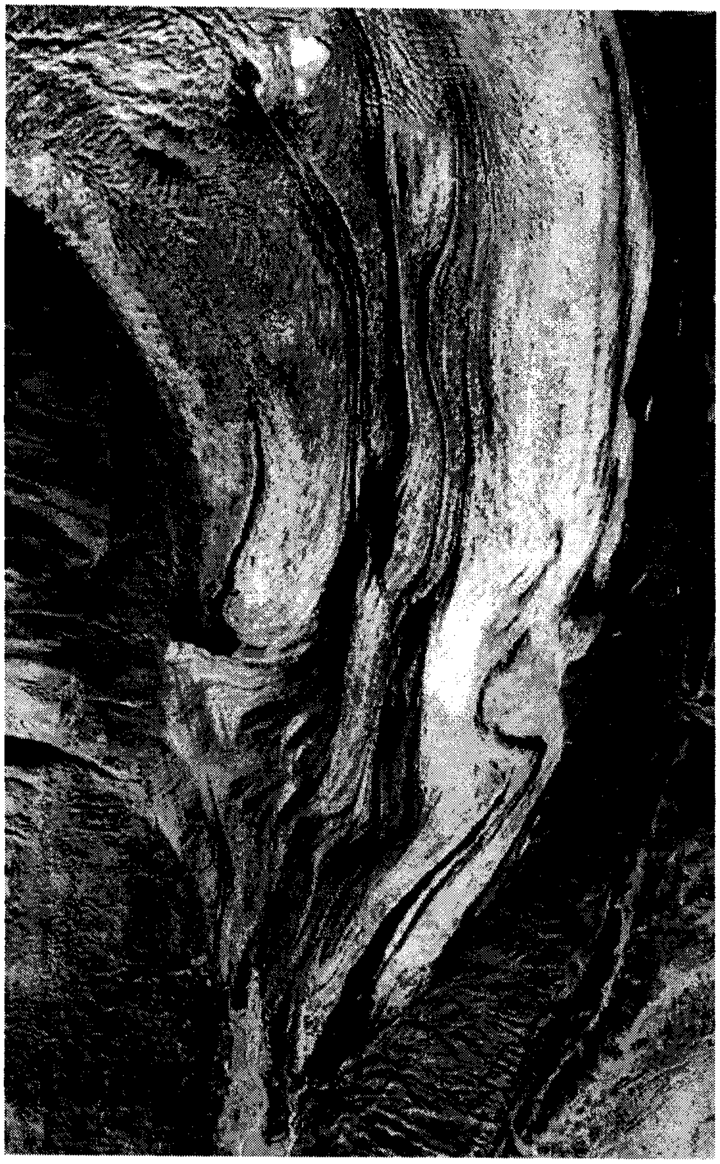
U.S. Department of the Interior
U.S. Geological Survey

Mass Balance, Meteorological, Ice Motion, Surface Altitude, Runoff, and Ice Thickness Data at Gulkana Glacier, Alaska, 1995 Balance Year

Water-Resources Investigations Report 00-4074



USGS
science for a changing world

Cover: Vertical photographs of lower Gulkana Glacier on August 31, 1967, left photo, and July 11, 1993, right photo. Up direction in the photos is approximately northeast. The 26-year comparison shows retreat at the terminus of 300-400 meters and significant retreat along the northwest (left in photo) glacier margin. The small bedrock outcrop in the middle of the glacier near the upper edge of the 1967 photo has roughly quadrupled in size in the 1993 photo. Photo scale is about 1:22,000 or 1 cm =220 m. Using this scale, at least one distinct moraine feature almost exactly in the center of the 1963 photo can be traced to have moved 2.2 cm at photo scale or about 500 m in 26 years for an average velocity of 19 m/yr. This is approximately equal to the 1988-99 average velocity of 20 m/yr at our nearby measurement site A. The 1963 image is composite of USGS photographs 670398 and 670399 by Austin Post. The 1993 image is photograph Gulkana Glacier 1-4 by AeroMap US.

Mass Balance, Meteorological, Ice Motion, Surface Altitude, Runoff, and Ice Thickness Data at Gulkana Glacier, Alaska, 1995 Balance Year

by Rod S. March

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 00-4074

Fairbanks, Alaska
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
4320 University Drive, Suite 201
Anchorage, AK 99508-4664

http://ak.water.usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

VERTICAL DATUM

Altitudes are measured relative 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 last 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 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 25-75 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 25-75 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 25-75 meter radius of the stake, in meters

$b_0'ss_1$ — initial stake height at the beginning of the measurement year of the first summer surface down from the glacier surface within a 25-75 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 25-75 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)	long-term, average 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_0(i)	initial old firn and ice balance at site
b_1(i)	final 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
h	ice thickness perpendicular to the glacier bed, in meters
H_t	height of the stake upper target above the stake bottom as measured along the stake, in meters

HY	hydrologic year; interval between October 1 and the end of the following September
k	horizontal scale factor between the UTM plane and sea level
$\bar{k}$	mean horizontal scale factor between the UTM plane and sea level
m_{we}	meters water equivalent
n	sample number
S	ice radar transmitter-receiver separation distance, in meters
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)
t_d	ice radar time delay, in microseconds
v_a	speed of light in air, in meters per microsecond
v_i	speed of light in ice, in meters per microsecond
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 1.5-2.0 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 1.5-2.0 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
$Z_i(ss_1)$	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 1.5-2.0 meters above the glacier surface, in meters
$dXYZ$	total three-dimensional displacement of the stake bottom between measurements
θ	down dip direction with zero east and positive counterclockwise
ϕ	dip angle with zero horizontal and positive angles up

Mass Balance, Meteorological, Ice Motion, Surface Altitude, Runoff, and Ice Thickness Data at Gulkana Glacier, Alaska, 1995 Balance Year

by Rod S. March

ABSTRACT

The 1995 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 obtained in the basin. Averaged over the glacier, the measured winter snow balance was 0.94 meter on April 19, 1995, 0.6 standard deviation below the long-term average; the maximum winter snow balance, 0.94 meter, was reached on April 25, 1995; the net balance (from September 18, 1994 to August 29, 1995) was -0.70 meter, 0.76 standard deviation below the long-term average. The annual balance (October 1, 1994, to September 30, 1995) was -0.86 meter. Ice-surface motion and altitude changes measured at three index sites document seasonal ice speed and glacier-thickness changes. Annual stream runoff was 2.05 meters averaged over the basin, approximately equal to the long-term average.

The 1976 ice-thickness data are reported from a single site near the highest measurement site (180 meters thick) and from two glacier cross profiles near the mid-glacier (270 meters thick on centerline) and low glacier (150 meters thick on centerline) measurement sites.

A new area-altitude distribution determined from 1993 photogrammetry is reported. Area-averaged balances are reported from both the 1967 and 1993 area-altitude distribution so the reader may directly see the effect of the update. Briefly, loss of ablation area between 1967 and 1993 results in a larger weighting being applied to data from the upper glacier site and hence, increases calculated area-averaged balances. The balance increase is of the order of 15 percent for net balance.

INTRODUCTION

The U.S. Geological Survey (USGS) operates a long-term program to monitor climate, glacier motion, mass balance, and stream runoff to understand glacier-related hydrologic processes and improve the quantitative prediction 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 glacier basins in the United States that clearly sample different climate-glacier-runoff regimes. Gulkana Glacier is one of three long-term, high-quality mass balance monitoring sites operated by the USGS. The other monitoring sites are Wolverine Glacier in southcentral Alaska and South Cascade Glacier in Washington. This report contains the mass balance, meteorological, ice motion, surface altitude, and basin runoff measurements made in the Gulkana Glacier basin for the 1995 hydrologic year (October 1 to September 30) and balance year (see "Measurement System and Terminology" section). In addition, it also contains ice thickness measurements made near our measurements sites in March of 1976.

Measurements began on Gulkana Glacier during the early 1960's with the University of Alaska Gulkana Glacier Project (Péwé and Reger, 1983). For several years this project measured the energy budget, mass balance, meteorology, foliation, flow, and glacier bottom topography (from gravity anomalies) at Gulkana Glacier. In 1966, a continuing series of meteorological, snow and ice balance, and runoff 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-1970's, after which spatial sampling was reduced to three sites used as indices for mass balance. Measurements at the three remaining sites were expanded to include ice-motion and surface-altitude observations (for determining glacier-volume change) in addition to the balance, runoff, and meteorological observations already in progress. Since 1966, part of the Gulkana data set (net balance, accumulation, ablation, accumulation area ratio (AAR), and equilibrium line altitude (ELA)) has been published by the World Glacier Monitoring Service (Kasser, 1967; Muller, 1977; Haeberli, 1985; Haeberli and Müller, 1988; Haeberli and Hoelzle, 1993; Haeberli and others, 1998). Index-site glacier-surface and summer-surface altitudes, measured winter balance, and net firn and ice balance from 1975 to 1983 are reported by Mayo and Trabant (1986). Data for 1992, 1993, and 1994 similar to those presented here were published by March and Trabant (1996, 1997) and March (1998).

A limited portion of the glacier data (annual values of winter, summer, and net balance, ELAs, AARs, monthly and daily temperature and precipitation, daily wind speed and runoff) for the period of record is available on the Internet (*http://ak.water.usgs.gov/glaciology/*)[1].

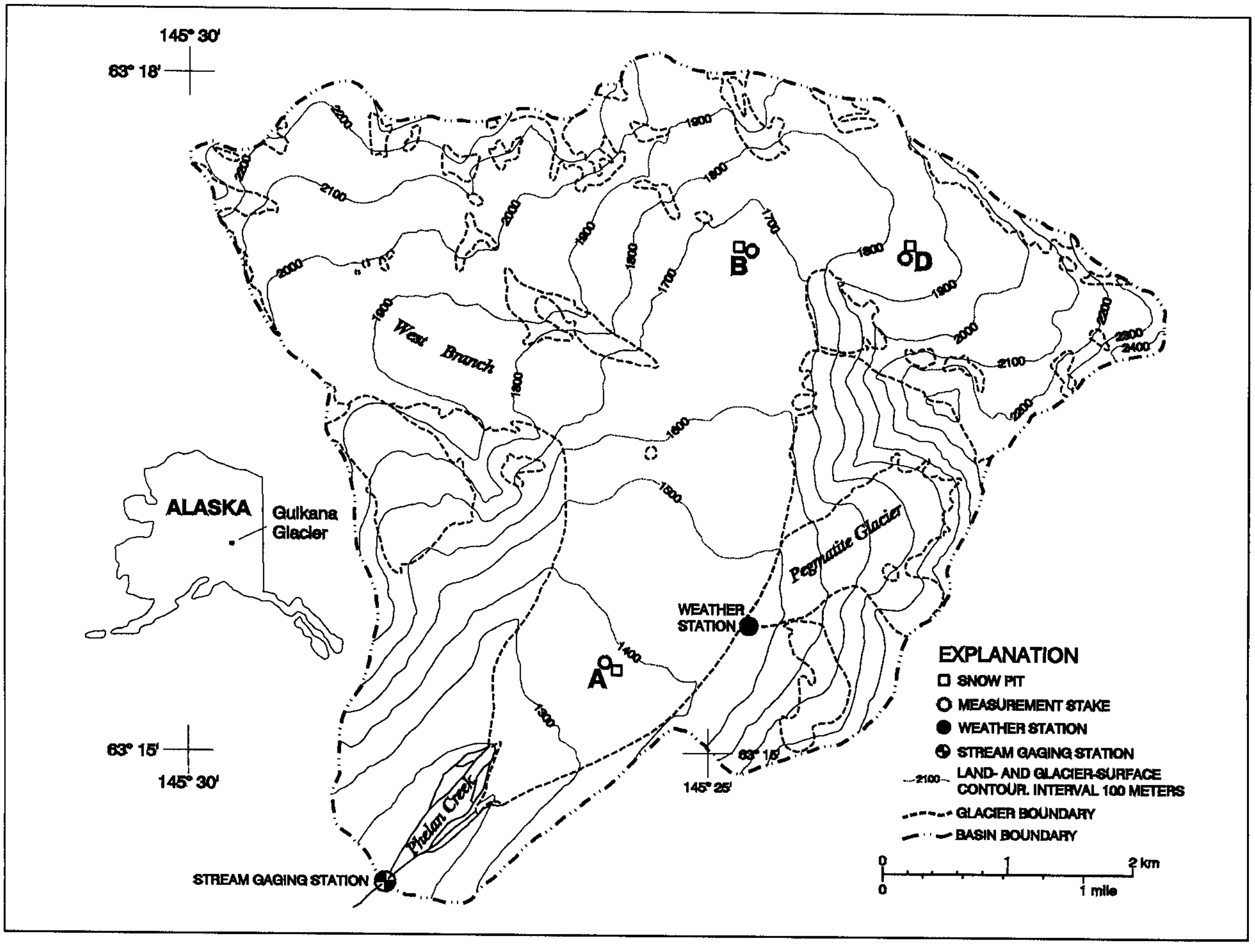
The Gulkana record (30 years of balance data, 29 years of meteorology data) is approaching the 30-year length-of-record criterion generally considered necessary to provide reasonable statistics for global climate monitoring (Karl and others, 1989). Interpretations of regional climate-glacier relations using the Gulkana data include papers by Fahl (1973), Walters and Meier (1989), Letréguilly and Reynaud (1989), Dowdeswell and others (1997), and Hodge and others (1998), Trabant and others (1998).

Description of the Gulkana Glacier Basin and its Climate

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

The mean 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

[1]Because of the rapidly evolving nature of the Internet, it is recognized that the Internet references in this report may change. In that event, the reader may alternatively find the information referenced by starting higher in the Internet hierarchy of the USGS either at the Water Resources homepage (*http://water.usgs.gov*) or at the USGS homepage (*http://www.usgs.gov*).



