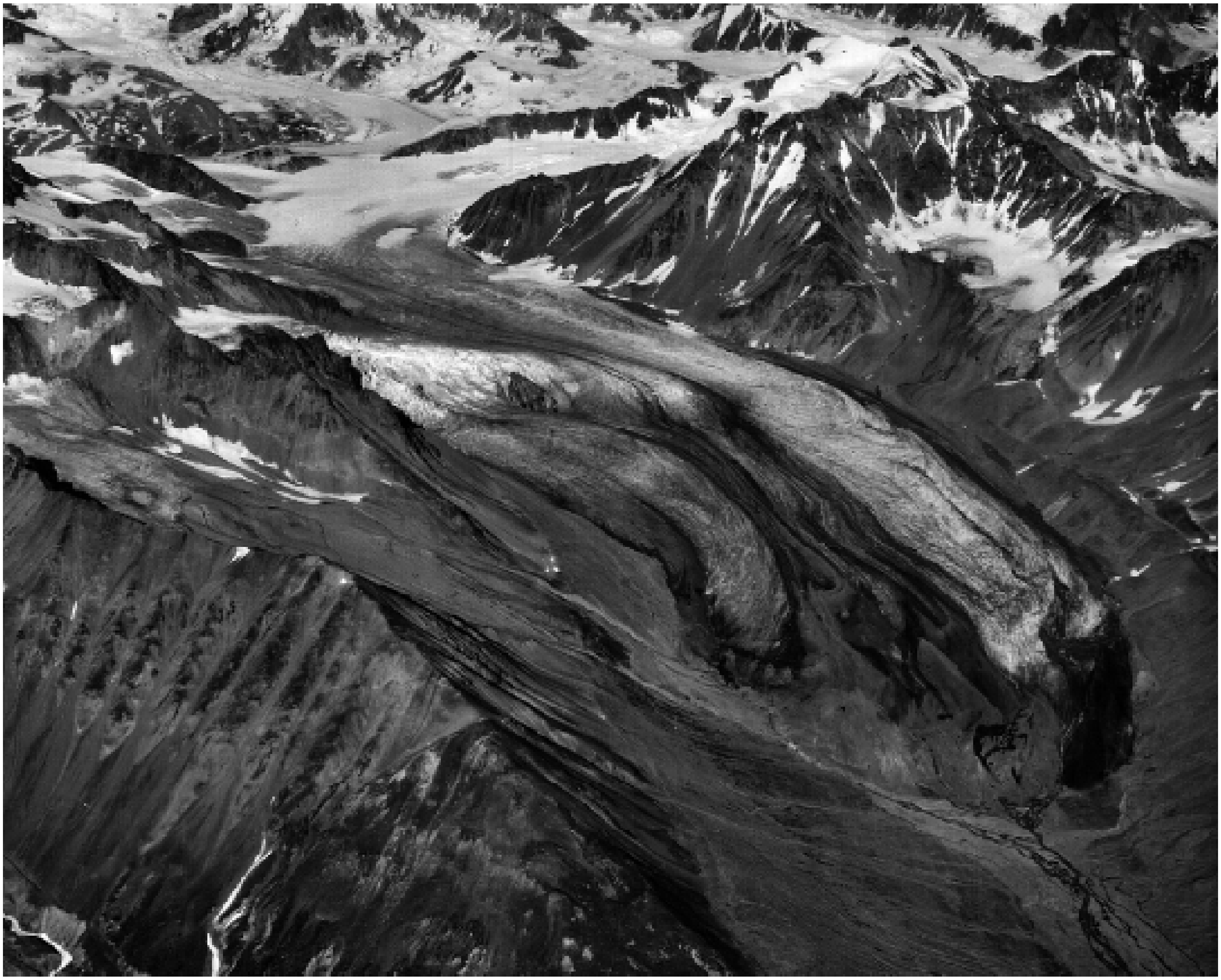
MASS BALANCE, METEOROLOGICAL, ICE MOTION, SURFACE ALTITUDE, AND RUNOFF DATA AT GULKANA GLACIER, ALASKA, 1992 BALANCE YEAR

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 95- 4277



U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Cover - Gulkana Glacier and basin, August 25, 1987, photograph #87R3-218 by Bob Krimmel.

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by Rod S. March and Dennis C. Trabant

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Fairbanks, Alaska
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CONVERSION FACTORS, VERTICAL DATUM, AND SYMBOLS

Multiply	by	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square kilometer (km^2)	0.3861	square mile
kilogram (kg)	2.205	pound
kilograms per liter (kg/L)	62.43	pound per cubic foot
kilograms per cubic meter (kg/m^3)	0.06243	pound per cubic foot
meters per year (m/yr)	3.281	feet per year
grad	0.9	degrees
degree Celsius (°C)	°F = 1.8 × °C + 32	degree Fahrenheit (°F)

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
$\bar{b}$	area-averaged balance value
b'	average stake height of the glacier surface within a 50-meter radius of the stake, in meters
b_0'	initial average stake height of the glacier surface within a 50-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 (i.e. as if the stake were vertical), in meters
b_a	annual balance at site
$\bar{b}_a$	area-averaged annual balance
b_a(fi)	annual firn and ice balance at site
$\bar{b}_a$(fi)	area-averaged annual firn and ice balance
b_n	net balance at site
$\bar{b}_n$	area-averaged net balance
$\bar{b}_s$	area-averaged summer balance
$\bar{b}_w$	area-averaged winter balance
b(f)	firn balance at site
b(i)	ice balance at site
b_0(i)	initial ice balance at site
b_1(i)	late ice balance at site
b(k)	internal accumulation at site
b_1(ls)	final late snow balance at site
$\bar{b}_1$(ls)	area-averaged final late snow balance
b(s)	snow balance at site
b_0(s)	initial snow balance at site
$\bar{b}_0$(s)	area-averaged initial snow balance
b_m(s)	measured winter snow balance at site
$\bar{b}_m$(s)	area-averaged measured winter snow balance
b_w(s)	maximum winter snow balance at site
$\bar{b}_w$(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_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
$\mathrm{m_{we}}$	meters water equivalent
n	sample number
$\mathrm{ss_1}$	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)
$\mathrm{ss_2}$	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)
X_g	local sea-level coordinate of measurement stake at glacier surface, in meters
X_i	horizontal coordinate of fixed index site
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	horizontal coordinate of fixed index site
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_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

