U.S. Department of the Interior
U.S. Geological Survey

Mass Balance, Meteorology, Area Altitude Distribution, Glacier-Surface Altitude, Ice Motion, Terminus Position, and Runoff at Gulkana Glacier, Alaska, 1996 Balance Year

Water-Resources Investigations Report 03–4095

USGS
science for a changing world

Cover: View looking north-northwest at the middle ablation zone of the main branch of Gulkana Glacier on August 8, 2002. The 1,480-meter weather station appears in the foreground. The main branch of the glacier starts out of the image to the right, then flows from right to left across the image, and finally terminates out of the image on the left. The icefall in the left center of the image is fed by the large western tributary of Gulkana Glacier, not visible here. Index site A lies just barely out of the image to the left; index site B lies in the right center of the image.

U.S. Department of the Interior
U.S. Geological Survey

Mass Balance, Meteorology, Area Altitude Distribution, Glacier-Surface Altitude, Ice Motion, Terminus Position, and Runoff at Gulkana Glacier, Alaska, 1996 Balance Year

By ROD S. MARCH

Water-Resources Investigations Report 03–4095

Fairbanks, Alaska
2003

U.S. Department of the Interior

Gale A. Norton, Secretary

U.S. Geological Survey

Charles G. Groat, Director

For additional information write to:

Alaska Science Center
Chief, Water Resources Office
U.S. Geological Survey
4320 University Drive, Suite 201
Anchorage, AK 99508–4664

http://ak.water.usgs.gov/glaciology/

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
Denver, CO 80225–0286

CONTENTS

FIGURES

FIGURES—Continued

TABLES

CONVERSION FACTORS, DATUMS, AND SYMBOLS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
kilogram (kg)	2.205	pound, avoirdupois (lb)
kilogram per liter (kg/L)	62.43	pound per cubic foot (lb/ft^3)
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot (lb/ft^3)
meter per year (m/yr)	3.281	foot per year (ft/yr)
meter per second (m/s)	3.281	foot per second (ft/s)
millimeter per day (mm/d)	0.039	inch per day (in/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
grad	0.9	degree (°)
degree Celsius (°C)	1.8, then add 32	degree Fahrenheit (°F)

Horizontal Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83), the North American Datum of 1927 (NAD 27), and to a local sea-level-based coordinate system described in detail in the text.

Vertical Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), which is defined as follows: a geodetic datum, formerly called SEA LEVEL DATUM OF 1929, derived from a general adjustment of the first-order level nets of both the United States and Canada. In the adjustment, sea levels from selected TIDE stations in both countries were held fixed. The year indicates the time of the general adjustment. This datum should not be confused with MEAN SEA LEVEL. Altitudes are the same in both the local coordinate system and the Universal Transverse Mercator (UTM) system.

Symbols Used in This Report

AAR accumulation area ratio

$\overline{b}$ area-averaged balance value

b' average stake height of the glacier surface within a 25- to 75-meter radius of the stake, in meters

$b'ss_1$ average stake height of the first summer surface down from the glacier surface within a 25- to 75-meter radius of the stake, in meters

$b'ss_2$ average stake height of the second summer surface down from the glacier surface within a 25- to 75-meter radius of the stake, in meters

b_0' initial value (on October 1) of the height of a stratigraphic surface on the stake

$b_0'ss_1$ initial stake height at the beginning of the measurement year of the first summer surface down from the glacier surface within a 25- to 75-meter radius of the stake, in meters

$b_0'ss_2$ initial stake height at the beginning of the measurement year of the second summer surface down from the glacier surface within a 25- to 75-meter radius of the stake, in meters

b^* stake height of surveyed point near b' on the stake, in meters

b^{**} calculated stake height of the glacier surface directly above the stake bottom (as if the stake were vertical), in meters

b_A measured mass balance at index site A, in meters

b_a	annual balance at site
$\overline{b}_a$	area-averaged annual balance
b_a(f)	annual firn balance
$\overline{b}_a$(j)	glacier-averaged annual internal ablation
b_B	measured mass balance at index site B, in meters
b_D	measured mass balance at index site D, in meters
b_n	net balance at site
b_{no}	initial net balance
b_{nl}	late net balance
$\overline{b}_n$	area-averaged net balance
$\overline{b}_s$	area-averaged summer balance
$\overline{b}_w$	area-averaged winter balance
b(f)	new firn balance at site
b(i)	old firn and ice balance at site
b_a(i)	annual old firn and ice balance at site
b(k)	internal accumulation at site
b_a(k)	annual internal accumulation at site
b(ls)	late snow balance at site
b_1(ls)	final late snow balance at site
b(s)	snow balance at site
b_0(s)	initial snow balance at site
$\overline{b}_0$(s)	area-averaged initial snow balance
b_m(s)	measured winter snow balance at site
$\overline{b}_m$(s)	area-averaged measured winter snow balance
b_w(s)	maximum winter snow balance at site
$\overline{b}_w$(s)	area-averaged maximum winter snow balance
d(s)	snow depth, in meters
d(nf)	new firn depth, in meters
E	UTM Easting
ELA	equilibrium line altitude
EMT	electrical metallic tubing
GPS	Global Positioning System
H_t	height of the stake upper target above the stake bottom as measured along the stake, in meters
HY	hydrologic year
k	horizontal scale factor between the UTM plane and sea level
$\overline{k}$	mean horizontal scale factor between the UTM plane and sea level
m_{we}	meters water equivalent
n	sample number
PLGR	Precision Lightweight GPS Receiver
ss_1	first glacier summer surface down from the glacier surface (this is typically glacier ice in the ablation zone and a firn surface in the accumulation zone)
ss_2	second glacier summer surface down from the glacier surface (this is typically a firn surface; multiple summer surfaces only occur in the accumulation zone of the glacier)
UTM	Universal Transverse Mercator

X_g local sea-level coordinate of measurement stake at glacier surface, in meters

X_i local sea-level coordinate of index site, in meters

X_L local sea-level coordinate, in meters

X_s local sea-level coordinate of bottom of measurement stake, in meters

X_t local sea-level coordinate of stake upper target, a point on the stake 1.5 to 2.0 meters above the glacier surface, in meters

Y_g local sea-level coordinate of measurement stake at glacier surface, in meters

Y_i local sea-level coordinate of index site, in meters

Y_L local sea-level coordinate, in meters

Y_s local sea-level coordinate of bottom of measurement stake, in meters

Y_t local sea-level coordinate of stake upper target, a point on the stake 1.5 to 2.0 meters above the glacier surface, in meters

Z altitude, in meters

Z_g altitude of measurement stake at glacier surface, in meters

Z_i altitude of glacier surface at index site, in meters

$Z_i(\mathrm{ss}_1)$ altitude of the first summer surface below the glacier surface at index site, in meters

Z_s altitude of bottom of measurement stake, in meters

Z_t altitude of stake upper target, a point on the stake 1.5 to 2.0 meters above the glacier surface, in meters

$dXYZ$ total three-dimensional displacement of the stake bottom between measurements

θ downdip direction with zero east and positive counterclockwise

ϕ dip angle with zero horizontal and positive angles up

Mass Balance, Meteorology, Area Altitude Distribution, Glacier-Surface Altitude, Ice Motion, Terminus Position, and Runoff at Gulkana Glacier, Alaska, 1996 Balance Year

By Rod S. March

Abstract

The 1996 measured winter snow, maximum winter snow, net, and annual balances in the Gulkana Glacier Basin were evaluated on the basis of meteorological, hydrological, and glaciological data. Averaged over the glacier, the measured winter snow balance was 0.87 meter on April 18, 1996, 1.1 standard deviation below the long-term average; the maximum winter snow balance, 1.06 meters, was reached on May 28, 1996; and the net balance (from August 30, 1995, to August 24, 1996) was -0.53 meter, 0.53 standard deviation below the long-term average. The annual balance (October 1, 1995, to September 30, 1996) was -0.37 meter. Area-averaged balances were reported using both the 1967 and 1993 area altitude distributions (the numbers previously given in this abstract use the 1993 area altitude distribution). Net balance was about 25 percent less negative using the 1993 area altitude distribution than the 1967 distribution.

Annual average air temperature was 0.9 degree Celsius warmer than that recorded with the analog sensor used since 1966. Total precipitation catch for the year was 0.78 meter, 0.8 standard deviations below normal. The annual average wind speed was 3.5 meters per second in the first year of measuring wind speed. Annual runoff averaged 1.50 meters over the basin, 1.0 standard deviation below the long-term average.

Glacier-surface altitude and ice-motion changes measured at three index sites document seasonal ice-speed and glacier-thickness changes. Both showed a continuation of a slowing and thinning trend present in the 1990s.

The glacier terminus and lower ablation area were defined for 1996 with a handheld Global Positioning System survey of 126 locations spread out over about 4 kilometers on the lower glacier margin. From 1949 to 1996, the terminus retreated about 1,650 meters for an average retreat rate of 35 meters per year.

INTRODUCTION

The U.S. Geological Survey (USGS) operates a long-term program to monitor mass balance, climate, glacier geometry, ice motion, and runoff to understand glacier-related hydrologic processes and to improve the quantitative estimates of water resources, glacier-related hazards, and the consequences of global change (Fountain and others, 1997). The approach has been to establish long-term mass-balance monitoring programs at three widely spaced glaciers in the United States that clearly sample different climate-glacier-runoff regimes. Gulkana Glacier is one of these. The others are Wolverine Glacier in south-central Alaska and South Cascade Glacier in Washington. This report contains the meteorological, area altitude distribution, mass-balance, surface-altitude, ice-motion, terminus-position, and runoff measurements made at Gulkana Glacier for the 1996 balance year (see “Measurement System and Terminology” section). The data are reported in order of their causal hierarchy as shown in figure 1.

Measurements began on Gulkana Glacier during the early 1960s with the University of Alaska Gulkana Glacier Project (Péwé and Reger, 1983). For

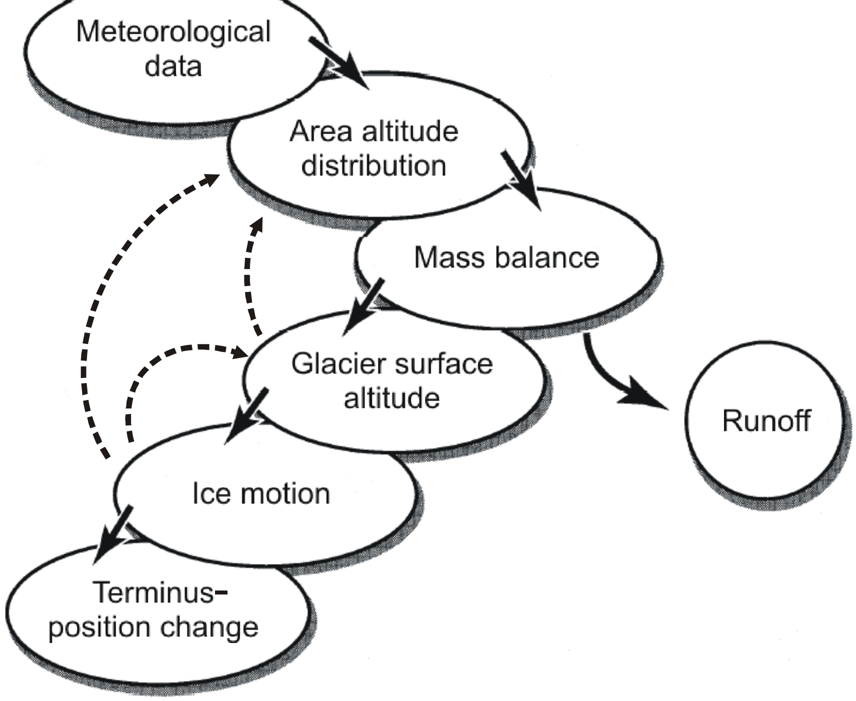


Figure 1. Diagram showing the cause and effect relationships for the data presented in this report (modified from Meier, 1965, and Fountain and others, 1997).

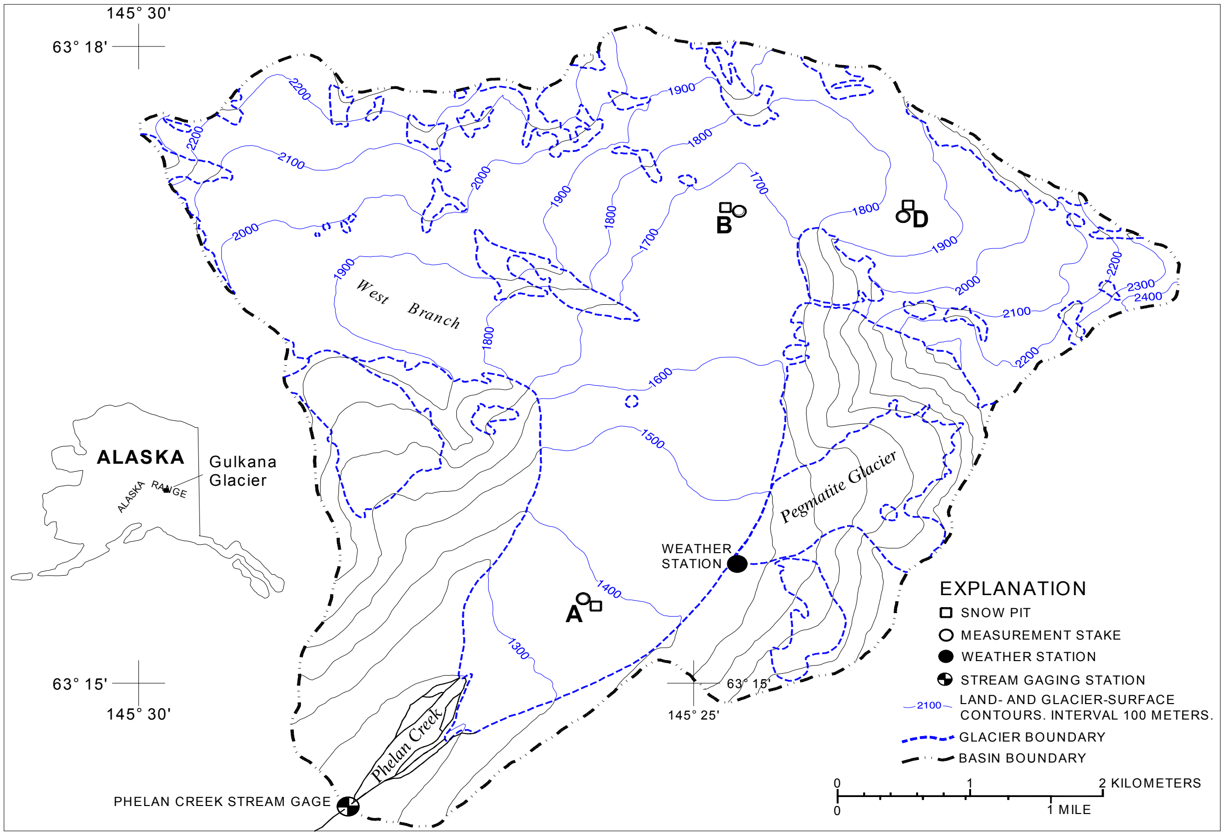
several years this project measured the energy budget, mass balance, meteorology, foliation, flow, and glacier-bottom topography at Gulkana Glacier. In 1966, a continuing series of measurements was begun by the USGS as part of the United States contribution to the International Hydrologic Decade study of mass balances on selected glaciers. Detailed results from 1966 and 1967 are reported by Meier and others (1971) and Tangborn and others (1977), respectively. Measured winter snow balance and annual balance from 1966–77 are reported by Meier and others (1980). Balance studies were relatively intensive until the mid-1970s, after which spatial sampling was reduced to three sites used as indexes for mass balance. Measurements at the three remaining sites were expanded to include ice-motion and surface-altitude observations (for determining glacier-volume change). Since 1966, part of the Gulkana balance data set has been published by the World Glacier Monitoring Service (http://www.geo.unizh.ch/wgms/) in both a 5-year "Fluctuations of Glaciers" series (Kasser, 1967; Muller, 1977; Haeberli, 1985; Haeberli and Müller, 1988; Haeberli and Hoelzle, 1993; Haeberli and others, 1998) and a 2-year "Glacier Mass Balance Bulletin" series (Haeberli and Herren, 1991; Haeberli and others, 1993, 1994, 1996, and 1999) and by Mayo and Trabant (1986). Data for 1992, 1993, 1994, and 1995, similar to those presented here, were published by March and Trabant (1996, 1997) and March (1998, 2000). Select data, maps, and photographs from Gulkana Glacier and a bibliography are available on the Internet at http://ak.water.usgs.gov/glaciology/

The Gulkana record (31 years of balance data, 30 years of meteorology data) has just reached the 30-year length-of-record criterion (generally considered necessary to provide reasonable statistics) used in the selection of stations for international exchange through the Global Telecommunications Service for global climate monitoring (Karl and others, 1989). Interpretations of regional climate-glacier relations using the Gulkana data include papers by Fahl (1973), Letréguilly and Reynaud (1989), Walters and Meier (1989), Dowdeswell and others (1997), Hodge and others (1998), and Trabant and others (1998).

Description of Gulkana Glacier Basin and Its Climate

Gulkana Glacier (figs. 2 and 3) (lat 63°16' N., long 145°25' W.) is a compound valley glacier on the south flank of the eastern Alaska Range. The accumulation area consists of four adjacent cirques with east, south, and west exposures that reach as high as 2,470 m. The ablation area flows south-southwestward, and the terminus is lightly covered with rock debris (fig. 3) at 1,160 m. Slightly contorted moraines near the terminus (fig. 3) suggest that Gulkana Glacier has possibly surged in the past, but no flow instabilities have been detected since scientific investigation began in the early 1960s.

The mean equilibrium line altitude (ELA) since 1966 is near 1,770 m, which is consistent with a continental mountain climate. The mean annual air temperature near the ELA is about -6 °C, lapsed from the weather station using the wet adiabatic rate of -6.6 °C per 1,000 m. The mean annual air temperature at the



Base map, including glacier contours and boundary, from Tangborn and others, 1977.

Figure 2. Gulkana Glacier and vicinity (NAD 27, NGVD of 1929).

weather station at 1,480 m is about -4 °C, and daily mean temperatures range from a low of -35 °C to a high of 15 °C. The average annual precipitation-gage catch is about 1 m. Over the entire basin, the average runoff for water years 1967–78 and 1990–96 is 1.91 m.

In 1967, the 31.5-km^2 basin was about 70 percent covered by perennial snow and ice. Gulkana Glacier is the largest glacier in the basin, covering 19.3 km^2 in 1967. The basin also contains Pegmatite Glacier (fig. 2), three small unnamed glaciers, and perennial snow and ice patches that had a total area of 2.9 km^2 in 1967.

Gulkana Glacier has been in general recession since the culmination of its last advance around 1900 (Péwé and Reger, 1983). The total recession since then has been about 3 km.

Measurement System and Terminology

Seasonal monitoring on Gulkana Glacier consists of three basic measurements: surface mass balance, surface altitude, and ice motion. These measurements are made repeatedly at three fixed locations on Gulkana Glacier, referred to as the “index sites” or “measurement sites” (labeled A, B, and D in figs. 2 and 3). Balance-motion stakes maintained near each index site support the long-term data collection.

The combined mass-balance system of measurement and reporting terminology (Mayo and others, 1972) is used in this report, with the addition of internal accumulation (Trabant and Mayo, 1985) and internal ablation (March and Trabant, 1997). The combined mass-balance system is based on balance measurements relative to time-transgressive stratigraphic horizons (summer surfaces) and evaluation of adjustment quantities for determining both net (stratigraphic) and annual (fixed-date) balances. The balance year used for the net mass balance is the interval between the minimum glacier-wide mass balance in 1 year and the minimum glacier-wide mass balance the following year. Thus, the net balance has a beginning and ending date. To calculate a true net balance it is necessary to run a simple balance model (see section on “Balance

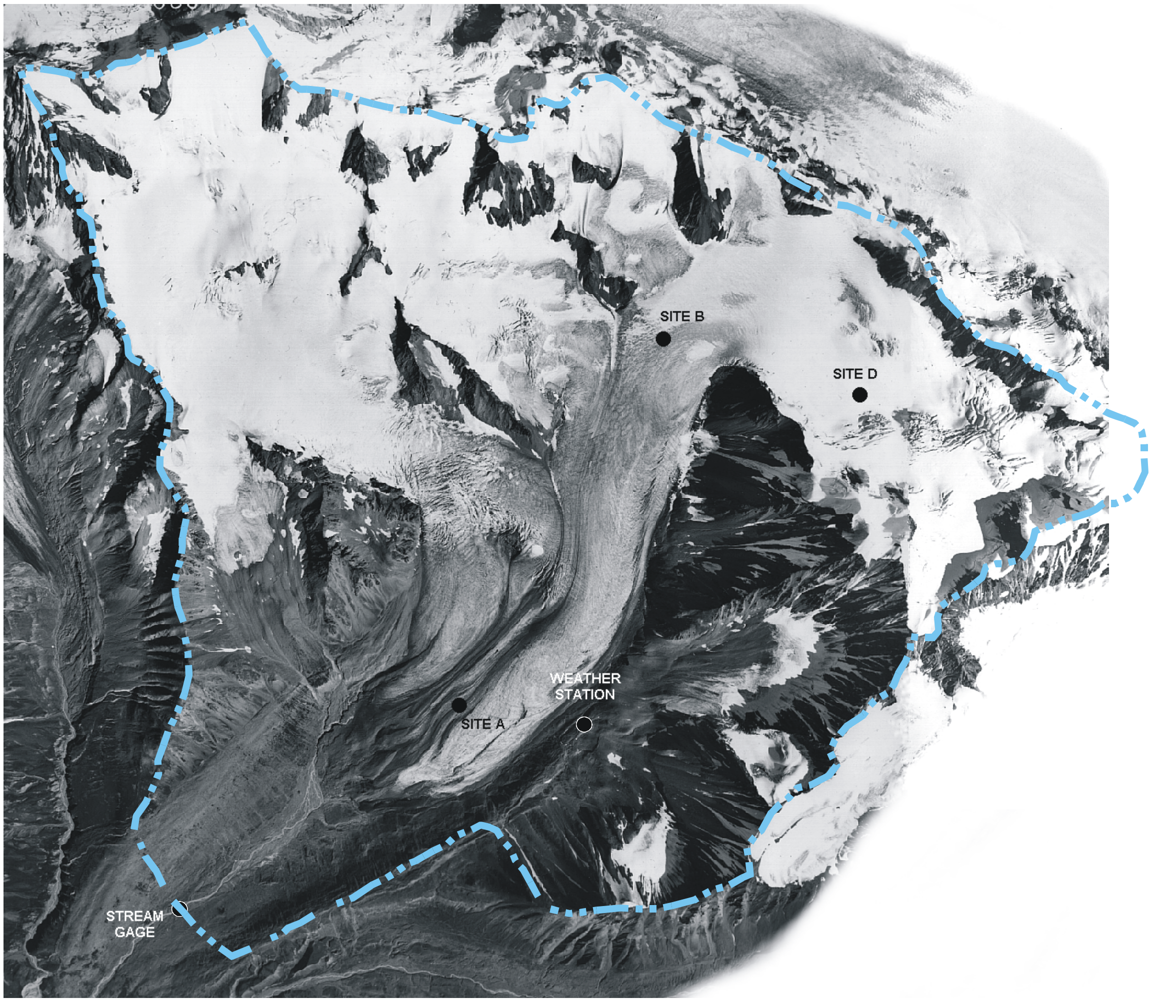


Figure 3. Composite vertical photograph of Gulkana Glacier and its basin showing index-measurement sites, stream-gaging station, weather station, and basin boundary, July 11, 1993 (photographs Gulkana Gl 1 No. 5 and Gulkana Gl 2 No. 4 by AeroMap U.S., Inc.). A, B, and D are measurement sites for mass balance, ice motion, and surface altitude. Dash-dot-dot-dash line indicates basin boundary.

at Specific Sites") to extrapolate from the nearest measurement to the time and value of the glacier-averaged net balance. In most years, the balance minimum occurs at different times on different parts of the glacier (earlier high on the glacier and later low on the glacier). Thus, an area integration of the local balance minimums yields a pseudo area-averaged balance that is not clearly defined with regard to time and does not represent the actual balance on the glacier at any moment.

