then be determined to estimate their contribution to sea-level rise. The work is a continuation of work done in KEFJ, but in KATM, our measurements represent the first comprehensive study of the glaciers in this remote, little-studied area.

GLIMS
Chapter 12: Alaska: Glaciers of Kenai Fjords National Park and Katmai National Park and Preserve

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Kenai Fjords National Park and Katmai National Park and Preserve

ABSTRACT

There are hundreds of glaciers in Kenai Fjords National Park (KEFJ) and Katmai National Park and Preserve (KATM) covering over 2373 sq km of park land. There are two primary areas of glaciation in KEFJ – the Harding Icefield and the Grewingk-Yalik Glacier Complex, and three primary areas of glaciation in KATM - the Mt. Douglas area, the Kukak Volcano to Mt. Katmai area and the Mt. Martin area. Most glaciers in these parks terminate on land, though a few terminate in lakes. Only KEFJ has tidewater glaciers, which terminate in the ocean. Glacier mapping and analysis of the change in glacier extent has been accomplished on a decadal scale using satellite imagery, primarily Landsat data from the 1970s, 1980s, and from 2000. Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery was used to map glacier extent on a park-wide basis. Classification of glacier ice using image processing software, along with extensive manual editing, was employed to create Geographic Information System (GIS) shapefiles of the glacier extent for each park. Many glaciers that originate in KEFJ but terminate outside the park boundaries, were also mapped. Results of the analysis indicate that there has been a reduction in the amount of glacier ice cover in the two parks over the study period of approximately 22 sq km of glacier ice, approximately -1.6% from 1986 to 2000 (for KEFJ), and of approximately 76 sq km of glacier ice, or about -7.7% from 1986/87 to 2000 (for KATM). Issues that complicate the mapping of glacier extent include: debris-cover (moraine and volcanic ash), shadows, clouds, fresh snow, lingering snow from the previous season, and differences in spatial resolution between the MSS abd TM or ETM+ sensors.

Keywords: Glaciers; Harding Icefield; Landsat; Katmai; Kenai Fjords; National Park

INTRODUCTION

Glaciers represent a significant landcover type in Kenai Fjords National Park (KEFJ) and Katmai National Park and Preserve (KATM). Any change in this landcover type will have impacts on the ecosystems of these parks. The glaciers are also intricately related to climate and are indicators of regional climate change. In general, land-based glaciers are known to be generally responsive to short-term climate change (however, there are many exceptions to this). Tidewater glaciers are known to have a cycle that is not necessarily directly related to short-term climate change (Meier and Post, 1987). Glaciers also influence local climate because of their high reflectivity. Alaska glaciers are also important contributors to global sea-level rise (Dyurgerov and Meier, 1997; Arendt et al., 2002). To improve our understanding of the extent and rate of change of the glacier movements, an effort to map the glacier extent, on a decadal scale, was initiated in the National Park Service (NPS) Southwest Alaska Network (SWAN), which consists of the following parks: KEFJ, KATM, Lake Clark National Park and Preserve, Aniakchak National Monument and Preserve, and the Alagnak National Wild River. Glacier extent mapping has been completed in KEFJ and KATM. This work is part of the long-term Inventory and Monitoring (I&M) Program of the NPS. Goals of the I&M Program are to collect, organize and make available, natural resource data to park management and staff, the scientific community and the public, to further the knowledge and understanding of natural resources and ecosystem function in national parks.

Glaciers throughout KEFJ have been in widespread recession since the Little Ice Age maxima (late 1700s through late 1800s) (Wiles, 1992). There are no detailed studies documenting the behavior of the KATM glaciers. The goal for this project was to map the glacier ice extent on a park-wide basis on a decadal scale

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beginning in the 1970s using multispectral satellite imagery to permit quantification of park-wide change in total area of glacier ice and to identify trends and areas of rapid glacier ice extent change. Landsat instrumentation was selected to be the primary tool for this work because of its resolution, footprint, and historic data availability.

Prior to this mapping effort, the most recent region-wide glacier mapping data available for KEFJ and KATM is the glacier ice permanent snowfield landscape cover type estimate from the Alaska-wide hydrography dataset, which was created by the USGS and BLM from USGS digital line graphs (1:63,360, circa 1950s) and updated using the Alaska High Altitude Aerial Photography (late 1970s through mid 1980s). This dataset shows that glaciers and permanent snow fields cover 1398 sq km in KEFJ and 994 sq km in KATM.

The extent of icefields and glaciers in KEFJ and KATM was mapped using the Landsat Multispectral Scanner (MSS) (79-m pixel resolution) first launched in 1972; Thematic Mapper (TM) (30-m pixel resolution), first launched in 1982; and Enhanced Thematic Mapper Plus (ETM+) (up to 15-m pixel resolution), launched in 1999. Geographic Information System (GIS) shapefiles were produced which can also be used in future analyses to measure changes, and to compare areal extent and terminus positions of the glaciers in these parks.

The interpretation of Landsat data was supplemented with the use of Alaska High Altitude Aerial Photography, flown during the late 1970s through the mid 1980s at a scale of approximately 1:65,000. Additionally, field work and local knowledge were used in the mapping effort. In KEFJ, Ikonos imagery was used to augment the mapping of glacier terminus positions for a few selected glaciers throughout the park.

REGIONAL CONTEXT

Geographic/Topographic/Environmental Setting

Located on the North American Plate, both KATM and KEFJ are along the convergent tectonic plate boundary, with the Pacific Plate subductcing beneath the North American Plate. KATM and the surrounding region contain at least 17 active volcanoes (Bennett et al., 2006) with elevations up to 2300 m. Though not volcanic, the mountains of KEFJ rise from sea level to >1800 m above sea level.

Climate

These two parks are aligned along the northern coast of the Gulf of Alaska where the climate is dominated by maritime influences. This region experiences a high frequency of marine cyclones making landfall in some of the most extreme and dramatic terrain in North America. Important features of the climate-hydrological cycle in these parks include the location of the Aleutian Low during the winter months (Davey et al., 2007) and the presence of mountains rising directly and steeply from the Gulf of Alaska (Davey et al., 2007; Bennett et al., 2006). Maritime influences interact with steep topography to create patterns of high precipitation on the windward side of the mountains, and rain shadows on the leeward side; regional winds have an easterly component (Davey et al., 2007), are predominant during the winter and common during the summer.

Glacier Characteristics - Kenai Fjords National Park

Harding Icefield and the Grewingk-Yalik Glacier Complex are predominately located within KEFJ (Figure 1). Fourteen glaciers in KEFJ are named. An excellent introduction to these icefields may be found in Field (1975).

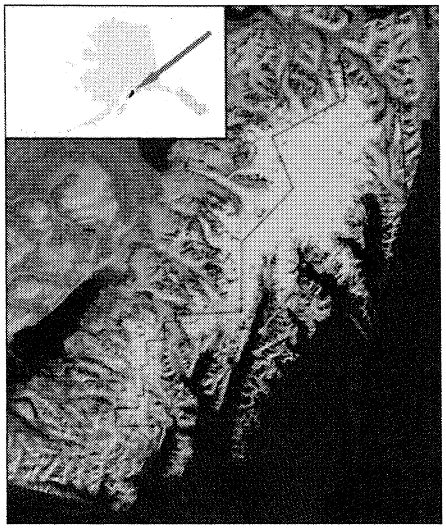

Figure 1. Landsat satellite image (September 12, 1986) of the Harding Icefield and the Grewingk-Yalik Glacier Complex with the KEFJ park boundary shown. Inset identifies the location of KEFJ in reference to Alaska.

The Harding Icefield is located on the southeast side of the Kenai Peninsula, with elevations reaching 1500 m above sea level. The Harding Icefield (approximately 80 km x 30 km in area) spawns several dozen outlet glaciers that flow down valleys and terminate on land, in lakes or in the Pacific Ocean. Some valley glaciers coalesce into larger valley glaciers.