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ABSTRACT

The 1992 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 measured in the basin and are reported herein. Averaged over the glacier, the measured winter snow balance was 0.97 meters on March 26, 1992; the maximum winter snow balance was 1.05 meters on May 19, 1992; the net balance (from September 8, 1991 to August 17, 1992) was -0.29 meters; and the annual balance (October 1, 1991 to September 30, 1992) was -0.38 meters. Ice surface, motion, and altitude changes measured at three index sites document seasonal changes in ice speed and glacier thickness. Annual stream runoff was 1.24 meters averaged over the basin.

INTRODUCTION

The U.S. Geological Survey has a long-term program to monitor climate, glacier motion, mass balance, and stream runoff to understand glacier-related hydrologic processes for improving the quantitative prediction of water resources, glacier-related hazards, and the consequences of global change. 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 U.S. Geological Survey. The other monitoring sites are Wolverine Glacier in south-central 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 during 1992 (table 1) as part of the long-term monitoring program.

Measurements began on Gulkana Glacier during the early 1960’s with the University of Alaska Gulkana Glacier Project. 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 meteorology, snow and ice balance, and runoff measurements was begun by the U.S. Geological Survey 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).

Table 1. Data collection summary, 1992 hydrologic year (the location of the stations are shown on figure 1)
[———, continuous record; - - - -, estimated record; •, occasional/discrete measurement]

Station	Altitude	Measurement		1992 Hydrologic Year												1993 Hydrologic Year					
			1991 Calendar Year				1992 Calendar Year												1993 Calendar Year		
	(meters)		Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
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		•					•				•		•						•
35 mm photography													•	••							
Surface profiles surveyed													•								
Control network resurvey													•								

Balance studies were relatively intensive until the mid-1970’s, after which spatial sampling was reduced to three index sites, but measurements were expanded to include ice motion and surface altitude observations (for glacier volume change) in addition to the balance, runoff, and meteorology observations previously being made. 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). 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).

The Gulkana record is just approaching the general 30-year length-of-record criterion (necessary to provide reasonable statistics) that is used in the selection of stations for international exchange through the Global Telecommunications Service (GTS) for global climate monitoring (Karl and others, 1989). Hence, the current record is only marginally valuable for long-term analysis. Preliminary regional climate-glacier interpretive work using the Gulkana data includes papers by Walters and Meier (1989) and by Letréguilly and Reynaud (1989).

Description and Climate

Gulkana Glacier (fig. 1) (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 glacier and basin area-altitude distributions (table 2; fig. 2) were defined in 1967 above the runoff gage at 1,125 m altitude. These values are used throughout this report. In 1967, the 31.6-km² basin was 70 percent covered by perennial snow and ice. Gulkana Glacier is the largest glacier in the basin covering 19.32 km². 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 km². The accumulation area of Gulkana Glacier is four adjacent cirques with east, south, and west exposures reaching as high as 2,470 m altitude. The cirque glaciers converge forming a south-flowing ablation area with a terminus lightly covered with rock-debris (cover photo) at 1,160 m altitude. Contorted moraines suggest that Gulkana Glacier has surged (see cover photo). However, no flow instabilities have been detected since scientific investigation began in the early 1960's. Gulkana Glacier has been in general recession since the culmination of its last advance around the turn of the century (Péwé and Reger, 1983). The total recession since then has been about 3 km.

Phelan Creek 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.