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

Figure 1. Gulkana Glacier basin, Alaska.

recorder site using the wet adiabatic rate of -6.6°C per 1,000 m. The mean annual air temperature at the recorder site at 1,480 m altitude is about -4°C, and the average annual precipitation-gage catch is about 1 m. Daily mean temperatures range from a low of -35°C to a high of 15°C. The average annual basin runoff for water years 1967-78 and 1990-95 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 19.32 km^2 in 1967. The basin also contains Pegmatite Glacier (fig. 1), 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.

Phelan Creek (fig. 1) drains the Gulkana Glacier basin and flows into the Delta River, which is a tributary of the Tanana River, and finally into the Yukon River north of the Alaska Range. In the past, Phelan Creek occasionally drained into Summit Lake at the head of the Gulkana and Copper Rivers. The alternating drainage was diverted into the Yukon River basin when the Richardson Highway was constructed in 1923.

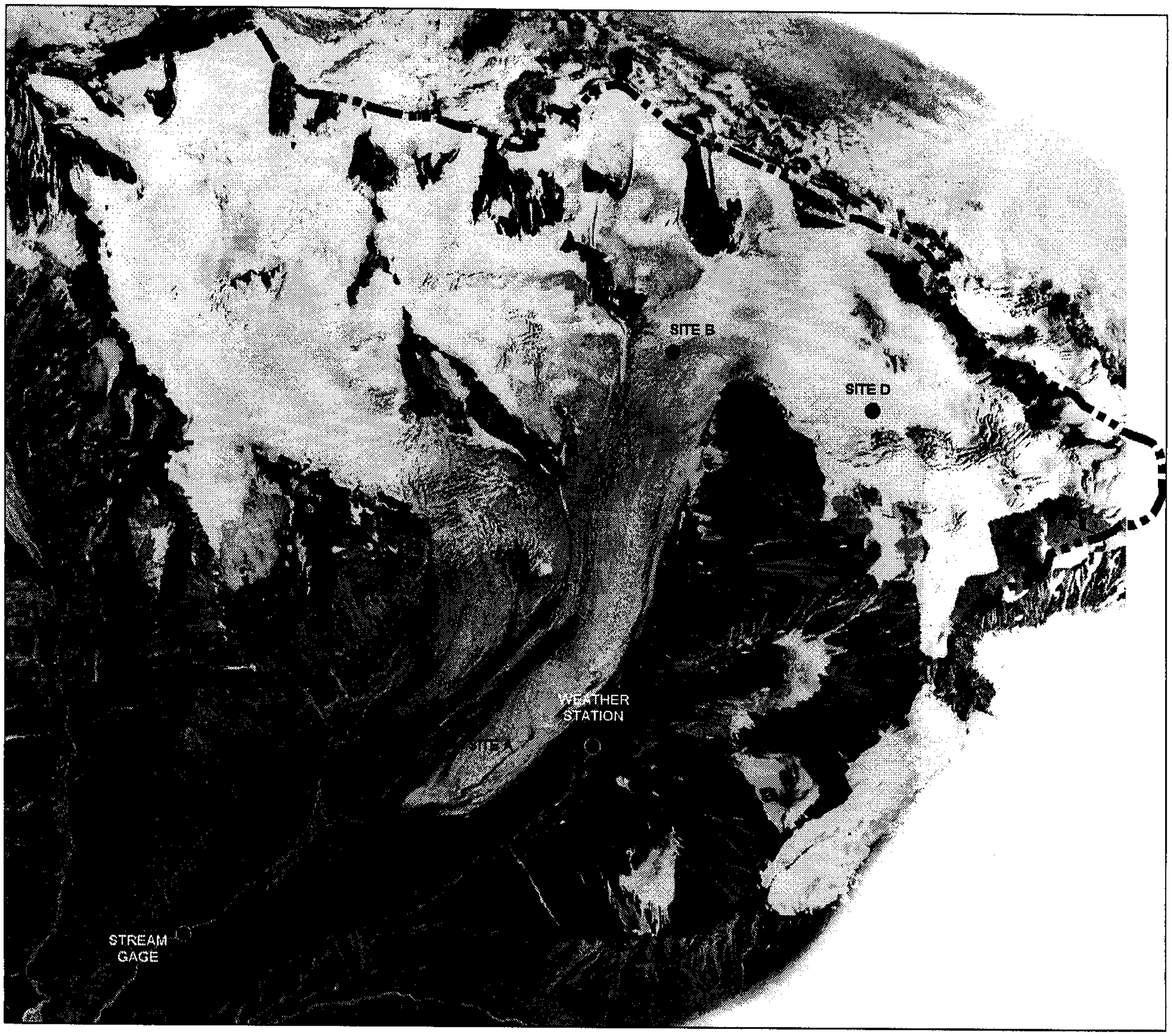


Figure 2. Composite vertical photograph of Gulkana Glacier and its basin, showing measurement sites, stream-gaging station, weather station, and basin boundary, July 11, 1993 (photographs Gulkana Gl 1 No. 5 and Gulkana Gl 2 No. 4 by AeroMap U.S., Inc.). A, B, and D are the primary measurement sites for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

Measurement System and Terminology

Seasonal monitoring on Gulkana Glacier consists of three basic measurements: surface mass balance, ice velocity, and surface altitude. These measurements are made repeatedly at three fixed locations on Gulkana Glacier, referred to as the "index sites" (labeled A, B, and D on figs. 1 and 2). 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 adhered to 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 adjustments for determining the maximum winter balance, net balance, and fixed-date annual balance. Both net (stratigraphic) and annual (fixed-date) balances are derived from field measurements. The balance year used for the net mass balance is the interval between the minimum glacier-wide mass balance in one year and the minimum glacier-wide mass balance the following year. Thus, the net balance has a beginning and ending date. To calculate net balance it is necessary to run a simple balance model (explained later) to extrapolate from the nearest measurement to the time and value of the glacier-averaged net balance. In general, net balances reported in the literature are approximations in which the net balance is determined as the difference between successive balance minimums for each measurement location on the glacier, and then combined as if the balance minimum occurred synchronously over the whole glacier. 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 (HY), which is the period used for the annual (fixed-date) mass balance, 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 "water year" used for publishing USGS hydrologic data. The temporal relations of the quantities defined and used for analyzing the index-site and glacier-averaged 1995 mass balances are illustrated in figures 3 and 4.

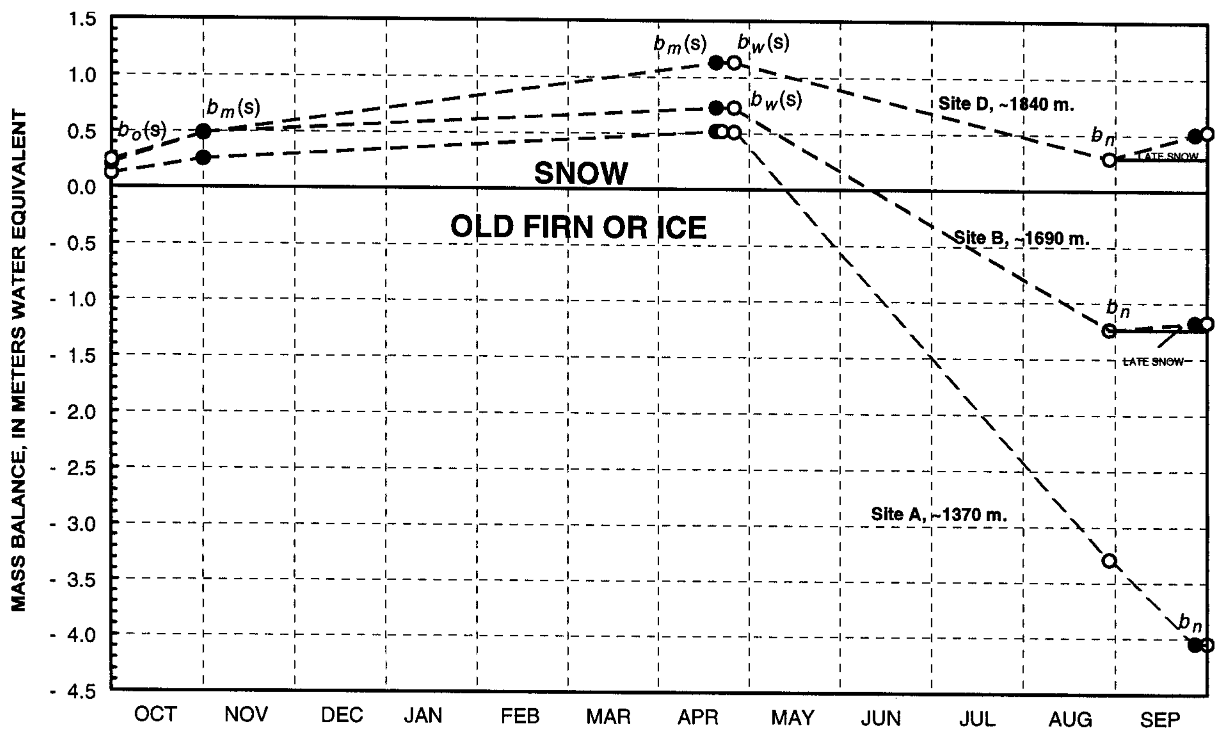


Figure 3. Time distribution of index-site mass balances for Gulkana Glacier, 1995 hydrologic year. (Solid circles are measured values; open circles are estimated values. Seasonal maximum balances occurred during mid-April. $b_0(s)$, initial snow balance at site; $b_m(s)$, measured winter snow balance 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 m.)

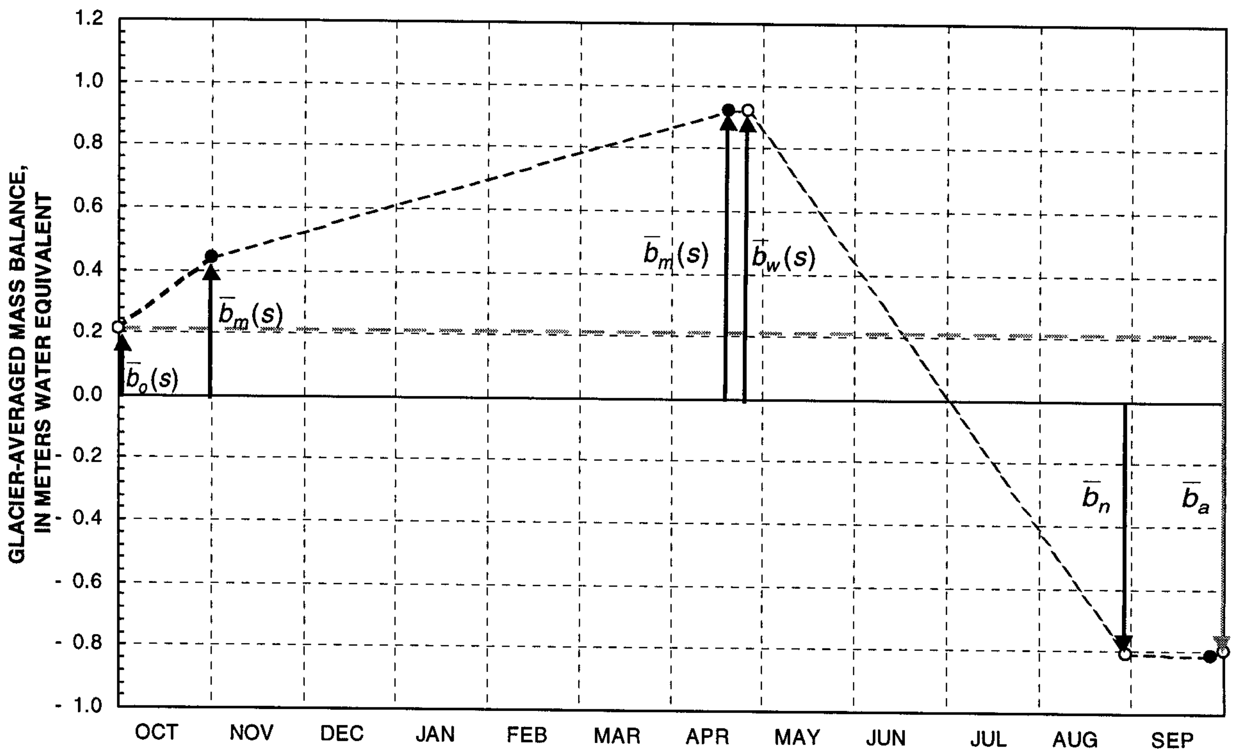


Figure 4. Time distribution of glacier-averaged mass balance of Gulkana Glacier, 1995 hydrologic year (using 1967 area-altitude distribution). (The initial balance, $\bar{b}_0(s)$, is the change in balance between the balance minimum that defines the beginning of the net balance year and the beginning of the hydrologic year (1 October). The measured winter snow balance, $\bar{b}_m(s)$, is the snow above the previous summer surface measured directly in the field near the time of the maximum winter snow balance, $\bar{b}_w(s)$. $\bar{b}_n$, net balance; $\bar{b}_a$, annual balance. Solid circles are measured values; open circles are estimated values. Symbols with a bar over them indicate the average value over the whole glacier.)

All balance, precipitation, and runoff values are reported in meters of 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 assumed to be 1,000 kg/m^3 or 1 kg/L and the relative density of glacier ice is assumed to be 0.9.

Except where otherwise noted, locations are reported in local metric coordinates, with the positive Y-axis approximately true north. Altitude is in meters above the National Geodetic Vertical Datum of 1929. Horizontal locations are defined in a local sea-level-scale network that may be converted to Universal Transverse Mercator (UTM) zone 6 coordinates North American Datum 1983 by:

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

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

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

The mean scale factor (March and Trabant, 1997) is estimated by:

$$\bar{k} = \frac{0.9996}{6}\left(\frac{1}{\sin\left(100 + \frac{500,000 - (575,000)}{100,000}\right)} + \frac{4}{\sin\left(100 + \frac{500,000 - (575,000) - \frac{1}{2}X_L}{100,000}\right)} + \frac{1}{\sin\left(100 + \frac{500,000 - (575,000) - X_L}{100,000}\right)}\right) \quad (3)$$

which yields results accurate at the centimeter level.