A few kilometers to the southwest of the Harding Icefield is the Grewingk-Yalik Glacier Complex with elevations reaching 1400 m above sea level. This accumulation of glacier ice is approximately 35 km by 10 km in area, and spawns several outlet valley glaciers that terminate on land and in lakes. There are no tidewater glaciers issuing from the Grewingk-Yalik Glacier complex.

Glacier termini characteristics include typical clean-ice boundaries of calving tidewater or lake-terminating glaciers. Many termini of land-terminating glaciers are covered in varying amounts of moraine material, a characteristic of glaciers in recession. The larger valley glaciers are striped with characteristic medial moraines as a result of coalescing valley glaciers; these valley glaciers also exhibit strong accumulations of lateral moraine material on the glacier surface. There are isolated cirque glaciers and small valley glaciers issuing from simple and compound basins beyond the main confines of the Harding Icefield and Grewingk-Yalik Glacier Complex. Innumerable small isolated permanent snowfields also occur at higher elevations beyond the limits of the glacier ice.

The Harding Icefield was the focus of extensive work during the 1990s (Echelmeyer et al., 1996; Adalgeirsdóttir et al., 1998; Sapiano et al., 1998; Arendt et al., 2002). Echelmeyer et al. (1996) used airborne altimetry to generate elevation profiles along centerlines of main glacier trunks and major tributaries and compared these profiles with contours on 15-minute USGS topographic maps made from aerial photographs acquired in the 1950s. They estimated that the total volume change for the Harding Icefield for this ~43-year period was –34 km^3, which corresponds to an area average glacier-surface elevation change of –21 ±5 m. Hall et al. (2005) provided preliminary mapping results of KEFJ, showing a general recession of the glaciers in and near KEFJ.

<u>Glacier Characteristics - Katmai National Park and Preserve</u>

There are over 50 glaciers within the boundaries of KATM originating from three primary areas of accumulation (Figure 2). Each of these areas is a center of active volcanic activity with elevations approaching 2300 m above sea level, and spawns dozens of valley glaciers, the most common glacier type in KATM. Most of the valley glaciers terminate on land, though a few terminate in lakes and the flow from both simple and compound basins coalescing into larger valley glaciers. Beyond the three primary accumulations of glacier ice on these volcanic mountains, there are small cirque glaciers and innumerable small isolated permanent snowfields. Only seven glaciers in KATM are named.

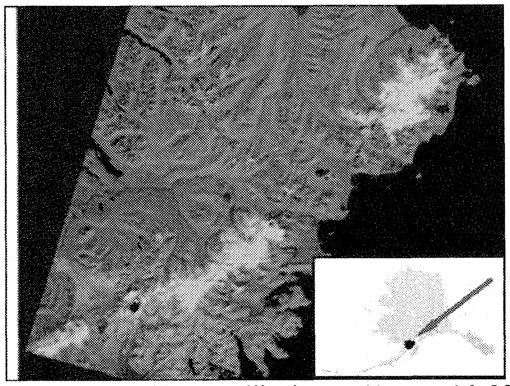

Figure 2. Landsat satellite image (August 16, 2000) of glaciated areas, KATM. Inset identifies the location of KATM in reference to Alaska.

There are no tidewater glaciers in KATM, however there are two large lake-terminating glaciers exhibiting clean-ice boundaries. Most glacier termini in KATM have a significant amount of moraine cover, which is common on glaciers in recession. The large valley glaciers of KATM exhibit significant accumulations of lateral and medial moraine material. In addition, since the volcanic eruption of Novarupta in 1912, vast exposures of volcanic ash remain. Frequent wind events in the area entrain volcanic ash and redeposit this ash over the landscape. Many glaciers in this portion of KATM are completely blanketed with a thick layer of volcanic ash (Figure 3).

Figure 3. Landsat satellite image (August 16, 2000) of volcanic ash covered glaciers (left); the yellow line delineates the glacier boundaries. Aerial oblique photograph of same volcanic ash covered glacier (center). Landsat satellite image (August 16,, 2000) showing the position of this glacier in reference to glaciated areas of Katmai National Park and Preserve (right); inset identifies the location of KATM in reference to Alaska.

Very little work has been done on the glaciers of KATM, and even fewer publications are in the open literature. Field (1975) provided a map of the area with some background, and Motyka (1977), documented observations of glacier growth within the Katmai Caldera. Our present work thus documents an important group of glaciers that has not been well-studied.

PROCEDURES FOR ANALYSIS OF GLACIER CHANGES

<u>Imagery Classification</u>

Initially, Landsat imagery was acquired that met the following standards:

- Cloud-free or minimal cloud cover;

- Late-season imagery (to maximize seasonal snow melt and minimize new seasonal snow (August and September).

Glacier mapping in KEFJ was performed using PCI image-processing software. The outlines of the glaciers were manually traced using vector segments to produce GIS shapefiles which were further edited using ArcGIS software. Higher-resolution aerial photography was used as a tool to help interpret the Landsat data. Ikonos data were also used for selected glacier termini in KEFJ. Very small glaciers, and areas that appeared to be snowfields (not glacier ice) were generally not traced.

Glacier mapping in KATM was also performed using PCI image-processing software. However, contrary to the work in KEFJ, training sites were defined and a "maximum likelihood" algorithm was used to classify the imagery. The classification was converted to GIS shapefiles and edited in ArcGIS.

<u>Complicating Issues</u>
There are several issues that influence the accuracy of the initial supervised delineation of glacier extent in both parks: debris-covered ice, shadowing, permanent snowfields and seasonal snow cover/new snow. These are discussed below.

Debris-covered ice (moraine and/or volcanic ash) -- debris-covered ice has a reflectance that is similar to surrounding moraine and/or mountain material (Hall el al., 2000 and 2003; Wowarth, 1986; Jacobs, 1997), thus, classification of ice that is completely covered with debris is not possible because its spectral reflectance cannot be distinguished from surrounding moraine/mountain material (Williams et al., 1991; Sidjak, 1999).

Shadows -- sun angle and extreme topography are factors affecting the extent of shadowing across an image, which can obscure glacier boundaries.

Permanent snowfields outside of the accumulation area -- every effort was made to eliminate permanent and seasonal snowfields from the classification. A snowfield and a glacier are spectrally similar (if the glacier is snow covered), so these two feature types cannot be distinguished using only a single satellite scene. Isolated small snowfield features were not mapped because they are not glacier ice.

Seasonal snow cover and /or new snow cover -- the date of the satellite image is directly related to the amount of remaining snowpack. A mid-September image vs. a mid-August image may show significantly less seasonal snow cover, thus increasing the reliability of the delineation of the full extent of the accumulation areas. Conversely, early season snowfall may render the mid-September image useless for accurately mapping the accumulation area.

<u>Manual Editing</u>
The initial supervised classification was converted to a GIS shapefile. Areas that were misclassified in the original classification were captured manually (debris-covered ice, shadowed ice) or removed (isolated small snowfields) during an edit session in ArcGIS. Editing of the shapefile is based on the judgment of the person doing the satellite image interpretation. The human eye can perceive textural differences in debris-covered ice that are typically missed in the original supervised classification. In addition, local knowledge and the use of high-resolution imagery can aid in the interpretation of Landsat data. Careful manual interpretation of these areas is required to optimize the accuracy of the mapping effort.

SATELLITE IMAGERY INTERPRETATION ACCURACY

Park-wide statistics estimating glacier ice extent for both KEFJ and KATM, for each scene studied, were generated using ArcGIS. Also, change in extent was calculated. The amount of change that can be detected in a Landsat image is dependent on the resolution of the imagery plus any registration error. The spatial accuracy of Terrain Corrected TM or ETM+ Landsat data is 30 meters between images (EROS Data Center, personal comm., 2006). If the registration between images is perfect, changes of terminus positions can be determined to within +- 42.4 meters when analyzing Landsat TM and ETM+ scenes; the accuracy decreases to +- 113 meters when analyzing data between Landsat MSS and TM or ETM+ scenes (Hall et al., 2003).

AREAL EXTENT – GLACIER ICE

Kenai Fjords National Park

The areal extent of the Harding Icefield, the Grewingk-Yalik Glacier Complex and surrounding glaciers was mapped for 1973, 1986 and 2000 using three Landsat scenes (see Table 1).