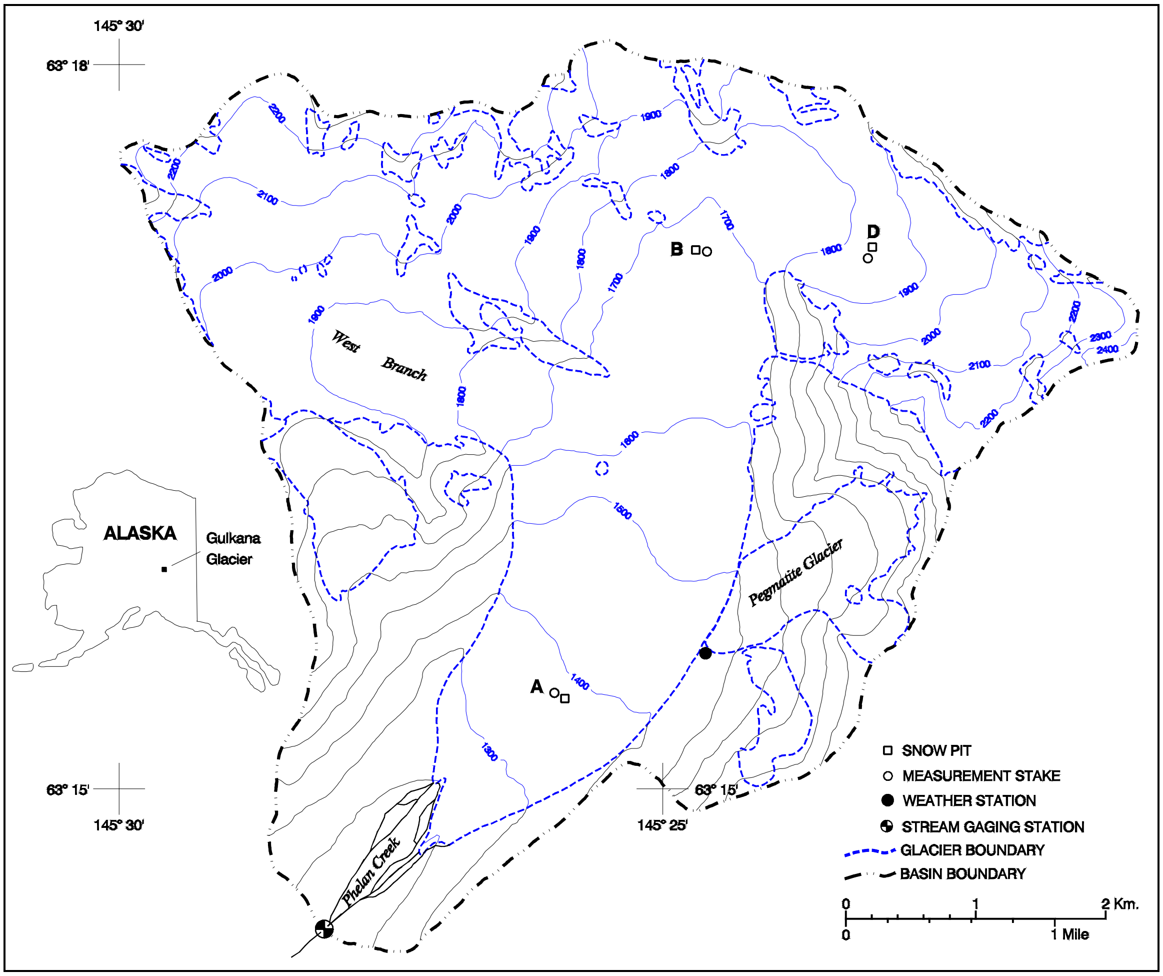

Figure 1. Gulkana Glacier basin area, Alaska. (Contour interval is 100 m. Base map from Tangborn and others, 1977.)

The mean ELA is near 1,735 m, which is consistent with a continental mountain climate. The mean annual air temperature near the ELA is about -6°C, lapsed from the recorder site using the wet adiabatic rate of -6.6°C per 1,000 meters. 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 1,160 mm. 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 1989-92 is 1.89 m.

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 repeatedly made at three fixed locations on Gulkana Glacier, referred to as the "index sites." Balance-motion stakes maintained near each index site support the long-term data collection.

Table 2. Area-altitude distribution of Gulkana Glacier and Gulkana Glacier basin by 100-meter altitude intervals

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

					Sub-areas of glacier represented by index sites:		
Altitude interval (m)	Average altitude (m)	Basin area (km^2)	Gulkana Glacier west branch area (km^2)	Gulkana Glacier area (km^2)	Site A 1373 (km^2)	Site B 1685 (km^2)	Site D 1837 (km^2)
1,161 - 1,200	1,180.5	0.84		0.12	0.12		
1,200 - 1,300	1,250	1.48		0.52	0.52		
1,300 - 1,400	1,350	1.92		1.20	1.20		
1,400 - 1,500	1,450	2.68		1.56	1.56		
1,500 - 1,600	1,550	2.44		1.36	0.39	0.97	
1,600 - 1,700	1,650	3.68	0.43	2.12		2.12	
1,700 - 1,800	1,750	4.00	0.44	2.04		1.24	0.80
1,800 - 1,900	1,850	4.28	0.91	2.72			2.72
1,900 - 2,000	1,950	4.32	1.31	2.92			2.92
2,000 - 2,100	2,050	2.72	0.96	2.28			2.28
2,100 - 2,200	2,150	1.92	0.78	1.44			1.44
2,200 - 2,300	2,250	1.04	0.37	0.80			0.80
2,300 - 2,400	2,350	0.24	0.06	0.20			0.20
2,400 - 2,473	2,436.5	0.04	0.00	0.04			0.04
Total area =		31.60	5.28	19.32	3.79	4.33	11.20
Average altitude =		1,748	1,965	1,797	1,393	1,656	1,988
Upper altitude limit of zone =					1,529	1,761	2,473
Lower altitude limit of zone =					1,161	1,529	1,761
Percent of total glacier area =					19.6%	22.4%	58.0%

The combined mass balance system of measurement and reporting terminology (Mayo, Meier, and Tangborn, 1972) is adhered to in this report, with the addition of internal accumulation (Trabant and Mayo, 1985). The combined mass balance system is based on measurements relative to time-transgressive stratigraphic horizons (summer surfaces) and evaluation of adjustment quantities for determining the 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, in principle, 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 would have a beginning and ending date. In actuality, reported net balances are approximations to this ideal and do not have a specific beginning and ending date most years because of the time transgressive formation of the glacier summer surface. In this and most other mass balance work, net balance is determined for each measurement location on the glacier as the difference between successive balance minimums and then combined for the whole glacier as if the balance minimum occurred synchronously over the whole glacier.