1995 DATA COLLECTION

The temporal distribution of the data used to analyze the 1995 mass balance is shown in table 1.

Field Visits

Four field visits to the Gulkana Glacier basin between late October 1994 and late April 1996 (table) were used to collect the data necessary to evaluate the 1995 glacier mass balance, motion, and surface altitudes and to service and calibrate recorders. Generally the trips are timed to define the mass balance maximums and minimums, usually during a spring trip (March/April/May) and a late-summer/early-fall trip (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 stakes, and hence support a regular assessment of errors in balance calculations made on the basis of stake readings.

Table 1. Data-collection summary for the 1995 hydrologic year analysis (the locations of the stations are shown on figure 1)

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

Station	Approximate Altitude[1] (meters)	Measurement	1995 Hydrologic Year												1996 Hydrologic Year						
			1994 Calendar Year			1995 Calendar Year												1996 Calendar Year			
			Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Phelan Creek Gaging Station	1140	Streamflow	– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –	———	———	——— – – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –
		Discharge Meas.							•	•	•	•	•	•		•			•		•
Site A	1370	Mass Balance	•						•					•							•
		Surface Motion	•						•					•							•
		Surface Altitude	•						•					•							•
Weather Station	1480	Air Temperature	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———	———
		Precipitation																			
Site B	1690	Mass Balance	•						•					•							•
		Surface Motion	•						•					•							•
		Surface Altitude	•						•					•							•
Site D	1840	Mass Balance	•						•					•							•
		Surface Motion	•						•					•							•
		Surface Altitude	•						•					•							•

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

Recorded Variables

Air temperature, precipitation-gage catch, and stream-runoff data are recorded continuously. Runoff data are not recorded after Phelan Creek freezes over in the early fall, and runoff must be estimated for the winter. The data sets are truncated to the hydrologic year, October 1 to September 30. Periods of good recorder data are shown in table 1.

Air Temperature

Air temperature is recorded by an analog recorder at 1,480 m altitude on the eastern ice-cored moraine of Gulkana Glacier (weather station, figs. 1 and 2). The air temperature sensor, data-reduction methodology, and data accuracy are described in detail by Kennedy and others (1997). The daily mean temperatures reported (fig. 5 and table 2) have an accuracy of about ±1.0°C (Kennedy and others, 1997). Following the National Climatic Data Center convention (1996), monthly mean temperatures are calculated for months with nine or fewer missing daily values.

The annual average temperature for 1995 was -4.1°C, equal to the long-term average (1968-91, 1993-95). The winter average temperature from September 1, 1994, to May 15,

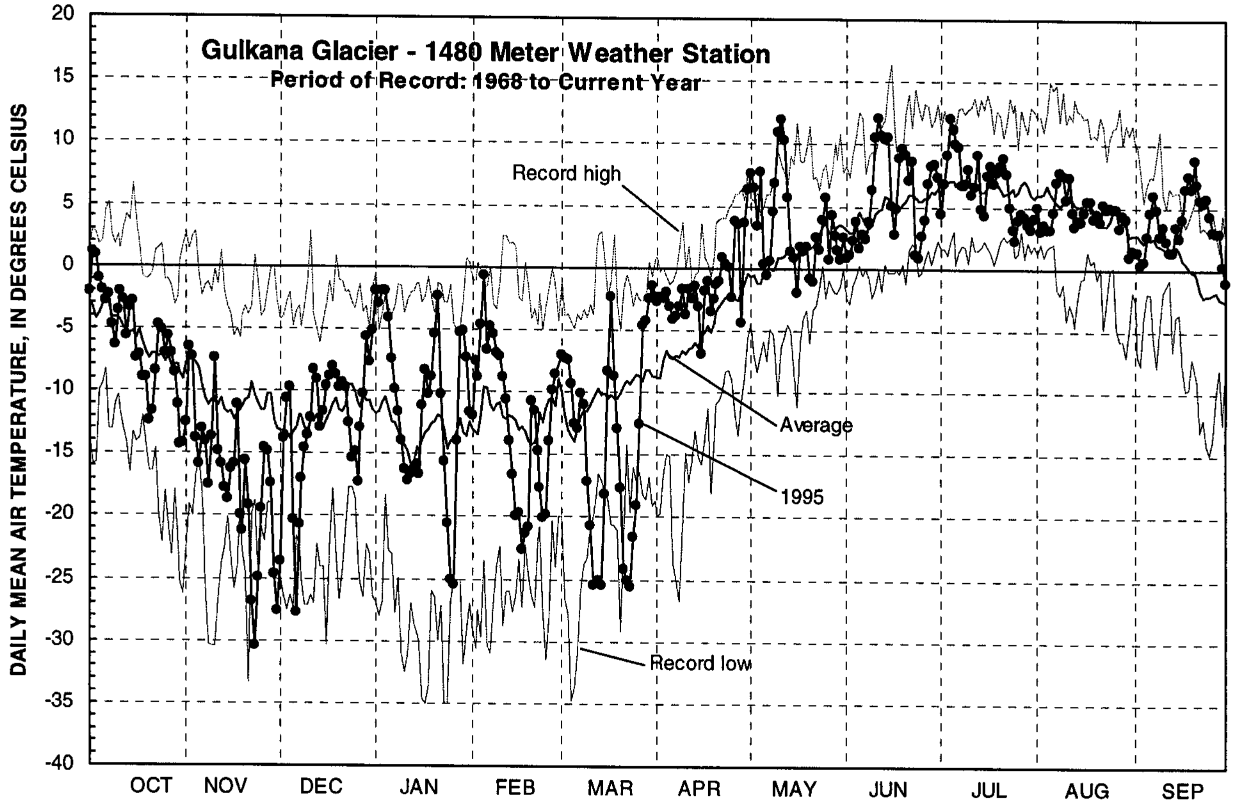


Figure 5. Daily mean air temperature recorded at 1,480 m altitude in the Gulkana Glacier basin, 1995 hydrologic year. For clarification: record high and low values represent extreme daily mean air temperatures for the period of record, not extreme daily maximum and daily minimum air temperatures.

Table 2. Daily, monthly, and annual average air temperatures from the recording gage at 1,480 meters altitude, 1995 hydrologic year
[Values in degrees Celsius]

	1994			1995								
Day	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1	-2.1	-12.5	-23.6	-2.0	-11.9	-7.0	-2.7	7.6	0.8	4.4	4.9	1.3
2	1.1	-6.6	-13.8	-3.0	-7.6	-7.3	-2.3	6.5	1.1	6.8	3.0	1.4
3	0.8	-7.3	-10.6	-2.0	-8.9	-7.4	-2.5	3.4	2.3	9.1	3.5	0.4
4	-1.0	-13.8	-9.8	-2.0	-4.6	-9.4	-2.0	7.8	3.8	12.1	3.1	0.6
5	-2.0	-15.9	-20.4	-4.1	-0.7	-12.5	-3.1	0.3	1.6	11.2	3.2	2.7
6	-2.9	-13.0	-27.8	-7.4	-6.7	-12.9	-4.1	-0.6	2.8	10.1	4.6	4.6
7	-2.3	-14.1	-20.7	-9.9	-4.8	-10.1	-3.9	0.6	2.4	9.8	7.0	5.9
8	-4.8	-17.5	-17.0	-11.7	-5.4	-11.0	-3.1	4.6	3.8	6.7	7.7	4.8
9	-6.4	-13.7	-14.6	-13.9	-6.9	-17.1	-1.7	6.9	6.4	6.8	7.5	2.6
10	-3.6	-7.5	-13.6	-16.3	-7.2	-20.7	-3.8	11.0	10.5	8.0	5.6	3.4
11	-2.1	-14.9	-12.2	-17.1	-8.9	-25.5	-1.7	11.9	12.1	5.9	7.3	2.3
12	-2.7	-15.9	-8.4	-16.7	-10.6	-25.3	-2.5	10.3	10.7	6.6	4.6	1.3
13	-5.6	-17.8	-9.1	-16.2	-13.9	-25.1	-1.4	5.7	10.4	9.2	3.4	1.4
14	-3.4	-18.7	-12.9	-15.9	-16.6	-25.4	-3.1	1.3	10.5	4.8	3.9	3.4
15	-2.8	-16.2	-11.7	-16.7	-19.9	-18.2	-6.9	0.9	5.1	4.3	3.8	2.5
16	-7.4	-15.9	-9.6	-11.2	-19.7	-8.4	-1.8	-2.0	2.8	7.5	4.5	4.0
17	-7.2	-11.1	-8.8	-8.3	-22.6	-2.3	-1.0	1.7	4.8	8.2	5.5	6.5
18	-9.0	-20.0	-8.1	-10.3	-21.4	-8.7	-3.5	1.4	8.9	6.9	5.4	7.5
19	-9.0	-21.2	-8.7	-8.9	-20.9	-12.9	-2.5	1.8	9.6	7.8	4.1	6.5
20	-12.4	-15.6	-9.7	-5.4	-10.8	-17.7	-1.3	-0.8	9.1	8.2	4.4	8.8
21	-11.6	-19.2	-9.4	-2.4	-11.5	-24.2	-1.0	-1.0	7.1	8.9	3.8	6.9
22	-8.5	-26.8	-9.8	-10.2	-14.7	-25.0	0.8	2.5	8.6	7.6	5.2	5.6
23	-4.8	-30.4	-12.6	-15.6	-17.7	-25.6	0.4	1.5	1.1	5.0	4.8	5.3
24	-5.2	-24.9	-15.4	-20.6	-20.1	-21.6	0.1	3.9	0.9	3.1	5.0	5.7
25	-7.1	-19.4	-14.9	-25.0	-19.8	-19.0	-2.3	5.7	2.7	2.3	4.8	4.3
26	-5.6	-14.6	-17.3	-25.5	-13.9	-12.6	3.8	0.7	3.9	3.9	4.8	3.0
27	-7.1	-14.8	-12.9	-13.9	-9.9	-4.7	3.5	4.3	6.9	4.4	3.3	2.9
28	-8.6	-17.4	-10.3	-5.3	-8.6	-4.2	-4.4	2.6	8.2	4.2	4.3	2.9
29	-11.2	-24.7	-5.6	-5.2		-2.5	3.6	1.5	8.4	3.5	4.1	0.2
30	-14.4	-27.6	-7.7	-7.3		-1.5	6.3	0.7	7.3	3.2	1.0	-1.0
31	-14.2		-5.1	-11.6		-2.3		2.5		4.0	1.5	
Monthly Average	-5.9	-17.0	-12.6	-11.0	-12.4	-13.8	-1.5	3.4	5.8	6.6	4.5	3.6
									Annual Average Temperature =			-4.1

1995, was -8.4°C, about 0.3 standard deviation below the long-term average. The summer average temperature from May 16, 1995, to August 30, 1995, was 5.1°C, about 0.1 standard deviation above the long-term average. The winter and summer periods are chosen to correspond with the average maximum and minimum glacier-averaged balances to the nearest half month.

Precipitation Catch

Precipitation catch is recorded by an analog recorder connected to a shielded storage-type precipitation gage at the weather station (figs. 1 and 2). The gage, data-reduction methodology, and data accuracy have been described by Kennedy and others (1997).

Unfortunately, the precipitation-catch record for the 1995 hydrologic year shows evidence of fluid loss throughout the year, most likely due to evaporation which is normally prevented by an oil film on the surface of the stored antifreeze-water solution. The record is considered unreliable and is not included in this report. Functioning of the gage returned to normal after replacing the oil film in the storage tank.

To estimate balance increments between measured values, which is necessary to determine the maximum winter balance, glacier-averaged net balance, and annual balance, the precipitation record from the nearest National Weather Service station, Paxson (station 50709704), has been used. Paxson is located at 823 m altitude, about 20 km south of the Gulkana weather station. The Paxson record is available from the Utah Climate Center web site at *http://climate.usu.edu/free/* or from the National Climatic Data Center, NOAA at *http://www.ncdc.noaa.gov/ol/climate/climatedata.html*. The relation between the Gulkana and the Paxson precipitation has not been examined in detail, but Paxson appears to be drier than the Gulkana weather station site because it catches only about half as much precipitation annually (on the basis of data from 1975-84 and 1986-92). However, this may also be caused by a reduced catch efficiency of the Paxson gage because it lacks a wind shield. The Pearson (conventional) correlation coefficient between Gulkana and Paxson daily values of precipitation is 0.62 (1975-84 and 1986-92).

Runoff

Stream-gaging station No. 15478040, Phelan Creek near Paxson[2], is part of the USGS gaging-station network in Alaska. Data collection and analysis are conducted by standard techniques developed by the USGS and daily values of discharge are generally reported along with those for the rest of Alaska in annual publications of the USGS Water-Data Report series (U.S. Geological Survey, 1968-99). The 1995 discharge data are published in USGS Water-Data Report AK-95-1 (Schellekens and others, 1996). The historical daily values of streamflow for this station may be obtained online through the Internet at *http://ak.water.usgs.gov* via the links to surface-water data.

The gaging station is located at 1,125 m altitude, about 1 km downstream from the present glacier terminus (figs. 1 and 2). The creek bed is composed of typical ground-moraine material: 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 (Bertrand and others, 1999). The typical minimum winter under-ice 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 the loss of potential energy from ice motion.

The instrumentation continuously records the stage, or level of water, in the creek. 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, 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 the records do not meet the criteria for "fair," which is defined as "about 95 percent of the daily discharges are within 15 percent of the true value" (Schellekens and others, 1996). This formal rating places no limit on the possible error but indicates that the standard error is greater than ±7.5 percent. It is estimated that the standard error of the non-estimated and estimated daily discharge values at Phelan Creek are 10 and 20 percent, respectively (Richard Kemnitz, USGS, oral commun., 1997).