The hydrologic year, which is the period used for the annual (fixed-date) mass balance, meteorological data, and runoff, is the interval between October 1 and the end of the following September. It is designated by the calendar year in which it ends. The hydrologic year coincides with the USGS "water year." For simplicity "this year" or the "current year" are used in this report to indicate the time period reported in this report, which may be either the balance year, hydrologic year, or some similar period depending on the data being discussed. The temporal relations of the quantities defined and used for analyzing the index-site and glacier-averaged 1996 mass balances are illustrated in figures 4 and 5.

All balance values are reported in meters water equivalent. Density values are reported in kilograms per liter and thus are numerically equivalent to the unitless relative density (the decimal fraction of the density of water). The density of water is 1,000 kg/m^3 or 1 kg/L, and that of glacier ice is assumed to be 900 kg/m^3.

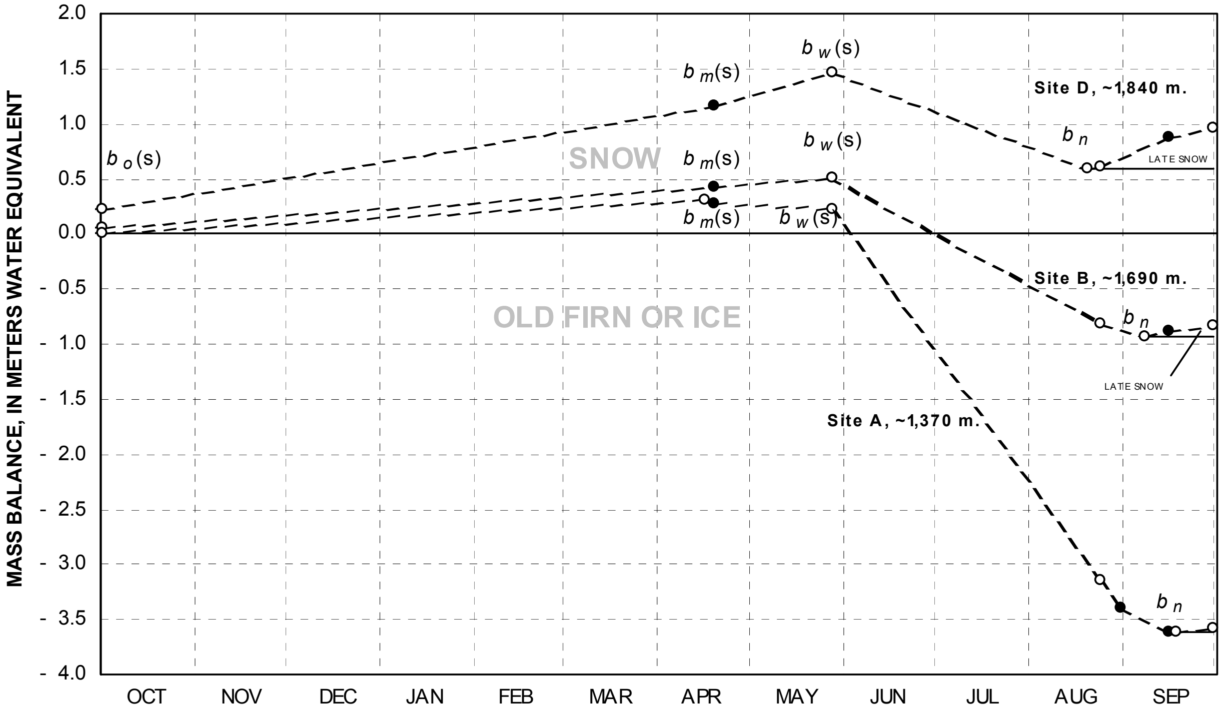


Figure 4. Time distribution of index-site mass balances for Gulkana Glacier, 1996 hydrologic year. Solid circles are measured values; open circles are estimated values. Seasonal maximum balances occurred during late May. b_0(s), initial snow balance at site; b_m(s), measured winter snow balance at site; b_n, net balance at site; b_W(s), maximum winter snow balance at site. Site altitudes are approximate long-term averages rounded to the nearest 10 meters.

Altitude is reported in meters above NGVD of 1929. Horizontal locations are defined in a local sea-level-scale network with the positive Y-axis approximately true north; these coordinates may be converted to Universal Transverse Mercator (UTM) zone 6 coordinates (NAD 83) by:

$$\text{UTM Easting} = \bar{k}X_L + 575{,}000 \text{ m, and} \qquad (1)$$

$$\text{UTM Northing} = \bar{k}Y_L + 7{,}011{,}000 \text{ m,} \qquad (2)$$

where $\bar{k}$ is the mean horizontal scale factor between the UTM plane and sea level and X_L and Y_L are local coordinates, in meters.

The scale factor, k, at a point is a variable defined by:

$$k = \frac{0.9996}{\sin\left(100 + \frac{500,000 - E}{100,000}\right)} \quad , \qquad (3)$$

where E is the UTM Easting of the point and the trigonometric function is evaluated in grad.

The mean scale factor used in equations 1 and 2 is the mean value of the nonlinear distribution of scale factors between the local origin and an observation point. E is approximated by the sum of the UTM Easting of the local origin (575,000 m) and X_L.

$$\bar{k} = \frac{1}{X_L}\int_{(575,000)}^{(575,000 + X_L)} k \, dE \ . \qquad (4)$$

Equation 5 is accurate within about 0.1 part per million of equations from U.S. Departments of the Army and the Air Force (1951, specifically see page 219 and appendixes IV and V) and, hence, yields results accurate at the centimeter level.

The mean scale factor is estimated using Simpson's rule (Cheney and Kincaid, 1980):

$$\bar{k} = \frac{0.9996}{6}\left(\frac{1}{\sin\left(100 + \frac{500,000 - (575,000)}{100,000}\right)} + \frac{4}{\sin\left(100 + \frac{500,000 - (575,000) - \frac{1}{2}X_L}{100,000}\right)} + \frac{1}{\sin\left(100 + \frac{500,000 - (575,000) - X_L}{100,000}\right)}\right) \ . \qquad (5)$$

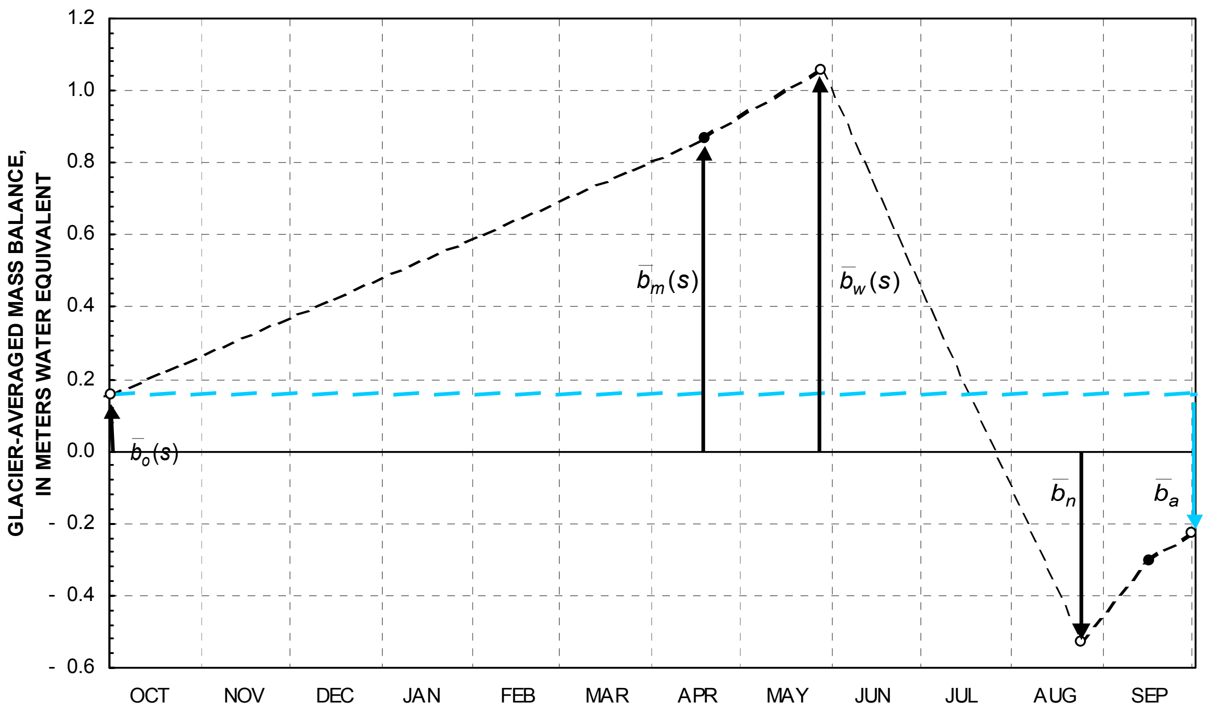


Figure 5. Time distribution of glacier-averaged mass balance of Gulkana Glacier, 1996 hydrologic year (using 1993 area altitude distribution). Solid circles are measured values; open circles are estimated values. Symbols with a bar over them indicate the average value over the whole glacier. The initial balance, $\bar{b}_0(s)$, is the change in balance between the balance minimum that defines the beginning of the net balance year and the beginning of the hydrologic year (October 1). The measured winter snow balance, $\bar{b}_m(s)$, is the snow above the previous summer surface measured near the time of the maximum winter snow balance, $\bar{b}_w(s)$. $\bar{b}_n$, net balance; $\bar{b}_a$, annual balance.

DATA COLLECTION

The temporal distribution of the data collected for the 1996 balance year is shown in table 1. Air temperature, precipitation catch, wind speed, and Phelan Creek stage data are recorded continuously. The stage data are not recorded after Phelan Creek freezes in the early fall, and runoff is estimated for most of the fall, winter, and spring. Phelan Creek discharge measurements to calibrate the stage are made during onsite visits several times during open water and several times during the ice-affected period. The meteorological and runoff data sets reported here are truncated to the hydrologic year, October 1 to September 30.

The mass-balance, glacier-surface altitude, and ice-motion data were collected during four onsite visits between late September 1995 and mid-April 1997 (table 1). Generally the visits were timed to define the mass-balance maximums and minimums, usually during spring (March/April/May) and late-summer/early-fall (September/October), respectively. In addition to measuring the near-maximum balance, observations during the spring add redundancy to the previous fall measurements of the height of the summer surface on the balance-motion stakes and, hence, support a regular assessment of errors in balance calculations made on the basis of stake measurements. Terminus position is measured during one onsite visit near the end of the summer.

METEOROLOGY

Air Temperature

Air temperature is recorded by an analog recorder at 1,480 m on the eastern ice-cored moraine of Gulkana Glacier (weather station, figs. 2 and 3; see Kennedy and others, 1997). The daily mean temperatures reported (fig. 6, table 2) have an accuracy of about ±1.0 °C (Kennedy and others, 1997). Following the National Climatic Data Center (1996) convention, monthly mean temperatures are calculated for months with nine or fewer missing daily values.

Table 1. Summary of data collection in Gulkana Glacier Basin for the 1996 balance year analysis

[———, continuous record; – – –, estimated record; •, occasional/discrete measurement]

Data collection sites (fig. 1 and 2)	Approximate altitude[1] (meters)	Measurement	1996 hydrologic year													1997 hydrologic year						
			1995 calendar year				1996 calendar year												1997 calendar year			
			Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Phelan Creek gaging station	1,140	Stage									———	———	———	———	———							
		Discharge	– – •	– – –	• – –	– – –	– – –	• – –	– – –	• – –	•———	•———	•———	•———	••——	– – –	– – –	• – –	– – –	– • –	– – –	– – –
Site A	1,370	Mass balance	•							•				•	•							•
		Surface motion	•							•					•							•
		Surface altitude	•							•					•							•
Weather station	1,480	Air temperature	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———
		Precipitation catch	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———
		Wind speed		———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———
Site B	1,690	Mass balance	•							•					•							•
		Surface motion	•							•					•							•
		Surface altitude	•							•					•							•
Site D	1,840	Mass balance	•							•					•							•
		Surface motion	•							•					•							•
		Surface altitude	•							•					•							•
		Firn interface temperature								•												•
Terminus position determined														•								

[1] Altitudes are approximate long-term averages rounded to the nearest 10 meters.

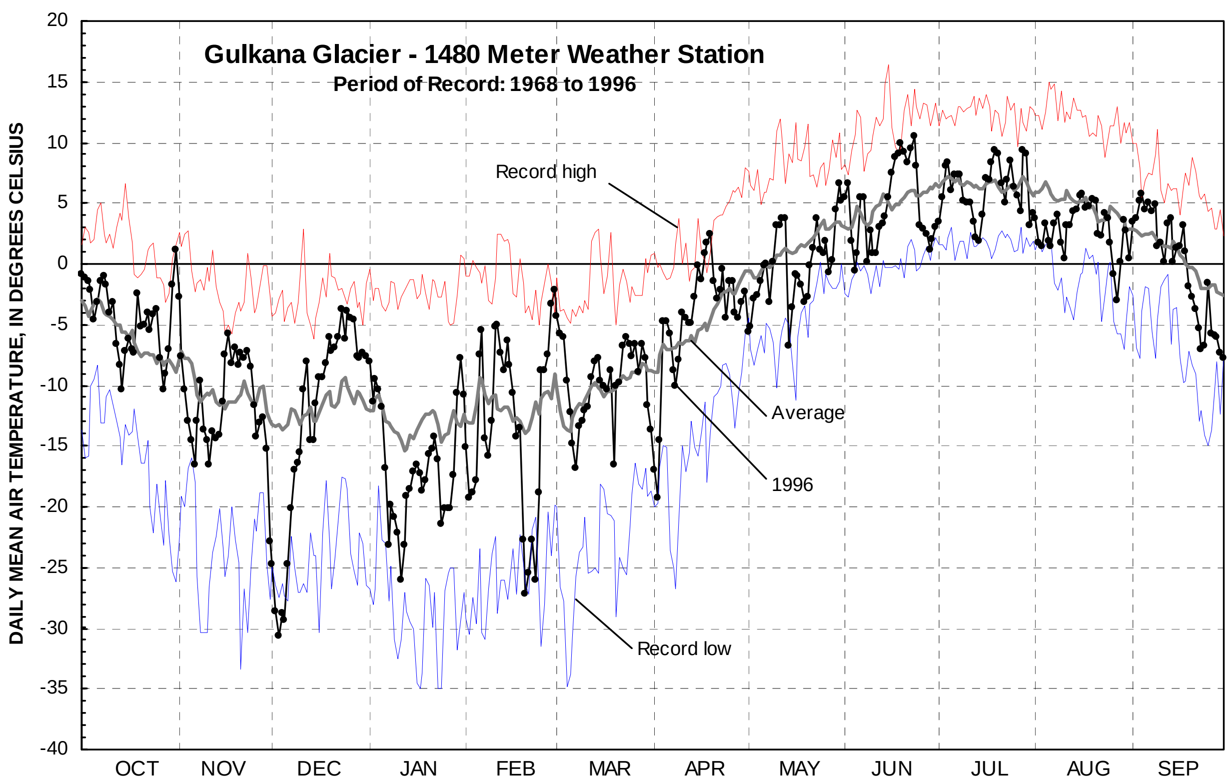


Figure 6. Daily mean air temperature recorded at 1,480-meter weather station, Gulkana Glacier Basin, 1996 hydrologic year. Also shown are record high, average, and record low daily mean temperatures since 1968.

Table 2. Daily, monthly, and annual average air temperatures from analog sensor recorded at 1,480-meter weather station, Gulkana Glacier Basin, 1996 hydrologic year

[Values in degrees Celsius]

	1995			1996									
Day	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Annual**
1	-0.9	-2.8	-24.7	-8.0	-15.1	-4.3	-17.0	-5.6	5.4	3.4	3.8	3.5	
2	-1.1	-7.6	-28.7	-11.4	-19.3	-5.8	-19.3	-5.2	6.6	5.4	1.7	3.7	
3	-1.5	-10.4	-30.6	-9.5	-18.8	-6.0	-14.5	-2.9	1.8	8.0	1.4	5.2	
4	-2.2	-12.9	-28.8	-10.4	-17.8	-9.7	-4.7	-2.6	-0.6	8.3	3.3	5.8	
5	-4.6	-14.6	-29.3	-11.8	-7.5	-12.2	-4.7	-1.5	0.8	6.1	1.9	4.5	
6	-3.1	-16.6	-24.8	-16.9	-5.4	-14.8	-5.8	-0.1	5.5	7.3	1.4	5.0	
7	-1.5	-13.0	-20.2	-23.1	-14.4	-16.8	-8.8	0.0	5.4	7.4	3.3	4.3	
8	-1.0	-9.7	-17.0	-19.8	-15.8	-13.4	-10.0	-3.1	0.2	7.4	4.1	4.9	
9	-1.7	-13.6	-16.4	-20.8	-13.0	-13.0	-7.9	0.2	2.8	5.2	1.7	1.5	
10	-4.1	-14.5	-15.5	-22.1	-5.2	-12.1	-4.0	3.2	0.9	5.0	0.4	1.7	
11	-3.1	-16.6	-10.4	-26.0	-5.1	-11.8	-4.5	3.1	0.8	5.1	3.2	0.2	
12	-6.6	-13.8	-8.1	-23.1	-7.3	-9.4	-4.9	3.7	3.0	3.4	3.2	3.3	
13	-8.3	-14.4	-14.5	-19.1	-8.8	-8.1	-4.9	3.8	3.3	2.2	4.3	3.7	
14	-10.4	-14.1	-14.6	-18.6	-6.4	-7.8	-2.8	-6.7	3.9	1.8	4.5	0.2	
15	-7.2	-11.4	-11.5	-17.1	-8.4	-9.7	-0.2	-3.6	5.5	4.1	5.6	1.3	
16	-6.2	-7.5	-9.3	-16.6	-10.7	-10.0	-1.3	-0.9	7.5	7.1	5.7	1.5	
17	-7.1	-5.8	-9.4	-17.3	-14.2	-10.4	0.8	-1.0	8.8	6.9	4.6	3.2	
18	-7.3	-8.2	-8.2	-18.7	-13.5	-8.8	1.7	-1.7	9.1	8.3	4.7	1.0	
19	-2.4	-6.9	-6.1	-17.8	-22.7	-16.5	2.5	-3.1	10.0	9.3	5.3	-1.9	
20	-5.2	-8.4	-7.2	-15.7	-27.2	-10.0	-1.4	-2.8	9.2	9.0	5.2	-2.8	
21	-5.1	-7.3	-6.9	-15.3	-25.4	-9.8	-2.9	-0.1	8.4	6.6	2.4	-3.7	
22	-4.0	-7.7	-6.1	-14.2	-22.7	-6.8	-2.1	1.3	9.5	5.0	2.3	-5.3	
23	-5.4	-7.2	-3.7	-16.1	-26.1	-6.1	-0.5	3.8	10.5	6.9	4.2	-7.1	
24	-4.2	-8.5	-6.2	-21.4	-18.9	-6.6	-4.4	1.1	8.1	8.5	3.7	-6.7	
25	-3.8	-11.7	-3.9	-20.1	-8.8	-7.6	-1.4	0.8	3.2	6.4	1.7	-1.6	
26	-7.7	-14.2	-4.5	-20.1	-8.8	-6.6	-1.5	1.8	2.9	5.6	-0.9	-5.7	
27	-10.3	-13.1	-4.6	-20.1	-7.5	-8.9	-4.1	-0.7	2.4	4.3	-3.0	-5.9	
28	-9.1	-12.7	-7.6	-17.4	-3.3	-6.6	-4.4	0.3	1.2	9.3	0.2	-6.0	
29	-7.1	-15.2	-7.7	-10.6	-2.2	-7.7	-3.2	4.4	2.0	9.1	3.6	-7.4	
30	-1.7	-22.9	-7.4	-7.8		-11.7	-2.3	6.6	3.0	3.2	2.7	-7.8	
31	1.2		-7.6	-10.8		-13.6		5.2		4.2	0.4		
Average	-4.6	-11.4	-13.0	-16.7	-13.1	-9.8	-4.6	-0.1	4.7	6.1	2.8	-0.2	**-5.0**
Departure from normal	1.2	-1.1	-1.1	-3.5	-1.3	0.7	0.3	-1.4	-0.2	-0.4	-2.0	-0.8	**-0.9**
Standardized value	0.6	-0.4	-0.4	-0.8	-0.4	0.3	0.1	-1.0	-0.1	-0.4	-1.2	-0.5	**-0.9**

Starting this year, a digital temperature sensor also was used (table 3). It is located adjacent to the analog sensor in the same shelter. It has an accuracy of ±0.1 °C and time constant of 10 seconds in air, considerably faster than the analog sensor. Fifteen-minute average temperatures are recorded by the digital sensor from which the daily average is determined.

The annual average temperature for 1996 with the analog sensor was -5.0 °C, 0.9 standard deviation below the long-term average of -4.1 °C (1968–91, 1993–95). The winter average temperature from September 1, 1995, to May 15, 1996, was -8.3 °C, about 0.2 standard deviation below the long-term average. The summer average temperature from May 16 to August 30, 1996, was 4.0 °C, about 1.0 standard deviation below the long-term average. (The winter and summer average temperature periods correspond to the average maximum and minimum glacier-averaged balance periods to within about one-half month.)

The annual average temperature for 1996 with the digital sensor was -4.1 °C, 0.9 °C warmer than the analog sensor. This average difference is within the accuracy of the analog sensor. Some difference between sensors was expected due to the large difference in their time constants. Plans are to collect several years of overlapping data for further analysis.