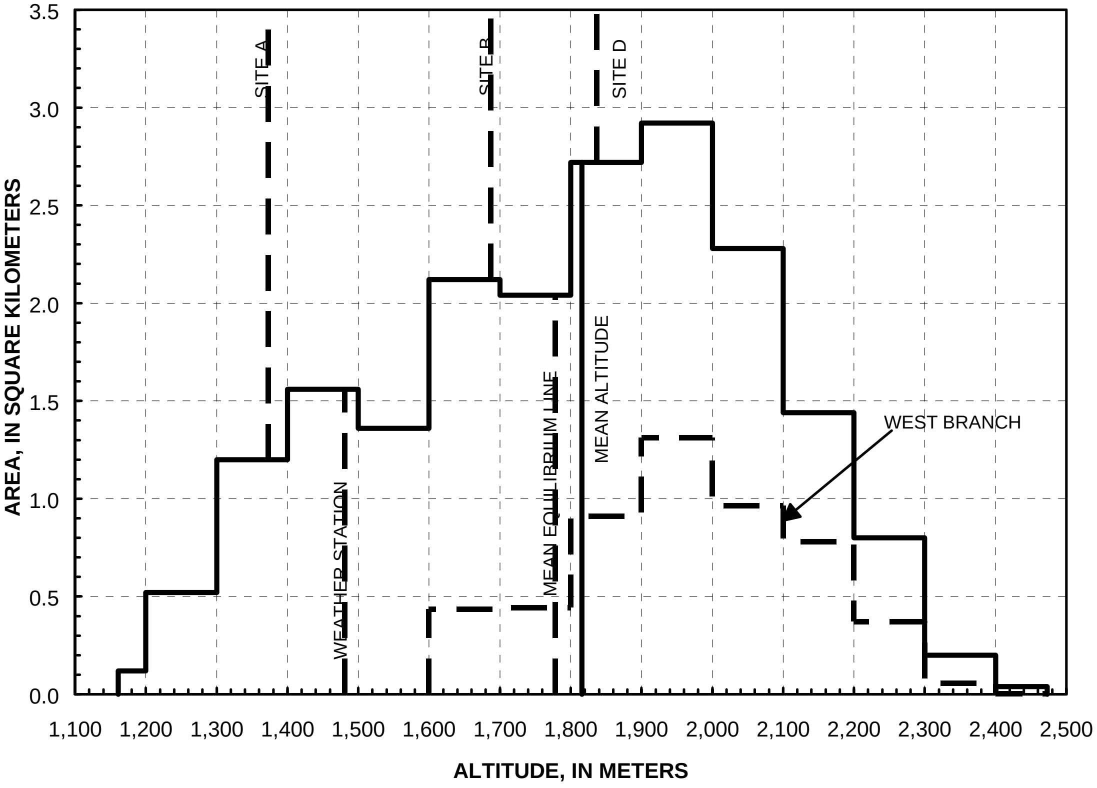

Figure 2. Area-altitude distribution of Gulkana Glacier and west branch of Gulkana Glacier in 1992. (Shown are altitudes of index sites, the weather station (air temperature and precipitation gage), the mean equilibrium line altitude, and mean glacier altitude.)

The hydrologic year (HY), which is the period used for the annual 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 U.S. Geological Survey hydrologic data. The temporal relation of the quantities defined and used for analyzing the index-site and glacier-averaged 1992 mass balances are illustrated in figures 3 and 4.

All balance, precipitation, and runoff values are reported in meters of water equivalent. All reported densities are relative densities; i.e. the decimal fraction of the density of water. The density of water is assumed to be 1,000 kg/m^3 and the relative density of glacier ice is assumed to be 0.9.

Balance-motion-stake and index-site-altitude 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 in the North American Datum 1983 by:

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

$$\text{UTM Northing} = \bar{k}Y_L + 7{,}011{,}000 \text{ m.} \tag{2}$$

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.

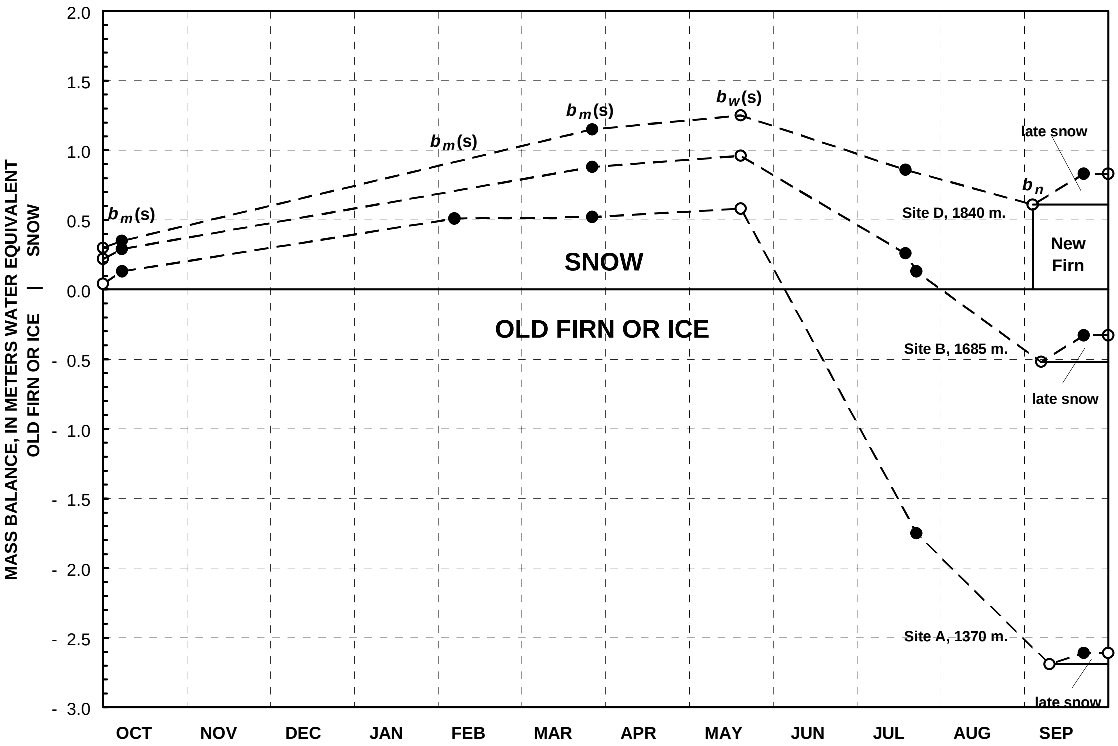

Figure 3. Time distribution of 1992 index-site mass balances for Gulkana Glacier. (Solid circles are measured values; open circles are estimated values. Seasonal maximum balances occurred in mid-May. b_m(s), measured winter snow balance at site; b_n, net balance at site; b_w(s), maximum winter snow balance at site.)