---

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

The 1995 daily mean discharge data were converted to runoff (fig. 6, table 3) by dividing the discharge values by the basin area. The 1995 runoff from the basin was 2.05 m, approximately 0.27 standard deviation above the period-of-record (1967-78, 1990-95) average. New daily maximums were set in early May and September that correlate with new record high daily average temperatures.

No continuous stage record is collected during the winter when Phelan Creek freezes over. Runoff values are estimated for this period on the basis of air temperature, precipitation, and winter discharge measurements (April 1, 1995). 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 shown in figure 7. Because the discharge measurements are so sparse in any one 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 rapidly increases with the onset of the melt season in mid-May to about ±5 mm/d by early June. The cumulative sum of winter estimated runoff represents about 15 percent of the annual runoff.

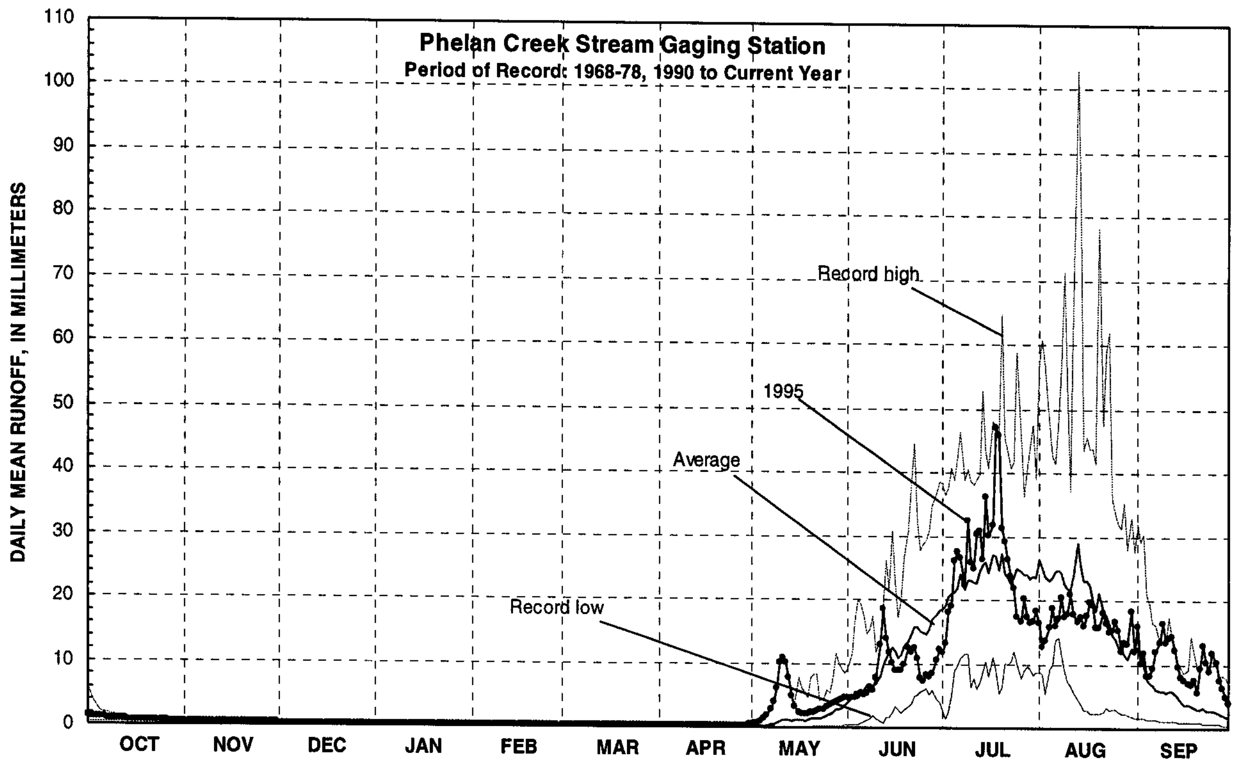


Figure 6. Daily runoff from Phelan Creek near Paxson (USGS stream-gaging station 15478040), and discharge measurements, expressed as runoff, used to define the stage-discharge relation, 1995 hydrologic year.

Table 3. Daily mean runoff from the Gulkana Glacier basin, 1995 hydrologic year

[Values in millimeters, averaged over the basin; () indicates value estimated (see text for explanation)]

	1994			1995									
Day	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1	(1.3)	(0.5)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.5)	(4.8)	11.8	16.6	(16.0)	
2	(1.2)	(0.5)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.6)	(4.8)	13.1	12.7	(10.1)	
3	(1.2)	(0.5)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.8)	(4.8)	18.1	13.7	(11.8)	
4	(1.2)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(1.0)	(5.0)	19.0	(15.9)	(8.2)	
5	(1.1)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(1.4)	(5.5)	26.3	18.7	(8.4)	
6	(1.1)	(0.5)	(0.3)	(0.2)	0.2	(0.2)	(0.2)	(1.9)	(5.3)	27.5	16.0	(9.5)	
7	(1.0)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.7)	(5.5)	26.6	17.3	(12.0)	
8	(1.0)	0.5	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(4.0)	(6.4)	22.5	20.5	(13.5)	
9	(0.9)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(6.2)	(6.0)	32.5	17.4	(16.6)	
10	(0.9)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(10.1)	(7.7)	25.9	18.0	(13.5)	
11	(0.9)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(10.8)	(13.0)	24.9	20.9	(14.0)	
12	(0.9)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(10.1)	(18.5)	30.3	17.9	(14.5)	
13	(0.9)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(7.7)	13.9	30.9	16.8	(12.2)	
14	(0.8)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(5.0)	11.7	26.4	17.4	(9.8)	
15	(0.8)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(3.3)	10.1	36.2	16.0	(8.0)	
16	(0.8)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.3)	9.1	30.0	17.7	(7.6)	
17	(0.8)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.1)	(9.0)	31.8	19.8	(7.0)	
18	(0.7)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.1)	(8.9)	47.0	19.4	(6.8)	
19	(0.7)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.2)	9.8	45.8	15.9	(7.6)	
20	(0.7)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.3)	12.5	31.4	15.9	(5.6)	
21	(0.7)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.4)	11.9	29.2	(18.1)	(9.4)	
22	(0.6)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.6)	12.5	26.5	(16.4)	(12.9)	
23	(0.6)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.7)	10.9	23.7	(15.1)	(10.3)	
24	(0.6)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(2.9)	7.8	22.0	(15.3)	(9.1)	
25	(0.6)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(3.3)	(7.2)	17.4	(16.7)	(11.8)	
26	(0.6)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(3.6)	(8.3)	16.7	(15.4)	(10.5)	
27	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	0.2	(0.2)	(3.8)	7.9	20.3	(12.0)	(7.4)	
28	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.3)	(4.0)	8.4	17.5	(13.3)	(6.3)	
29	(0.5)	(0.4)	(0.3)	(0.2)		(0.2)	(0.3)	(4.2)	10.7	16.5	(13.2)	(5.0)	
30	(0.5)	(0.4)	(0.3)	(0.2)		(0.2)	(0.4)	(4.5)	12.2	16.7	(18.3)	(4.1)	
31	(0.5)		(0.3)	(0.2)		(0.2)		(4.7)		18.3	(11.9)		
Total	(25.2)	(12.9)	(9.6)	(7.4)	(6.4)	(5.9)	(6.3)	(115.6)	(270.1)	782.6	(510.0)	(299.1)	2,051.0
Total of measured values	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	149.4	782.6	494.1	0.0	1,426.1
Total of estimated values	(25.2)	(12.9)	(9.6)	(7.4)	(6.4)	(5.9)	(6.3)	(115.6)	(120.7)	(0.0)	(15.9)	(299.1)	(624.9)
Percent measured	0	0	0	0	0	0	0	0	55	100	97	0	70

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. 8) (Tangborn and others, 1977; see March, 1998, for tabulation of these values). The 1967 values have been used to calculate and report all glacier-averaged balances since 1967.

The second is a newly determined area-altitude distribution based on the photogrammetric analysis of 1993 vertical photography (see fig. 8 and table 4). Color vertical photography was acquired on July 11, 1993 at a scale of 1:36,000 (1 inch: 3,000 feet). A digital elevation model (DEM) of about 100,000 irregularly spaced points along breaklines was derived from this photography. (Breaklines are lines representing discontinuities in the ground or glacier surface; ridges and valley bottoms are extreme examples of breaklines.) The DEM was contracted to be of a quality such that a 2-m contour interval map derived from the DEM would comply with U.S. National Map Accuracy Standards (see *http://mapping.usgs.gov/mac/isb/pubs/factsheets/fs17199.html*). Preliminary analysis shows that the DEM has a random vertical error on the glacier of about ±0.7 m and a systematic error of +1.3 m. The glacier

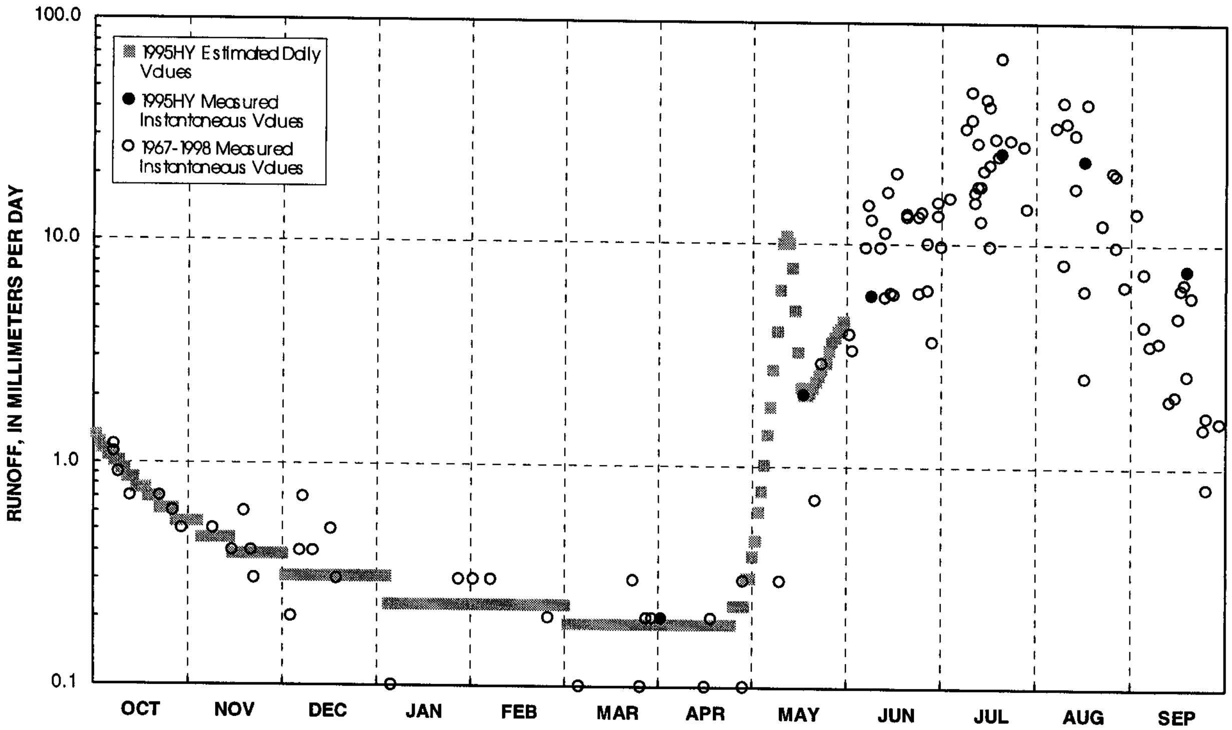


Figure 7. Estimated daily runoff from Phelan Creek near Paxson (USGS stream-gaging station 15478040) for the 1995 hydrologic year, with measured values for both the 1995 hydrologic year and the entire period of record (1967-95).

and basin boundaries were also re-determined from the 1993 photography. The irregularly spaced DEM was converted to a 30- by 30-m regularly spaced DEM from which the 1993 area-altitude distribution was determined.

Comparison of the basin area from each area-altitude determination yields some information about the accuracy of the earlier determination. A basin area of 31.6 km^2 was determined for 1967, whereas the 1993 determination yielded 31.1 km^2. This difference suggests an error of about 2 percent in the 1967 determination.

In 1967, about 70 percent of the basin was covered by perennial snow and ice. Gulkana Glacier covered 19.3 km^2; Pegmatite Glacier (fig.), three small unnamed glaciers, and perennial snow and ice patches had a total area of 2.9 km^2. In 1993, snow and ice coverage in the basin had been reduced to 64 percent of the basin. 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.