Precipitation Catch

Precipitation catch (fig. 7, table 4) is recorded at the weather station (figs. 2 and 3) by an analog recorder connected to a storage-type precipitation gage with a modified Nipher shield (see Kennedy and others, 1997). Previously, precipitation catch data have been processed with a temperature and water-concentration dependent density correction. However, new analysis, not possible at the beginning of the USGS Gulkana Glacier monitoring program, shows that the density correction is incomplete and actually increases

Table 3. Daily, monthly, and annual average air temperatures from digital sensor recorded at 1,480-meter weather station, Gulkana Glacier Basin, 1996 hydrologic year

[Values in degrees Celsius; —, daily value missing; M appended to value, insufficient or partial data, up to 9 days missing in average]

		1995						1996					
Day	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Annual**
1	—	- 1.5	-24.0	—	-14.4	- 3.5	-16.2	- 4.6	6.1	5.2	4.7	2.2	
2	—	- 6.7	-27.7	-10.4	-18.7	- 5.5	-18.9	- 4.8	7.7	7.0	2.8	4.4	
3	- 0.3	- 9.4	-30.1	- 8.2	-18.2	- 6.0	-13.7	- 1.4	3.2	9.0	3.1	5.9	
4	- 1.5	-12.2	-27.5	- 9.6	—	- 8.7	- 3.6	- 1.7	1.1	8.2	4.7	6.6	
5	- 3.7	-13.8	-28.8	-10.7	—	-11.4	- 3.7	- 0.5	1.5	6.6	2.4	4.7	
6	- 2.0	-16.4	-23.9	-16.3	- 4.7	-14.4	—	1.1	6.2	8.5	2.9	4.8	
7	- 0.7	-12.0	-18.7	-21.8	-13.5	-16.5	- 8.4	0.7	6.7	9.7	4.9	4.6	
8	- 1.0	- 9.0	-16.3	-18.9	-15.2	-12.2	- 9.6	- 1.9	1.6	8.1	5.4	4.9	
9	- 1.6	-12.9	-15.5	-20.3	-11.4	-12.3	- 7.2	0.8	3.6	6.2	2.6	2.2	
10	- 3.4	-13.4	-14.7	-21.2	- 3.8	-11.8	- 4.0	3.9	2.2	6.1	1.7	2.0	
11	- 2.4	-15.9	- 9.4	-25.5	- 4.4	-11.3	- 3.8	3.9	2.1	5.9	4.6	—	
12	- 5.8	-12.7	- 7.3	-22.3	- 6.7	- 8.6	- 4.4	4.9	3.9	4.5	4.6	—	
13	- 7.1	-13.4	-13.6	-18.5	- 7.4	- 7.3	- 4.3	4.9	3.9	3.0	4.4	4.3	
14	- 9.9	-12.9	-13.6	-17.8	- 6.1	- 7.0	- 2.0	- 1.2	4.9	2.8	5.5	1.1	
15	- 6.1	-10.8	- 9.9	-16.3	- 7.6	- 8.7	- 0.1	- 2.2	6.6	5.4	7.0	2.0	
16	- 5.7	- 6.6	- 8.3	-15.5	-10.0	- 9.3	- 1.0	0.4	8.7	8.3	6.7	1.9	
17	- 6.0	- 4.6	- 8.4	-16.7	-13.6	-10.2	1.9	0.1	9.7	7.5	5.7	3.3	
18	- 7.1	- 7.8	- 6.7	-17.7	-12.3	- 8.7	2.6	- 0.3	9.6	9.2	6.0	2.0	
19	- 1.5	- 6.0	- 5.2	-16.9	-21.9	-15.3	—	- 2.0	10.6	10.2	7.0	- 1.4	
20	- 4.7	- 7.9	- 6.7	-14.4	-26.9	- 9.7	- 0.6	- 1.1	9.9	9.9	6.0	- 2.2	
21	- 4.0	- 6.4	- 6.0	-14.2	-25.3	-10.1	- 1.3	1.0	9.2	7.4	3.4	- 2.6	
22	- 2.8	- 7.1	- 5.0	-13.2	-21.6	- 7.1	- 0.9	2.9	10.4	6.0	3.8	- 4.7	
23	- 4.8	- 6.3	- 3.0	-15.9	-26.1	- 5.9	0.4	4.0	11.0	8.1	5.1	- 6.6	
24	- 3.1	- 7.4	- 4.8	-20.9	-17.1	- 5.9	- 3.2	2.5	8.8	10.0	4.7	- 5.9	
25	- 2.9	-10.7	- 2.8	-19.9	- 7.8	- 7.8	- 0.6	1.5	4.9	7.3	2.8	- 0.4	
26	- 6.3	-13.1	- 3.7	-19.4	- 8.2	- 6.0	- 0.3	0.9	3.9	6.9	0.7	- 5.0	
27	- 9.0	-12.6	- 4.0	-19.5	- 6.4	- 7.9	- 2.7	0.6	4.1	5.9	- 1.9	- 5.6	
28	- 8.4	-11.6	- 6.2	-16.5	- 2.6	- 6.5	- 3.2	1.3	2.2	11.2	2.3	- 6.7	
29	- 5.6	-13.7	- 6.3	- 9.5	- 1.6	- 6.3	- 1.9	5.5	2.1	9.8	4.8	- 7.7	
30	0.0	-22.2	- 6.2	- 6.7		-10.6	- 1.2	7.5	4.1	4.2	3.5	- 6.6	
31	—		- 7.0	- 9.9		-12.9		5.9		5.4	—		
Average	- 4.2M	-10.6	-12.0	-16.2M	-12.4M	- 9.2	- 4.0M	1.1	5.7	7.2	4.1M	0.1M	**- 4.1M**

the measurement error rather than reducing it. Hence, it was not used in this year's data processing. Comparison of density-corrected data to non-density-corrected data for previous years shows monthly and annual differences of several percent. These differences are judged to be minor compared to other errors. Daily value differences can be much greater, with precipitation occasionally shifted from 1 day to an adjacent day.

The precipitation-catch record for the 1996 hydrologic year shows evidence of fluid loss through April 19, 1996. This could have been caused either by a fluid leak in the storage tank or by evaporation, which is normally prevented by an oil film on the surface of the stored antifreeze-water solution. Because the functioning of the precipitation gage returned to normal after replacing the oil film in the storage tank on April 20, 1996, it is concluded that the oil film was inadequate prior to that. As a result, the record up through April 19 was processed separately to compensate for the evaporation as best as possible. This process is complicated because even when the gage is working normally, the fluid height in the gage frequently drops by small amounts due to temperature-driven gage and fluid expansion/contraction and measurement error. Hence, all negative gage-height changes can not be thrown out of the data set. Instead, the quantity of negative gage-height changes was reduced to a level comparable to years when the gage was functioning normally.

Despite the problems, processing the precipitation-catch record to compensate for evaporation is considered better than using the precipitation record from the nearest National Weather Service station, Paxson (station 50709704, located at 823 m, about 20 km south of the Gulkana weather station). On the basis of data from 1975–84 and 1986–92, the Paxson gage catches only about one-half as much precipitation annually, and the Pearson (conventional) correlation coefficient between Gulkana and Paxson daily precipitation values is only 0.62.

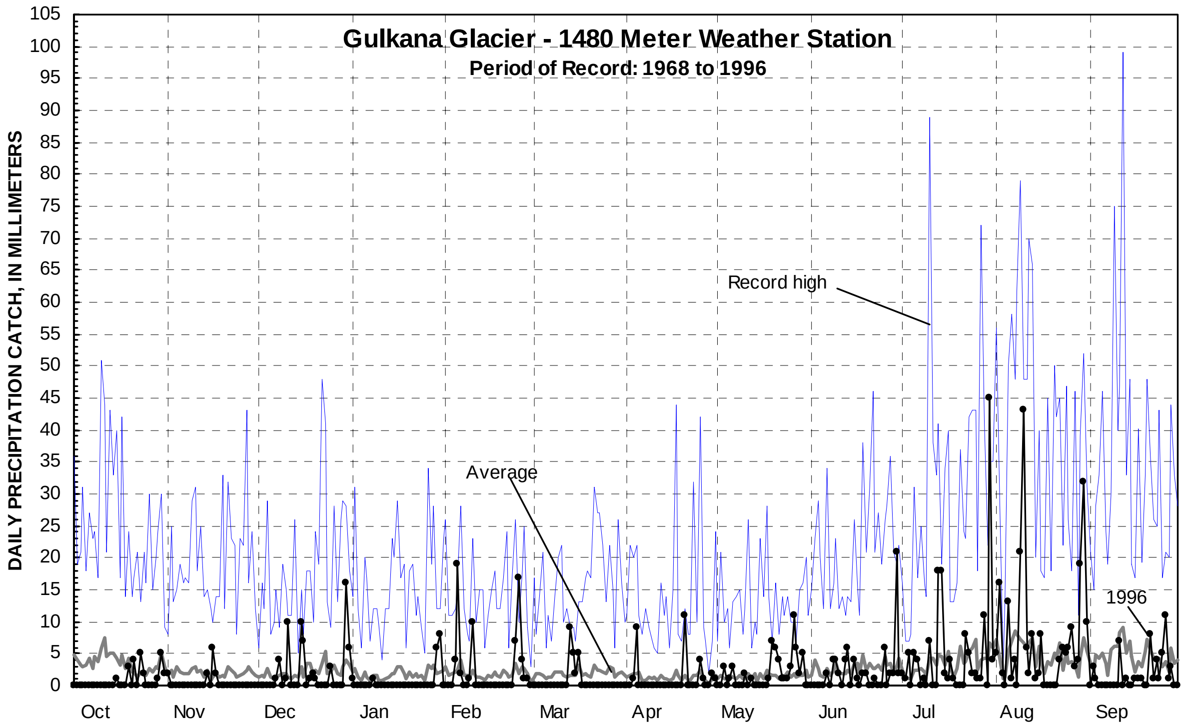


Figure 7. Daily precipitation catch recorded at 1,480-meter weather station, Gulkana Glacier Basin, 1996 hydrologic year. Also shown are record high and average daily precipitation catch since 1968.

Daily precipitation catch (fig. 7, table 4) has an estimated accuracy of ±0.001 m normally, and prior to April 20, 1996, the estimated accuracy was ±0.003 m. Cumulative precipitation catch for the month is estimated to have an accuracy of ±0.002 m (Mayo and others, 1992; Kennedy, 1995).

The complex relation between precipitation catch and true basin precipitation has not been thoroughly analyzed at Gulkana. It is generally well known that catch efficiencies are not constant but vary with wind speed, direction, and the nature of the precipitation. At Wolverine Glacier, which has a windier environment than Gulkana, the gage-catch efficiency was found to be about 0.31 relative to true basin precipitation for a 10-year period (Mayo and others, 1992). From April 27, 1967, to September 30, 1967, the catch efficiency of the Gulkana gage was calculated at 0.52 (Tangborn and others, 1977), although the wind shield has since been modified to what is believed to be a more efficient design. For hydrologic years 1968–78 and 1990–91, the average catch efficiency for the Gulkana Basin was 0.57. Despite the low catch efficiencies, precipitation catch is useful as an indicator of true basin precipitation.

Wind Speed

The 1996 hydrologic year is the first full year of wind-speed data collection from the 1,480-m weather station (fig. 8, table 5). The sensor is a Taylor Scientific Engineering WS-3 rotor anemometer designed for a very windy, rugged mountain environment and installed on a 3-m mast. The threshold wind speed is 1.34 m/s, and it has a time constant of 7 to 8 seconds for a step increase in wind speed and 19 to 20 seconds for a step decrease. The sensor's accuracy is about ±0.5 m/s. Fifteen-minute average wind speeds are recorded.

Annual average wind speed for 1996 was 3.5 m/s. Maximum daily average wind speed for the year was 15.0 m/s recorded on November 4, 1995, and March 9, 1996. Maximum 15-minute average wind speed was 23.5 m/s on February 19, 1996. Wind speeds greater than 5 to 8 m/s, the threshold for blowing snow (Barry, 1989), occur 15 to 20 percent of the time. Wind entrainment and redeposition of snow may be an important mass-balance process at Gulkana Glacier. Average monthly wind speed is shown in figure 9.

Table 4. Daily and monthly precipitation catch recorded at 1,480-meter weather station, Gulkana Glacier Basin, 1996 hydrologic year

[Values in millimeters]

Day	1995 Oct	1995 Nov	1995 Dec	1996 Jan	1996 Feb	1996 Mar	1996 Apr	1996 May	1996 June	1996 July	1996 Aug	1996 Sept	Annual
1	0	2	0	1	0	0	0	0	0	2	5	0	
2	0	0	0	0	0	0	0	0	0	1	16	3	
3	0	0	0	0	0	0	1	3	0	5	2	1	
4	0	0	0	0	4	0	9	0	0	0	0	0	
5	0	0	0	0	19	0	0	1	0	5	13	0	
6	0	0	0	0	2	0	0	3	2	4	1	0	
7	0	0	1	0	0	0	0	0	0	0	4	0	
8	0	0	4	1	0	0	0	0	4	1	0	0	
9	0	0	0	0	1	0	0	0	4	0	21	0	
10	0	0	1	0	10	0	0	2	2	7	43	0	
11	0	0	10	0	0	0	0	0	0	0	6	7	
12	0	0	0	0	0	0	0	1	4	0	2	0	
13	0	0	0	0	0	9	0	0	6	18	8	1	
14	0	2	0	0	0	5	0	0	0	18	1	0	
15	1	0	10	0	0	2	0	0	4	2	2	0	
16	0	6	7	0	0	5	0	0	1	1	8	1	
17	0	2	0	0	0	0	0	0	0	4	0	1	
18	0	0	1	0	0	0	0	1	2	1	0	1	
19	3	0	2	0	0	0	0	7	2	0	0	0	
20	0	0	1	0	0	0	11	6	0	0	0	0	
21	4	0	0	0	0	0	0	4	0	0	0	8	
22	0	0	0	0	0	0	0	1	1	8	4	1	
23	5	0	0	0	0	0	0	1	0	5	6	4	
24	2	0	0	0	7	0	0	1	0	2	5	1	
25	0	0	3	0	17	0	4	3	6	2	6	5	
26	0	0	0	0	4	0	1	11	0	1	9	11	
27	0	0	0	0	1	0	0	6	2	1	3	1	
28	0	0	0	0	1	0	0	2	2	11	4	3	
29	1	0	0	6	0	0	2	5	21	0	19	0	
30	5	0	16	8		0	1	0	2	45	32	0	
31	2		6	0		0		0		4	10		
Total	23	12	62	16	66	21	29	58	65	148	230	49	**779**
Departure from normal	-86	-49	- 6	-42	12	-40	-11	11	-19	34	80	-89	**-204**
Standardized value	- 1.4	- 1.1	- 0.1	- 1.3	0.4	- 1.0	- 0.4	0.5	- 0.4	0.4	0.8	- 1.0	**- 0.8**

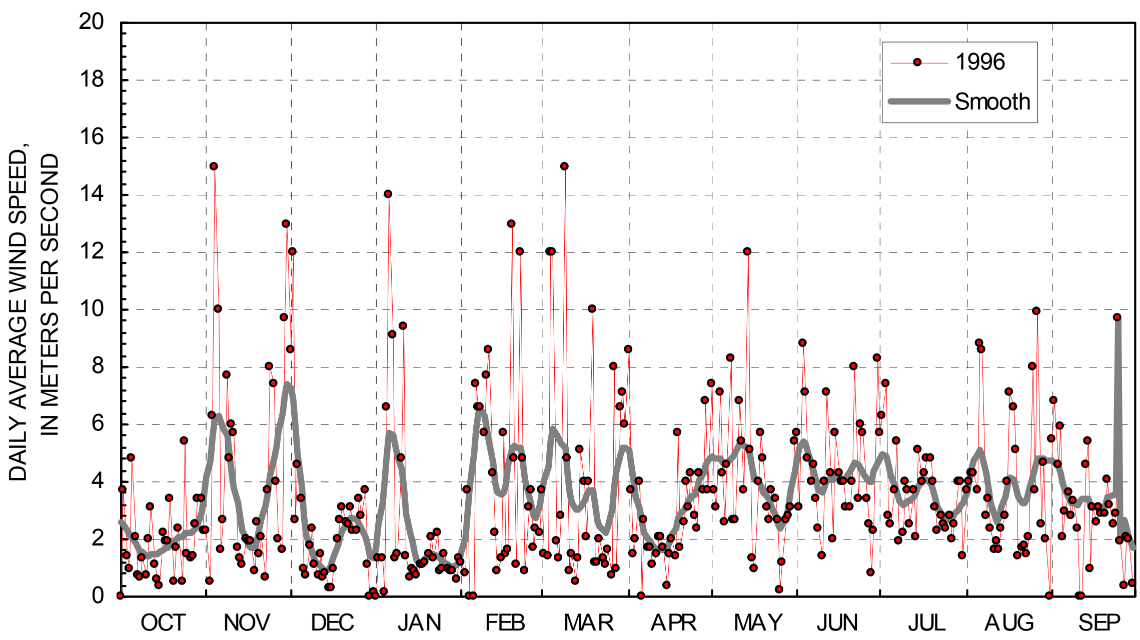


Figure 8. Daily average wind speed recorded at 1,480-meter weather station in Gulkana Glacier Basin, 1996 hydrologic year. Smooth is an inverse distance weighted smooth of the data using an 11-day window.

Table 5. Daily mean wind speed from the Gulkana Glacier Basin, 1996 hydrologic year

[Values in meters per second; M appended to value, insufficient or partial data, up to 9 days missing in average; —, daily value missing]

Day	1995 Oct	1995 Nov	1995 Dec	1996 Jan	1996 Feb	1996 Mar	1996 Apr	1996 May	1996 June	1996 July	1996 Aug	1996 Sept	Annual
1	—	2.3	8.6	—	1.2	3.7	8.6	7.4	5.7	5.7	3.7	5.5	
2	3.7	0.5	12.0	1.3	0.8	1.5	3.7	3.7	3.1	6.3	4.0	6.8	
3	1.4	6.3	2.7	1.3	3.7	1.4	1.5	3.1	8.8	7.4	4.3	4.6	
4	1.0	15.0	4.6	0.2	—	12.0	2.0	7.1	7.1	2.8	4.3	5.9	
5	4.8	10.0	3.4	6.6	—	12.0	4.0	4.3	4.8	2.5	3.7	2.1	
6	2.1	1.6	0.9	14.0	7.4	1.9	—	2.6	4.0	3.7	8.8	3.0	
7	0.8	2.7	0.7	9.1	6.6	1.3	2.7	4.6	4.6	5.4	8.6	3.6	
8	0.6	7.7	1.8	1.3	6.6	2.8	1.7	8.3	3.4	1.9	2.8	2.8	
9	1.3	4.8	2.4	1.5	5.7	15.0	1.7	2.7	2.4	2.2	3.4	3.3	
10	0.7	6.0	1.1	4.8	7.7	4.8	1.1	2.7	1.4	4.0	2.4	2.4	
11	2.0	5.7	0.7	9.4	8.6	0.9	1.5	6.8	4.0	3.7	1.6	—	
12	3.1	1.7	1.5	1.4	4.3	1.5	2.1	5.4	7.1	2.5	1.9	—	
13	1.1	1.3	0.7	0.7	2.2	0.5	2.1	3.7	4.3	3.7	1.6	4.6	
14	0.6	1.1	0.8	1.0	0.9	1.3	1.7	12.0	2.0	2.1	2.4	5.4	
15	0.3	2.0	0.3	0.9	1.3	5.1	0.4	5.1	5.7	5.1	2.8	1.0	
16	2.2	1.9	0.3	0.8	5.7	4.0	1.5	1.3	4.3	4.0	4.0	3.1	
17	1.9	1.9	1.0	1.1	1.5	2.1	2.0	0.9	4.0	4.3	7.1	2.6	
18	1.9	0.9	2.0	1.1	1.6	4.0	1.4	4.0	4.0	4.8	6.6	3.1	
19	3.4	2.6	2.7	1.2	13.0	10.0	5.7	5.7	3.1	4.8	5.1	2.9	
20	0.5	1.5	3.1	1.5	4.8	1.2	1.7	4.8	3.1	4.0	1.4	2.9	
21	1.7	2.1	2.6	2.1	1.1	1.2	2.6	3.1	4.0	3.1	1.7	4.1	
22	2.4	0.7	2.5	1.3	12.0	2.0	4.0	2.7	8.0	2.3	1.8	3.2	
23	0.5	3.7	3.1	2.2	4.8	1.3	3.1	3.7	3.4	2.8	1.5	2.5	
24	5.4	8.0	2.3	0.9	0.9	1.1	4.3	3.4	6.0	2.5	2.1	2.9	
25	1.5	7.4	2.3	1.0	3.1	1.6	2.8	2.7	5.7	2.4	8.0	9.7	
26	1.3	4.0	3.4	1.5	3.7	0.8	2.4	0.2	3.4	2.8	3.7	1.9	
27	1.4	2.0	2.8	1.0	1.7	8.0	4.3	1.2	2.5	2.0	9.9	0.4	
28	2.5	1.6	3.7	0.9	2.4	1.0	3.7	2.7	0.8	2.5	2.5	2.1	
29	3.4	9.7	1.1	0.9	2.2	6.6	6.8	2.8	2.3	4.0	4.7	2.0	
30	3.4	13.0	0.0	0.6		7.1	3.7	3.1	8.3	4.0	2.0	0.5	
31	2.3		0.1	1.3		6.0		5.4		1.4	—		
Average	2.0M	4.3	2.4	2.4M	4.3M	4.0	2.9M	4.1	4.4	3.6	3.9M	3.4M	**3.5M**

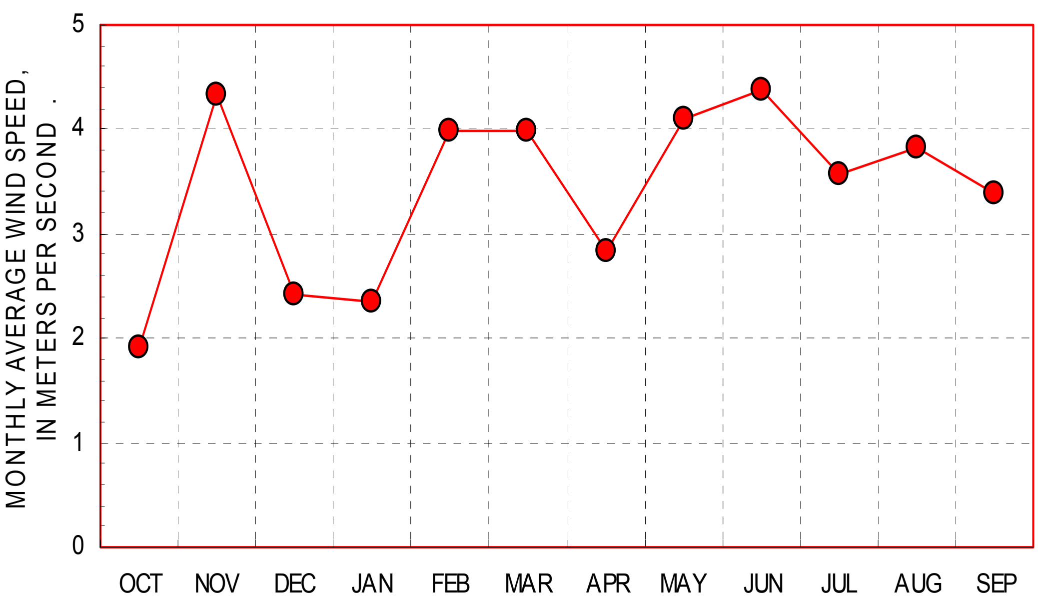


Figure 9. Monthly average wind speed recorded at 1,480-meter weather station in Gulkana Glacier Basin for 1996 hydrologic year.