Table 1 - Landsat Scenes used in KEFJ

Date	Sensor	Scene i.d. number
17-Aug-73	MSS	LM1074018007322990
12-Sep-86	TM	TM5 LT5069018008625510
9-Aug-00	ETM+	LE7069018000022250

Table 2 presents the results of the glacier extent mapping effort for KEFJ. Because of the resolution difference between the MSS and TM or ETM+ data, it is difficult to make a quantitative comparison of the 1973 data with the 1986 or 2000 data, thus, 1973 data are not presented in Table 2. However, it is reasonable to compare the 1986 and 2000 measurements. A reduction of about 2.2% (-53 sq km) was measured between 1986 and 2000 and is shown in Figure 4 as a difference map for the Harding Icefield, the Grewingk-Yalik Glacier Complex and surrounding glaciers.

Table 2 - Summary of the extent of the Harding Icefield, the Grewingk-Yalik Glacier Complex and surrounding glaciers as measured using Landsat data (in sq km)*

	1986 (sq km)	2000 (sq km)	1986 to 2000 Change in Glacier Cover (sq km)	% Change
Harding Icefield main body**	1828.41	1786.38	-42.03	-2.3%
Harding Icefield and surrounding glaciers	1935.03	1902.79	-32.24	-1.7%
Grewingk-Yalik Glacier Complex main body	423.37	411.69	-11.68	-2.8%
Grewingk-Yalik Glacier Complex and surrounding glaciers	444.81	424.32	-20.50	-4.6%
Harding Icefield and Grewingk-Yalik Glacier Complex and surrounding glaciers	2379.84	2327.11	-52.73	-2.2%
Glacier Ice within park boundary	1388.20	1366.52	-21.68	-1.6%

*This reflects the removal of areas represented by nunataks or other areas barren of glacier ice but inside of the mapped boundary of glacier extent.

**Adalgeirsdóttir et al. (1998) state that the extent of the Harding Icefield is ~1800 sq km.

Note that the 2000 image is an early-August image and the 1986 image is a mid-September image. One additional month into the melt season for the 1986 image is quite noticeable in terms of the amount of remaining seasonal snow. Though this does not affect the accuracy of the mapping of the terminus positions, it does affect mapping of glacier boundaries and nunataks in higher elevation areas.

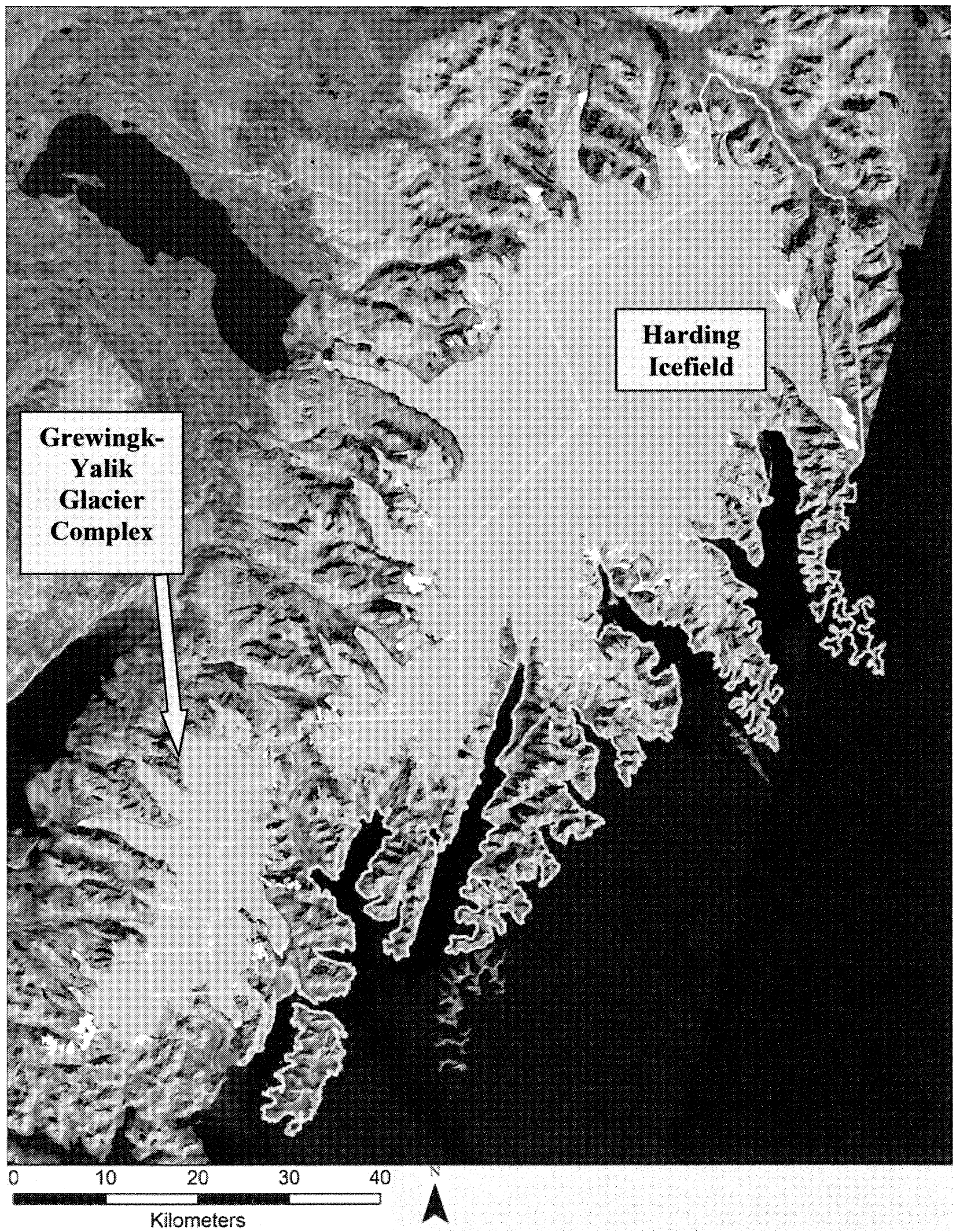

Figure 4. Changes in areal extent from 1986 to 2000, Harding Icefield and the Grewingk-Yalik Glacier Complex. The white represents the area of glacier ice in 1986 and the gray represents the area of glacier ice in 2000. Boundary of KEFJ shown in light gray.

Katmai National Park and Preserve

The areal extent of glacier ice in KATM was mapped for 1974, 1987 (1986 Mt. Martin area only) and 2000 using four Landsat scenes (see Table 3).

Table 3 - Landsat Scenes used in KATM

Date	Sensor	Scene i.d. number
27-Jul-74	MSS	LM1076019007420890
*24-Jul-86	TM	LT5071019020086205
21-Aug-87	TM	LT5070018019087233
16-Aug-00	ETM+	L7_P70R19S00_2000AUG16

* Mt. Martin area only

Table 4 presents the results of the glacier extent mapping effort for KATM. Because of resolution differences between the MSS and TM or ETM+ data, it is difficult to make a meaningful comparison of the 1974 data with the 1986/87 or 2000 data, as discussed previously. Additionally, the 1974 image has more seasonal snow remaining because it was captured earlier in the snowmelt season than the other images. Thus, 1974 data is not presented in Table 4. However, it is reasonable to compare the 1986/87 and 2000 measurements. A reduction of about 7.7% (-75 sq km) was measured between 1986/87 and 2000 and is depicted on a park-wide basis in Figure 5 as a difference map for the three primary glaciated areas of KATM.

Table 4 - Glacier Areal extent of glaciers in KATM as measured using Landsat data (in sq km)*

	1986/87 (sq km)	2000 (sq km)	1986/87 to 2000 Change in Glacier Cover (sq km)	% Change
Mt. Douglas area	347.74	330.18	-17.57	-5.1%
Mt. Katmai, Snowy Mountain, Kukak Volcano area	563.46	509.85	-53.60	-9.5%
Mt. Mageik Mt. Martin	74.32	69.72	-4.60	-6.2%
Glacier ice within park boundary	985.52	909.75	-75.77	-7.7%

*The data above reflects the removal of areas represented by nunataks or other areas barren of glacier ice but inside of the mapped boundary of glacier extent.