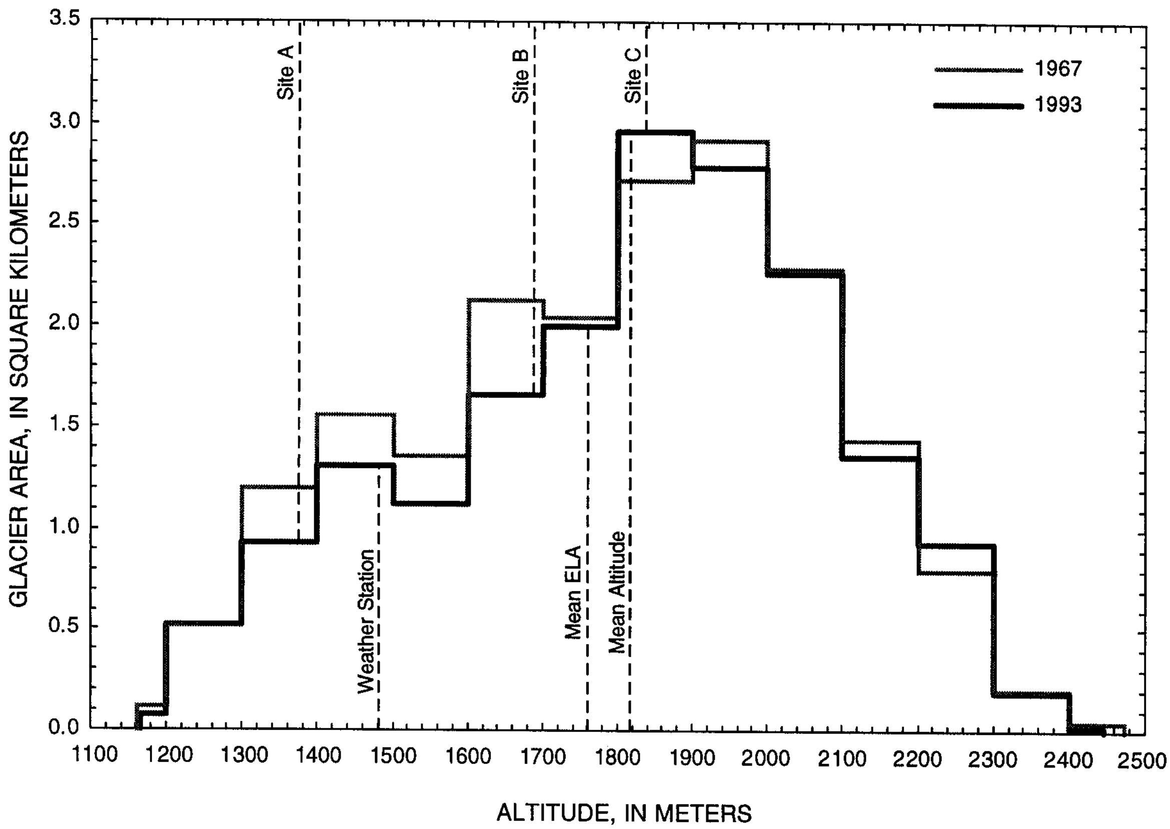


Figure 8. Area-altitude distribution of Gulkana Glacier in 1967 and 1993. (Shown are altitudes of index sites, the weather station (air temperature and precipitation gage), the mean equilibrium line altitude (ELA), and mean glacier altitude.)

1995 MASS BALANCE EVALUATION

Mass Balance Measurement Errors

Mass balance analysis seeks relatively small net changes in a system where accumulation and ablation are large. Because of this, even small measurement errors can significantly change the result, including the sign of the result. Furthermore, mass balance measurement errors are difficult to treat analytically because of problems inherent in sampling and extrapolation. Uncertainties in the mass balance determination at index sites (the sampling points) arise from a combination of the uncertainties in determining stake measurements, snow and firn densities, snow depths, and internal accumulation. Indeed, many errors must be estimated because the number of independent samples is insufficient to warrant error analysis; for example, seldom are there more than two balance-motion stakes at an index site or more than one snow-density pit. The error introduced by extrapolating from a few index-site values to glacier-wide and basin values is uncertain at this time. An independent assessment of long-term glacier-volume change by means of profile surveying and photogrammetric mapping is in progress to assess this error and, if necessary, revise the algorithm for extrapolating glacier-wide balance from index-site values. Errors are included in the tabular balance data only for quantities with multiple samples, the snow and firn depths.

Table 4. Area-altitude distribution of Gulkana Glacier and Gulkana Glacier basin by 100-m altitude intervals from a digital DEM derived from July 11,1993 photography. Measurement site altitudes, in meters, are approximate averages for 1995

[m, meters; km^2, square kilometers; %, percent]

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)	Sub-areas of glacier represented by index sites: Site A 1368 (km^2)	Site B 1682 (km^2)	Site D 1834 (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	0.28	0.85	
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		1.16	0.84
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 - 2,473	2,437	0.02		0.02	0.02				0.02
	Total area =	31.10	11.27	19.84	18.13	1.71	3.12	3.67	11.35
	Average altitude, 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 =							1,525	1,758	2,473
Lower altitude limit of zone, in m =							1,161	1,525	1,758
Fraction of Gulkana Glacier area =							17.2%	20.2%	62.6%
	Fraction of basin area =	100%	36%	64%	58%	5%			

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 Brugman, 1991; and Østrem and Stanley, 1969). The stake, pit, probing, and coring data are shown in tables 5, 6, and 7 and the resulting site balances in figure 3.

Although mass balance measurement locations are commonly 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 samples are taken and the balance averaged. The area chosen is large enough and enough samples 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.

Table 5. Stake readings, snow depths, and snow-density data for sites A, B, and D on Gulkana Glacier, October 1994 through September 1996

[mm/dd/yy, 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. 1); a number following the letter is used to differentiate multiple stakes installed at the same site in one 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-m 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 (i.e. as if the stake were vertical). Pit *d*(s), snow depth measured in snow pit. Probe *d*(s), snow depth measured by probing to the summer surface with a metal rod. 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, or estimated and mean density. m, meter; kg/L, kilograms per liter]

Date	Stake	Surface Strata	Stake Readings & Data: Found /Left	Obs. b' No Lean Correct.	Surveyed b*	Surveyed b**	Diff. b*-b**	Total Stake Slip	Best Stake b'	Snow Depth: Pit d(s)	n	Probe d(s)	n	Obs. d(s)	Mean d(s)	s.e. d(s)	n	Snow Density: Pit	Est.	Mean
mm/dd/yy	Name	Type	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)		(m)		(m)	(m)	(m)		(kg/L)	(kg/L)	(kg/L)
SITE A, ~1370 m[1]																				
10/31/94	94-A	Snow	6/4.5	2.47	2.48	2.46	0.02	0.00	2.45			0.78	16	0.78	0.78	0.08	16		0.30	0.30
4/19/95	94-A	Snow	4.5/3	2.69	2.68	2.67	0.01	0.00	2.68	1.53	1	1.34	20	1.35	1.35	0.05	21	0.39		0.39
10/31/94	94-A2	Snow	9/7.5	4.95	4.96	4.87	0.09	0.00	4.86			0.78	16	0.78	0.78	0.08	16		0.36	0.36
4/19/95	94-A2	Snow	7.5/6	5.31	5.31	5.19	0.12	0.00	5.19	1.53	1	1.34	20	1.35	1.35	0.05	21	0.39		0.39
4/19/95	95-A	Snow	0/9		10.24	10.18	0.06	0.00	10.18	1.53	1	1.34	20	1.35	1.35	0.05	21	0.39		0.39
4/21/95	95-A	Snow																		
4/25/95	95-A	Snow																		
8/29/95	95-A	Ice																		
9/26/95	95-A	Ice	9/7	4.21	4.19	3.87	0.32	0.00	3.89					0.00	0.00		1			
9/28/95	95-A	Ice																		
9/30/95	95-A	LSnow																		
4/19/96	95-A	Snow	7/6	5.33	5.31	4.95	0.36	0.00	4.97	0.98	1	0.79	23	0.80	0.80	0.06	24	0.35		0.35
4/19/95	95-A2	Snow	0/9		10.21	10.14	0.07	0.00	10.14	1.53	1	1.34	20	1.35	1.35	0.05	21	0.39		0.39
4/21/95	95-A2	Snow																		
4/25/95	95-A2	Snow																		
8/29/95	95-A2	Ice																		
9/26/95	95-A2	Ice	9/7	4.38	4.37	4.26	0.11	0.00	4.27					0.00	0.00		1			
9/28/95	95-A2	Ice																		
9/30/95	95-A2	LSnow																		
4/19/96	95-A2	Snow	7/6	5.41	5.40	5.26	0.14	0.00	5.27	0.98	1	0.79	23	0.80	0.80	0.06	24	0.35		0.35
SITE B, ~1690 m[1]																				
10/31/94	94-B	Snow	9/11	7.16	7.16	7.12	0.04	0.00	7.12			1.36	19	1.36	1.36	0.07	19		0.36	0.36
4/19/95	94-B	Snow	11/9	8.15	8.15	8.03	0.12	0.00	8.03	1.95	1	2.11	15	2.10	2.10	0.04	16	0.35		0.35
4/25/95	94-B	Snow																	0.35	0.35
8/29/95	94-B	Ice																		
9/26/95	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
9/30/95	94-B	LSnow																		
4/18/96	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
Site D, ~1840 m[1]																				
10/31/94	94-D	Snow	9/13	8.84	8.83	8.86	0.03	0.00	8.87	1.45	1	1.39	6	1.40	1.40	0.01	7	0.33		0.33
4/19/95	94-D	Snow	13/12	10.17	10.15	10.11	0.04	0.00	10.13	2.62	1	2.73	15	2.72	2.72	0.06	16	0.42		0.42
4/25/95	94-D	Snow																		
8/29/95	94-D	Firn																		
9/26/95	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
9/30/95	94-D	LSnow																	0.45	0.45
4/18/96	94-D	Snow	12/12	10.03	10.04	10.03	0.01	0.00	10.02	2.29	1	2.39	16	2.39	2.39	0.02	17	0.48		0.48
9/16/96	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

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

Table 6. Snow-temperature, firn-thickness, and firn-density data for sites A, B, and D on Gulkana Glacier, October 1994 through September 1996

[mm/dd/yy, month/day/year; 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, McCall, 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	Stake	Surface Strata	Summer Surf. Temp. Pit or Core	Summer Surf. Temp. Est.	Summer Surf. Temp. Mean	Stake Height of Top of 1st Firn Initial	Obs.	Mean		Depth to Bottom of 1st Firn Layer Pit		Probe		Mean	s.e.		Firn Density Initial	Obs. Pit	Est.	Mean	Stake Height of 1st Firn Bottom Initial	Obs.	Mean
						$b_0'ss_1$	$b'ss_1$	$b'ss_1$	ss_1 Diff	d(nf)	n	d(nf)	n	d(nf)	d(nf)	n					$b_0'ss_2$	$b'ss_2$	$b'ss_2$
mm/dd/yy	Name	Type	(degrees Celsius)			(meters)				(m)		(m)		(m)	(m)		(kg/L)	(kg/L)	(kg/L)	(kg/L)	(meters)		
SITE A, ~1370 m[1]																							
10/31/94	94-A	Snow																					
4/19/95	94-A	Snow	- 3.7		- 3.7																		
10/31/94	94-A2	Snow																					
4/19/95	94-A2	Snow	- 3.7		- 3.7																		
4/19/95	95-A	Snow	- 3.7		- 3.7																		
4/21/95	95-A	Snow		- 3.7	- 3.7																		
4/25/95	95-A	Snow		- 3.7	- 3.7																		
8/29/95	95-A	Ice																					
9/26/95	95-A	Ice																					
9/28/95	95-A	Ice																					
9/30/95	95-A	LSnow																					
4/19/96	95-A	Snow	- 5.2		- 5.2																		
4/19/95	95-A2	Snow	- 3.7		- 3.7																		
4/21/95	95-A2	Snow		- 3.7	- 3.7																		
4/25/95	95-A2	Snow		- 3.7	- 3.7																		
8/29/95	95-A2	Ice																					
9/26/95	95-A2	Ice																					
9/28/95	95-A2	Ice																					
9/30/95	95-A2	LSnow																					
4/19/96	95-A2	Snow	- 5.2		- 5.2																		
SITE B, ~1690 m[1]																							
10/31/94	94-B	Snow																					
4/19/95	94-B	Snow	- 4.2		- 4.2																		
4/25/95	94-B	Snow		- 4.2	- 4.2																		
8/29/95	94-B	Ice																					
9/26/95	94-B	LSnow																					
9/30/95	94-B	LSnow																					
4/18/96	94-B	Snow	- 4.5		- 4.5																		
Site D. ~1840 m[1]																							
10/31/94	94-D	Snow	- 1.6		- 1.6	7.42	7.47	7.42	0.09								0.59	0.58	0.60	0.59			
4/19/95	94-D	Snow	- 4.8		- 4.8	7.42	7.41	7.42	0.01								0.59	0.73	0.75	0.74			
4/25/95	94-D	Snow		- 4.8	- 4.8	7.42											0.63						
8/29/95	94-D	Firn				7.42		7.58									0.63		0.63	0.63			
9/26/95	94-D	LSnow		0.0	0.0	7.42	7.49	7.58	0.09	0.91	1			0.91		1	0.59	0.63		0.63	7.16	7.16	7.42
9/30/95	94-D	LSnow		0.0	0.0	7.42		7.58									0.59		0.63	0.63			
4/18/96	94-D	Snow	- 5.1		- 5.1	7.58	7.63	7.58	0.05								0.63						
9/16/96	94-D	LSnow				7.58	8.49	8.36		1.39	2	1.58	24	1.57	0.06	26	0.63	0.46		0.46	7.16	7.60	7.58

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

Table 7. Ice data and mass balance calculations for sites A, B, and D on Gulkana Glacier, October 1994 through September 1996

[mm/dd/yy, 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 0.05-0.15 m; 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)]