AREA ALTITUDE DISTRIBUTION

Two area altitude distributions are used in this report. The first is the area altitude distribution of the glacier and basin defined for the 1967 balance analysis (fig. 10) (Tangborn and others, 1977; see March, 1998, for tabulation of these values). These values are based on a 100-m contour topographic map that was defined from examination of the 1:63,360-scale USGS topographic maps, Mt. Hayes A–3 (1950) and B–3 (1955), the original 1954 vertical mapping photography, and more recent oblique aerial photography (dates unknown) taken by Austin Post and Larry Mayo (aerial photographs are part of the USGS Ice and Climate Project Photography Collection, GeoData Center, Fairbanks, Alaska). The 1967 values have been used to calculate and report all glacier-averaged balances since 1967.

The second area altitude distribution (see fig. 10 and table 6) is based on a 30-m grid version of a higher resolution, but irregularly spaced, digital elevation model (DEM) that was photogrammetrically derived from 1:36,000-scale 1993 vertical photography (March, 2000). In 1993, snow and ice coverage in the basin had been reduced to 64 percent of the basin from 70 percent in 1967. Gulkana Glacier had shrunk by 6 percent to 18.1 km^2, and other small glaciers and perennial snow areas had shrunk by 42 percent to 1.7 km^2. Virtually all of the Gulkana Glacier shrinkage occurred below the ELA. The lack of an area reduction in the 1,200- to 1,300-m altitude zone could be due to the extensive presence of surficial debris in this zone. Surficial debris retards ablation when it continuously covers the ice surface and is thicker than a few centimeters.

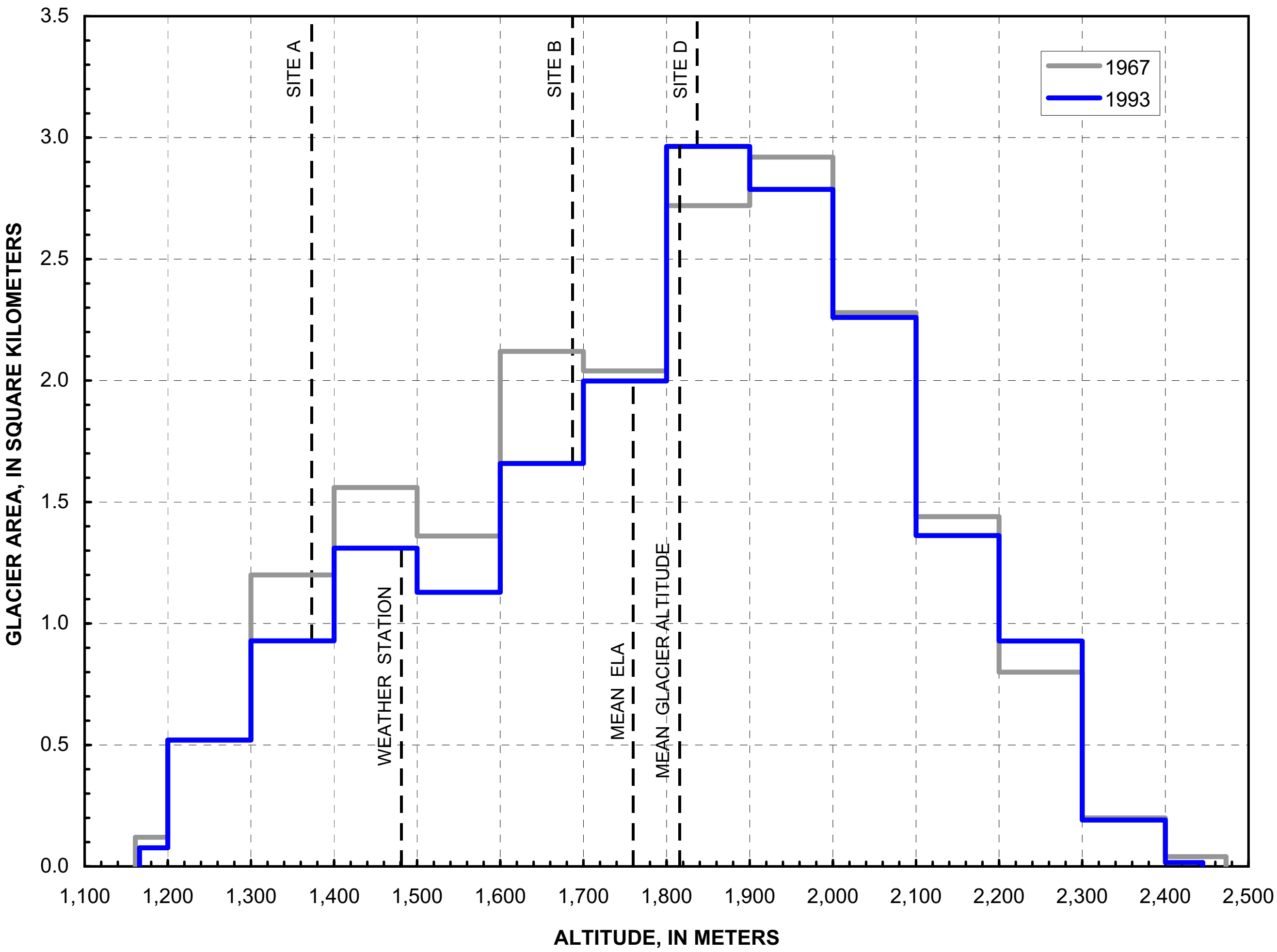


Figure 10. Area altitude distribution of Gulkana Glacier in 1967 and 1993. Shown are altitudes of index sites, the weather station, the mean equilibrium line altitude (ELA), and mean altitude of the glacier.

Table 6. Area altitude distribution of Gulkana Glacier and Gulkana Glacier Basin by 100-meter altitude intervals as defined from a digital elevation model derived from July 11,1993, photography

[Measurement site altitudes, in meters, are approximate averages for 1996 balance year. m, meters; km^2, square kilometers]

Altitude interval (m)	Average altitude (m)	Basin area (km^2)	Non-glacier area (km^2)	Total glacier area (km^2)	Gulkana Glacier area (km^2)	Other glacier area (km^2)	Subareas of glacier represented by index sites: Site A (km^2)	Site B (km^2)	Site D (km^2)
1,166 - 1,200	1,181	1.31	1.23	0.08	0.08		0.08		
1,200 - 1,300	1,250	1.60	1.08	0.52	0.52		0.52		
1,300 - 1,400	1,350	1.86	0.93	0.93	0.93		0.93		
1,400 - 1,500	1,450	2.45	1.14	1.31	1.31		1.31		
1,500 - 1,600	1,550	2.43	1.24	1.20	1.13	0.07	0.27	0.86	
1,600 - 1,700	1,650	3.26	1.34	1.92	1.66	0.26		1.66	
1,700 - 1,800	1,750	3.67	1.09	2.57	2.00	0.58		1.14	0.86
1,800 - 1,900	1,850	4.64	1.11	3.53	2.96	0.57			2.96
1,900 - 2,000	1,950	3.90	0.89	3.01	2.79	0.22			2.79
2,000 - 2,100	2,050	2.78	0.51	2.27	2.26	0.01			2.26
2,100 - 2,200	2,150	1.74	0.38	1.36	1.36				1.36
2,200 - 2,300	2,250	1.20	0.27	0.93	0.93				0.93
2,300 - 2,400	2,350	0.24	0.05	0.19	0.19				0.19
2,400 - 2,445	2,423	0.02		0.02	0.02				0.02
Total area, in km^2 =		31.10	11.27	19.84	18.13	1.71	3.11	3.66	11.37
Altitude of index site in 1996, in m =							1,366	1,681	1,833
Average altitude of zone, in m =		1,740	1,609	1,814	1,817	1,788	1,389	1,658	1,985
Upper altitude limit of zone, in m =							1,524	1,757	2,473
Lower altitude limit of zone, in m =							1,161	1,524	1,757
Fraction of Gulkana Glacier area =							0.171	0.202	0.627
Fraction of basin area=		1.000	0.362	0.638	0.583	0.055			

GLACIER MASS BALANCE

Balance at Specific Sites

Measured winter snow balance, maximum winter snow balance, net mass balance, and the annual mass balance are determined at each index site using largely traditional methods (Østrem and Stanley, 1969; Østrem and Brugman, 1991). The stake, pit, probing, coring, and meteorological data are shown in tables 7, 8, and 9 and figure 4.

Although mass-balance measurement locations commonly are referred to as “points” on a glacier, they are treated as small areas 25 to 75 m in radius, centered on each index site, over which measurements are made and the balance averaged. The area chosen is large enough and enough measurements are taken in the area so that when a quantity, such as snow depth, is averaged over the area, the error caused by the glacier-surface and summer-surface roughness (up to several meters on some glaciers) is small. Likewise, stake readings are made at the intersection of the average, “visually smoothed” glacier surface (out to 25 to 75 m) with the stake and not just where the snow, ice, or firn is right at the stake.

One departure from traditional methods is surveying of the stake and glacier-surface geometry and subsequent analysis to correct for the lean and bending, which commonly occur after the initial near-vertical installation of the stakes (March, 2000). These corrections affect the stake position for ice motion (see section on “Ice Motion”) and the height on the stake of the glacier surface, *b´* (table 7), which is used for some balance determinations. Another departure from traditional methods is the recording and combining of multiple measurements of the height of a summer surface on a stake to reduce balance errors (March, 2000), such as a fall measurement of the summer surface after fall snow has fallen and another measurement of the same summer surface in the spring near the peak snowpack.

Table 7. Stake, snow depth, and snow-density data for index sites A, B, and D on Gulkana Glacier, September 1995 through April 1997

[mm/dd/yyyy, month/day/year; stake name: the first two digits represent the year the stake was installed; letter (A, B, D) represents the site on the glacier (fig. 3); a number following the letter is used to differentiate multiple stakes installed at the same site in 1 year. LSnow (late snow), snow on top of the current year's summer surface, occurs only after the summer surface has formed. Found/left, total height on the stake before and after adjustments are made during a visit to improve its survivability. Obs. (observed) *b'*, the average height on the stake of the glacier surface within a 50-meter radius of the stake. *b**, stake height of surveyed point on the stake near *b'*. *b***, surveyed *b** corrected for stake lean, bend, or bow. *b**-*b***, value to be applied to correct *b'* for stake lean, bend, or bow. Total stake slip, cumulative distance the stake bottom has moved into the glacier since installed; it is generally assumed that the stake bottom is fixed in the glacier. Best *b'*, observed *b'* corrected for stake lean, bend, bow, and/or slippage or, in other words, the calculated height of the glacier surface directly above the stake bottom (that is as if the stake were vertical). Stake *d*(s), snow depth as determined from the best *b'* and previous or subsequent determinations of the stake height of the summer surface. Pit *d*(s), snow depth measured in snow pit. McCall *d*(s), snow depth measured with a McCall snow sampler, a small-diameter sampler used to core the entire snowpack. Probe *d*(s), snow depth measured by probing to the summer surface with a metal rod. Obs. *d*(s), observed snow depth measured directly on date without relying on stake readings from other dates. Mean *d*(s), average snow depth. s.e. *d*(s), standard error of snow depth. *n*, number of snow-depth samples. Snow density, measured in snow pit, by McCall snow sampler (a long, tube-type sampler), or estimated. m, meter; kg/L, kilograms per liter]

			Stake data							Snow depth											Snow density			
					Surveyed						Pit		McCall		Probe									
Date (mm/dd/yyyy)	Stake name	Surface strata type	Found /left (m)	Obs. *b'* no lean correct. (m)	*b** (m)	*b*** (m)	Diff. *b**-*b*** (m)	Total stake slip (m)	Best stake *b'* (m)	Stake *d* (s) (m)	*d* (s) (m)	*n*	*d* (s) (m)	*n*	*d* (s) (m)	*n*	Obs. *d* (s) (m)	Mean *d* (s) (m)	s.e. *d* (s) (m)	*n*	Pit (kg/L)	McCall (kg/L)	Est. (kg/L)	Mean (kg/L)
SITE A, 1,370 m[1]																								
04/19/1996	96-A	Snow	0/8	9.54	9.52	9.58	0.06	0.00	9.60		0.98	1			0.79	23	0.80	0.80	0.06	24	0.35			0.35
05/06/1996	96-A	Snow																					0.35	0.35
05/28/1996	96-A	Snow																					0.35	0.35
08/24/1996	96-A	Ice																						
08/31/1996	96-A	Ice	8/8	4.95				0.00	4.95								0.00	0.00		1				
09/16/1996	96-A	Ice	8/8	4.65	4.65	4.68	0.03	0.00	4.68								0.00	0.00		1				
09/18/1996	96-A	Ice																						
09/30/1996	96-A	LSnow																						
04/18/1997	96-A	Snow	8/6	5.85	5.85	5.88	0.03	0.00	5.88				1.43	3	1.29	20	1.31	1.31	0.06	23		0.35		0.35
04/16/1996	96-A1	Snow																					0.35	0.35
04/19/1996	96-A1	Snow	0/8	9.49	9.47	9.48	0.01	0.00	9.50		0.98	1			0.79	23	0.80	0.80	0.06	24	0.35			0.35
05/28/1996	96-A1	Snow																					0.35	0.35
08/24/1996	96-A1	Ice																						
08/31/1996	96-A1	Ice	8/8	5.00				0.00	5.00								0.00	0.00		1				
09/16/1996	96-A1	Ice	8/8	4.66	4.73	4.74	0.01	0.00	4.67								0.00	0.00		1				
09/18/1996	96-A1	Ice																						
09/30/1996	96-A1	LSnow																						
04/18/1997	96-A1	Snow	8/6	6.30	6.30	6.34	0.04	0.00	6.34				1.43	3	1.29	20	1.31	1.31	0.06	23		0.35		0.35
SITE B, 1,690 m[1]																								
09/26/1995	94-B	LSnow	9/9	4.61	4.60	4.55	0.05	0.00	4.56		0.15	2			0.15	18	0.15	0.15	0.01	20	0.42			0.42
09/30/1995	94-B	LSnow																						
04/18/1996	94-B	Snow	9/6	5.93	5.95	5.86	0.09	0.00	5.84		1.57	1			1.34	29	1.34	1.34	0.03	30	0.32			0.32
05/28/1996	94-B	Snow																					0.32	0.32
05/28/1996	94-B	Snow																					0.32	0.32
09/15/1997	94-B		6/0					-0.04																
04/18/1996	96-B	Snow	0/9	8.95	8.95	8.99	0.04	0.00	8.99		1.57	1			1.34	29	1.34	1.34	0.03	30	0.32			0.32
05/28/1996	96-B	Snow																					0.32	0.32
05/28/1996	96-B	Snow																					0.32	0.32
08/24/1996	96-B	Ice																						
09/08/1996	96-B	Ice																						
09/16/1996	96-B	LSnow	9/11	6.74	6.72	6.75	0.03	0.00	6.77		0.25	3			0.15	21	0.16	0.16	0.01	24	0.31			0.31
09/30/1996	96-B	LSnow																						
04/19/1997	96-B	Snow	11/9	8.57	8.59	8.62	0.03	0.00	8.60	1.99								1.99					0.35	0.35
Site D, 1,840 m[1]																								
09/26/1995	94-D	LSnow	12/12	8.05	8.05	8.07	0.02	0.00	8.07		0.53	1			0.58	14	0.58	0.58	0.01	15	0.45			0.45
09/30/1995	94-D	LSnow																					0.45	0.45
04/18/1996	94-D	Snow	12/12	10.03	10.03	10.02	0.01	0.00	10.02		2.29	1			2.39	16	2.39	2.39	0.02	17	0.48			0.48
05/28/1996	94-D	Snow																					0.48	0.48
05/28/1996	94-D	Snow																					0.48	0.48
08/21/1996	94-D	Firn																					0.36	0.36
08/24/1996	94-D	LSnow																					0.36	0.36
09/16/1996	94-D	LSnow	12/12	9.14	9.22	9.25	0.03	0.00	9.17		0.68	2					0.68	0.68	0.02	2	0.36			0.36
09/30/1996	94-D	LSnow																					0.45	0.45
04/19/1997	94-D	Snow	12/12	11.45	11.46	11.36	0.10	0.00	11.35		3.12	1					3.12	3.12		1	0.39			0.39
04/18/1996	96-D	Snow	0/11	9.00	8.99	9.00	0.01	0.00	9.01		2.29	1			2.39	16	2.39	2.39	0.02	17	0.48			0.48
05/28/1996	96-D	Snow																					0.48	0.48
05/28/1996	96-D	Snow																					0.48	0.48
08/21/1996	96-D	Firn																					0.36	0.36
08/24/1996	96-D	LSnow																					0.36	0.36
09/16/1996	96-D	LSnow	11/12	8.19	8.19	8.23	0.04	0.00	8.23		0.68	2					0.68	0.68	0.02	2	0.36			0.36
09/30/1996	96-D	LSnow																					0.45	0.45
04/19/1997	96-D	Snow	11/11	10.64	10.66	10.67	0.01	0.00	10.65		3.12	1					3.12	3.12		1	0.39			0.39

[1] Site altitudes are approximate long-term averages rounded to the nearest 10 meters.

Table 8. Snow-temperature, firn-thickness, and firn-density data for index sites A, B, and D on Gulkana Glacier, September 1995 through April 1997

[mm/dd/yyyy, month/day/year; LSnow (late snow), snow on top of the current year's summer surface, occurs only after the summer surface has formed. Summer surface temperature, observed with dial (±1.0 °C) or digital (±0.1 °C) thermometer in snow pit or core sample. Est., estimated from previous measurements. Heights are above the stake bottom. Depths are measured from the glacier surface. Initial values are those at the beginning of the hydrologic year. Obs., observed values on a date, generally the difference between the best stake *b'* and multiple snow- or firn-depth observations. Mean (stake heights), average stake height of a stratigraphic surface (summer surface) observed on different dates. b_0', initial value (on October 1) of the height of a stratigraphic surface on the stake. *d*(nf), depth to bottom of first firn layer. Mean depth, average of all pit and probing depths for a given date. s.e., standard error; *n*, number of observations. ss_1, first glacier summer surface down from the glacier surface (this is typically a bare ice surface in the ablation zone and a firn surface in the accumulation zone); ss_2, second glacier summer surface down from the glacier surface (this is typically a firn surface; multiple summer surfaces only occur in the accumulation zone of the glacier). m, meter; kg/L, kilograms per liter]

Date (mm/dd/yyyy)	Stake name	Surface strata type	Summer surface temperature: Pit or core (°C)	Est. (°C)	Mean (°C)	Stake height of top of 1st firn: Initial $b_0'ss_1$ (m)	Obs. $b'ss_1$ (m)	Mean $b'ss_1$ (m)	ss_1 Diff. (m)	Depth to bottom of 1st firn layer: Pit d(nf) (m)	n	Probe d(nf) (m)	n	Mean d(nf) (m)	s.e. d(nf) (m)	n	Firn density: Initial (kg/L)	Obs. Pit (kg/L)	Est. (kg/L)	Mean (kg/L)	Stake height of 1st firn bottom: Initial $b_0'ss_2$ (m)	Obs. $b'ss_2$ (m)	Mean $b'ss_2$ (m)
SITE A, 1,370 m[1]																							
04/19/1996	96-A	Snow	- 5.2		- 5.2																		
05/06/1996	96-A	Snow		- 5.2	- 5.2																		
05/28/1996	96-A	Snow		- 5.2	- 5.2																		
08/24/1996	96-A	Ice																					
08/31/1996	96-A	Ice																					
09/16/1996	96-A	Ice																					
09/18/1996	96-A	Ice																					
09/30/1996	96-A	LSnow																					
04/18/1997	96-A	Snow																					
04/16/1996	96-A1	Snow		- 5.2	- 5.2																		
04/19/1996	96-A1	Snow	- 5.2		- 5.2																		
05/28/1996	96-A1	Snow		- 5.2	- 5.2																		
08/24/1996	96-A1	Ice																					
08/31/1996	96-A1	Ice																					
09/16/1996	96-A1	Ice																					
09/18/1996	96-A1	Ice																					
09/30/1996	96-A1	LSnow																					
04/18/1997	96-A1	Snow																					
SITE B, 1,690 m[1]																							
09/26/1995	94-B	LSnow																					
09/30/1995	94-B	LSnow																					
04/18/1996	94-B	Snow	- 4.5		- 4.5																		
05/28/1996	94-B	Snow		- 4.5	- 4.5																		
05/28/1996	94-B	Snow		- 4.5	- 4.5																		
09/15/1997	94-B																						
04/18/1996	96-B	Snow	- 4.5		- 4.5																		
05/28/1996	96-B	Snow		- 4.5	- 4.5																		
05/28/1996	96-B	Snow		- 4.5	- 4.5																		
08/24/1996	96-B	Ice																					
09/08/1996	96-B	Ice																					
09/16/1996	96-B	LSnow																					
09/30/1996	96-B	LSnow																					
04/19/1997	96-B	Snow																					
Site D, 1,840 m[1]																							
09/26/1995	94-D	LSnow		0.0	0.0	7.42	7.49	7.58	0.08	0.91	1			0.91		1	0.59	0.63		0.63	7.16	7.16	7.42
09/30/1995	94-D	LSnow		0.0	0.0	7.42		7.58									0.59		0.63	0.63			
04/18/1996	94-D	Snow	- 5.1		- 5.1	7.58	7.63	7.58	0.05								0.63						
05/28/1996	94-D	Snow		- 5.1	- 5.1	7.58		7.58									0.63						
05/28/1996	94-D	Snow		- 5.1	- 5.1	7.58		7.58															
08/21/1996	94-D	Firn				7.58		8.36									0.63		0.48	0.48			
08/24/1996	94-D	LSnow				7.58		8.36									0.63		0.48	0.48			
09/16/1996	94-D	LSnow				7.58	8.49	8.36		1.39	2	1.58	24	1.57	0.06	26	0.63	0.48		0.48	7.16	7.60	7.58
09/30/1996	94-D	LSnow		0.0	0.0	7.58		8.36									0.63		0.48	0.48			
04/19/1997	94-D	Snow	-2.9		- 2.9	8.36	8.23	8.36									0.48		0.48	0.48			
04/18/1996	96-D	Snow	- 5.1		- 5.1	6.64	6.62	6.64									0.63						
05/28/1996	96-D	Snow		- 5.1	- 5.1	6.64		6.64									0.63						
05/28/1996	96-D	Snow		- 5.1	- 5.1	6.64		6.64															
08/21/1996	96-D	Firn				6.64		7.54									0.63		0.48	0.48			
08/24/1996	96-D	LSnow				6.64		7.54									0.63		0.48	0.48			
09/16/1996	96-D	LSnow				6.64	7.55	7.54	0.01	1.39	2	1.58	24	1.57	0.06	26	0.63	0.48		0.48		6.66	6.64
09/30/1996	96-D	LSnow		0.0	0.0	6.64		7.54									0.63		0.48	0.48			
04/19/1997	96-D	Snow	-2.9		- 2.9	7.54	7.53	7.54	0.01								0.48		0.48	0.48			

[1] Site altitudes are approximate long-term averages rounded to the nearest 10 meters.