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

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

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

The mean scale factor used in equations 1 and 2 to convert between the local sea-level system coordinates and UTM coordinates is the mean value of the nonlinear distribution of scale factors between the local sea-level system origin and an observation point. E is approximated by the sum of the UTM Easting of the local system origin (575,000 m) and X_L. The mean scale factor is estimated using Simpson's 1/3 rule:

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

Equation 4 is accurate within about 0.1 part per million of equations from U.S. Departments of the Army and the Air Force (1941) and hence yields results accurate at the centimeter level.

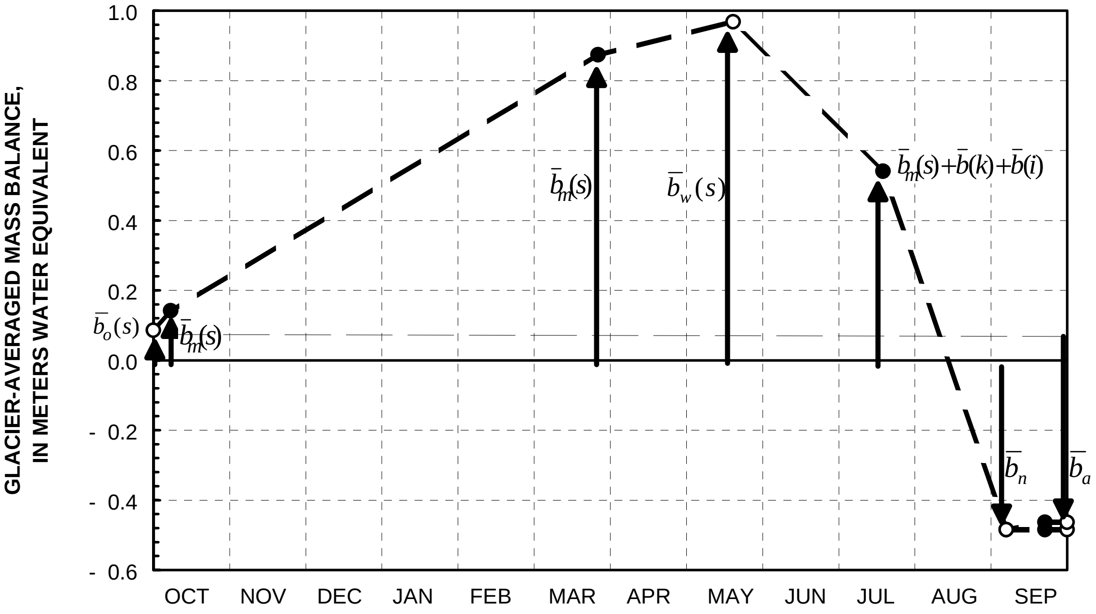

Figure 4. Time distribution of glacier-averaged mass balance of Gulkana Glacier, 1992 hydrologic and balance years. (The initial balance, $\bar{b}_0$(s), is the change in balance between the balance minimum that defines the beginning of the balance year and the beginning of the hydrologic year (1 October). 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 snow balance, $\bar{b}_w$(s). Solid circles are measured values; open circles are estimated values. Symbols with a bar over them indicate the mean value over the whole glacier.)

1992 DATA COLLECTION

The temporal distribution of the data used to analyze the 1992 mass balance is shown in table 1.

Field Visits

Six field visits to the Gulkana Glacier basin between early September 1991 and late March 1993 (table 1) were used to collect the data necessary to evaluate the 1992 glacier mass balance, motion, and surface altitudes and to service and calibrate recorders. Site visits are made by foot, snowmachine, or helicopter depending on the conditions and work to be done. 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. Sometimes for safety reasons, the fall trip is split (table 1, fall 1991): one trip on foot to the lower glacier and recorders and a second trip with a helicopter to measure the upper glacier (fall glacier travel is notoriously unsafe in crevassed regions). An additional trip was made during July 1992 to measure mass balance and glacier motion, and to resurvey glacier longitudinal profiles, cross profiles, and control points for analysis of long-term glacier volume change and in preparation for photogrammetric mapping. Measurements in March 1993 add redundancy to the September and October 1992 measurements of the height of the 1992 summer surface on stakes and allow for the regular assessment of errors in balance calculations based on stake readings.

Recorded Variables

Data on air temperature, precipitation-gage catch, and stream runoff are recorded continuously, although the runoff data typically become meaningless after Phelan Creek freezes over in the early fall. The data sets are truncated to the hydrologic year. 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, fig. 1). The air temperature sensor, data reduction methodology, and data accuracy described for a similar gage at Wolverine Glacier (Mayo, March, and Trabant, 1992; Kennedy, 1995) are applicable to the Gulkana gage and data. Briefly, the sensor is a copper-finned, 20-x-300 mm, liquid-filled sensor designed for use in water. It has a slow response time in air that makes it good for determining daily average temperature, but poor for daily maximum and minimum temperatures. The sensor is housed in a small white shelter with slatted walls and an open bottom, 1.5-2.0 m above the ground. Snow accumulation is minimal at the site, so the height above the ground is not significantly reduced during the winter. A glass thermometer with one- or two-tenths graduations is used several times a year to make calibration measurements. The preliminary daily mean temperatures reported (fig. 5, table 3) have an accuracy of about ±1.0°C (Mayo, March, and Trabant, 1992; Kennedy, 1995). Part of the 1992 record was lost because of recorder failure.