Date mm/dd/yy	Stake Name	Surface Strata Type	Stake Height of Top of Ice: Initial $b_0'ss_1$ (meters)	Obs. $b'ss_1$ (meters)	Mean $b'ss_1$ (meters)	ss_1 Diff. (meters)	Water Equivalent Balances: 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, ~1370 m[1]															
10/31/94	94-A	Snow	1.48	1.67	1.48	0.19	0.12	0.23	0.00	0.00	0.00	0.00	0.23	0.11	
4/19/95	94-A	Snow	1.48	1.33	1.48	0.15	0.12	0.52	0.00	0.00	0.00	0.00	0.52	0.40	
10/31/94	94-A2	Snow	3.94	4.08	3.94	0.14	0.12	0.28	0.00	0.00	0.00	0.00	0.28	0.16	
4/19/95	94-A2	Snow	3.94	3.84	3.94	0.10	0.12	0.52	0.00	0.00	0.00	0.00	0.52	0.40	
4/19/95	95-A	Snow	8.83	8.83	8.83		0.12	0.52	0.00	0.00	0.00	0.00	0.52	0.40	
4/21/95	95-A	Snow	8.83		8.83		0.12	0.52	0.00	0.00	0.00	0.00	0.52	0.40	Estimated local-site b_w(s)
4/25/95	95-A	Snow	8.83		8.83		0.12	0.51	0.00	0.00	0.00	0.00	0.51	0.39	Estimated glacier-averaged b_w(s)
8/29/95	95-A	Ice	8.83				0.12	0.00	0.00	0.00	0.00	- 3.41	-3.41	-3.53	Est. glacier-averaged net mimimum
9/26/95	95-A	Ice	8.83	3.89	4.16		0.12	0.00	0.00	0.00	0.00	- 4.20	-4.20	-4.32	
9/28/95	95-A	Ice	8.83		4.16		0.12	0.00	0.00	0.00	0.00	- 4.20	-4.20	-4.32	Est. local-site net minimum
9/30/95	95-A	LSnow	8.83		4.16		0.12	0.00	0.00	0.00	0.00	- 4.20	0.00	-4.32	Estimated annual balance
4/19/96	95-A	Snow	4.16	4.17	4.16		0.00	0.28	0.00	0.00	0.00	0.00	0.28	0.28	
4/19/95	95-A2	Snow	8.79	8.79	8.79		0.12	0.52	0.00	0.00	0.00	0.00	0.52	0.40	
4/21/95	95-A2	Snow	8.79		8.79		0.12	0.52	0.00	0.00	0.00	0.00	0.52	0.40	Estimated local-site b_w(s)
4/25/95	95-A2	Snow	8.79				0.12	0.51	0.00	0.00	0.00	0.00	0.51	0.39	Estimated glacier-averaged b_w(s)
8/29/95	95-A2	Ice	8.79		4.46		0.12	0.00	0.00	0.00	0.00	- 3.17	-3.17	-3.29	Est. glacier-averaged net mimimum
9/26/95	95-A2	Ice	8.79	4.27	4.46		0.12	0.00	0.00	0.00	0.00	- 3.90	-3.90	-4.02	
9/28/95	95-A2	Ice	8.79		4.46		0.12	0.00	0.00	0.00	0.00	- 3.90	-3.90	-4.02	Est. local-site net minimum
9/30/95	95-A2	LSnow	8.79		4.46		0.12	0.00	0.00	0.00	0.00	- 3.90	0.00	-4.02	Estimated annual balance
4/19/96	95-A2	Snow	4.46	4.47	4.46		0.00	0.28	0.00	0.00	0.00	0.00	0.28	0.28	
SITE B. ~1690 m[1]															
10/31/94	94-B	Snow	5.84	5.76	5.84	0.08	0.21	0.49	0.00	0.00	0.00	0.00	0.49	0.28	
4/19/95	94-B	Snow	5.84	5.93	5.84	0.09	0.21	0.73	0.00	0.00	0.00	0.00	0.73	0.52	
4/25/95	94-B	Snow	5.84		5.84		0.21	0.73	0.00	0.00	0.00	0.00	0.73	0.52	Estimated local-site b_w(s)
4/25/95	94-B	Snow	5.84		5.84		0.21	0.73	0.00	0.00	0.00	0.00	0.73	0.52	Estimated glacier-averaged b_w(s)
8/29/95	94-B	Ice	5.84		4.46		0.21	0.00	0.00	0.00	0.00	- 1.24	-1.24	-1.45	Est. local-site net minimum
8/29/95	94-B	Ice	5.84		4.46		0.21	0.00	0.00	0.00	0.00	- 1.24	-1.24	-1.45	Est. glacier-averaged net mimimum
9/26/95	94-B	LSnow	5.84	4.41	4.46	0.054	0.21	0.06	0.06	0.00	0.00	- 1.24	0.06	-1.39	
9/30/95	94-B	LSnow	5.84		4.46		0.21	0.07	0.07	0.00	0.00	- 1.24	0.07	-1.38	Estimated annual balance
4/18/96	94-B	Snow	4.46	4.50	4.46	0.036	0.07	0.43	0.00	0.00	0.00	0.00	0.43	0.36	
Site D. ~1840 m[1]															
10/31/94	94-D	Snow					0.21	0.48	0.00	0.00	0.00	0.00	0.48	0.27	
4/19/95	94-D	Snow					0.21	1.13	0.00	0.00	0.00	0.00	1.13	0.92	
4/25/95	94-D	Snow					0.21	1.13	0.00	0.00	0.00	0.00	1.13	0.92	Estimated glacier-averaged b_w(s)
4/25/95	94-D	Snow					0.21	1.13	0.00	0.00	0.00	0.00	1.13	0.92	Estimated local-site b_w(s)
8/29/95	94-D	Firn					0.21	0.00	0.00	0.10	0.19	0.00	0.29	0.08	Est. local-site net minimum
8/29/95	94-D	Firn					0.21	0.00	0.00	0.10	0.19	0.00	0.29	0.08	Est. glacier-averaged net mimimum
9/26/95	94-D	LSnow					0.21	0.22	0.22	0.10	0.19	0.00	0.22	0.30	
9/30/95	94-D	LSnow					0.21	0.24	0.24	0.10	0.19	0.00	0.24	0.32	Estimated annual balance
4/18/96	94-D	Snow					0.24	1.17	0.00	0.00	0.00	0.00	1.17	0.93	
9/16/96	94-D	LSnow					0.24	0.30	0.30	0.35	0.20	0.00	0.30	0.61	

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

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. These corrections affect the stake position for motion (see "Ice Motion Measurement and Errors" section) and the height on the stake of the glacier surface, b' (table 5), that is used for some balance determinations. It is assumed that the bottom of the stake is the most likely point on the stake to be "locked" into the glacier and not move relative to the glacier. The stake's geometry above the glacier surface is surveyed, assumptions about the stake's geometry (lean, bend, or bow) below the glacier surface are made, and the position of the bottom of the stake is calculated. The height of the point on the glacier surface directly above the stake bottom is then calculated using the surveyed geometry of the glacier surface and is used as a corrected b' as if the stake were vertical. The local glacier surface slope is measured during every field visit for use in this calculation. The stake b' corrections typically change the balance readings by about 5 cm, but occasionally up to 0.5 m.

Another departure from traditional methods is the way multiple measurements of the height of a summer surface on a stake are used to reduce balance errors. (Stake heights of stratigraphic layers are measured with positive up from the bottom of the stake. Labels on each stake segment allow the stake height measurements to made without excavating the stake for each visit.) For example, snow depth and stake height of the snow surface are usually measured during the fall and again during the winter or spring, resulting in two measurements of the stake height of the previous summer surface. If the measurements were made in the accumulation zone, a third measurement may be made the following fall by subtracting the snow depth and new firn depth from the stake height of the glacier surface. Because of measurement error, these successive measurements of the height of a summer surface on the stake are usually different; however, barring stake slip or firn compaction (in the accumulation zone), the height of the summer surface on the stake should not have changed. The interpretation that the differing stake measurements are the result of measurement error is reinforced by the fact that multiple measurements vary randomly, sometimes increasing and sometimes decreasing. For this analysis, the multiple measurements are combined using a weighted average. The weight for each measurement is proportional to the number of observations that went into the measurement. For instance, a measurement that is the average of 20 snow-depth probings is given twice the weight of a measurement with 10 snow-depth probings. The weighted average stake height of the summer surface is used for all calculations of balance relative to that summer surface.

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 (for 1995, not routinely) 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 altitude increase. 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; Braithwaite and Olesen, 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—this time 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 index-site balance values are combined using weighting factors to yield glacier-wide index values that approximate the average balances for the glacier area. Because 1995 was the first year that an updated area-altitude distribution was available, area-averaged balances are reported (table 8) using both the old (1967) and new (1993) area-altitude distributions, to demonstrate how the balances are affected by the update.

Using the 1967 area-altitude distribution:

$$\overline{b} = 0.194\ (b_A) + 0.224\ (b_B) + 0.582\ (b_D) + \overline{b}_a(\mathrm{j})$$

Using the 1993 area-altitude distribution:

$$\overline{b} = 0.172\ (b_A) + 0.202\ (b_B) + 0.626\ (b_D) + \overline{b}_a(\mathrm{j})$$

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 (in 1967, 0.194 for site A, 0.224 for site B, and 0.582 for site D) are derived by splitting the glacier into three subareas (index regions) at altitudes midway between the index sites (table 4). 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 of the glacier change. However, prior to this report, an unvarying area-altitude distribution had been used as that was all that was available. As can be seen in the equations above, 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 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 in 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 1995 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 the 1966 and 1967 test years. The weighted index-site method and its error are considered preliminary until further verification and adjustment from an independent assessment of the long-term, glacier mass balance change is obtained from a photogrammetric or surveyed volume change of the entire glacier.

Table 8. Site and area-integrated balance quantities for Gulkana Glacier and Gulkana Glacier basin, 1995 hydrologic year from both the 1967 and 1993 area altitude distributions.

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

Parameter	Site, glacier average, or sub-parameter	Data		Units
Area-altitude distribution determination		1967	1993	(year)
Index site weighting factors	Site A	0.194	0.172	
	Site B	0.224	0.202	
	Site D	0.582	0.626	
b_{n0}, initial net balance	Site A	0.00	0.00	(m)
	Site B	0.00	0.00	(m)
	Site D	-0.01	-0.01	(m)
	Glacier average	-0.01	-0.01	(m)
$b_0(s)$, initial snow balance	Site A	0.12	0.12	(m)
	Site B	0.21	0.21	(m)
	Site D	0.21	0.21	(m)
	Glacier average	0.19	0.19	(m)
$b_m(s)$, measured winter snow balance	Date of measurement	4/19/95	4/19/95	(mm/dd/yy)
	Site A	0.52	0.52	(m)
	Site B	0.73	0.73	(m)
	Site D	1.13	1.13	(m)
	Glacier average	0.92	0.94	(m)
$b_w(s)$, maximum winter snow balance	Date of maximum	4/25/95	4/25/95	(mm/dd/yy)
	Site A	0.51	0.51	(m)
	Site B	0.73	0.73	(m)
	Site D	1.13	1.13	(m)
	Glacier average	0.92	0.94	(m)
b_{nl}, late net balance	Site A	0.76	0.76	(m)
	Site B	0.00	0.00	(m)
	Site D	0.00	0.00	(m)
	Glacier average	0.15	0.13	(m)
$b_1(ls)$, final late snow balance	Site A	0.00	0.00	(m)
	Site B	0.07	0.07	(m)
	Site D	0.24	0.24	(m)
	Glacier average	0.16	0.17	(m)
$b_a(f)$, new firn balance	Site A	0.00	0.00	(m)
	Site B	0.00	0.00	(m)
	Site D	0.10	0.10	(m)
	Glacier average	0.06	0.06	(m)
$b_a(k)$, annual internal accumulation	Site A	0.00	0.00	(m)
	Site B	0.00	0.00	(m)
	Site D	0.19	0.19	(m)
	Glacier average	0.11	0.12	(m)
$b_a(i)$, annual old firn and ice balance	Site A	-4.05	-4.05	(m)
	Site B	-1.24	-1.24	(m)
	Site D	0.00	0.00	(m)
	Glacier average	-1.06	-0.95	(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)	-0.051	-0.054	(m)
	Total	-0.06	-0.06	(m)
b_n, net balance	Start of net balance year for glacier average	9/18/94	9/18/94	(mm/dd/yy)
	End of net balance year for glacier average	8/29/95	8/29/95	(mm/dd/yy)
	Site A	-3.29	-3.29	(m)
	Site B	-1.24	-1.24	(m)
	Site D	0.28	0.28	(m)
	Glacier average (includes $b_a(j)$)	-0.81	-0.70	(m)
b_a, annual balance	Site A	-4.17	-4.17	(m)
	Site B	-1.38	-1.38	(m)
	Site D	0.32	0.32	(m)
	Glacier average (includes $b_a(j)$)	-0.99	-0.86	(m)
ELA		1,806	1,806	(m)
Accumulation area		10.24	10.33	(km^2)
Ablation area		9.08	7.80	(km^2)
AAR		0.53	0.57	
Annual average air temperature	1480 meter weather station	-4.1	-4.1	(°C)
Annual total precipitation gage catch	1480 meter weather station	failed	failed	(m)
Calculated annual precipitation	Basin average	1.48	1.58	(m)
Annual basin runoff	1125 meter stream gage	2.05	2.08	(m)

Because of the time- and space-transgressive nature of glacier balance, the b_A, b_B, and b_D values 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 (see fig. 3).

The glacier-averaged internal ablation, $\bar{b}_a$(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).

Weather in 1994-95

The 1995 net balance year began on September 18, 1994, when the middle and lower glacier was covered by fresh snow. The seasonal runoff recession began in late August 1994. As is typical, no surface melt occurred on the glacier between October 1 and mid-April. The lowest daily mean winter air temperature was -30.4°C on November 23, 1994. Winter (September to mid-May) temperature averaged -8.4°C, -0.4°C below normal. The 1995 glacier-averaged mass balance maximum occurred early, on April 25, due to the start of melt low on the glacier. The maximum daily mean summer temperature was 12.1°C on June 11. Summer (mid-May to September 1) temperature averaged 5.1°C, 0.1°C above normal. The final glacier-averaged mass balance minimum occurred on August 29, 1995, although ablation continued at site A into late September (fig. 3). The seasonal runoff recession began in late September 1995. The total runoff for the 1995 water year, 2.05 m, was about equal to the mean for the 18-year period of record (1967-78 and 1990-95 hydrologic years).

Measured and Maximum Winter Snow Balances

The measured winter snow balance, $\bar{b}_m$(s), is the snow balance measured to the previous summer surface during late winter or spring (Mayo and others, 1972). It was 0.94 m on April 19, 1995 (table 8). This value was derived from the weighted index-site method and the April field visit data (tables 5, 6, and 7).

The maximum winter snow balance, $\bar{b}_w$(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 discussed earlier. The normal time of the maximum winter snow balance tends to be a time of low balance flux at Gulkana Glacier. The 1995 maximum winter snow balance of 0.94 m (table 8) was reached on April 25, 1995.

Changes in both the measured and maximum winter balance values due to using the 1993 area altitude distribution instead of the 1967 distribution are small; both increased 0.02 m or about 2 percent. The change is small in part because the winter balances are dominated by the high glacier balance where there has been little change in the glacier area.