Table 9. Ice data and mass-balance calculations for index sites A, B, and D on Gulkana Glacier, September 1995 through April 1997

[mm/dd/yyyy, month/day/year; LSnow (late snow), snow on top of the current year's summer surface, occurs only after the summer surface has formed. Initial values are those at the beginning of the hydrologic year. Obs., observed values on a date, generally the difference between the best stake *b'* and multiple snow- or firn-depth observations. Mean (stake height), average stake height of a stratigraphic surface (summer surface) observed on different dates. Diff., the difference between the observed value and the mean value for that date, a good unbiased indication of the error in the stake height and snow- and firn-depth data at a site, commonly 0.05 to 0.15 meter; b_0', initial value (on October 1) of the height of a stratigraphic surface on the stake; ss_1, first glacier summer surface down from the glacier surface (this is typically a bare ice surface in the ablation zone and a firn surface in the accumulation zone); $b_0(s)$, initial snow balance (on October 1); *b*(s), snow balance; *b*(ls), late snow balance; *b*(f), firn balance; *b*(k), internal accumulation; *b*(i), ice balance; b_n, net balance; b_a, annual balance; $b_w(s)$, maximum winter snow balance; m_{we}, meters water equivalent (see Mayo and others (1972) for detailed explanation of this terminology)]

			Stake height of top of ice				Mass balance quantities								
Date (mm/dd/yyyy)	Stake name	Surface strata type	Initial $b_0'ss_1$ (m)	Obs. $b'ss_1$ (m)	Mean $b'ss_1$ (m)	ss_1 Diff. (m)	Init. snow $b_0(s)$ (m_{we})	Snow $b(s)$ (m_{we})	Late snow $b(ls)$ (m_{we})	Firn $b(f)$ (m_{we})	Int. acc. $b(k)$ (m_{we})	Ice $b(i)$ (m_{we})	Net b_n (m_{we})	Annual b_a (m_{we})	Notes
SITE A, 1,370 m[1]															
04/19/1996	96-A	Snow	8.80	8.80	8.80		0.00	0.28	0.00	0.00	0.00	0.00	0.28	0.28	
05/06/1996	96-A	Snow	8.80		8.80		0.00	0.30	0.00	0.00	0.00	0.00	0.30	0.30	Estimated local-site $b_w(s)$
05/28/1996	96-A	Snow	8.80		8.80		0.00	0.23	0.00	0.00	0.00	0.00	0.23	0.23	Estimated glacier-averaged $b_w(s)$
08/24/1996	96-A	Ice	8.80		5.31		0.00	0.00	0.00	0.00	0.00	- 3.14	-3.14	-3.14	Estimated glacier-averaged net mimimum
08/31/1996	96-A	Ice	8.80	4.95	4.95		0.00	0.00	0.00	0.00	0.00	- 3.47	-3.47	-3.47	
09/16/1996	96-A	Ice	8.80	4.68	4.63	0.05	0.00	0.00	0.00	0.00	0.00	- 3.76	-3.76	-3.76	
09/18/1996	96-A	Ice	8.80		4.63		0.00	0.00	0.00	0.00	0.00	- 3.76	-3.76	-3.76	Estimated local-site net minimum
09/30/1996	96-A	LSnow	8.80		4.63		0.00	0.04	0.04	0.00	0.00	- 3.76	0.04	-3.72	Estimated annual balance
04/18/1997	96-A	Snow	4.63	4.57	4.63	0.05	0.04	0.46	0.00	0.00	0.00	0.00	0.46	0.42	
04/16/1996	96-A1	Snow	8.70		8.70		0.00	0.30	0.00	0.00	0.00	0.00	0.30	0.30	Estimated local-site $b_w(s)$
04/19/1996	96-A1	Snow	8.70	8.70	8.70		0.00	0.28	0.00	0.00	0.00	0.00	0.28	0.28	
05/28/1996	96-A1	Snow	8.70		8.70		0.00	0.23	0.00	0.00	0.00	0.00	0.23	0.23	Estimated glacier-averaged $b_w(s)$
08/24/1996	96-A1	Ice	8.70		5.21		0.00	0.00	0.00	0.00	0.00	- 3.14	-3.14	-3.14	Estimated glacier-averaged net mimimum
08/31/1996	96-A1	Ice	8.70	5.00	5.00		0.00	0.00	0.00	0.00	0.00	- 3.33	-3.33	-3.33	
09/16/1996	96-A1	Ice	8.70	4.67	4.85	0.18	0.00	0.00	0.00	0.00	0.00	- 3.47	-3.47	-3.47	
09/18/1996	96-A1	Ice	8.70		4.85		0.00	0.00	0.00	0.00	0.00	- 3.47	-3.47	-3.47	Estimated local-site $b_w(s)$
09/30/1996	96-A1	LSnow	8.70		4.85		0.00	0.04	0.04	0.00	0.00	- 3.47	0.04	-3.43	Estimated annual balance
04/18/1997	96-A1	Snow	4.85	5.03	4.85	0.18	0.04	0.46	0.00	0.00	0.00	0.00	0.46	0.42	
SITE B, 1,690 m[1]															
09/26/1995	94-B	LSnow	5.84	4.41	4.46	0.05	0.21	0.06	0.06	0.00	0.00	- 1.24	0.06	-1.39	
09/30/1995	94-B	LSnow	5.84		4.46		0.21	0.00	0.00	0.00	0.00	- 1.24	0.00	-1.45	Estimated annual balance
04/18/1996	94-B	Snow	4.46	4.50	4.46	0.04	0.00	0.43	0.00	0.00	0.00	0.00	0.43	0.43	
05/28/1996	94-B	Snow	4.46		4.46		0.00	0.53	0.00	0.00	0.00	0.00	0.53	0.53	Estimated glacier-averaged $b_w(s)$
05/28/1996	94-B	Snow	4.46		4.46		0.00	0.53	0.00	0.00	0.00	0.00	0.53	0.53	Estimated local-site $b_w(s)$
09/15/1997	94-B														
04/18/1996	96-B	Snow	7.65	7.65	7.65		0.00	0.43	0.00	0.00	0.00	0.00	0.43	0.43	
05/28/1996	96-B	Snow	7.65		7.65		0.00	0.53	0.00	0.00	0.00	0.00	0.53	0.53	Estimated glacier-averaged $b_w(s)$
05/28/1996	96-B	Snow	7.65		7.65		0.00	0.53	0.00	0.00	0.00	0.00	0.53	0.53	Estimated local-site $b_w(s)$
08/24/1996	96-B	Ice	7.65		6.74		0.00	0.00	0.00	0.00	0.00	- 0.82	-0.82	-0.82	Estimated glacier-averaged net mimimum
09/08/1996	96-B	Ice	7.65		6.61		0.00	0.00	0.00	0.00	0.00	- 0.94	-0.94	-0.94	Estimated local-site net minimum
09/16/1996	96-B	LSnow	7.65	6.61	6.61		0.00	0.05	0.05	0.00	0.00	- 0.94	0.05	-0.89	
09/30/1996	96-B	LSnow	7.65		6.61		0.00	0.11	0.11	0.00	0.00	- 0.94	0.11	-0.83	Estimated annual balance
04/19/1997	96-B	Snow	6.61		6.61		0.11	0.70	0.00	0.00	0.00	0.00	0.70	0.59	
Site D, 1,840 m[1]															
09/26/1995	94-D	LSnow					0.21	0.22	0.22	0.10	0.19	0.00	0.22	0.30	
09/30/1995	94-D	LSnow					0.21	0.23	0.23	0.10	0.19	0.00	0.23	0.31	Estimated annual balance
04/18/1996	94-D	Snow					0.23	1.17	0.00	0.00	0.00	0.00	1.17	0.94	
05/28/1996	94-D	Snow					0.23	1.46	0.00	0.00	0.00	0.00	1.46	1.23	Estimated glacier-averaged $b_w(s)$
05/28/1996	94-D	Snow					0.23	1.46	0.00	0.00	0.00	0.00	1.46	1.23	Estimated local-site $b_w(s)$
08/21/1996	94-D	Firn					0.23	0.00	0.00	0.37	0.20	0.00	0.57	0.34	Estimated local-site net minimum
08/24/1996	94-D	LSnow					0.23	0.01	0.01	0.37	0.20	0.00	0.01	0.35	Estimated glacier-averaged net mimimum
09/16/1996	94-D	LSnow					0.23	0.29	0.29	0.37	0.20	0.00	0.29	0.63	
09/30/1996	94-D	LSnow					0.23	0.36	0.36	0.37	0.20	0.00	0.36	0.70	Estimated annual balance
04/19/1997	94-D	Snow					0.36	1.18	0.00	0.00	0.00	0.00	1.18	0.82	
04/18/1996	96-D	Snow					0.23	1.14	0.00	0.00	0.00	0.00	1.14	0.91	
05/28/1996	96-D	Snow					0.23	1.46	0.00	0.00	0.00	0.00	1.46	1.23	Estimated glacier-averaged $b_w(s)$
05/28/1996	96-D	Snow					0.23	1.46	0.00	0.00	0.00	0.00	1.46	1.23	Estimated local-site $b_w(s)$
08/21/1996	96-D	Firn					0.23	0.00	0.00	0.43	0.20	0.00	0.63	0.40	Estimated local-site net minimum
08/24/1996	96-D	LSnow					0.23	0.01	0.01	0.43	0.20	0.00	0.01	0.41	Estimated glacier-averaged net mimimum
09/16/1996	96-D	LSnow					0.23	0.25	0.25	0.43	0.20	0.00	0.25	0.65	
09/30/1996	96-D	LSnow					0.23	0.36	0.36	0.43	0.20	0.00	0.36	0.76	Estimated annual balance
04/19/1997	96-D	Snow					0.36	1.23	0.00	0.00	0.00	0.00	1.23	0.87	

[1] Site altitudes are approximate long-term averages rounded to the nearest 10 meters.

Temporal extrapolations between measurements are necessary to estimate index-site balances such as the maximum winter balance, net balance, and annual balance. The extrapolations are made by a simple two-parameter linear model that relates the air temperature recorded at the Gulkana weather station and precipitation-gage catch (from Paxson through August 1996 and from the Gulkana weather station for September 1996) to the mass balance at each index site. The temperature is lapsed from the recorder altitude to each of the index-site altitudes using the wet-adiabatic lapse rate of -0.66 °C per 100 m. The model estimates glacier ablation at the rate of about 3.5 to 5 mm water equivalent per degree Celsius above 0 °C per day when the surface is snow and twice that when the surface is ice or old firn. This range of values agrees closely with those common in the literature (Braithwaite and Olesen, 1985, 1993; Braithwaite, 1995; Jóhannesson and others, 1995). Glacier accumulation is estimated by the model to be about 1.5 to 4.0 times the precipitation-gage catch when the lapsed temperature at the site is below 1.8 °C.

The melt (ablation) rate and the precipitation-catch multipliers are not fixed. Separate values are determined for each measurement period at each index site so that the modeled balances always agree with the measured balances. Thus the model serves only to distribute the measured balance at each index site over each measurement interval. During the fall-to-spring measurement period, no ablation usually occurs, so the model is reduced to a one-parameter model dependent only on precipitation. During the spring-to-fall measurement period, little or no accumulation occurs, so the model again is reduced to a one-parameter model dependent only on temperature. Small quantities of accumulation early in the spring-to-fall measurement period are modeled using the precipitation-catch multiplier determined for the previous winter. Small quantities of accumulation near the end of the spring-to-fall measurement period are modeled by adjusting a separate precipitation-catch multiplier until the measured late snow balance is matched.

Area-Averaged Balances

The three index-site balance values are combined using weighting factors to yield glacier-wide index values that approximate the average balances for the glacier area. Area-averaged balances are reported (table 10) using both the old (1967) and newer (1993) area altitude distributions to demonstrate how the balances are affected by the update.

Using the 1967 area altitude distribution:

$$\overline{b} = 0.193\ (b_A) + 0.224\ (b_B) + 0.583\ (b_D) + \overline{b}_a(\mathrm{j})\ . \quad (6)$$

Using the 1993 area altitude distribution:

$$\overline{b} = 0.171\ (b_A) + 0.202\ (b_B) + 0.627\ (b_D) + \overline{b}_a(\mathrm{j})\ , \quad (7)$$

where $\overline{b}$ is the glacier-averaged balance, b_A, b_B, and b_D are measured index-site balance values, and $\overline{b}_a(\mathrm{j})$ is glacier-averaged internal ablation. The weighting factors are derived by splitting the glacier into three subareas (index regions) at altitudes midway between the index sites (table 6). The fraction of total glacier area in each index region is the weighting factor for the index site within that region. Using this scheme, the weighting factors are allowed to change with time as the index-site altitudes and area altitude distribution change. However, prior to the work of March (2000), an unvarying area altitude distribution had been used as that was all that was available. As can be seen in equations 6 and 7, the loss of ablation area between 1967 and 1993 results in a decrease in the weighting factor for sites A and B in the ablation zone and an increase in the weighting of site D in the accumulation zone. Overall, the change in weighting factors results in increases to the calculated glacier-averaged balances.

For the index-site weighting method to be valid, the index-site balance value should equal the average balance in the index region. March and Trabant (1996) applied the weighted index-site method to 1966 and 1967 data and compared the results with the balances determined from detailed surface-balance mapping available for those years. The weighted index-site balances were found to be within the estimated errors of the mapped balances and suggest that glacier-averaged balance values determined using the weighted index-site method have an error of ±0.2 m. The estimated error for 1996 could be larger than ±0.2 m due to changes in the area altitude distribution and changes in the gradient of mass balance with altitude since 1966 and 1967.

Because of the time- and space-transgressive nature of glacier balance, the b_A, b_B, and b_D used to calculate a glacier-averaged balance, such as the net balance, may not be the same as the site net balances. This discrepancy occurs because when the glacier-averaged balance reaches its minimum, snow may have already accumulated at sites D and B. For instance, figure 4 shows both the local net balances that occurred on different dates at the different

Table 10. Index-site and area-integrated balance quantities for Gulkana Glacier and Gulkana Glacier Basin, 1996 hydrologic year, from both 1967 and 1993 area altitude distributions

[m, meters; mm/dd/yyyy, month/day/year; km^2, square kilometers; °C, degrees Celsius]

Parameter	Site, glacier average, or subparameter	Data		Units
Year of area-altitude distribution determination =		1967	1993	
Index-site weighting factors	Site A	0.193	0.171	
	Site B	0.224	0.202	
	Site D	0.583	0.627	
b_{n0}, initial net balance	Site A	-0.77	-0.77	(m)
	Site B	0.00	0.00	(m)
	Site D	0.00	0.00	(m)
	Glacier average	-0.15	-0.13	(m)
$b_0(s)$, initial snow balance	Site A	-0.00	-0.00	(m)
	Site B	0.00	0.00	(m)
	Site D	0.23	0.23	(m)
	Glacier average	0.13	0.14	(m)
$b_m(s)$, measured winter snow balance	Date of measurement	04/18/1996	04/18/1996	(mm/dd/yyyy)
	Site A	0.28	0.28	(m)
	Site B	0.43	0.43	(m)
	Site D	1.17	1.17	(m)
	Glacier average	0.83	0.87	(m)
$b_w(s)$, maximum winter snow balance	Date of maximum	05/28/1996	05/28/1996	(mm/dd/yyyy)
	Site A	0.23	0.23	(m)
	Site B	0.53	0.53	(m)
	Site D	1.46	1.46	(m)
	Glacier average	1.01	1.06	(m)
b_{nl}, late net balance	Site A	0.33	0.33	(m)
	Site B	0.12	0.12	(m)
	Site D	0.01	0.01	(m)
	Glacier average	0.10	0.09	(m)
$b_1(ls)$, final late snow balance	Site A	0.04	0.04	(m)
	Site B	0.11	0.11	(m)
	Site D	0.36	0.36	(m)
	Glacier average	0.24	0.25	(m)
$b_a(f)$, annual firn balance	Site A	0.00	0.00	(m)
	Site B	0.00	0.00	(m)
	Site D	0.40	0.40	(m)
	Glacier average	0.23	0.25	(m)
$b_a(k)$, annual internal accumulation	Site A	0.00	0.00	(m)
	Site B	0.00	0.00	(m)
	Site D	0.20	0.20	(m)
	Glacier average	0.12	0.13	(m)
$b_a(i)$, annual old firn and ice balance	Site A	-3.62	-3.62	(m)
	Site B	-0.94	-0.94	(m)
	Site D	0.00	0.00	(m)
	Glacier average	-0.91	-0.81	(m)
$b_a(j)$, annual internal ablation (glacier averaged)	From geothermal heat flux	-0.005	-0.005	(m)
	From potential energy loss from ice motion	-0.005	-0.005	(m)
	From potential energy loss from water flow (estimated)	-0.035	-0.037	(m)
	Total	-0.04	-0.05	(m)
b_n, net balance	Start of net balance year for glacier average	08/30/1995	08/30/1995	(mm/dd/yyyy)
	End of net balance year for glacier average	08/24/1996	08/24/1996	(mm/dd/yyyy)
	Site A (09/29/1995 to 09/18/1996)	-4.05	-4.05	(m)
	Site B (08/30/1995 to 09/08/1996)	-0.82	-0.82	(m)
	Site D (08/30/1995 to 08/2119/96)	0.61	0.61	(m)
	Glacier average (includes $b_a(j)$)	-0.65	-0.53	(m)
b_a, annual balance	Site A	-3.57	-3.57	(m)
	Site B	-0.83	-0.83	(m)
	Site D	0.73	0.73	(m)
	Glacier average (includes $b_a(j)$)	-0.49	-0.37	(m)
ELA, equilibrium line altitude		1,768	1,768	(m)
Accumulation area		11.05	11.15	(km^2)
Ablation area		8.27	6.98	(km^2)
AAR, accumulation area ratio		0.57	0.61	
Calculated annual precipitation	Basin average	1.04	1.13	(m)
Annual basin runoff	1,125-meter stream gage	1.50	1.50	(m)

measurement sites and the August 26 estimated balances used to calculate the glacier-averaged net balance.

The glacier-averaged internal ablation, $\overline{b}_a(j)$, is calculated by combining three internal and subglacial energy sources: (1) the geothermal heat at the bed of the glacier, (2) the potential energy loss from ice motion, and (3) the potential energy loss from water flowing through the glacier and along the bed of the glacier (Mayo, 1992; March and Trabant, 1997). These terms are quite small annually (table 10) but, if neglected, would accumulate as a bias error over time.

Measured and Maximum Winter Snow Balances[1]

The measured winter snow balance, $\overline{b}_m(s)$, is the snow balance measured to the previous summer surface during late winter or spring (Mayo and others, 1972). It was 0.87 m on April 18, 1996 (fig. 11, table 10), using the 1993 area altitude distribution. This value was derived from the weighted index-site method and the April onsite-visit data (tables 7, 8, and 9).

The maximum winter snow balance, $\overline{b}_w(s)$, is the maximum snow mass during the balance year and may occur either before or after the measured winter snow balance (Mayo and others, 1972). It generally occurs after the time of the measured winter snow balance at Gulkana Glacier. The balance change between the time of the measured winter snow balance and the time of the glacier-averaged maximum winter snow balance is estimated for each index site by the simple balance model previously described. Following this method, the 1996 maximum winter snow balance was estimated to be 1.06 m (table 10) on May 28, 1996.

Net Balance

Net balance is the change in snow, firn, and ice storage between times of minimum glacier-averaged mass (Mayo and others, 1972). The net balance, b_n, at each index site is calculated directly from stake, pit, and probing data (tables 7, 8, and 9). Because of the time-transgressive nature of balance, the net balance at one site may not represent the same time period as the net balance at another site. Therefore, the simple linear balance model, discussed previously, is run to determine the glacier-averaged net balance on the basis of calculated site balances for the same time period. The net balance year ends almost a month earlier at sites B and D than it does at site A (fig. 4). The estimated balance at site A for August 29, 1995, which was used for calculating the glacier-averaged net balance, is also shown in figure 4. These calculated site balances differ from the tabulated net balances by small increments, which are the initial and late net balance increments, b_{n0} and b_{nl} (table 9 and 10). Onsite measurements made near the end of the balance year are checked by and combined with measurements made during the next balance year before final values are assigned (tables 7, 8, and 9). The glacier-averaged net balance, $\overline{b}_n$, includes the additional balance term, internal ablation, which is not included in the net balances at individual sites. The 1996 net balance year began on about August 30, 1995, and ended on about August 24, 1996; the net balance was -0.53 m (fig. 11, table 10).

Summer Balance

Summer balance is the algebraic difference between the winter balance, $\overline{b}_w(s)$, and the net balance, $\overline{b}_n$ (UNESCO/IASH, 1970)[2]. The UNESCO/IASH definition of winter balance corresponds to the maximum winter balance term, $\overline{b}_w(s)$, from Mayo and others (1972). Thus, the following equation defines the summer balance:

$$\overline{b}_s = \overline{b}_n - \overline{b}_w(s) = -1.59 \text{ m} . \quad (8)$$

Annual Mass Balance

Annual mass balance is the change in snow, firn, and ice storage between the beginning (October 1, 1995) and end (September 30, 1996) of the hydrologic year. Evaluation of the 1996 annual balance required estimating two adjustment quantities for each index site: the initial snow balance, $b_0(s)$, at the beginning of

---

[1]Mayo and others (1972) define three “winter” balance values in the stratigraphic system: the measured winter snow balance, $\overline{b}_m(s)$, the maximum winter snow balance, $\overline{b}_w(s)$, and the winter balance, $\overline{b}_w$. The World Glacier Monitoring Service (WGMS) publishes a “winter” balance that is not clearly identified as any of these and may vary from glacier to glacier. The measured winter snow balance, $\overline{b}_m(s)$, is probably the most common “winter” balance value reported by WGMS.

[2]The summer balance, $\overline{b}_s$, was not defined by Mayo and others (1972).