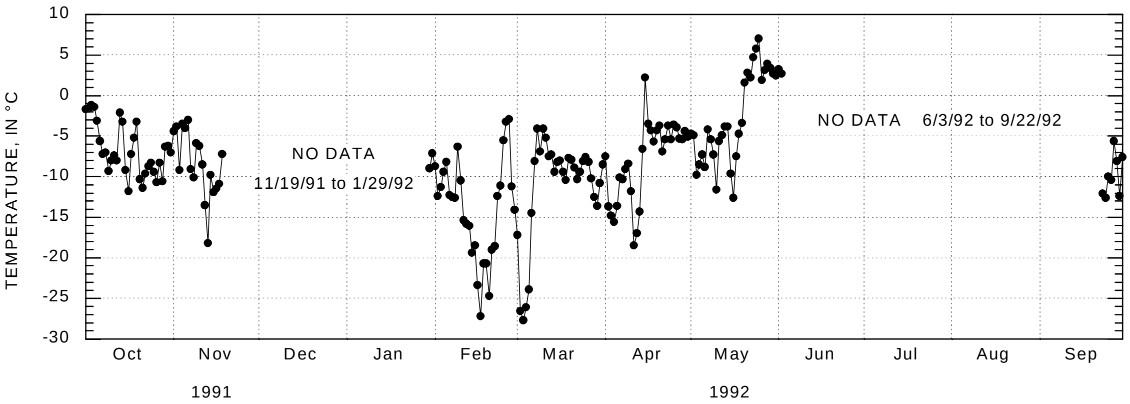

Figure 5. Daily mean air temperature recorded at 1,480 meters altitude in the Gulkana Glacier basin.

Table 3. Daily mean air temperature from the recording gage at 1,480 meters altitude
[Values in degrees Celsius; Not Valid indicates monthly average temperature has more than 9 days missing;
—, daily value missing.]

		1991						1992				
Day	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
1	- 1.7	- 4.4	—	—	- 8.7	-17.2	- 7.5	- 4.7	3.2	—	—	—
2	- 1.6	- 3.8	—	—	-12.4	-26.6	-13.7	- 4.9	2.7	—	—	—
3	- 1.2	- 9.2	—	—	-11.3	-27.7	-14.8	- 9.8	—	—	—	—
4	- 1.4	- 3.5	—	—	- 9.4	-26.1	-15.6	- 8.5	—	—	—	—
5	- 3.1	- 4.0	—	—	- 8.2	-23.9	-13.6	- 7.3	—	—	—	—
6	- 5.6	- 3.0	—	—	-12.3	-14.5	-10.1	- 8.8	—	—	—	—
7	- 7.2	- 9.1	—	—	-12.5	- 8.1	-10.3	- 4.2	—	—	—	—
8	- 7.0	-10.1	—	—	-12.6	- 4.1	- 9.1	- 5.4	—	—	—	—
9	- 9.3	- 5.9	—	—	- 6.3	- 6.9	- 8.4	- 7.3	—	—	—	—
10	- 8.0	- 6.2	—	—	-10.5	- 4.1	-11.8	-11.6	—	—	—	—
11	- 7.4	- 8.5	—	—	-15.4	- 5.2	-18.5	- 5.6	—	—	—	—
12	- 8.0	-13.5	—	—	-15.8	- 7.5	-17.0	- 4.9	—	—	—	—
13	- 2.1	-18.2	—	—	-16.1	- 7.3	-14.3	- 3.8	—	—	—	—
14	- 3.2	- 9.8	—	—	-19.4	- 9.4	- 6.6	- 3.8	—	—	—	—
15	- 9.2	-11.9	—	—	-18.5	- 8.2	2.2	- 9.6	—	—	—	—
16	-11.8	-11.5	—	—	-23.4	- 8.0	- 3.5	-12.6	—	—	—	—
17	- 7.2	-10.9	—	—	-27.2	- 9.4	- 4.3	- 7.5	—	—	—	—
18	- 5.2	- 7.2	—	—	-20.7	-10.4	- 5.7	- 4.7	—	—	—	—
19	- 3.2	—	—	—	-20.7	- 7.7	- 4.3	- 3.4	—	—	—	—
20	-10.3	—	—	—	-24.7	- 7.9	- 3.7	1.6	—	—	—	—
21	-11.4	—	—	—	-19.0	- 8.9	- 6.9	2.8	—	—	—	—
22	- 9.6	—	—	—	-18.6	-10.3	- 5.4	2.2	—	—	—	—
23	- 8.7	—	—	—	-12.4	- 9.4	- 3.7	4.7	—	—	—	-12.1
24	- 8.3	—	—	—	-11.1	- 8.1	- 5.4	5.8	—	—	—	-12.6
25	- 9.4	—	—	—	- 5.5	- 7.6	- 3.6	7.0	—	—	—	-10.0
26	-10.7	—	—	—	- 3.2	- 8.2	- 3.9	1.9	—	—	—	-10.4
27	- 8.3	—	—	—	- 2.9	-10.2	- 5.3	3.1	—	—	—	- 5.6
28	-10.6	—	—	—	-11.2	-12.5	- 5.4	3.9	—	—	—	- 8.1
29	- 6.3	—	—	—	-14.1	-13.6	- 4.4	3.4	—	—	—	-12.4
30	- 6.2	—	—	- 9.0		-10.8	- 5.1	2.7	—	—	—	- 7.6
31	- 7.0		—	- 7.1		- 8.5		2.5		—	—	
Month Average	- 6.8	Not Valid	Not Valid	Not Valid	-13.9	-11.2	- 8.0	- 2.8	Not Valid	Not Valid	Not Valid	Not Valid
											Annual Average Temperature =	**Not Valid**

PRECIPITATION CATCH

Precipitation catch is recorded by an analog recorder at the air temperature site (fig. 1). The gage, data reduction methodology, and data accuracy have been described for a similar gage at Wolverine Glacier (Mayo, March, and Trabant, 1992; Kennedy, 1995). Briefly, the gage consists of a steel storage tank that tapers to a conical orifice, 0.305 m in diameter, 3 m above the ground. A modified Nipher shield (Warnick, 1953) is installed around the orifice to improve the catch efficiency during windy conditions. The preliminary daily precipitation catch (fig. 6, table 4) has an estimated accuracy of ±0.001 m and the cumulative gage catch for monthly and annual values is estimated to have an accuracy of ±0.002 m (Mayo, March, and Trabant, 1992; Kennedy, 1995).