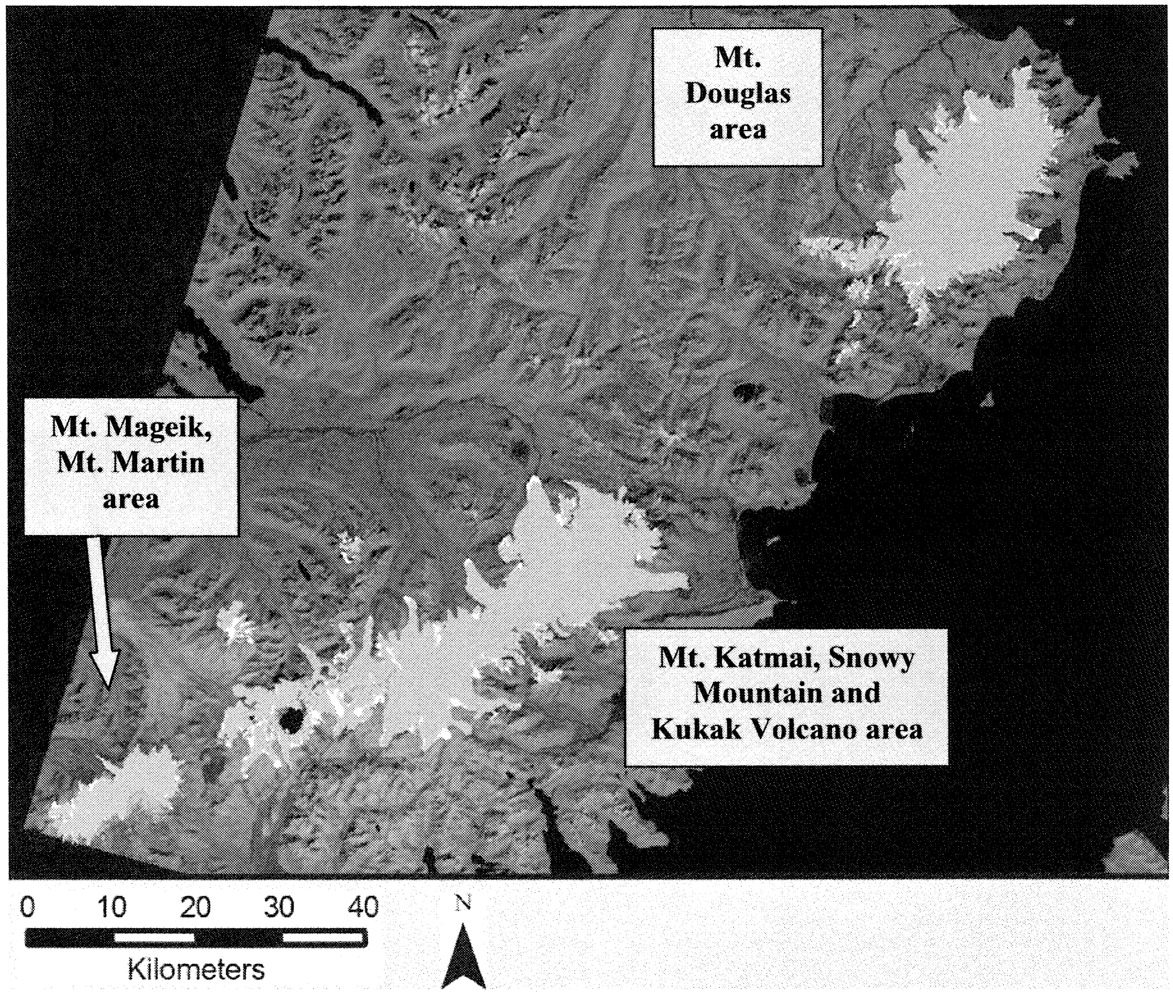

Figure 5. Changes in areal extent from 1986/87 to 2000, KATM. The white represents the area of glacier ice in 1986/87 and the dark gray represents the area of glacier ice in 2000.

TERMINUS POSITION MEASUREMENTS

Methodology

The terminus "position" can be measured at various points along the terminus of the glacier. Changes in the terminus positions and rates of recession are approximate because they are highly dependent on the exact spot on the terminus that was selected to make the measurement. For this study, a standard method was developed to select a point on a glacier terminus for each terminus measurement. First, a down-valley vector parallel to the direction of glacier flow was determined for each glacier terminus to be measured. Then the farthest down-valley point on the terminus was identified and a line was projected from this point, and normal to the down-valley flow vector was drawn. The result is a series of parallel lines intersecting the down-valley flow vector. The distance between these parallel lines is the distance assigned to the terminus movement. Change in terminus position was determined using ArcGIS software.

This analysis shows rates and trends of glacier terminus movement, and also identifies which glaciers are most active. The 1951/1952 terminus positions were determined from the USGS 1:63,360 quadrangle maps produced from high quality aerial photography (approximately 1:40,000). Terminus positions from 1986, 1987 and 2000 were determined from Landsat imagery. Terminus positions from 2005 were mapped from Ikonos imagery (KEFJ only). In addition to the use of these data, local knowledge and careful manual interpretation was undertaken to optimize the accuracy of the final product.

Kenai Fjords National Park

The terminus positions were mapped for 27 glaciers emanating from the Harding Icefield and the Grewingk-Yalik Glacier Complex, as shown in Table 5; 10 of these glaciers terminate within the park and are marked with an * in Table 5. Figure 7 identifies these glaciers on a Landsat image (2000) by name (or alpha code) which corresponds with Table 5.

Table 5 - Glacier Terminus Movement in KEFJ

Glacier Name	Change (in m) from 1950(51) - 1986; Second number is average annual rate of change (in m/yr)		Change (in m) from 1950(51) - 2000; Second number is average annual rate of change (in m/yr)		Change (in m) from 1950(51) - 2005; Second number is average annual rate of change (in m/yr)		Change (in m) from 1986 - 2000; Second number is average annual rate of change (in m/yr)		Change (in m) from 1986 - 2005; Second number is average annual rate of change (in m/yr)		Change (in m) from 2000 - 2005; Second number is average annual rate of change (in m/yr)	
Lowell*	-741	-21	-1375	-28	-1505	-28	-634	-45	-764	-40	-130	-26
A	-586	-17	-906	-18	*	*	-320	-23	*	*	*	*
Skilak	-2267	-65	-4053	-83	*	*	-1786	-128	*	*	*	*
Killey	-798	-23	-1229	-25	*	*	-431	-31	*	*	*	*
Indian	-692	-20	-973	-20	*	*	-281	-20	*	*	*	*
Tustumena	-1254	-36	-1800	-37	*	*	-546	-39	*	*	*	*
Truuli	-1065	-30	-971	-20	*	*	94	7	*	*	*	*
Chernof	-1366	-39	-1461	-30	*	*	-95	-7	*	*	*	*
Dinglestadt (West)	-2823	-81	-3052	-62	*	*	-229	-16	*	*	*	*
Kachemak	-801	-23	-989	-20	*	*	-188	-13	*	*	*	*
Nuka	-226	-6	-189	-4	*	*	37	3	*	*	*	*
B	-728	-21	-997	-20	*	*	-269	-19	*	*	*	*
Dixon	-422	-12	-589	-12	*	*	-167	-12	*	*	*	*
Portlock	-1188	-34	-1322	-27	*	*	-134	-10	*	*	*	*
Greywingk	-1350	-39	-2298	-47	*	*	-948	-68	*	*	*	*
Wosnesenski	-1268	-36	-1436	-29	*	*	-168	-12	*	*	*	*
Doroshin	-751	-21	-1495	-31	*	*	-744	-53	*	*	*	*
Petrof	-1261	-36	-1576	-32	*	*	-315	-23	*	*	*	*
Yalik*	-1057	-30	-1854	-38	-2160	-40	-797	-57	-1103	-58	-306	-61
Dinglestadt (East)*	-347	-10	-446	-9	-521	-10	-99	-7	-174	-9	-75	-15
McCarty*	-1599	-46	-1730	-35	-2248	-42	-131	-9	-649	-34	-518	-104
Northwestern*	-5198	-149	-6553	-134	-6367	-118	-1355	-97	-1169	-62	186	37
Holgate*	-245	-7	-349	-7	-359	-7	-104	-7	-114	-6	-10	-2
Pederson*	-706	-20	-860	-18	-1140	-21	-154	-11	-434	-23	-280	-56
Aialik*	186	5	183	4	-105	-2	-3	0	-291	-15	-288	-58
Bear*	-158	-5	-1123	-23	-2968	-55	-965	-69	-2810	-148	-1845	-369
Exit*	-488	-14	-481	-10	-621	-12	7	1	-133	-7	-140	-28
Average Rate of Terminus Change (m/yr)	**-1081.4**	**-30.9**	**-1478.7**	**-30.2**	**-1799.4**	**-33.3**	**-397.2**	**-28.4**	**-764.1**	**-40.2**	**-340.6**	**-68.1**
North and West flowing (Interior)	-1045.2	-24.1	-1423.1	-22.0	-1063.0	-19.7	-377.9	-27.0	-448.5	-23.6	-135.0	-27.0
South and East Flowing (Coastal)	-1153.9	-33.0	-1589.8	-32.4	-1983.5	-36.7	-435.9	-31.1	-843.0	-44.4	-392.0	-78.4