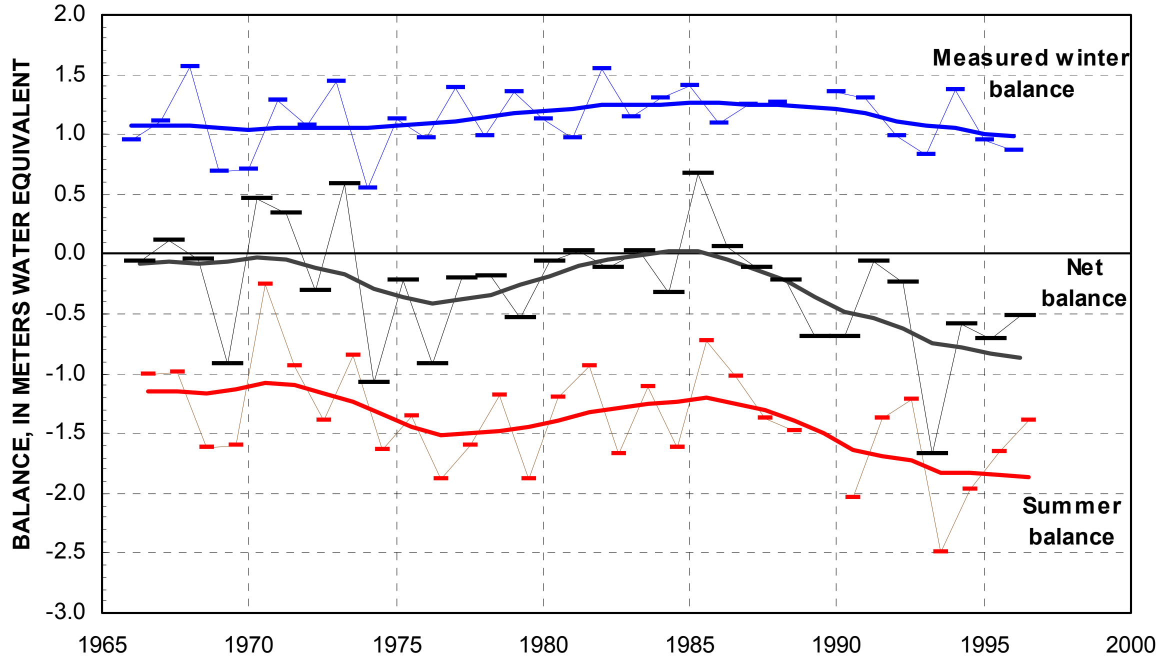


Figure 11. Glacier-averaged measured winter balance, net balance, and summer balance, 1966–96, and smoothed data. Horizontal length of data symbols represents approximate time period of each data value. Smooth is an inverse distance-weighted smooth of the data using a 7-day window.

the hydrologic year and the final late snow balance, b_1(ls) (tables 9 and 10), at the end of the hydrologic year (Mayo and others, 1972). These quantities were estimated using the simple linear balance model discussed earlier. The 1996 annual balance at each index site, b_a, is derived from the net balance and adjustment quantities: $b_a = b_n - b_0(s) + b_1(ls)$ (table 9). The index-site annual balances are combined using the weighted index-site method, with the addition of the internal ablation, to yield the 1996 annual balance, $\overline{b}_a$, of -0.37 m (table 10).

Accumulation Area Ratio and Equilibrium Line Altitude

The accumulation area ratio (AAR) is the accumulation area of the glacier divided by the total area of the glacier. The accumulation area is the area of the glacier that undergoes net mass gain and includes areas of firn accumulation, superimposed ice, and areas where internal accumulation exceeds old firn loss. The 1996 AAR was 0.61 using the 1993 photogrammetry glacier-surface area and 0.57 using the 1967 glacier-surface area determination (table 10).

The equilibrium line altitude (ELA) is the average altitude where the net mass balance is zero. Sometimes the ELA will correspond to the highest transient snow or firn line reached in the melt season (the line where snow ablation equals snow accumulation), but commonly the ELA is lower on the glacier because of internal accumulation in old firn or the presence of superimposed ice. The ELA seldom crosses a glacier along a single altitude contour. At Gulkana Glacier, the ELA can be extremely complicated, and its determination would require well-timed vertical or high-angle oblique aerial photography to define it over the whole glacier. Obtaining this kind of photography near the time of formation of the ELA on a consistent basis year after year is impractical. Therefore, the ELA is calculated by linear interpolation from the balance-altitude curve of the three index sites. The 1996 ELA for Gulkana Glacier was determined to be 1,768 m (table 10).

GLACIER-SURFACE ALTITUDE

The altitude of the glacier surface and the uppermost glacier summer surface at each index site is measured during each onsite visit (fig. 12, tables 11–12). At least three points on the glacier surface in the vicinity of each index site are optically surveyed. One of the points is placed as closely as possible to the index site. The mathematical plane defined by the three surveyed points is calculated as an approximation of the local

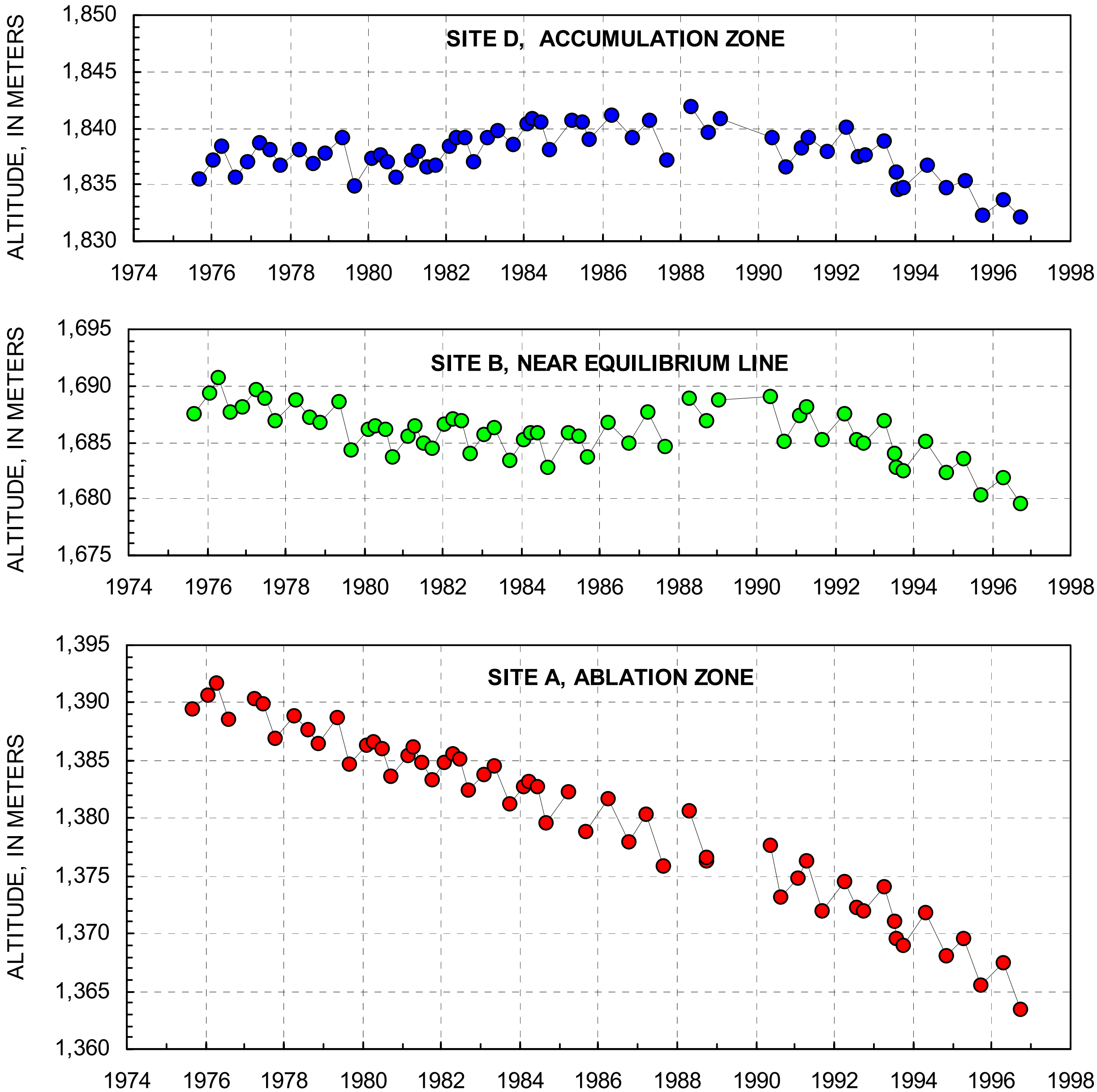


Figure 12. Glacier-surface altitudes at index sites A, B, and D. An unresolved datum shift exists between the 1975–87 data and the 1988–96 data.

glacier surface. The altitude of this plane at the fixed horizontal position of the index site is calculated to determine the index-site altitude (Mayo and Trabant, 1982). Snow depth is subtracted from the glacier surface to get the uppermost glacier summer surface altitude. The 1996 altitude data appeared to continue the glacier-wide thinning trend of the 1990s (fig. 12).

Surveyed glacier-surface points typically have an altitude uncertainty of about ±0.05 m. Additionally, the locations used to define the plane of the glacier surface may not be representative of the average glacier surface; hence, extrapolating along this plane to the index site may introduce further error. The glacier-surface orientation and slope determinations have a small random variability that is used to assess the magnitude of this error. Although this error is site-specific, depending largely on the local surface roughness of the glacier, an average glacier-surface-slope error of 0.5 grad was applied to the distance between the closest surveyed point and the index site. This error, combined with the surveying error, yielded an average error of ±0.15 m for the index-site altitudes.

Table 11. Glacier-surface and summer-surface altitude measurements and analysis at index sites, Gulkana Glacier Basin, September 1995 to September 1996

[mm/dd/yyyy, month/day/year; P, Q, and R are three locations on the glacier surface near the index site determined by optical surveying. X_i, Y_i are the horizontal locations of the fixed index site. Z_i is the calculated altitude of the glacier surface at the index site. θ is the aspect of the glacier surface, with zero east and positive counterclockwise. ϕ is the slope of the glacier surface, with positive angles up from horizontal. Grad is a unit of measure for a plane angle and is equal to the plane angle in degrees multiplied by (100/90). Distance to closest point is the horizontal distance from the index site to the closest of points P, Q, or R. Z_i error is the altitude error in Z_i, derived by combining the resection errors with the error in extrapolating the glacier-surface altitude from the closest point to the index site assuming that the local glacier-surface slope is linear]

Index site	Date	P			Q			R			Index Site			Glacier-surface slope		Distance to closest point	Z_i error
		X	Y	Z	X	Y	Z	X	Y	Z	X_i	Y_i	Z_i	θ	ϕ		
	(mm/dd/yyyy)	(meters)			(meters)			(meters)			(meters)			(grad)		(meters)	
Site A	09/26/1995	3,835.56	4,450.42	1,366.68	3,820.95	4,434.18	1,363.97	3,797.94	4,457.84	1,363.89	3,825.10	4,447.27	1,365.46	-152.13	-7.89	10.92	0.10
	04/19/1996	3,814.47	4,445.02	1,366.44	3,801.35	4,476.66	1,367.62	3,792.21	4,451.28	1,365.00	3,825.10	4,447.27	1,367.50	-154.98	-7.09	10.87	0.09
	09/16/1996	3,822.09	4,443.95	1,362.88	3,804.77	4,464.37	1,363.39	3,808.81	4,449.59	1,362.40	3,825.10	4,447.27	1,363.39	-144.54	-7.23	4.48	0.04
Site B	09/26/1995	4,722.55	7,383.93	1,679.46	4,723.78	7,354.50	1,676.94	4,737.67	7,369.04	1,678.94	4,728.61	7,391.17	1,680.41	-133.91	-6.47	9.44	0.19
	04/18/1996	4,743.93	7,419.85	1,684.96	4,731.76	7,389.68	1,681.78	4,731.96	7,427.31	1,685.16	4,728.61	7,391.17	1,681.79	-126.32	-6.21	3.48	0.03
	09/16/1996	4,731.70	7,386.11	1,679.22	4,735.00	7,402.25	1,680.77	4,712.56	7,391.72	1,678.91	4,728.61	7,391.17	1,679.53	-128.51	-6.16	5.93	0.05
Site D	09/26/1995	5,997.81	7,355.60	1,832.13	5,979.49	7,367.49	1,830.09	5,983.16	7,381.16	1,829.81	5,999.01	7,353.57	1,832.32	169.98	-5.96	2.36	0.03
	04/18/1996	5,987.59	7,360.72	1,832.46	5,993.84	7,371.10	1,832.77	6,021.61	7,345.60	1,836.07	5,999.01	7,353.57	1,833.73	182.35	-6.21	13.47	0.11
	09/16/1996	5,964.75	7,356.25	1,828.36	6,001.91	7,350.75	1,832.38	5,970.61	7,379.27	1,829.16	5,999.01	7,353.57	1,832.08	-196.04	-6.94	4.05	0.03
														Average =		7.22	0.07

Table 12. Continuation of glacier-surface and summer-surface altitude measurements and analysis at index sites, Gulkana Glacier Basin, September 1995 to September 1996

[mm/dd/yyyy, month/day/year; stake name: the first two digits represent the year the stake was installed; letters (A, B, D) represent the index site on the glacier (fig. 2); a number following the letter is used to differentiate multiple stakes installed at the same site in 1 year. Best *b′* is the height of the glacier surface directly above the stake bottom. Change in *b′* is the change from the previous measurement to the current measurement. Emergence is the change in Z_i minus the change in *b′* divided by the measurement period in years. Snow depth is the mean depth from the glacier surface to the summer surface (see table 7). $Z_i(ss_1)$ summer surface (altitude) at index site is Z_i minus snow depth. m, meters; m/yr, meters per year]

Index site	Date	Stake 1			Stake 2			Stake 3			Stake 4			Average emergence	Emergence rate	Snow depth	Summer surface $Z_i(ss_1)$
		Name	Best *b′*	Change *b′*	Name	Best *b′*	Change *b′*	Name	Best *b′*	Change *b′*	Name	Best *b′*	Change *b′*				
	(mm/dd/yyyy)		(m)	(m)		(m)	(m)		(m)	(m)		(m)	(m)	(m)	(m/yr)	(m)	(m)
Site A	09/26/1995							95-A	3.89	-6.29	95-A2	4.27	-5.87	1.90	4.33	0.00	1,365.46
	04/19/1996	96-A	9.60		96-A1	9.50		95-A	4.97	1.08	95-A2	5.27	1.00	1.00	1.77	0.80	1,366.70
	09/16/1996	96-A	4.68	-4.92	96-A1	4.67	-4.83							0.77	1.86	0.00	1,363.39
Site B	09/26/1995	94-B	4.56	-3.47										0.34	0.78	0.15	1,680.26
	04/18/1996	94-B	5.84	1.28	96-B	8.99								0.10	0.19	1.34	1,680.45
	09/16/1996				96-B	6.77	-2.22							-0.04	- 0.10	0.16	1,679.37
Site D	09/26/1995	93-D	6.36		94-D	8.07	-2.06							-0.98	- 2.24	0.58	1,831.74
	04/18/1996				94-D	10.02	1.95	96-D	9.02					-0.54	- 0.96	2.39	1,831.34
	09/16/1996				94-D	9.17	-0.85	96-D	8.23	-0.79				-0.83	- 2.00	0.68	1,831.40

Index-site errors were calculated separately for each measurement and are included in table 11.

Emergence (table 12), the change in the glacier surface altitude due to ice motion, showed the normally expected positive emergence in the ablation zone (compressing flow), submergence in the accumulation zone (extending flow), and intermediate values near the ELA.

ICE MOTION

Surface-ice displacements near the fixed index sites are measured by optical surveying of balance-motion stakes. The stakes are installed about 1 year's flow displacement upglacier from each index site. Replacement stakes are installed every year or two. Thus, the stakes are kept within 1 year's displacement of the index site (usually less than 80 m) to maximize the year-to-year comparability of the motion and altitude data (Mayo and others, 1979; Mayo and Trabant, 1982). Reported stake-motion data have been corrected for changes in stake geometry (table 13; see March, 2000).

The position of the bottom of the stake is determined by surveying two points on each stake (one at the glacier surface and the other 1 or 2 m higher on the stake) and calculating the location of the stake bottom using a lean (linear), bend (multiple straight sections separated by sharp bends), or bowed (gradual bend spread out over a meter or more) stake geometry. In the long history of field observations at Gulkana Glacier, it has been rare to find bent or bowed melted-out stakes, so a "lean" geometry generally is assumed unless the stake is severely tilted. Occasionally, when a stake is severely tilted, it is partly excavated to determine if it is bent or bowed, and where. Some of the stakes tend to straighten as they are dug up and the snow-creep load is removed, a sign that the stake was elastically bowed. Three-meter sections of the 2.5-cm-diameter thinwall EMT conduit used for stakes can be elastically bowed about 13 grads (an arc radius of about 15 m). When a bend or bow does occur, it is generally at or above the most-recent summer surface.

Location uncertainty is largely a result of the survey-control net errors (GPS for horizontal and optical surveying for vertical) and resection survey errors. Resection surveys are conducted by surveying four or five backsight targets, instead of the minimum of three backsight targets, to allow error evaluation. The net and resection errors combined yield position errors of about ±0.15 m in the horizontal and ±0.05 m in the vertical. The error of extrapolating to the bottom of the stake is estimated to be ±0.15 m, resulting in a total horizontal error for stake-bottom positions of ±0.2 m. Vertical errors are significantly less, about ±0.05 m. Hence, reported displacements have errors of about ±0.3 m.

Ice motion this year was 40 to 50 m/yr in the central reach of the glacier and about one-half that in the lower ablation zone. There has been a general slowing trend through the 1990s with a reduction of about 20 percent since 1990 and about 5 percent since 1995.

TERMINUS POSITION

On August 31 and September 1, 1996, 126 locations along the lower glacier margin were surveyed with a handheld Collins Rockwell Precision Lightweight GPS Receiver (PLGR+) to define the glacier terminus and lower ablation area for 1996 (fig. 13**,** table 14). The Collins Rockwell PLGR+ is a military-grade, single-frequency (L1) encrypted P(Y) code GPS receiver capable of Precise Positioning Service (PPS) operation. PPS, as opposed to the Standard Positioning Service (SPS) used by civilian GPS receivers, uses encrypted signals to correct for the deliberate GPS signal degradation of Selective Availability (SA) that was active until May 2, 2000.

The instrument has a stated positioning accuracy of less than 16 m spherical error probable (SEP) using PPS and less than 4 m circular error probable (CEP) with its firmware Wide Area GPS Enhancement (WAGE) feature activated (processes enhanced clock corrections). (Error probable corresponds to a 50-percent confidence interval.) In an assessment of recent GPS enhancements to the satellite-broadcast navigation message, Wilson and others (1999) report PLGR errors of about 4.5 m horizontal and 6 m vertical prior to April 1999 and about 4.5 m horizontal and 5 m vertical after that date. To partially check the PLGR's accuracy during the survey, an off-glacier survey monument (Péwé, fig. 13) along the walk in to the terminus (NAD 83 UTM Easting 576816.78 m, Northing 7012770.41 m, NGVD 29 altitude 1,152.7 m), was surveyed at the beginning and end of each 3- to 6-hour-long terminus survey. Horizontal errors at Péwé varied from 1 to 5 m and averaged 3 m. The vertical errors (bias) varied from -9 to 3 m and averaged -3 m. Some concern exists over the applicability of errors measured at Péwé because the valley is more

Table 13. Stake locations, stake lean corrections, and motion determined from optical surveys, September 1995 to September 1996

[mm/dd/yyyy, month/day/year; stake name: the first two digits represent the year the stake was installed; letters (A, B, D) represent the index site on the glacier (fig. 2); a number following the letter is used to differentiate multiple stakes installed at the same site in 1 year. X_g, Y_g, Z_g, stake lower target is where the stake intersects the glacier surface. X_t, Y_t, Z_t, stake upper target is a point on the stake 1.5 to 2.0 meters above the glacier surface. H_t is the height of the stake upper target above the stake bottom as measured along the stake. θ is the downdip direction with zero east and positive counterclockwise. ϕ is the dip angle with zero horizontal and positive angles up. Solution type: lean, treats the stake as a linear segment; bend, treats the stake as multiple linear segments. X_s, Y_s, Z_s, stake bottom location. b^* is the calculated height of the stake lower target above the stake bottom as measured along the stake. b^{**} is the calculated height of the glacier surface directly above the stake bottom (as if the stake were vertical). $dXYZ$ is the total three-dimensional displacement of the stake bottom between measurements. Speed is the stake displacement divided by the measurement period in years. Horizontal displacement angle is measured positive counterclockwise; zero is east. Vertical displacement angle is measured positive up from horizontal. grad is a unit of measure for a plane angle and is equal to the plane angle in degrees multiplied by (100/90). m, meters; m/yr, meters per year]