The complex relation between precipitation catch and true basin precipitation has not been thoroughly analyzed at Gulkana. It is generally well known that gage catch efficiency is reduced by strong winds, especially for snow precipitation. Worse, catch efficiencies are not constant but vary with wind speed, direction, and the nature of the precipitation. At Wolverine Glacier, which has a windier environment than Gulkana, the gage-catch efficiency was found to be about 0.31 relative to the basin precipitation for a 10-year period (Mayo, March, and Trabant, 1992). From April 27, 1967 to September 30, 1967 the catch efficiency of the Gulkana gage was calculated at 0.52 (Tangborn and others, 1977), though the wind shield has since been modified to what we believe is a more efficient design. Despite the low catch efficiencies, precipitation catch is useful as a precipitation indicator.

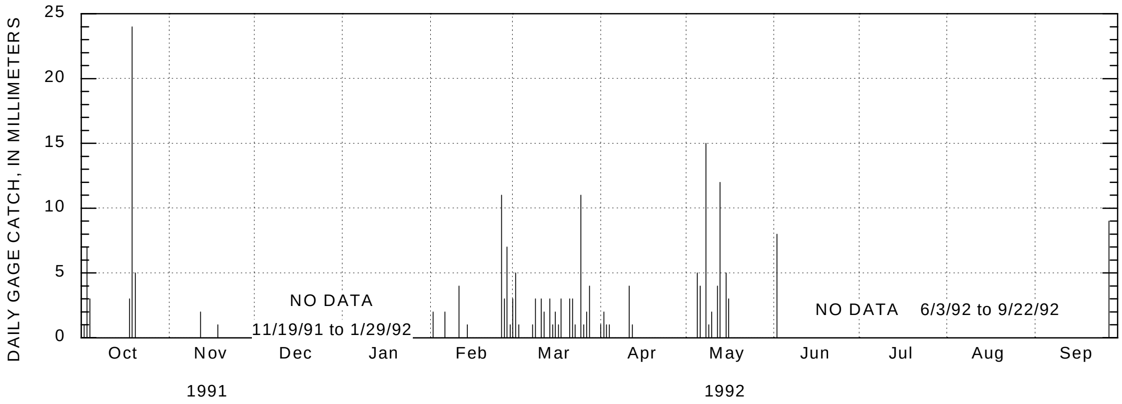

Figure 6. Daily precipitation-gage catch recorded at 1,480 meters altitude in the Gulkana Glacier basin.

RUNOFF

The Phelan Creek stream-gaging station, USGS no. 15478040, is located at 1,125 m altitude, about 1 km downstream from the present glacier terminus (fig. 1). 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. The published discharge record is rated as "poor" meaning that the records do not meet the criteria for a “fair”

Table 4. Daily precipitation-gage catch from the recording gage at 1,480 meters altitude

[Values in millimeters; Not Valid indicates monthly accumulated precipitation has more than 9 days missing; — , daily value missing]

	1991			1992								
Day	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
1	9	0	—	—	0	3	1	0	0	—	—	—
2	1	0	—	—	2	5	2	0	8	—	—	—
3	7	0	—	—	0	1	1	0	—	—	—	—
4	3	0	—	—	0	0	1	0	—	—	—	—
5	0	0	—	—	0	0	0	5	—	—	—	—
6	0	0	—	—	2	0	0	4	—	—	—	—
7	0	0	—	—	0	0	0	0	—	—	—	—
8	0	0	—	—	37	1	0	15	—	—	—	—
9	0	0	—	—	0	3	0	1	—	—	—	—
10	0	0	—	—	0	0	0	2	—	—	—	—
11	0	0	—	—	4	3	4	0	—	—	—	—
12	0	2	—	—	0	2	1	4	—	—	—	—
13	0	0	—	—	0	0	0	12	—	—	—	—
14	0	0	—	—	1	3	0	0	—	—	—	—
15	0	0	—	—	0	1	0	5	—	—	—	—
16	0	0	—	—	0	2	0	3	—	—	—	—
17	0	0	—	—	0	1	0	0	—	—	—	—
18	3	1	—	—	0	3	0	0	—	—	—	—
19	24	—	—	—	0	0	0	0	—	—	—	—
20	5	—	—	—	0	0	0	0	—	—	—	—
21	0	—	—	—	0	3	0	0	—	—	—	—
22	0	—	—	—	0	3	0	0	—	—	—	—
23	0	—	—	—	0	1	0	0	—	—	—	0
24	0	—	—	—	0	0	0	0	—	—	—	0
25	0	—	—	—	0	11	0	0	—	—	—	0
26	0	—	—	—	11	1	0	0	—	—	—	0
27	0	—	—	—	3	2	0	0	—	—	—	9
28	0	—	—	—	7	4	0	0	—	—	—	0
29	0	—	—	—	1	0	0	0	—	—	—	0
30	0	—	—	144		0	0	0	—	—	—	0
31	0		—	0		0		0		—	—	
Month Total	52	Not Valid	Not Valid	Not Valid	68	53	10	51	Not Valid	Not Valid	Not Valid	Not Valid
											Annual Total =	**Not Valid**

rating which is defined as “about 95 percent of the daily discharges are within 15 percent of the true value” (Kemnitz and others, 1993). This formal rating places no limit on the possible error. It is estimated that the standard error of the measured daily discharge values during the open-water season at Phelan Creek is about 8 percent (Richard Kemnitz, U.S. Geological Survey, oral commun., 1995). No stage record was collected during the winter when Phelan Creek freezes over. Discharge values are estimated for the ice period on the basis of air temperature, precipitation, and winter discharge measurements (November 8, 1991; February 6, 1992; and March 27, 1992). The 1992 daily mean discharge data (Kemnitz and others, 1993) were converted to runoff (fig. 7, table 5) by dividing the discharge values by the basin area. The 1992 stream runoff from the basin was 1.24 m.