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 (tables 7 and 8), at each index site is calculated directly from stake, pit, and probing data (tables 5 and 6). 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, described above, is run to determine the glacier-averaged net balance based on 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. 3). 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 3. 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 8). Field 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 5, 6, and 7). 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 1995 net balance year began on about September 18, 1994, and ended on about August 29, 1995; the net balance was -0.70 m (table 8).

Changes in net balance values due to using the 1993 area altitude distribution instead of the 1967 distribution are larger than for winter balances; an increase of 0.11 m or about 14 percent. This is because the magnitude of the net balance is greatest low on the glacier where most of the area change in the glacier has occurred .

Summer Balance

Summer balance is the algebraic difference between the winter balance, $\overline{b}_w(s)$, and the net balance, $\overline{b}_n$ (United Nations Educational, Scientific, and Cultural Organization/ International Association of Scientific Hydrology (UNESCO/IASH), 1970)[3]. The UNESCO/IASH definition of winter balance corresponds to the maximum winter balance, $\overline{b}_w(s)$, term from Mayo and others (1972). Thus, the following equation defines the summer balance:

$$\overline{b}_s = \overline{b}_n - \overline{b}_w(s) = -1.64 \text{ m}$$

Annual Mass Balance

Annual mass balance is the change in snow, firn, and ice storage between the beginning (October 1, 1994) and end (September 30, 1995) of the hydrologic year. Evaluation of the 1995 annual balance required estimating two adjustment quantities for each index site: the initial snow balance, $b_0(s)$ (table 8), at the beginning of the hydrologic year, and the final late snow balance, $b_l(ls)$ (table 8), at the end of the hydrologic year (Mayo and others, 1972). These quantities were estimated using the simple linear balance model discussed earlier along with stake, air temperature, and precipitation data. The 1995 annual balance at each index site, b_a, is derived from the net balance and adjustment quantities: $b_a = b_n - b_0(s) + b_l(ls)$ (table 7). The index-site annual balances are combined using the weighted index-site method, with the addition of the internal ablation, to yield the 1995 annual balance, $\overline{b}_a$, of -0.86 m (table 8).

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 1995 AAR was 0.57 using the 1993 photogrammetry glacier surface area and 0.53 using the 1967 glacier surface area determination (table 8).

---

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

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 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. Additionally, ELA detection on aerial or satellite imagery can be difficult when the visual contrast is low between snow and old firn or between glacier ice and superimposed ice; currently, ELA detection is not possible when the ELA occurs down-glacier from the snow line because of internal accumulation in old firn. Therefore, the ELA is calculated by linear interpolation from the balance-altitude curve of the three index sites. The 1995 ELA for Gulkana Glacier was determined to be 1,806 m (table 8).

ICE MOTION MEASUREMENT AND ERRORS

Surface-ice displacements near the fixed index sites are measured during each field visit by optical surveying of balance-motion stakes. The stakes are installed about one year's flow displacement up-glacier from each index site. Replacement stakes are installed every year or two. Thus, the stakes are kept within one year's displacement of the index site (usually less than 80 m) to maximize the year-to-year comparability of the motion data. The optical surveying techniques have been described by Mayo and others (1979) and Mayo and Trabant (1982). Reported velocities (table 9) are the average velocities derived from the linear displacement of the bottom of the stake divided by the measurement interval in years. The bottom of the stake is used for the velocity determination because stakes installed vertically are usually found later to be leaning, and on rare occasions bent or bowed. (The terms "bent" and "bend" are used to describe stakes with a sharp bend that are treated analytically as two line segments. The term "bow" is used to describe stakes with a gradual bend that are treated analytically as if part of the stake were an arc.) Movement of the bottom of the stake is the most representative of the motion of the glacier ice near the surface. Hence, reported stake-motion data have been corrected for changes in stake geometry.

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, or bowed stake geometry. In the long history of field observations at Gulkana Glacier, it has been rare to find melted-out stakes bent or bowed, so a "lean" geometry is generally assumed unless the stake is severely tilted; if so, 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) in the lab. When a bend or bow does occur, it is generally at or above the most recent summer surface.

Determining, measuring, and correcting the stake geometry is an important process. It is, however, imprecise. Stake connectors, which join 3-m sections to make taller stakes, allow a stake tilt of about ±1.5 grad at connec-

Table 9. Stake locations, stake lean corrections, and motion determined from optical surveys, October 1994 to September 1995

[mm/dd/yy, month/day/year; stake name: the first two digits represent the year the stake was installed; letters (A, B, D) represent the site on the glacier (fig.); a number following the letter is used to differentiate multiple stakes installed at the same site in one 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 1.5-2.0 m 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 down-dip 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. Velocity is the stake displacement divided by the measurement period in years. Horizontal (Horiz.) displacement angle is measured positive counterclockwise, zero is east. Vertical (Vert.) 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]

	Date	Stake	Stake, Lower Target			Stake, Upper Target				Glacier Surface		Bend	Solution	Stake Angles		Stake Angles		Stake Bottom								Displ. Angles	
			X_g	Y_g	Z_g	X_t	Y_t	Z_t	H_t	θ	ϕ	Depth	Type	$θ_1$	$ϕ_1$	θ	ϕ	X_s	Y_s	Z_s	b^*	b^{**}	H_tBend	*dXYZ*	Velocity	Horiz.	Vert.
	mm/dd/yy	Name	(meters)			(meters)				(grad)		(m)		(grad)		(grad)		(meters)			(meters)		(meters)	(m)	(m/yr)	(grad)	
Site A	10/31/94	94-A	3,807.08	4,451.45	1,367.46	3,806.75	4,451.53	1,369.45	4.50	-143.83	-6.85		lean			- 15.14	-89.24	3,807.49	4,451.35	1,365.02	2.48	2.46					
	4/19/95	94-A	3,801.35	4,445.28	1,367.74	3,801.09	4,445.35	1,369.54	4.50	-152.65	-6.88		lean			- 16.74	-90.55	3,801.73	4,445.18	1,365.09	2.68	2.67		8.44	18.12	-147.75	0.56
	10/31/94	94-A2	3,804.85	4,454.78	1,367.25	3,805.16	4,454.30	1,369.73	7.50	-143.83	-6.85		lean			136.51	-85.58	3,804.25	4,455.72	1,362.42	4.96	4.87					
	4/19/95	94-A2	3,799.18	4,448.56	1,367.67	3,799.43	4,448.10	1,369.80	7.50	-152.65	-6.88		lean			131.69	-84.66	3,798.57	4,449.67	1,362.51	5.31	5.19		8.29	17.80	-147.99	0.74
	4/19/95	95-A	3,805.79	4,466.03	1,369.48	3,805.83	4,466.10	1,371.24	12.00	-152.65	-6.88		lean			-133.05	-97.09	3,805.56	4,465.62	1,359.25	10.24	10.18					
	9/26/95	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		12.03	27.44	-151.76	3.31
	4/19/95	95-A2	3,810.32	4,461.16	1,369.43	3,810.39	4,461.22	1,371.22	12.00	-152.65	-6.88		lean			-154.89	-96.72	3,809.92	4,460.82	1,359.23	10.21	10.14					
	9/26/95	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		10.55	24.07	-155.89	3.08
Site B	10/31/94	94-B	4,740.54	7,393.29	1,683.12	4,740.27	7,393.34	1,684.94	9.00	-136.96	-6.13		lean			- 11.66	-90.47	4,741.59	7,393.10	1,676.04	7.16	7.12					
	4/19/95	94-B	4,732.74	7,376.61	1,682.49	4,732.35	7,376.64	1,684.30	10.00	-131.12	-6.09		lean			- 4.89	-86.45	4,734.46	7,376.48	1,674.52	8.15	8.03		18.15	38.97	-125.82	- 5.33
	9/26/95	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		24.56	56.03	-126.88	- 5.52
Site D	10/31/94	94-D	6,017.32	7,344.78	1,836.58	6,017.15	7,344.95	1,838.23	10.50	158.03	-6.12		lean			- 50.00	-90.79	6,018.22	7,343.88	1,827.84	8.83	8.86					
	4/19/95	94-D	6,000.00	7,355.19	1,835.44	5,999.47	7,355.48	1,837.19	12.00	190.53	-6.52	2.72	bend	- 31.87	-90.79	- 31.87	-78.84	6,001.73	7,354.24	1,825.52	10.15	10.11	7.37	19.62	42.13	164.28	- 7.56
	9/26/95	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		24.82	56.62	165.79	- 8.68

tors. This translates into a horizontal position change of 0.15 m at the bottom of the typical stake that extends 6 m into the glacier. The uncertainty in determining the stake's geometry (lean, bend, or bow) is estimated to double this error, resulting in a total error in the horizontal of ±0.3 m from geometric corrections. Measuring this error would require digging up a statistically significant number of stakes, an unreasonable task. The bottom of the stake (X_sY_s in table 9) is typically offset horizontally 0.3 to 1.5 m from the surveyed target on the stake at the glacier surface (X_gY_g in table 9). Therefore, the stake-geometry corrections are significant, and their omission would typically lead to motion errors of 5 to 20 percent in the Gulkana data.

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. Additionally, glacier-motion errors include the error in assuming a stake geometry and extrapolating from surveyed points on the stake to the bottom of the stake. This error is estimated to be ±0.15 m in the horizontal and ±0.05 m in the vertical. The errors are added in quadrature to result in a total error for the stake-bottom positions of ±0.2 m in the horizontal and ±0.07 m in the vertical. Reported displacements have errors of about ±0.3 m and velocities have errors 2-3 times greater or ±0.6–0.9 m/yr depending on the displacement time period.

GLACIER-SURFACE ALTITUDE MEASUREMENT AND ERRORS

The glacier-surface altitude at each index site is measured during each field visit (tables 10 and 11). At least three points on the glacier surface in the vicinity of the 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 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).

Surveyed glacier-surface points typically have an altitude uncertainty of about ±0.05 m; this uncertainty is a combination of survey and net errors. 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. While 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 yields an average error of ±0.15 m for the index-site altitudes. Index-site errors are calculated separately for each measurement and are included in table 10.

Table 10. Glacier-surface and summer-surface altitude measurements and analysis at index sites, October 1994 to September 1995

[mm/dd/yy, 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). Dist (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 the local glacier-surface slope is linear]

		P			Q			R			Index Site			Glacier Surface Slope		Dist. to Closest Point	Z_i Error
	Date mm/dd/yy	X (meters)	Y (meters)	Z (meters)	X (meters)	Y (meters)	Z (meters)	X (meters)	Y (meters)	Z (meters)	X_i (meters)	Y_i (meters)	Z_i (meters)	θ (grad)	ϕ (grad)	(meters)	(meters)
Site A	10/31/94	3,823.62	4,444.01	1,367.64	3,804.85	4,454.78	1,367.25	3,818.09	4,461.54	1,368.72	3,825.10	4,447.27	1,368.01	-143.83	-6.85	3.58	0.03
	4/19/95	3,826.58	4,444.93	1,369.59	3,799.18	4,448.56	1,367.67	3,805.79	4,466.03	1,369.48	3,825.10	4,447.27	1,369.64	-152.65	-6.88	2.77	0.02
	9/26/95	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
Site B	10/31/94	4,731.62	7,377.83	1,681.40	4,740.54	7,393.29	1,683.12	4,732.53	7,398.79	1,683.14	4,728.61	7,391.17	1,682.32	-136.96	-6.13	8.57	0.09
	4/19/95	4,734.60	7,394.03	1,684.05	4,732.74	7,376.61	1,682.49	4,747.86	7,392.46	1,684.52	4,728.61	7,391.17	1,683.54	-131.12	-6.09	6.64	0.06
	9/26/95	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
Site D	10/31/94	5,999.66	7,355.33	1,834.61	6,017.32	7,344.78	1,836.58	6,005.75	7,373.34	1,834.01	5,999.01	7,353.57	1,834.66	158.03	-6.12	1.88	0.02
	4/19/95	6,018.37	7,351.02	1,837.37	6,000.00	7,355.19	1,835.44	6,011.61	7,343.10	1,836.80	5,999.01	7,353.57	1,835.36	190.53	-6.52	1.90	0.02
	9/26/95	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
														Average =		5.34	0.06

Table 11. Continuation of glacier-surface and summer-surface altitude measurements and analysis at index sites, October 1994 to September 1995

[mm/dd/yy, month/day/year; Stake naming convention is described in headnote for table . 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. Emerg. (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). $Z_i(ss_1)$ summer surface (altitude) at index site is Z_i minus snow depth. m/yr, meters per year]

	Date	Stake 1			Stake 2			Stake 3			Stake 4			Avg.			$Z_i(ss_1)$
	mm/dd/yy	Name	Best *b'* (meters)	Change *b'* (meters)	Name	Best *b'* (meters)	Change *b'* (meters)	Name	Best *b'* (meters)	Change *b'* (meters)	Name	Best *b'* (meters)	Change *b'* (meters)	Emerg. (meters)	Emerg. (m/yr)	Snow Depth (meters)	Summer Surface (meters)
Site A	10/31/94	94-A	2.45	-4.77	94-A2	4.86	-5.02							1.09	2.13	0.78	1,367.23
	4/19/95	94-A	2.68	0.23	94-A2	5.19	0.33	95-A	10.18		95-A2	10.14		1.35	2.90	1.35	1,368.29
	9/26/95							95-A	3.89	-6.29	95-A2	4.27	-5.87	1.90	4.33		1,365.46
Site B	10/31/94	94-B	7.12	-2.77										0.08	0.16	1.36	1,680.96
	4/19/95	94-B	8.03	0.91										0.31	0.67	2.10	1,681.44
	9/26/95	94-B	4.56	-3.47										0.34	0.78	0.15	1,680.26
Site D	10/31/94	93-D	7.37		94-D	8.87	-1.55							-0.55	- 1.08	1.40	1,833.26
	4/19/95	93-D			94-D	10.13	1.26							-0.56	- 1.20	2.72	1,832.64
	9/26/95	93-D	6.36		94-D	8.07	-2.06							-0.98	- 2.24	0.58	1,831.74

ICE THICKNESS

On March 28, 1976, ice thickness was measured at 19 locations: one near measurement site D, seven along a cross profile of the glacier near measurement site B, and 11 along a cross profile of the glacier near measurement site A (fig. 9, table 12).