Index site	Date (mm/dd/yyyy)	Stake Name	Stake lower target X_g (m)	Stake lower target Y_g (m)	Stake lower target Z_g (m)	Stake upper target X_t (m)	Stake upper target Y_t (m)	Stake upper target Z_t (m)	H_t (m)	Glacier surface θ (grad)	Glacier surface ϕ (grad)	Bend depth (m)	Solution type	Stake angles $θ_1$ (grad)	Stake angles $ϕ_1$ (grad)	Stake angles θ (grad)	Stake angles ϕ (grad)	Stake bottom X_s (m)	Stake bottom Y_s (m)	Stake bottom Z_s (m)	b^* (m)	b^{**} (m)	$dXYZ$ (m)	Speed (m/yr)	Displacement angles Horizontal (grad)	Displacement angles Vertical (grad)
Site A	09/26/1995	95-A	3,797.94	4,457.84	1,363.89	3,798.55	4,458.10	1,366.10	6.50	-152.13	-7.89		lean			-174.35	-81.44	3,796.83	4,457.37	1,359.88	4.19	3.87				
	04/17/1996	95-A	3,792.21	4,451.28	1,365.00	3,792.63	4,451.48	1,366.62	7.00	-154.98	-7.09		lean			-171.71	-82.20	3,790.89	4,450.65	1,359.90	5.31	4.95	8.97	16.05	-146.12	0.14
	09/26/1995	95-A2	3,802.49	4,453.43	1,364.01	3,802.82	4,453.11	1,366.09	6.50	-152.13	-7.89		lean			150.98	-86.15	3,801.81	4,454.09	1,359.74	4.37	4.26				
	04/17/1996	95-A2	3,796.61	4,446.54	1,365.04	3,796.83	4,446.24	1,366.60	7.00	-154.98	-7.09		lean			140.28	-85.10	3,795.87	4,447.55	1,359.79	5.40	5.26	8.83	15.80	-146.98	0.32
	04/17/1996	96-A	3,801.35	4,476.66	1,367.62	3,801.24	4,476.57	1,369.08	11.00	-154.98	-7.09		lean			43.65	-93.82	3,802.06	4,477.24	1,358.13	9.53	9.59				
	09/16/1996	96-A	3,796.12	4,470.85	1,363.03	3,795.95	4,470.74	1,365.36	7.00	-144.54	-7.23		lean			36.56	-94.48	3,796.46	4,471.07	1,358.39	4.66	4.69	8.34	20.03	-146.92	1.93
	04/17/1996	96-A1	3,810.23	4,470.56	1,367.88	3,810.18	4,470.59	1,369.41	11.00	-154.98	-7.09		lean			- 34.40	-97.57	3,810.54	4,470.37	1,358.42	9.47	9.48				
	09/16/1996	96-A1	3,804.77	4,464.37	1,363.39	3,804.76	4,464.34	1,365.66	7.00	-144.54	-7.23		lean			79.52	-99.11	3,804.79	4,464.43	1,358.66	4.73	4.74	8.27	19.86	-148.95	1.88
Site B	09/26/1995	94-B	4,723.78	7,354.50	1,676.94	4,723.51	7,354.64	1,678.82	6.50	-133.91	-6.47		lean			- 30.45	-89.79	4,724.43	7,354.16	1,672.40	4.60	4.55				
	04/18/1996	94-B	4,716.09	7,335.49	1,676.34	4,715.69	7,335.57	1,678.35	8.00	-126.32	-6.21		lean			- 12.57	-87.25	4,717.25	7,335.26	1,670.51	5.95	5.86	20.31	36.16	-123.11	- 5.93
	04/18/1996	96-B	4,743.93	7,419.85	1,684.96	4,743.83	7,419.71	1,687.01	11.00	-126.32	-6.21		lean			60.51	-94.67	4,744.36	7,420.46	1,676.05	8.94	8.98				
	09/16/1996	96-B	4,735.00	7,402.25	1,680.77	4,734.91	7,402.11	1,683.03	9.00	-128.51	-6.16		lean			63.63	-95.32	4,735.27	7,402.67	1,674.06	6.73	6.76	20.08	48.54	-130.09	- 6.33
Site D	09/26/1995	94-D	5,979.49	7,367.49	1,830.09	5,979.22	7,367.65	1,832.01	10.00	169.98	-5.96		lean			- 34.06	-89.68	5,980.61	7,366.83	1,822.15	8.05	8.07				
	04/18/1996	94-D	5,957.60	7,380.43	1,829.27	5,957.10	7,380.66	1,831.15	12.00	182.35	-6.21	2.39	bend	- 27.45	-89.68	- 27.45	-81.87	5,959.33	7,379.63	1,819.43	10.04	10.03	24.98	44.48	165.51	- 6.94
	09/16/1996	94-D	5,939.62	7,391.14	1,826.12	5,939.47	7,391.22	1,827.39	10.50	-196.04	-6.94		lean			- 31.19	-91.53	5,940.70	7,390.56	1,816.98	9.22	9.25	21.74	52.55	166.22	- 7.18
	04/18/1996	96-D	6,020.25	7,339.93	1,835.75	6,020.21	7,339.98	1,837.76	11.00	182.35	-6.21		lean			- 57.04	-97.97	6,020.43	7,339.71	1,826.76	8.99	9.01				
	09/16/1996	96-D	6,001.91	7,350.75	1,832.38	6,001.80	7,350.78	1,834.20	10.00	-196.04	-6.94		lean			- 16.95	-96.02	6,002.40	7,350.62	1,824.22	8.18	8.22	21.22	51.29	165.35	- 7.66

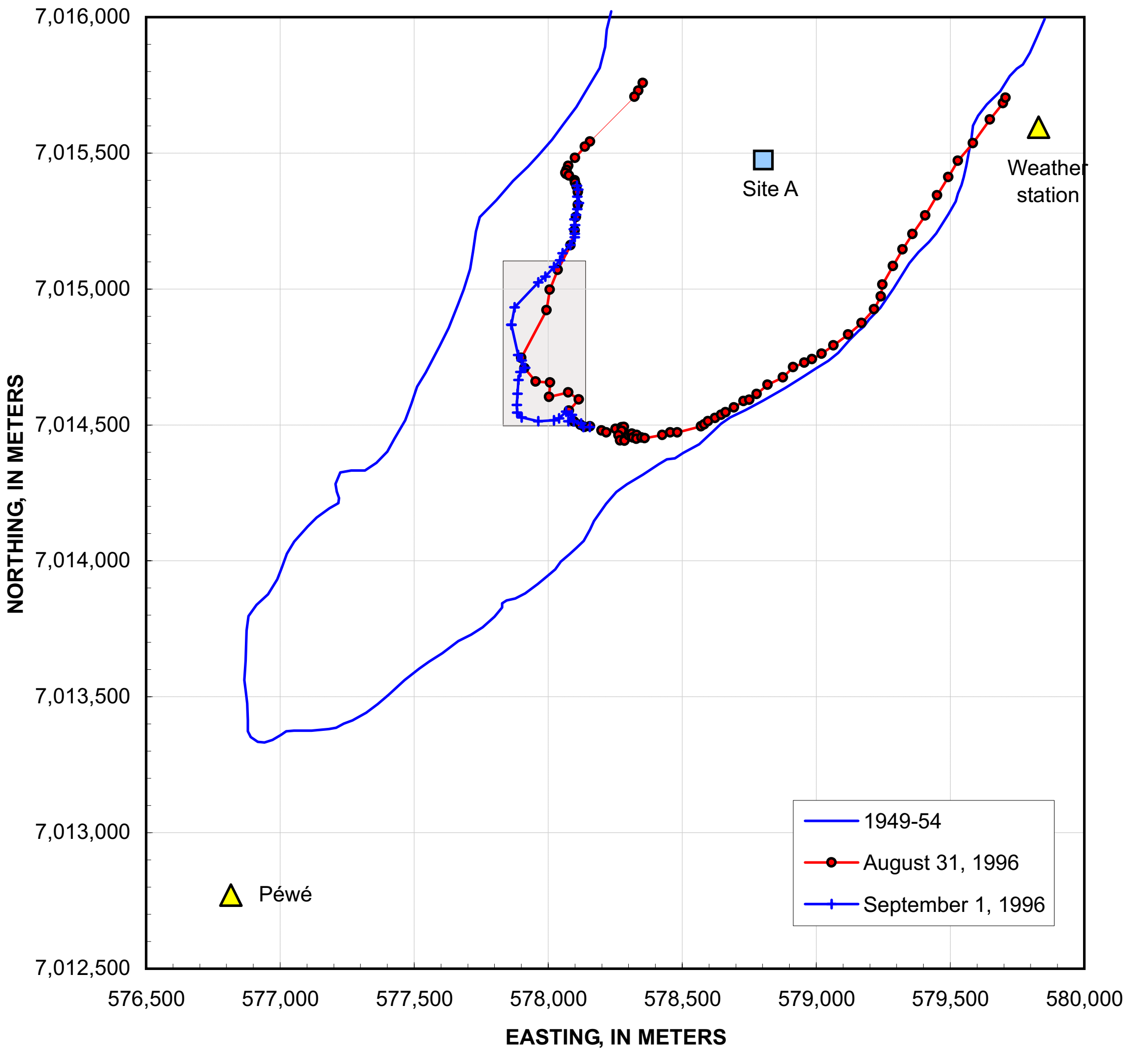


Figure 13. **Glacier terminus positions from Global Positioning System surveys on August 31 and September 1, 1996, and from U.S. Geological Survey 1:63,360-scale Mt. Hayes A3 quadrangle (1949 photography; area south of about 7,014,200 m Northing) and B3 quadrangle (1954 photography; area north of about 7,014,200 m Northing) digital raster graphic (DRG) files. DRG files were converted from NAD 27 datum to NAD 83 datum. (Shaded area indicates large uncertainty in defining terminus position. Coordinates are Universal Transverse Mercator, datum is NAD 83.)**

open here than at the glacier terminus and hence the satellite constellation visibility is better. Estimated horizontal PLGR errors recorded at locations on the terminus during surveys other years are summarized here to help assess the applicability of the errors determined by Wilson and others (1999) and by our measurements at Péwé. The average horizontal error was 5 to 6 m for approximately 180 terminus locations surveyed in 1999 and 2000. About 5 percent of the errors were greater than 10 m, and the maximum errors were 15 and 20 m, respectively, in the 2 years. We conclude that the average horizontal and vertical error was ±6 m for the 1996 terminus data.

PLGR elevations were referenced to the WGS 84 (World Geodetic System 1984) geoid model, a mathematical approximation to mean sea level. A correction of 9 m was subtracted from these altitudes to yield the reported altitudes (table 14) in the NGVD 29 datum so as to be compatible with previous Gulkana Glacier publications. This correction is based on survey-grade GPS and optical surveys of 12 locations in the glacier basin.

In 1996, surveyed locations were spaced an average of 30 m apart. The total distance surveyed along the glacier terminus was about 4 km.

Debris covers much of the terminus (fig. 3). In some areas, the downvalley transition from clean

Table 14. Global Positioning System terminus-position surveys at Gulkana Glacier on August 31 and September 1, 1996

[UTM coordinates are in UTM zone 6. Coordinates in parentheses indicate large uncertainty in defining terminus position. m, meters; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929]

UTM (zone 6) - NAD 83		NGVD 29	UTM (zone 6) - NAD 83		NGVD 29	UTM (zone 6) - NAD 83		NGVD 29
Easting (m)	Northing (m)	Altitude (m)	Easting (m)	Northing (m)	Altitude (m)	Easting (m)	Northing (m)	Altitude (m)
August 31, 1996			August 31, 1996 - Continued			September 1, 1996		
Péwé:			579,407	7,015,270	1,370	Péwé:		
576,816	7,012,769	1,145	579,451	7,015,344	1,383	576,813	7,012,773	1,144
576,816	7,012,767	1,146	579,493	7,015,411	1,392	576,813	7,012,774	1,146
576,816	7,012,768	1,144	579,529	7,015,471	1,400	576,813	7,012,773	1,144
576,817	7,012,768	1,144	579,585	7,015,536	1,408	Terminus positions:		
Terminus positions:			579,648	7,015,623	1,415	578,155	7,014,492	1,179
578,199	7,014,479	1,177	579,697	7,015,684	1,417	578,131	7,014,493	1,159
578,217	7,014,472	1,180	579,707	7,015,704	1,421	578,123	7,014,505	1,157
578,252	7,014,485	1,183				(578,096)	(7,014,514)	1,158
578,274	7,014,491	1,183	578,353	7,015,758	1,338	(578,075)	(7,014,514)	1,155
578,283	7,014,492	1,181	578,336	7,015,729	1,329	(578,088)	(7,014,537)	1,181
578,274	7,014,478	1,182	578,322	7,015,707	1,321	(578,067)	(7,014,549)	1,181
578,262	7,014,462	1,182	578,156	7,015,542	1,280	(578,041)	(7,014,524)	1,180
578,268	7,014,443	1,186	578,137	7,015,523	1,278	(578,022)	(7,014,517)	1,173
578,285	7,014,442	1,186	578,100	7,015,482	1,272	(577,963)	(7,014,514)	(1,171)
578,301	7,014,462	1,187	578,075	7,015,453	1,262	(577,901)	(7,014,528)	(1,170)
578,310	7,014,465	1,188	578,069	7,015,438	1,259	(577,884)	(7,014,545)	(1,172)
578,313	7,014,468	1,187	578,067	7,015,423	1,254	(577,883)	(7,014,574)	(1,173)
578,316	7,014,454	1,188	578,065	7,015,427	1,233	(577,885)	(7,014,615)	(1,175)
578,331	7,014,463	1,189	578,077	7,015,418	1,234	(577,889)	(7,014,666)	(1,182)
578,329	7,014,449	1,187	578,099	7,015,400	1,236	(577,896)	(7,014,695)	(1,182)
578,349	7,014,454	1,189	578,100	7,015,391	1,236	(577,914)	(7,014,710)	(1,184)
578,360	7,014,451	1,190	578,106	7,015,378	1,231	(577,901)	(7,014,737)	(1,186)
578,426	7,014,463	1,195	578,111	7,015,356	1,237	(577,888)	(7,014,757)	(1,189)
578,456	7,014,472	1,200	578,111	7,015,309	1,231	(577,863)	(7,014,868)	(1,205)
578,482	7,014,472	1,201	578,104	7,015,264	1,227	(577,863)	(7,014,869)	(1,206)
578,570	7,014,495	1,235	578,099	7,015,215	1,225	(577,875)	(7,014,933)	(1,215)
578,582	7,014,502	1,236	(578,084)	(7,015,161)	(1,224)	(577,963)	(7,015,024)	(1,220)
578,597	7,014,514	1,233	(578,036)	(7,015,070)	(1,221)	(577,989)	(7,015,045)	(1,221)
578,623	7,014,525	1,237	(578,006)	(7,014,997)	(1,221)	(578,022)	(7,015,081)	(1,224)
578,645	7,014,537	1,242	(577,994)	(7,014,922)	(1,217)	(578,044)	(7,015,106)	(1,225)
578,662	7,014,546	1,244	(577,900)	(7,014,747)	(1,177)	(578,054)	(7,015,132)	(1,226)
578,693	7,014,564	1,248	(577,912)	(7,014,709)	(1,174)	(578,082)	(7,015,162)	(1,226)
578,729	7,014,588	1,255	(577,953)	(7,014,660)	(1,178)	578,099	7,015,190	1,224
578,750	7,014,593	1,257	(578,007)	(7,014,656)	(1,182)	578,099	7,015,203	1,225
578,778	7,014,614	1,262	(578,003)	(7,014,603)	(1,175)	578,096	7,015,220	1,227
578,819	7,014,648	1,269	(578,075)	(7,014,620)	(1,175)	578,100	7,015,235	1,228
578,876	7,014,675	1,274	(578,114)	(7,014,594)	(1,176)	578,098	7,015,256	1,230
578,914	7,014,712	1,278	(578,077)	(7,014,552)	(1,164)	578,104	7,015,273	1,230
578,956	7,014,729	1,282	(578,097)	(7,014,512)	(1,164)	578,108	7,015,294	1,231
578,985	7,014,742	1,285	578,121	7,014,501	1,162	578,115	7,015,316	1,241
579,020	7,014,762	1,290	578,136	7,014,493	1,162	578,109	7,015,340	1,239
579,064	7,014,792	1,297	578,156	7,014,495	1,162	578,112	7,015,366	1,240
579,119	7,014,832	1,306	Péwé:			578,107	7,015,380	1,236
579,169	7,014,875	1,311	576,813	7,012,769	1,152	Péwé:		
579,216	7,014,926	1,318	576,812	7,012,769	1,150	576,818	7,012,772	1,155
579,241	7,014,973	1,323	576,812	7,012,768	1,149	576,818	7,012,770	1,150
579,247	7,015,016	1,330	576,813	7,012,769	1,153	576,818	7,012,770	1,150
579,286	7,015,084	1,342	576,813	7,012,768	1,154	576,817	7,012,771	1,153
579,322	7,015,146	1,352	576,813	7,012,768	1,153			
579,359	7,015,202	1,361						

glacier ice to debris-covered active glacier ice to stagnant ice-cored moraine and finally to a proglacial till is very gradual and indistinct. In such areas, it is extremely difficult to identify the location of the glacier terminus either on the ground or on stereo aerial photographs. In particular, there is a 0.5-km area of the southwest terminus (shaded area in figure 13 and locations in parentheses in table 14) where the error in defining the terminus is large, possibly as great as 200 m. The terminus position in this area was surveyed on 2 different days. The difference in the positions for the 2 days is due mostly to the error in deciding where the terminus is. Instrument error and real terminus-position change between the two surveys are negligible at the plotted scale in figure 13. Elsewhere the terminus position generally can be defined within 1 to 2 m on the ground.

For terminus change, the USGS 1:63,360-scale digital raster graphic (DRG) file for the Mt. Hayes A3 quadrangle, which shows the terminus position in 1949 (aerial photograph date) for the lowest 1.5 km of the glacier, was examined. The DRG terminus position was traced in its NAD 27 datum and then converted to NAD 83 for comparison with the 1996 GPS survey (fig. 13). U.S. National Map Accuracy Standards for 1:63,360-scale maps would indicate the horizontal standard error is ±20 m, but errors may be greater as it is not stated on these quadrangle maps that they meet the standard. From 1949 to 1996, the terminus retreated about 1,650 m for an average retreat rate of 35 m/yr.

RUNOFF

Stream-gaging station 15478040, Phelan Creek near Paxson[3], is part of the USGS stream-monitoring network in Alaska. Data collection and analysis are conducted by standard techniques developed by the USGS, and daily values of discharge generally are reported along with those for the rest of Alaska in the annual USGS Water-Data Report series (U.S. Geological Survey, 1968–97; see also http://ak.water.usgs.gov/glaciology/gulkana/streamflow/).

The gaging station is located at 1,125 m, about 1 km downstream from the present glacier terminus (figs. 2 and 3). The creek bed consists of poorly sorted gravel and small boulders. The channel is subject to frequent changes during high flows. Typical winter under-ice discharge is about 0.1 m^3/s; typical summer discharge ranges from 4 to 20 m^3/s; the period-of-record peak discharge is 65 m^3/s (Linn and others, 1997). The typical minimum winter discharge is about 0.04 m^3/s, which is about three to four times the average contribution from the combined geothermal melt of the bed of the glacier and melting caused by ice motion.

Stream stage is continuously recorded, and discharge measurements are made periodically to determine the relation between stage and discharge at different streamflows and to detect any shifts in the relation due to changes in the creek bed. Because of the low frequency of discharge measurements (fig. 14), the poor quality of gage-height record, and the changeable nature of the creek bed, the published discharge record is rated as "poor," meaning that less than 95 percent of the daily discharges are within 15 percent of the true value (Linn and others, 1997). This published rating places no limit on the possible error but indicates that the standard error is greater than ±7.5 percent. The standard error of the daily discharge values at Phelan Creek gaging station is estimated at 10 percent normally and 20 percent for the few values estimated during open-water conditions (Richard Kemnitz, USGS, oral commun., 1997).

The 1996 discharge record was reported with the rest of the 1996 Alaska water data in the USGS Water-Data Report AK–96–1 (Linn and others, 1997). The 1996 daily mean discharge data were converted to runoff (fig. 14, table 15) by dividing the discharge values by the basin area. The 1996 runoff was 1.50 m, approximately 1.0 standard deviation below the period-of-record (1967–78, 1990–96) average. New record-high daily runoff occurred on June 19–20 following record-high temperatures on June 18–19. New record-low daily runoffs occurred during cold snaps on June 11–12, 30, July 1, and August 7; the August 7 record low followed a new record-low daily temperature on August 6.

Runoff values were estimated for the ice period on the basis of air temperature, precipitation, and winter discharge measurements (November 9, 1995, February 1, 1996, and April 19, 1996). The relation between estimated daily runoff and the winter discharge measurements (converted to daily runoff) for the current year and for the entire period of record is

---

[3]Before October 1968, data for this station were published as "Gulkana Creek near Paxson."

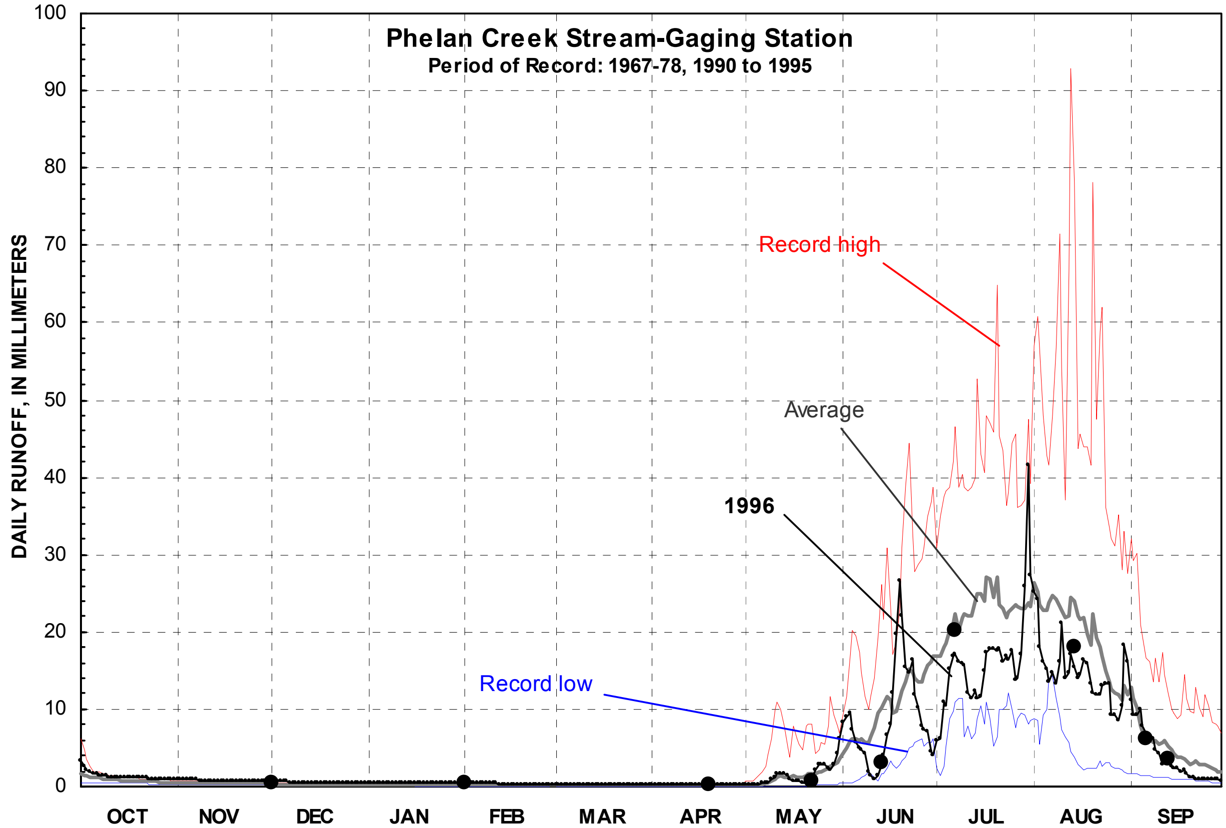


Figure 14. Daily runoff from Phelan Creek near Paxson (USGS stream-gaging station 15478040), 1996 hydrologic year. Large filled circles are instantaneous discharge measurements, expressed as runoff, that are used to define the stage-discharge relation. Also shown are the record-high, average, and record-low daily runoff for the period of record (1967–78, 1990–96).

shown in figure 15. New estimated record high daily runoff values occurred during most of the winter from October 20, 1995, to February 11, 1996, but previous record highs were exceeded only by 0.1 to 0.2 mm/d. Because the discharge measurements are so sparse in any 1 year, display of these measurements for the entire period of record is useful to help gage the possible error in these estimates. The range of measured values over the entire period of record suggests that the standard error in the estimates from October into early May is less than ±0.2 mm/d, but then the error rapidly increases with the onset of the melt season in mid-May to about ±5 mm/d by early June. The cumulative sum of estimated winter runoff represents about 15 percent of the annual runoff.