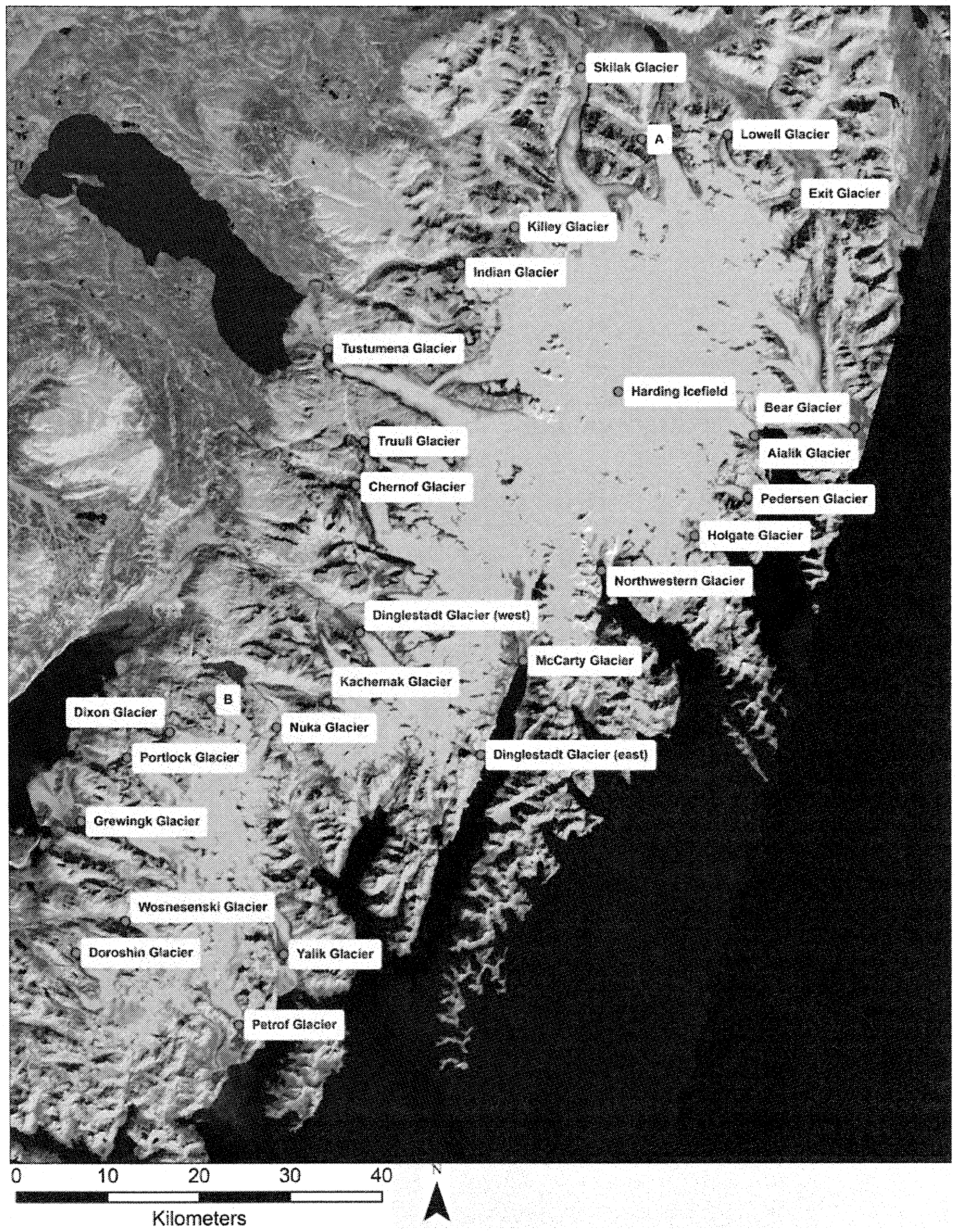

Figure 7. This is a true-color September 12, 1986 TM5 Landsat image of the glacierized portion of KEFJ. The glacier names in this figure identify which glacier termini were measured and correspond to data presented in Table 5.

Glacier termini in and around KEFJ have been steadily retreating since the early 1950s (Table 5). During the study period, the rate of recession appears to be slightly higher for tidewater or coastal glaciers (easterly and southerly flowing) as compared to northerly and westerly flowing glaciers. The rates of recession appear to be slightly increasing as we move through time, though we do not have enough Landsat scenes to confirm this.

There is a dramatic increase in the rate of recession of glaciers in KEFJ in the 2000 to 2005 time interval (based on the measurement of only eight glaciers). Most of this observed increased rate of recession can be attributed to the collapse of the Bear Glacier terminus during these years.

The Bear Glacier terminates in a lake (Figure 8) and may have lost its footing on its terminal moraine, becoming buoyant, resulting in a dramatic retreat in the 2000 to 2005 timeframe. Aialik and Holgate glaciers show little terminus movement since 1951 (Figure 8). Pederson, McCarty and Dinglestadt (east) glaciers all show recession in the 1951 to 2005 time interval, though these glaciers show little terminus change between 1986 to 2000. Yalik, Lowell and Exit glaciers all show steady recession in the 1951 to 2005 time interval (Figure 9). From Table 5, the annual rate of recession for the Yalik, Lowell and Exit glaciers has remained fairly consistent throughout the 1951 to 2005 time interval. Northwester Glacier showed a small advance in the 2000 to 2005 time interval (Table 5 and Figure 9).

Tustumena, Truuli, Skilak, Dinglestadt (west) and Kachemak glaciers all show recession in the 1951 to 2000 time interval (Table 5 and Figure 10). The annual rates of recession vary among these glaciers, though Skilak Glacier, terminating in a lake, shows dramatic recession in the 1986 to 2000 time interval, likely due to the glacier terminus loosing its footing on the terminal moraine, becoming buoyant and breaking up.