A portable ground-based 5 MHz monopulse ice-radar system was used, similar to that described by Watts and Wright (1981), Driedger and Kennard (1984, 1986a,b), and March and others (1997). The distance between the monopulse transmitter and the oscilloscope receiver was typically about 100 m (see table 12 for site specific separations).

The standard method used for estimating ice thickness perpendicular to the subglacial bed from a measured time delay is explained in Mayo and Trabant (1982) and Driedger and Kennard (1984, 1986a). The ice thickness, h (in meters), perpendicular to the glacier bed is:

$$h = \frac{1}{2}\sqrt{v_i^2\left(t_d + \frac{S}{v_a}\right)^2 - S^2}$$

where v_a and v_i are the speed of light in air and ice respectively (in meters per microsecond), S is the transmitter-receiver separation distance (in meters), and t_d is the time delay (in microseconds).

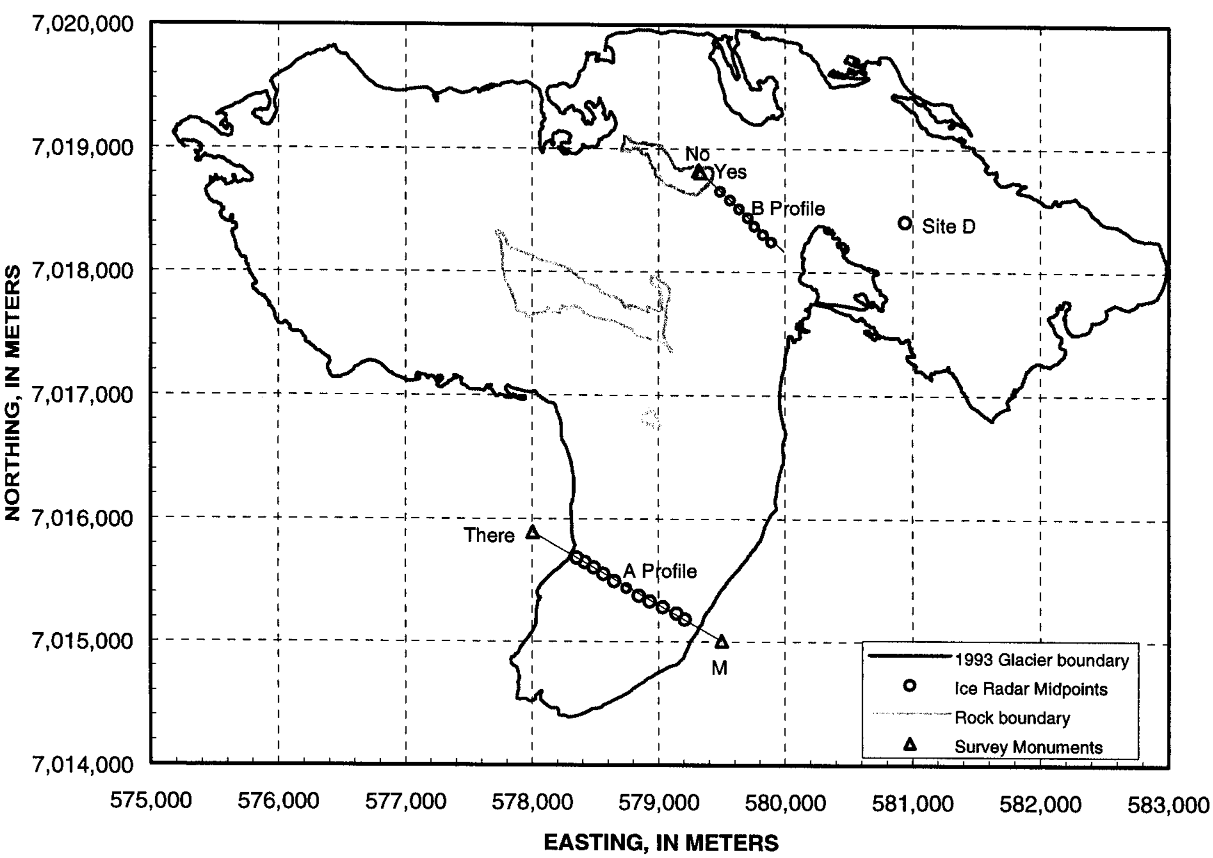


Figure 9. Location of ice radar midpoints and survey monuments M, There, No, and Yes in Gulkana Glacier Basin. No, which is difficult to distinguish from Yes at the scale of this map, lies about 23 m to the northwest of Yes.

Table 12. Ice radar data from March 28, 1976

Glacier Location	Ice Radar Location (UTM, Zone 6 - NAD1983, NGVD29) — Transmitter Easting	Transmitter Northing (meters)	Transmitter Altitude	Receiver Easting	Receiver Northing (meters)	Receiver Altitude	Midpoint Easting	Midpoint Northing (meters)	Midpoint Altitude	Position Error	Transmitter Receiver Separation (meters)	Ice Thickness Data — Radar Delay Time (microsec)	Ice Thickness (meters)
Site D	580,983	7,018,382	1,835	580,903	7,018,431	1,828	580,943	7,018,406	1,832	<1	95	1.90	180
B cross profile	579,905	7,018,213	1,680	579,875	7,018,270	1,686	579,890	7,018,242	1,683	<1	65	1.75	160
	579,875	7,018,270	1,686	579,775	7,018,338	1,691	579,825	7,018,304	1,689	10	121	2.25	210
	579,775	7,018,338	1,691	579,736	7,018,404	1,624	579,755	7,018,371	1,657	10	102	2.85	260
	579,736	7,018,404	1,624	579,674	7,018,476	1,695	579,705	7,018,440	1,660	10	118	2.90	270
	579,674	7,018,476	1,695	579,598	7,018,549	1,695	579,636	7,018,512	1,695	10	105	2.10	200
	579,598	7,018,549	1,695	579,527	7,018,615	1,696	579,563	7,018,582	1,695	<1	97	1.25	120
	579,527	7,018,615	1,696	579,443	7,018,694	1,700	579,485	7,018,654	1,698	<1	115	0.65	70
A cross profile	579,236	7,015,159	1,387	579,183	7,015,204	1,391	579,210	7,015,181	1,389	<1	69	1.25	120
	579,183	7,015,204	1,391	579,097	7,015,256	1,392	579,140	7,015,230	1,391	<1	101	1.45	140
	579,097	7,015,256	1,392	578,972	7,015,308	1,392	579,035	7,015,282	1,392	10	136	1.35	140
	578,972	7,015,308	1,392	578,891	7,015,349	1,392	578,931	7,015,328	1,392	15	90	1.40	140
	578,891	7,015,349	1,392	578,797	7,015,405	1,389	578,844	7,015,377	1,390	10	110	1.40	140
	578,797	7,015,405	1,389	578,694	7,015,466	1,385	578,745	7,015,436	1,387	10	120	1.55	150
	578,694	7,015,466	1,385	578,605	7,015,522	1,377	578,649	7,015,494	1,381	15	105	1.35	130
	578,605	7,015,522	1,377	578,524	7,015,579	1,376	578,565	7,015,551	1,376	15	99	1.25	120
	578,524	7,015,579	1,376	578,454	7,015,626	1,375	578,489	7,015,602	1,375	15	84	1.10	110
	578,454	7,015,626	1,375	578,382	7,015,667	1,371	578,418	7,015,646	1,373	15	83	0.95	90
	578,382	7,015,667	1,371	578,325	7,015,700	1,376	578,353	7,015,683	1,373	15	67	0.50	50

For the constants in this equation, the values v_a=299.7 m/µs and v_i=168 m/µs are assumed (Watts and England, 1976; Mayo and Trabant, 1982).

The cross profile of the glacier near measurement site B was roughly located in the field by walking along a range line that extends from survey monument "No" through survey monument "Yes" and on across the glacier. A similar process was executed for the cross profile near measurement site A except that in this case the reference survey monuments, "There" and "M," are located on opposite sides of the glacier.

Optical surveys were conducted of each transmitter and receiver location from a temporary nearby location on the glacier. Typically this method yields locations accurate to ±0.1 m, though positions are only reported (table 12) to the nearest meter due to other errors in the ice radar. Unfortunately, the microwave distance meter was intermittently failing during this field work so some of the surveys are of significantly poorer quality than others. In these cases, locations were determined by intersecting the surveyed site line with the range line through monuments "No" and "Yes" or the cross-glacier line from monument "There" to "M." These transmitter and receiver positions are estimated to have an error of ±20 m and hence yield radar midpoint errors of ±10 m or ±15 m depending on whether only one or both of the transmitter and receiver positions lacked precise distance measurements.

Ice thickness errors arise from a combination of the oscilloscope sweep rate error, the error in reading the time delay from the scope, our assumption that glacier surface and bed slopes are the same when migrating the data, and possible false or oblique reflections. The oscilloscope used to make these measurements is no longer available and its sweep rate error is uncertain. The combined standard error of the ice thickness values is estimated to be about

±10 percent. Values are reported to the nearest 10 m (table 12). Possible false reflections could result from dirty ice and debris above the glacier bed. Recent ground-penetrating radar of the Gulkana Glacier bed shows a relatively clean reflection pulse suggesting a fairly clean ice-bedrock contact (Steve Arcone, CRREL, written comm., 1999). Also, the same unpublished ground-penetrating radar ice thickness measurements (Steve Arcone, CRREL, written comm., 1999) are very consistent with our soundings. As an example, their deepest measurement on a glacier cross profile a few hundred meters up glacier from our B-profile was 269 m compared with our deepest reading on the B-profile of 270 m.

From our measurements of the glacier surface altitude at sites A, B, and D, we know that the glacier ice thickness undergoes both seasonal variation and longer term variations as the glacier adjusts itself to changes in climate. If we assume that the glacier bed has not eroded significantly over the last 20 years, then the surface lowering indicates that the cumulative glacier thinning from March 1976 (the date of our radar measurements) to March 1995 along the glacier centerline is about 23 m at site A and 7 m at site B with no cumulative change at site D. The seasonal variation in glacier surface altitude indicates that the ice thickness varies over the whole glacier by about 2-5 m from a peak thickness in May or June to a minimum in August or September.

REFERENCES CITED

Bertrand, C.M., Hess, D.L., Meyer, D.F., Jackson, M.L., and Smith, C.W., 1999, Water resources data, Alaska, water year 1998: U.S. Geological Survey Water-Data Report AK-98-1, 321 p.

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.

Driedger, C.L., and Kennard, P.M., 1984, Ice volumes on Cascade Volcanoes: Mount Rainier, Mount Hood, Three Sisters, and Mount Shasta: U.S. Geological Survey Open-File Report 84-581, 55 p.

Driedger, C.L., and Kennard, P.M., 1986a, Ice volumes on Cascade Volcanoes: Mount Rainier, Mount Hood, Three Sisters, and Mount Shasta: U.S. Geological Survey Professional Paper 1365, 28 p.

Driedger, C.L., and Kennard, P.M., 1986b, Glacier volume estimation on Cascade Volcanoes: An analysis and comparison with other methods. Annals of Glaciology: v. 8, p. 59-64.

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., available from World Wide Web: <http:/water.usgs.gov/lookup/get?CIR1132>.

Haeberli, Wilfried, 1985, Fluctuations of glaciers 1975-1980 (Vol. 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, Wilfried, and Hoelzle, Martin, 1993, Fluctuations of glaciers 1985-1990 (Vol. 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., Suter, S., and Frauenfelder, R., 1998, Fluctuations of glaciers 1990-1995 (Vol. 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.

Haeberli, Wilfried, and Müller, Peter, 1988, Fluctuations of glaciers 1980-1985 (Vol. 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, available from World Wide Web: <http://ak.water.usgs.gov/glaciology/gulkana/reports/>.

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 (Vol. 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., 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., abstract available from World Wide Web: <http://ak.water.usgs.gov/glaciology/gulkana/reports/>.

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.

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., available from World Wide Web: <http://ak.water.usgs.gov/glaciology/gulkana/reports/>.

March, R.S., Mayo, L.R., and Trabant, D.C., 1997, Snow and ice volume on Mount Spurr Volcano, Alaska, 1981: U.S. Geological Survey Water-Resources Investigations Report 97-4142, 36 p., abstract available from World Wide Web: <http://ak.water.usgs.gov/Publications/Abstracts/1997.Abstracts/spurr_ice_abs.htm>.

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., available from World Wide Web: <http:/water.usgs.gov/lookup/get?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., abstract available from World Wide Web: <http://ak.water.usgs.gov/glaciology/gulkana/reports/>.

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., 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., 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 (Vol. 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): 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, Ottawa, Ontario, 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.

Schellekens, M.F., Linn, K.R., Bigelow, B.B., Shaw, S.K., and Hiner, M.M., 1996, Water resources data for Alaska, water year 1995: U.S. Geological Survey Water-Data Report AK-95-1, 278 p.

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, available from World Wide Web: <http://ak.water.usgs.gov/glaciology/gulkana/reports/>.

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, 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. Geological Survey, 1968-99, Water resources data for Alaska, water years 1967-98: U.S. Geological Survey Water-Data Report AK71-1 to AK 98-1 (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.

Watts, R.D., and England, A.W., 1976, Radio echo sounding of temperate glaciers: Ice properties and sounder design criteria: Journal of Glaciology, v. 17, no. 75, p. 39-48.

Watts, R. D., and Wright D. L., 1981, Systems for measuring thickness of temperate and polar ice from the ground or from the air: Journal of Glaciology, v. 27, no. 97, p. 459-469.