SUMMARY

The 1996 measured winter snow, maximum winter snow, net, and annual balances in the Gulkana Glacier Basin were evaluated on the basis of meteorological, hydrological, and glaciological data. Averaged over the glacier, the measured winter snow balance was 0.87 m on April 18, 1996, 1.1 standard deviation or 0.27 m below the long-term average; the maximum winter snow balance, 1.06 m, was reached on May 28, 1996; and the net balance (from August 30, 1995, to August 24, 1996) was -0.53 m, 0.53 standard deviation or 0.27 m below the long-term average. The annual balance (October 1, 1995, to September 30, 1996) was -0.37 m. Area-averaged balances were reported using both the 1967 and 1993 area altitude distributions (the numbers previously given in this summary use the 1993 area altitude distribution). Net balance was about 25 percent less negative using the 1993 area altitude distribution than the 1967 distribution.

The annual average air temperature sensed with the analog sensor at 1,480 m was -5.0 °C, 0.9 standard deviations below the long-term average. In the first year of use, the digitally sensed annual average air temperature was 0.9 °C warmer than that recorded with the analog sensor used since 1966. Total precipitation catch for the year was 0.78 m, 0.8 standard deviations below normal. Despite a wind shield, the gage's

Table 15. Daily mean runoff from the Gulkana Glacier Basin, 1996 hydrologic year

[Values in millimeters, averaged over the basin; except standardized values which are in units of standard deviation; () indicates value estimated (see text for explanation)]

		1995						1996					
Day	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1	3.3	(0.9)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	8.3	6.0	25.1	11.2	
2	2.7	(0.9)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	9.1	6.3	24.2	(9.3)	
3	2.3	(0.9)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)	9.5	10.8	18.1	(9.3)	
4	2.0	(0.9)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)	7.4	10.4	16.1	10.1	
5	1.8	(0.9)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)	5.7	15.2	15.1	(7.7)	
6	1.6	(0.9)	(0.6)	(0.5)	0.4	(0.3)	(0.3)	(0.4)	4.9	17.0	13.6	(7.0)	
7	1.5	(0.9)	(0.5)	(0.5)	(0.4)	(0.3)	(0.2)	(0.5)	4.7	(17.0)	14.7	6.6	
8	1.4	0.8	(0.5)	(0.5)	(0.4)	(0.3)	(0.2)	(0.5)	4.3	16.2	13.4	6.1	
9	1.3	(0.8)	(0.5)	(0.5)	(0.4)	(0.3)	(0.2)	(0.9)	2.0	15.8	16.3	4.7	
10	1.2	(0.8)	(0.5)	(0.5)	(0.4)	(0.3)	(0.2)	(1.2)	1.4	15.6	21.1	4.2	
11	(1.2)	(0.8)	(0.5)	(0.4)	(0.4)	(0.3)	(0.2)	(1.6)	0.9	12.2	14.0	2.9	
12	(1.2)	(0.8)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(1.7)	1.4	11.3	14.8	3.3	
13	(1.2)	(0.8)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(1.7)	2.9	12.5	17.0	3.6	
14	(1.2)	(0.8)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(1.3)	4.0	11.3	15.4	2.6	
15	(1.2)	(0.8)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.9)	6.6	11.6	13.9	2.4	
16	(1.2)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.8)	8.1	14.9	14.4	2.4	
17	(1.2)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.7)	12.1	17.4	16.4	2.0	
18	(1.1)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.6)	19.8	17.8	15.9	2.2	
19	(1.1)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.5)	26.6	17.9	13.4	1.6	
20	(1.1)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.5)	22.0	17.5	12.1	1.2	
21	(1.1)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.6)	15.3	17.8	11.8	1.1	
22	(1.1)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(1.0)	14.6	16.1	11.9	0.9	
23	(1.0)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	2.1	16.3	16.8	13.0	0.9	
24	(1.0)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	2.9	11.9	16.4	13.3	0.9	
25	(1.0)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	2.9	10.3	17.5	13.2	1.0	
26	(1.0)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	2.8	7.8	13.7	(9.3)	1.0	
27	(1.0)	(0.6)	(0.5)	(0.4)	(0.3)	0.3	(0.2)	2.3	7.3	13.9	(9.3)	0.9	
28	(0.9)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	2.1	7.1	17.0	(8.5)	0.9	
29	(0.9)	(0.6)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	2.9	4.6	25.9	10.5	0.9	
30	(0.9)	(0.6)	(0.5)	(0.4)		(0.3)	(0.2)	4.2	4.0	41.7	18.2	0.7	
31	(0.9)		(0.5)	(0.4)		(0.3)		6.3		27.4	16.2		
Total	(41.7)	(22.2)	(16.4)	(12.8)	(9.9)	(9.6)	(7.4)	(45.4)	260.6	498.9	(460.4)	(109.4)	1,494.7
Departure from normal	15.2	9.4	6.9	5.3	4.2	4.2	2.4	3.9	-47.9	-200.8	-152.9	-40	
Standardized value	0.6	0.7	0.7	0.7	0.7	0.8	0.5	0.1	- 0.2	- 0.3	- 0.2	- 0.3	
Total of measured values	19.1	0.0	0.0	0.0	0.0	0.0	0.0	28.4	260.6	481.9	433.3	76.1	1,299.5
Total of estimated values	(22.5)	(22.2)	(16.4)	(12.8)	(9.9)	(9.6)	(7.4)	(17.0)	(0.0)	(17.0)	(27.1)	(33.3)	(195.2)
Percent measured	46	0	0	0	0	0	0	63	100	97	94	70	87

catch efficiency is strongly affected by wind. Catch efficiency averages about 0.57. The annual average wind speed was 3.5 m/s.

Glacier-surface altitude and ice-motion changes measured at three index sites document glacier-thickness and seasonal ice-speed changes. The 1996 glacier-surface altitude data continued the glacier-wide thinning trend of the 1990s. Ice motion in the central reach of the glacier was 40 to 50 m/yr with a slow down in the lower ablation zone to about one-half that. There has been a general slowing trend through the 1990s with a reduction of about 20 percent since 1990 and about 5 percent since 1995.

The glacier terminus and lower ablation area were defined for 1996 with a handheld GPS survey of 126 locations spread out over about 4 km of the lower glacier margin. From 1949 to 1996, the terminus retreated about 1,650 m for an average retreat rate of 35 m/yr. Annual stream runoff averaged 1.50 m over the basin, 1.0 standard deviation below the long-term average.

REFERENCES CITED

Barry, R.G., 1989, Climate of the Arctic Ocean, *in* Herman, Y., ed., The Arctic Seas—climatology, oceanography, geology, and biology: New York, Van Nostrand Reinhold, p. 1–46.

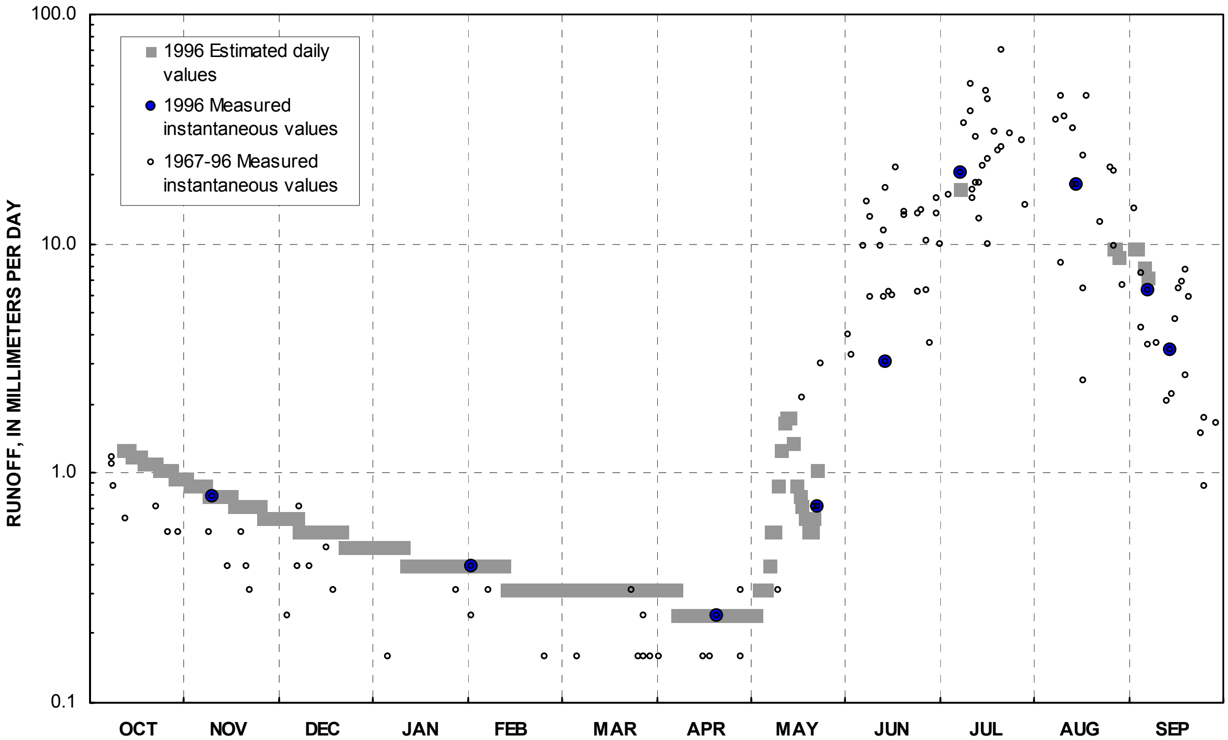


Figure 15. Estimated daily runoff from Phelan Creek near Paxson, 1996 hydrologic year (USGS stream-gaging station 15478040), with measured values for both 1996 hydrologic year and entire period of record (1967–78, 1990–96).

Braithwaite, R.J., 1995, Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling: Journal of Glaciology, v. 41, no. 137, p. 153–160.

Braithwaite, R.J., and Olesen, O.B., 1985, Ice ablation in West Greenland in relation to air temperature and global radiation: Zeitschrift für Gletscherkunde und Glazialgeologie, v. 20, no. 1984, p. 155–168.

Braithwaite, R.J., and Olesen, O.B., 1993, Seasonal variation of ice ablation at the margin of the Greenland ice sheet and its sensitivity to climate change, Qamanârssûp sermia, West Greenland: Journal of Glaciology, v. 39, no. 132, p. 267–274.

Cheney, Ward, and Kincaid, David, 1980, Numerical mathematics and computing (2d ed.): Monterey, Calif., Brooks/Cole Publishing Co., a division of Wadsworth, Inc., 562 p.

Dowdeswell, J.A., Hagen, J.O., Björnsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Korner, R.M., Lefauconnier, B., Ommanney, C.S.L., and Thomas, R.H., 1997, The mass balance of circum-Arctic glaciers and recent climate change: Quaternary Research, v. 48, p. 1–14.

Fahl, C.B., 1973, Some relationships between glaciers and climate in Alaska: Fairbanks, Alaska, University of Alaska, Ph.D. dissertation, 191 p.

Fountain, A.G., Krimmel, R.M., and Trabant, D.C., 1997, Glacier monitoring program of the U.S. Geological Survey: U.S. Geological Survey Circular 1132, 19 p., accessed on July 1, 2003, at http://pubs.water.usgs.gov/cir1132

Haeberli, Wilfried, 1985, Fluctuations of glaciers 1975–1980 (volume IV): International Association of Hydrologic Sciences (International Commission of Snow and Ice) and United Nations Educational, Scientific and Cultural Organization, 265 p., maps, and plates.

Haeberli, W., and Herren, E., eds., 1991, Glacier mass balance bulletin no. 1: ETH Zurich, World Glacier Monitoring Service, IAHS(ICSI)/UNEP/UNESCO, 70 p.

Haeberli, W., Herren, E., and Hoelzle, M., eds., 1993, Glacier mass balance bulletin no. 2: ETH Zurich, World Glacier Monitoring Service, IAHS(ICSI)/UNEP/UNESCO, 74 p.

Haeberli, Wilfried, and Hoelzle, Martin, 1993, Fluctuations of glaciers 1985–1990 (volume VI): International Association of Hydrologic Sciences (International Commission on Snow and Ice) and United Nations Environment Programme and United Nations Educational, Scientific and Cultural Organization, 322 p., maps, and plates.

Haeberli, W., Hoelzle, M., and Bösch, H., eds., 1994, Glacier mass balance bulletin no. 3: ETH Zurich, World Glacier Monitoring Service, IAHS(ICSI)/UNEP/UNESCO, 80 p.

Haeberli, W., Hoelzle, M., and Frauenfelder, R., eds., 1999, Glacier mass balance bulletin no. 5: University and ETH Zurich, World Glacier Monitoring Service, IAHS(ICSI)/UNEP/UNESCO, 96 p., accessed on July 1, 2003, at http://www.geo.unizh.ch/wgms/mbb/mbb5/MBB5.pdf

Haeberli, W., Hoelzle, M., and Suter, S., eds., 1996, Glacier mass balance bulletin no. 4: University and ETH Zurich, World Glacier Monitoring Service, IAHS(ICSI)/UNEP/UNESCO, 90 p., accessed on July 1, 2003, at http://www.geo.unizh.ch/wgms/mbb/mbb4/mbb4.html

Haeberli, W., Hoelzle, M., Suter, S., and Frauenfelder. R., 1998, Fluctuations of glaciers 1990–1995 (volume VII): International Association of Hydrologic Sciences (International Commission on Snow and Ice) and United Nations Environment Programme and United Nations Educational, Scientific and Cultural Organization, 296 p., maps, and plates, accessed on July 1, 2003, at http://www.geo.unizh.ch/wgms/fog/fogaa.pdf

Haeberli, Wilfried, and Müller, Peter, 1988, Fluctuations of glaciers 1980–1985 (volume V): International Association of Hydrologic Sciences (International Commission on Snow and Ice) and United Nations Environment Programme and United Nations Educational, Scientific and Cultural Organization, 290 p., maps, and plates.

Hodge, S.M., Trabant, D.C., Krimmel, R.M., Heinrichs, T.A., March, R.M., and Josberger, E.G., 1998, Climate variations and changes in mass of three glaciers in western North America: Journal of Climate, v. 11, no. 9, p. 2161–2179, accessed on July 3, 2003, at http://ak.water.usgs.gov/glaciology/gulkana/reports/index.html

Jóhannesson, T., Sigurdsson, O., Laumann, T., and Kennett, M., 1995, Degree-day glacier mass-balance modelling with applications to glaciers in Iceland, Norway, and Greenland: Journal of Glaciology, v. 41, no. 138, p. 345–358.

Karl, T.H., Tarpley, J.D., Quayle, R.G., Diaz, H.F., Robinson, D.A., and Bradley, R.S., 1989, Recent climate record—what it can and cannot tell us: Reviews of Geophysics, v. 27, no. 3, p. 405–430.

Kasser, Peter, 1967, Fluctuations of glaciers 1959–1965 (volume I): International Association of Scientific Hydrology (International Commission of Snow and Ice) and United Nations Educational, Scientific and Cultural Organization (no pagination).

Kennedy, B.W., 1995, Air temperature and precipitation data, Wolverine Glacier basin, Alaska, 1967–94: U.S. Geological Survey Open-File Report 95–444, 79 p., plus diskette.

Kennedy, B.W., Mayo, L.R., Trabant, D.C., and March, R.S., 1997, Air temperature and precipitation data, Gulkana Glacier, Alaska, 1968–96: U.S. Geological Survey Open-File Report 97–358, 144 p., accessed on July 3, 2003, abstract at http://ak.water.usgs.gov/glacioogy/gukana/reports/ofr97-358/

Letréguilly, Anne, and Reynaud, Louis, 1989, Spatial patterns of mass-balance fluctuations of North American glaciers: Journal of Glaciology, v. 35, no. 120, p. 163–168.

Linn, K.R., Shaw, S.K., Swanner, W.C., Rickman, R.L., and Schellekens, M.F., 1997, Water resources data for Alaska, water year 1996: U.S. Geological Survey Water-Data Report AK–96–1, 270 p., accessed on July 3, 2003, at http://ak.water.usgs.gov/Publications/Water-Data/WY96/Default.htm

March, R.S., 1998, Mass balance, meteorological, ice motion, surface altitude, and runoff data at Gulkana Glacier, Alaska, 1994 balance year: U.S. Geological Survey Water-Resources Investigations Report 97–4251, 31 p., accessed on July 3, 2003, at http://pubs.water.usgs.gov/wri97-4251

March, R.S., 2000, Mass balance, meteorological, ice motion, surface altitude, runoff, and ice thickness data at Gulkana Glacier, Alaska, 1995 balance year: U.S. Geological Survey Water-Resources Investigations Report 00–4074, 33 p., accessed on July 3, 2003, at http://pubs.water.usgs.gov/wri00-4074/

March, R.S., and Trabant, D.C., 1996, Mass balance, meteorological, ice motion, surface altitude, and runoff data at Gulkana Glacier, Alaska, 1992 balance year: U.S. Geological Survey Water-Resources Investigations Report 95–4277, 32 p., accessed on July 3, 2003, at http://pubs.water.usgs.gov/wri95-4277

March, R.S., and Trabant, D.C., 1997, Mass balance, meteorological, ice motion, surface altitude, and runoff data at Gulkana Glacier, Alaska, 1993 balance year: U.S. Geological Survey Water-Resources Investigations Report 96–4299, 30 p., accessed on July 3, 2003, abstract at http://ak.water.usgs.gov/glaciology/gulkana/reports/wrir96-4299/

Mayo, L.R., 1992, Internal ablation—an overlooked component of glacier mass balance [abs.]: EOS, Transactions, American Geophysical Union, v. 73, no. 43, supplement, p. 180.

Mayo, L.R., March, R.S., and Trabant, D.C., 1992, Air temperature and precipitation data, 1967–88, Wolverine Glacier basin, Alaska: U.S. Geological Survey Open-File Report 91–246, 80 p.

Mayo, L.R., Meier, M.F., and Tangborn, W.V., 1972, A system to combine stratigraphic and annual mass-balance systems—a contribution to the International Hydrologic Decade: Journal of Glaciology, v. 11, no. 61, p. 3–14.

Mayo, L.R., and Trabant D.C., 1982, Geodetic trisection, altitude, and ice-radar surveying techniques used at Knik Glacier, Alaska and summary of 1979, 1980, and 1981 data: U.S. Geological Survey Open-File Report 82–685, 26 p.

Mayo, L.R., and Trabant D.C., 1986, Recent growth of Gulkana Glacier, Alaska Range, and its relation to glacier-fed runoff, *in* Subitsky, Seymour, ed., Selected papers in the hydrologic sciences: U.S. Geological Survey Water-Supply Paper 2290, p. 91–99.

Mayo, L.R., Trabant, D.C., March, Rod, and Haeberli, Wilfried, 1979, Columbia Glacier stake locations, mass balance, glacier surface altitude, and ice radar data, 1978 measurement year: U.S. Geological Survey Open-File Report 79–1168, 72 p.

Meier, M.F., 1965, Glaciers and climate, *in* Wright, H.E., and Frey, D.G., eds., The Quaternary of the United States: Princeton, N.J., Princeton University Press, p. 795–805.

Meier, M.F., Mayo, L.R., Trabant, D.C., and Krimmel, R.M., 1980, Comparison of mass balance and runoff at four glaciers in the United States, 1966 to 1977: Academy of Sciences of USSR, Section of Glaciology, Data of Glaciological Studies, Publication No. 38, p. 138–147 (Russian text with figures), p. 214–219 (English text).

Meier, M.F., Tangborn, W.V., Mayo, L.R., and Post, Austin, 1971, Combined ice and water balances of Gulkana and Wolverine Glacier, Alaska, and South Cascade Glacier, Washington, 1965 and 1966 hydrologic years: U.S. Geological Survey Professional Paper 715–A, 23 p.

Muller, Fritz, 1977, Fluctuations of glaciers 1970–1975 (volume III): International Association of Hydrologic Sciences (International Commission of Snow and Ice) and United Nations Educational, Scientific and Cultural Organization, 269 p., maps, and plates.

National Climatic Data Center, 1996, Climatological data annual summary, Alaska, 1995: v. 81, no. 13, 23 p.

Østrem, G., and Brugman, M., 1991, Glacier mass-balance measurements—a manual for field and office work: Environment Canada, National Hydrology Research Institute Science Report No. 4, 224 p.

Østrem, G., and Stanley, A.D., 1969, Glacier and mass balance measurements—a manual for field and office work, revised edition: Ottawa, Ontario, Canadian Department of Energy, Mines, and Resources and Norwegian Water Resources and Electricity Board, IWB Reprint Series No. 66, Inland Waters Branch, Department of the Environment, 118 p.

Péwé, T.L., and Reger, R.D., 1983, Delta River area, Alaska Range, *in* Péwé, T.L., and Reger, R.D., eds., Guidebook to permafrost and Quaternary geology along the Richardson and Glenn Highways between Fairbanks and Anchorage, Alaska, Fourth International Conference on Permafrost: Alaska Division of Geological and Geophysical Surveys—Guidebook 1, p. 47–135.

Tangborn, W.V., Mayo, L.R., Scully, D.R., and Krimmel, R.M., 1977, Combined ice and water balances of Maclure Glacier, California, South Cascade Glacier, Washington, and Wolverine and Gulkana Glaciers, Alaska—1967 hydrologic year: U.S. Geological Survey Professional Paper 715–B, 20 p.

Trabant, D.C., March, R.S., and Kennedy, B.W., 1998, Glacier mass-balance trends in Alaska and climate-regime shifts [abs.]: EOS, Transactions, American Geophysical Union, v. 79, no. 48, p. F277, accessed on July 3, 2003, at http://ak.water.usgs.gov/glaciology/reports/AGU98/98AGU_balance_trend_poster.htm

Trabant, D.C., and Mayo, L.R., 1985, Estimation and effects of internal accumulation on five glaciers in Alaska: Annals of Glaciology, v. 6, p. 113–117.

United Nations Educational, Scientific, and Cultural Organization/International Association of Scientific Hydrology (UNESCO/IASH), 1970, Combined heat, ice and water balances at selected glacier basins: Paris, United Nations Educational, Scientific, and Cultural Organization/International Association of Scientific Hydrology, Technical Papers in Hydrology 5, 20 p.

U.S. Departments of the Army and the Air Force, 1951, TM 5–241– to 16–1–233, The universal grid systems (Universal Transverse Mercator) and (Universal Polar Stereographic): Washington, Government Printing Office, 324 p.

U.S. Geological Survey, 1968–97, Water resources data for Alaska, water years 1967–96: U.S. Geological Survey Water-Data Report 67–1 to 70–1 and AK–71–1 to AK–96–1 (published annually; AK designation not used before 1971).

Walters, R.A., and Meier, M.F., 1989, Variability of glacier mass balances in western North America, *in* Peterson, D.H., Aspects of climate variability in the Pacific and Western Americas: American Geophysical Union, Geophysical Monograph 55, p. 365–374.

Wilson, B.D., Yinger, C.H., Feess, W.A., and Shank, Capt. C., 1999, New and improved—the broadcast interfrequency biases: GPS World, v. 10, no. 9, p. 56–64.