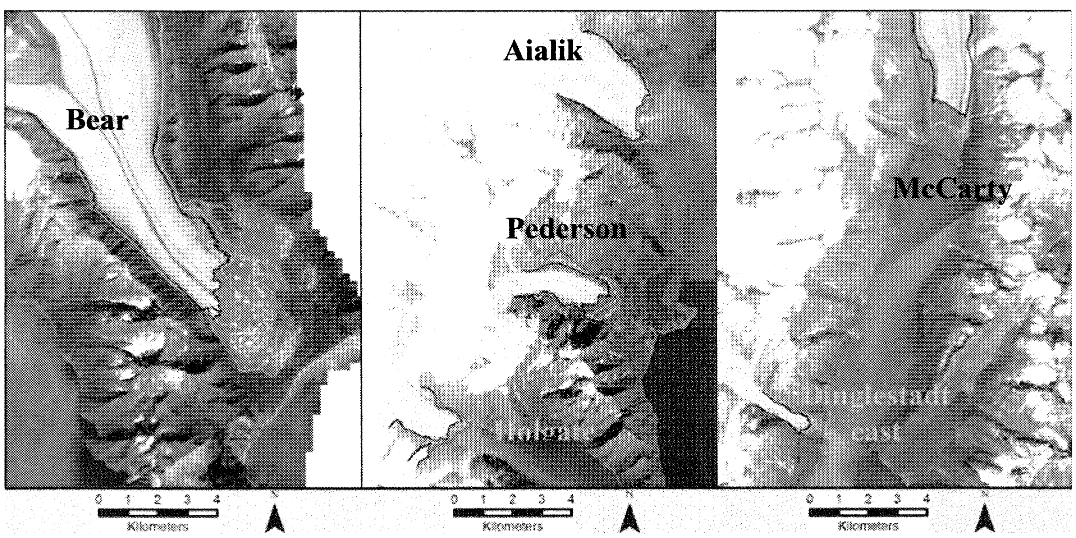

Figure 8. Bear Glacier (left), Aialik, Pederson and Holgate Glaciers (center), and McCarty and Dinglestadt Glaciers (right), KEFJ, Alaska. Glacier terminus positions indicated for 1951 (red), 1986 (orange), 2000 (yellow) and 2005 (black). (Images from 2005 are from Ikonos.)

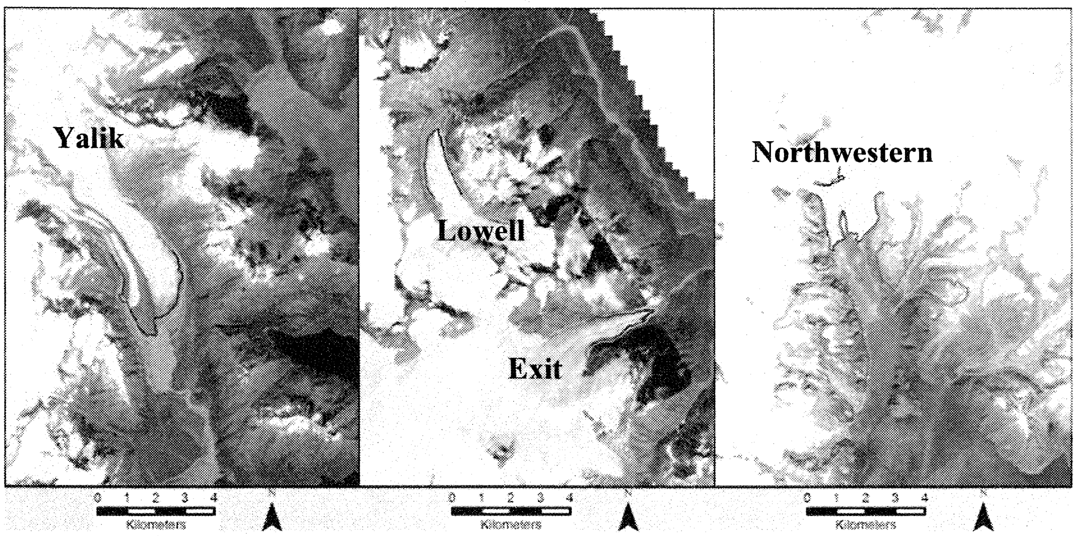

Figure 9. Yalik Glacier (left), Lowell and Exit Glaciers (center), and Northwestern Glacier (right), KEFJ, Alaska. Glacier terminus positions indicated for 1951 (red), 1986 (orange), 2000 (yellow) and 2005 (black). (Images from 2005 are from Ikonos.)

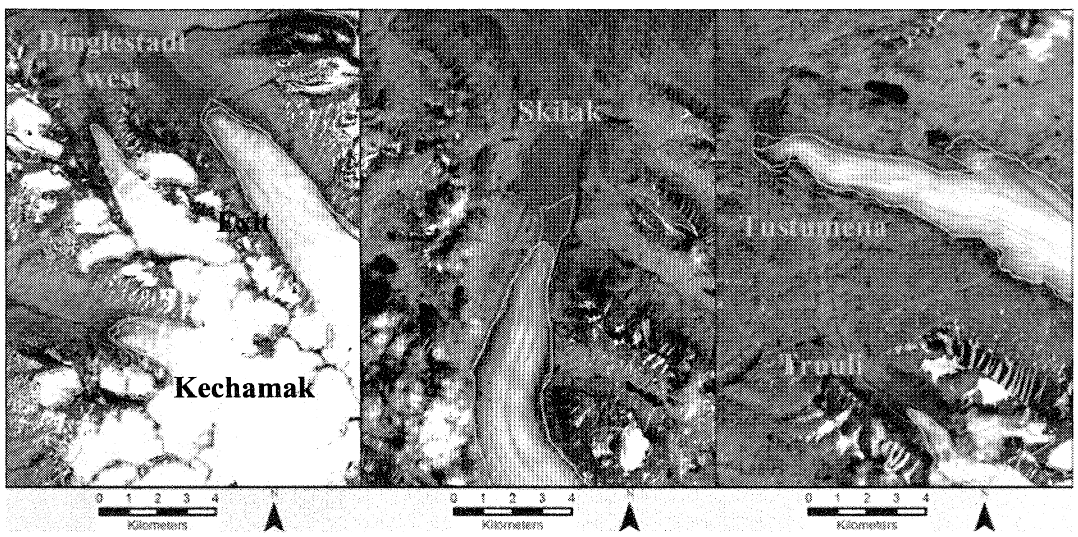

Figure 10. Dinglestadt-west and Kachemak Glaciers (left) , Skilak Glacier (center) and Tustumena and Truuli Glaciers (right), Kenai Kenai Penninsula, Alaska. Glacier terminus positions indicated for 1951 (red), 1986 (orange) and 2000 (yellow). The terminus position from 2000 was derived from Landsat ETM+ imagery. Each of these glaciers shows recession in the 1951 to 2000 time interval. (Images from 2000 are from Landsat ETM+.)

Katmai National Park and Preserve

The terminus positions were mapped for 20 glaciers flowing from the three glaciated regions of KATM in the same way as was done for KEFJ. Table 6 presents terminus movement data for 20 glaciers in KATM. Figure 11 identifies these glaciers on a Landsat image (2000) by name (or alpha code) which corresponds with Table 6.

Table 6 - Glacier Terminus Movement in KATM

Glacier Name	Change (m) from 1951-1986/87; Second number is average annual rate of change (m/yr)		Change (m) from 1951-2000; Second number is average annual rate of change (m/yr)		Change (m) from 1986/87-2000; Second number is average annual rate of change (m/yr)	
A (Spotted Glacier)	-1186	-33	-1452	-30	-266	-20
B	-760	-21	-871	-18	-111	-9
C	-869	-24	-832	-17	37	3
D	-452	-13	-728	-15	-276	-21
E	-383	-11	-511	-10	-128	-10
F (Fourpeaked Glacier)	-3432	-95	-3595	-73	-163	-13
G (Hook Glacier)	-633	-18	-1212	-25	-579	-45
H	-632	-18	-1062	-22	-430	-33
I	-189	-5	-671	-14	-482	-37
J	101	3	-47	-1	-148	-11
K	88	2	69	1	-19	-1
L	108	3	-19	0	-127	-10
M	-541	-15	-615	-13	-74	-6
N	-1105	-31	-1357	-28	-252	-19
O	-1182	-33	-1298	-26	-116	-9
P (Hallo Glacier)	-916	-25	-766	-16	150	12
Q	-68	-2	-166	-3	-98	-8
R	-432	-12	-735	-15	-303	-23
S (Knife Creek Glacier)	176	5	95	2	-81	-6
T (Serpents Tongue Glacier)	-1276	-35	-1276	-26	0	0
Average Rate of Terminus Change (m/yr) (includes questionable 1972 data)	**-679.2**	**-18.9**	**-852.5**	**-17.4**	**-173.3**	**-13.3**
North and west flowing (Interior)	-646.778	-18.0	-889.889	-18.2	-243.111	-18.7
South and East Flowing (Coastal)	-705.636	-19.6	-821.818	-16.8	-116.182	-8.9

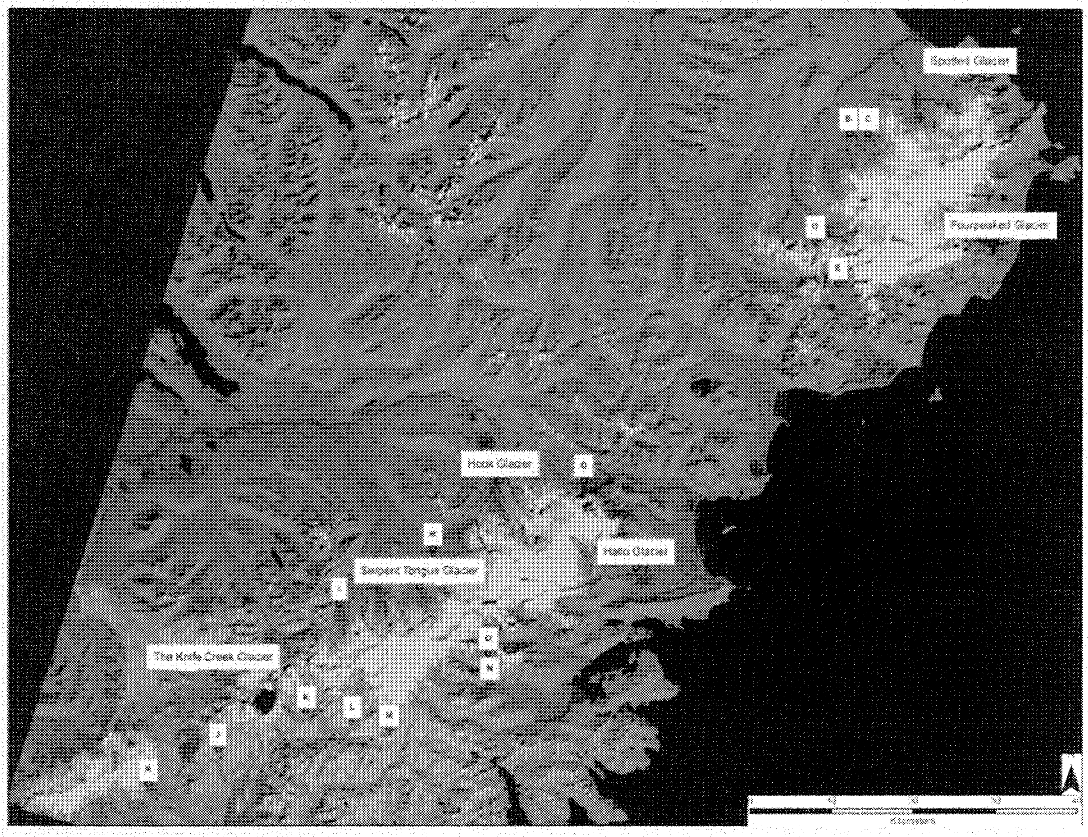

Figure 11. This is a true-color August 16, 2000 ETM+ Landsat image of the glaciated portion of KATM. The glacier names (or alpha code) in this figure identify which glacier termini were measured and correspond to data presented in Table 6.

Glacier termini in and around KATM have been retreating since the early 1950s (Table 6). The rate of recession on a park-wide basis may be slowing slightly in the most recent study period (1986/87 to 2000). The rates of recession of interior-flowing glaciers (northerly and westerly flowing) and coastal glaciers (easterly and southerly flowing) are very similar for the 1950s to 1986/87 timeframe. However, in the 1986/87 to 2000 timeframe, coastal glaciers showed markedly slower rates of recession than did the interior flowing glaciers.

The Spotted Glacier terminates in a lake (Figure 12), is a north flowing glacier and exhibits a consistent rate of recession, though that rate showed a reduction in the 1986/87 to 2000 time interval. Fourpeaked Glacier (Figure 12) may have lost its footing on its terminal moraine, becoming buoyant, resulting in a dramatic retreat in the 1951 to 1986/87 time interval; recession here has slowed in the most recent time interval (1986/87 to 2000). Glaciers identified as "B" and "C" (Figure 12) exhibit higher rates of recession during the 1951 to 1986/87 time interval as compared with the more recent time interval of 1986/87 to 2000. Glaciers identified as "K" and "L" (Figure 13) exhibit very little terminus movement during the period (1951 to 2000): this is likely attributable to a thick covering of volcanic ash on the surface of these glaciers. Hallo Glacier (Figure 13) may have lost its footing on its terminal moraine, becoming buoyant, and resulting in a dramatic retreat in the 1951 to 1986/87 timeframe; recession here has slowed in the most recent time interval (1986/87 to 2000). The Hook and "H" glaciers exhibit similar recession rates throughout the study period (1951-2000) with rates of recession increasing in the 1986/87 to 2000 time interval.

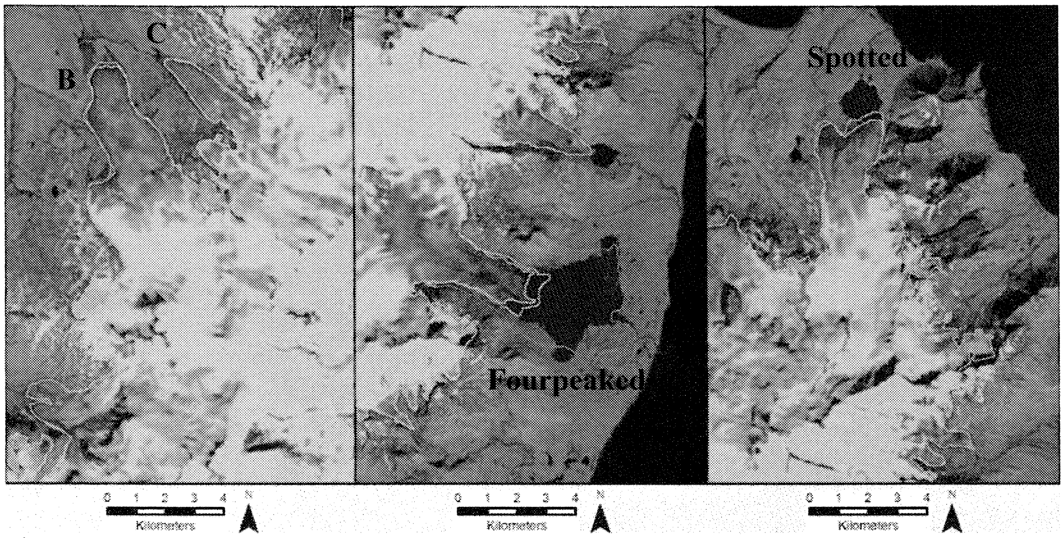

Figure 12. "B" and "C" glaciers (left), Fourpeaked Glacier (center) and Spotted Glacier (right), Katmai National Park, Alaska. Glacier terminus positions indicated for 1951 (red), 1987 (orange) and 2000 (yellow). (2000 Landsat ETM+ imagery.) Each of these glaciers shows recession in the 1951 to 2000 time interval.

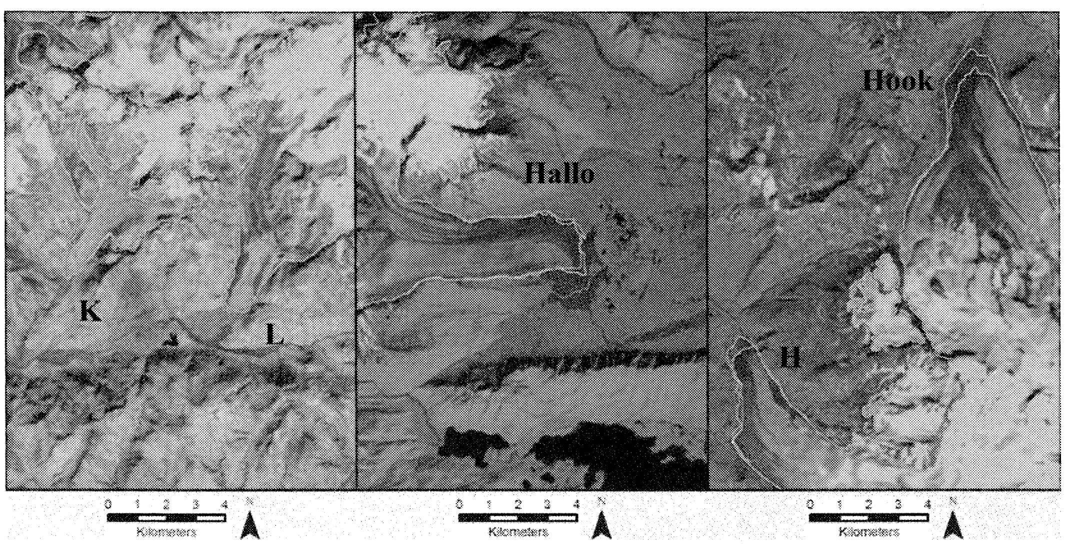

Figure 13. "K" and "L" glaciers (left), Hallo Glacier (center) and Hook and "H" glaciers (right), Katmai National Park, Alaska. Glacier terminus positions indicated for 1951 (red), 1987 (orange) and 2000 (yellow). (2000 Landsat ETM+ imagery.)

DISCUSSION AND CONCLUSIONS

All glacier termini measured in KEFJ have receded, as shown in Table 5, between the early 1950s and 2005 (based on the USGS quadrangle maps (1950s), Landsat data (1986 and 2000), and Ikonos data (2005)); some have moved back dramatically. Two glaciers, Truuli and Nuka, terminating outside the park, show a small amount of advancement from 1986 to 2000. From the early 1950s through 2000, interior-flowing glaciers exhibit rates of recession averaging 22 meters per year. Coastal glaciers show higher rates of recession during the same time period, averaging 32 meters per year. However, between 2000 and 2005, the coastal glaciers in KEFJ show a dramatic increase in the rate of recession (~78 meters per year). Because of lack of imagery, an estimate of the recession rates for interior-flowing glaciers from 2000 to 2005 is not possible to provide.

Measurement of the areal extent of the Harding Icefield and the Grewingk-Yalik Glacier Complex in 1986 and 2000 shows a reduction in extent of 2.2% or about 53 sq km (see Table 2 and Figure 4).

Most glaciers in KATM have receded, as shown in Table 6, between the early 1950s and 2000 (based on the USGS quadrangle maps (1950s) and Landsat data (1986/87 and 2000)), though several show very little or no change. From the early 1950s through 2000, interior-flowing glaciers exhibit rates of recession averaging 18 meters per year. Coastal glaciers show slightly lower rates of recession during the same time period, averaging 17 meters per year. During the 1986/87 to 2000 time period, coastal-flowing glaciers exhibit rates of recession of averaging 9 meters per year and the interior-flowing glaciers exhibit recession rates of 19 meters per year. The glacier termini that exhibit very little change are completely mantled in a thick layer of volcanic ash (see Figure 3).

Measurement of the areal extent of the three primary glaciated regions in KATM in 1986/87 and 2000, shows a reduction in extent of 7.7% or about 76 sq km (see Table 4 and Figure 5).

We know that glaciers are undergoing a steady pace of recession, however to fully appreciate the impact of this recession, measurement of the third dimension, the elevation of the surface of the ice, is needed. To accomplish this, and to determine rate of change of ice volume, high quality digital elevation models (DEM) should be acquired decadally during the August-September time frame.

Mapping of the glacier extent in Lake Clark National Park and Preserve (LACL) is underway, using a similar approach. When mapping in LACL is completed, the glacier extent of the three primary glacier parks in the SWAN will be documented. GIS shapefiles will be made available to the Global Land Ice Measurements from Space (GLIMS) project and to other researchers. Because of the careful mapping, as described herein, it will be possible in the future to continue the mapping effort to document changes in glacier ice extent in the SWAN, for land-cover and climate studies with a high degree of accuracy. In addition, in conjunction with surface-elevation measurements, changes in the volume of ice in the SWAN will be possible to determine.

REFERENCES

Adalgeirsdóttir, G., K.A. Echelmeyer and W.D. Harrison, 1998: Elevation and volume changes on the Harding Icefield, Alaska, *Journal of Glaciology*, 44(148):570-582.

Arendt, A.A., Echelmeyer, K.A., Harrison, C.A., Lingle, C.A. and Valentine, V.B. 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science*, 297:382-386.

Bennett, A., Thompson, B., Mortenson, D., 2006: Vital Signs Monitoring Plan Southwest Alaska Network Inventory and Monitoring Program, National Park Service, 223 p.

Davey, C.A., Redmond, K.T., Simeral, D.B., 2007: Weather and Climate Inventory-National Park Service-Southwest Alaska Network, Western Regional Climate Center, Desert Research Institute, WRCC Report 2007-20, 96p.

Dyurgerov, M. and M. Meier, 1997: Mass balance of mountain and subpolar glaciers: a new global assessment for 1961-1990, *Arctic and Alpine Research*, 27(4):379-391.

Echelmeyer, K.A., W.D. Harrison, C.F. Larsen, J. Sapiano, J.E. Mitchell, J. DeMallie, B. Rabus, G. Adalgeirsdóttir, and L. Sombardier, 1996: Airborne surface profiling of glaciers: a case-study in Alaska, *Journal of Glaciology*, 42(142):538-547.

Field, W.O. (ed.), 1975: *Mountain Glaciers of the Northern Hemisphere*, vols. 1&2, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Hall, D.K., R.S. Williams, Jr., J.S. Barton, O. Sigurdsson, L.C. Smith and J.B. Garvin, 2000:

Evaluation of remote-sensing techniques to measure decadal-scale changes of Hofsjökull ice cap, Iceland, *Journal of Glaciology,* 46(154):375-388).

Hall, D.K., K.J. Bayr, W. Schöner, R.A. Bindschadler, J.Y.L. Chien, 2003: Changes in the Pasterze and the Kleines Fleißkees glaciers, Austria, as Measured from the Ground and Space, *Remote Sensing of Environment,* 86:566-577.

Hall, D.K., B.A. Giffen, J.Y.L. Chien, 2005: Changes in the Harding Icefield and the Grewengk-Yalik Glacier Complex, Proceedings of the 62nd Eastern Snow Conference, Waterloo, ON, Canada.

Howarth, P., Ommanney, C.S., 1987: The use of Landsat Digital Data for Glacier Inventories, *Annals of Glaciology*, 8:90-92.

Jacobs, J.D., Simms, E.L., Simms, A., 1997: Recession of the Southern Part of Barns Ice Cap, Baffin Island, Canada, between 1961 and 1993, determined from Digital Mapping of Landsat TM, *Journal of Glaciology*, 43(143):98-102.

Meier, M. and A. Post, 1987: Fast tidewater glaciers, *Journal of Geophysical Research,* 92:9051-9058.

Motyka, R.J., 1977: Katmai Caldera: Glacier Growth, Lake Rise and Geothermal Activity, State of Alaska, Department of Natural Resources, Geologic Report No. 55, p. 17-21.

Sapiano, J.J., W.D. Harrison and K.A. Echelmeyer, 1998: Elevation, volume and terminus changes of nine glaciers in North America, *Journal of Glaciology*, 44(146):119-135.

Sidjak, R.W., Wheate, R.D., 1999: Glacier Mapping of Illecillewaet Icefield, Britsih Columbia, Canada, using Landsat TM andDigital Elevation Data, *International Journal of Remote Sensing*, 20(2):273-284.

Wiles, Gregory C., 1992, Holocene Glacial Fluctyations in the Southern Kenai Mountains, Alaska, Thesis – University of New York-Buffalo, 333 p.

Williams, R.S., Jr., D.K. Hall, and C.S. Benson, 1991: Analysis of Glacier Facies Using Satellite Techniques, *Journal of Glaciology,* 37:120-128.