Photography

Parts of the Gulkana Glacier basin were photographed from low altitude and the ground with a hand-held 35-mm camera during the 1992 HY (table 1).

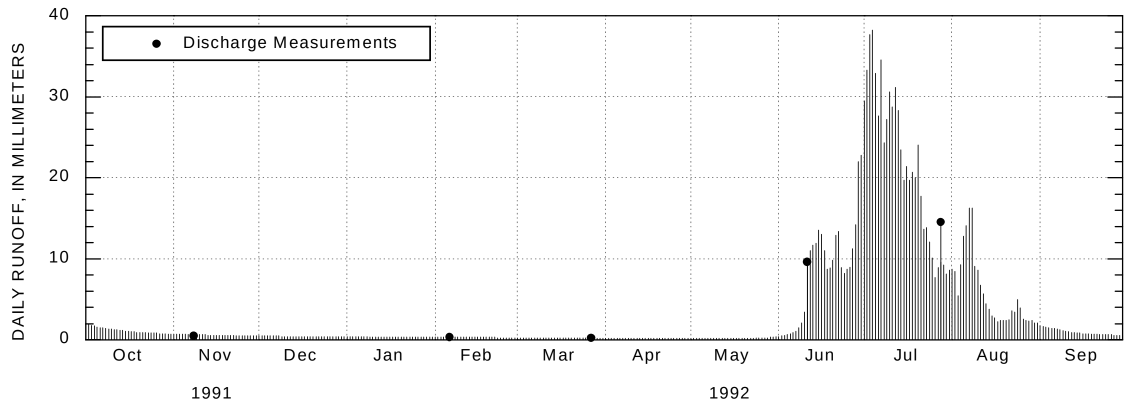

Figure 7. Daily runoff from Phelan Creek near Paxson (USGS stream-gaging station no. 15478040) (Kemnitz and others, 1993).

Table 5. Daily mean runoff of the Gulkana Glacier basin calculated from the published discharge of USGS stream-gaging station no. 15478040, Phelan Creek near Paxson, at 1,125 meters altitude, and the basin area (Kemnitz and others, 1993)

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

		1991						1992				
Day	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1	1.9	(0.7)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.4)	29.5	8.7	1.7	
2	1.9	(0.7)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.5)	33.3	8.4	1.6	
3	1.8	(0.7)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.5)	37.6	5.4	1.5	
4	(1.7)	(0.7)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.6)	38.3	9.3	1.5	
5	(1.5)	(0.7)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.8)	32.9	12.8	1.4	
6	(1.5)	(0.6)	(0.5)	(0.4)	0.3	(0.2)	(0.2)	(0.2)	(0.9)	27.6	14.1	1.4	
7	(1.5)	(0.6)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(1.1)	34.5	16.3	1.3	
8	(1.4)	0.6	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(1.5)	24.3	16.3	1.2	
9	(1.3)	(0.6)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(2.1)	27.2	9.1	1.1	
10	(1.3)	(0.6)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(3.4)	30.6	8.6	(1.1)	
11	(1.2)	(0.6)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(9.6)	28.7	6.7	(1.1)	
12	(1.2)	(0.6)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	11.0	31.1	5.7	(1.1)	
13	(1.2)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	11.7	28.3	4.4	(1.1)	
14	(1.2)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	11.9	23.5	3.8	(1.0)	
15	(1.1)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	13.6	19.7	2.9	(1.0)	
16	(1.1)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	13.0	21.4	2.7	(1.0)	
17	(1.0)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	11.0	19.7	2.2	(1.0)	
18	(1.0)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	8.7	20.7	2.4	(0.9)	
19	(0.9)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	8.8	20.0	2.4	(0.9)	
20	(0.9)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	9.8	24.1	2.4	(0.9)	
21	(0.9)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	12.9	17.7	2.5	(0.9)	
22	(0.9)	(0.5)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	13.4	13.6	3.6	(0.9)	
23	(0.9)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	8.9	13.9	3.4	(0.9)	
24	(0.9)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	8.2	12.1	5.0	(0.9)	
25	(0.9)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	8.7	10.1	3.9	(0.9)	
26	(0.9)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	9.0	7.7	2.6	(0.9)	
27	(0.8)	(0.5)	(0.4)	(0.3)	(0.2)	0.2	(0.2)	(0.2)	11.2	8.9	2.4	(0.9)	
28	(0.8)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	14.2	9.6	2.3	(0.9)	
29	(0.8)	(0.5)	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.3)	22.0	9.2	2.4	(0.9)	
30	(0.7)	(0.5)	(0.4)	(0.3)		(0.2)	(0.2)	(0.3)	22.8	8.1	2.1	(0.9)	
31	(0.7)		(0.4)	(0.3)		(0.2)		(0.4)		8.6	2.1		
Sum	(35.6)	(17.0)	(12.6)	(10.2)	(8.4)	(6.9)	(4.6)	(5.7)	(252.1)	672.4	176.8	(33.3)	1,235.7
Sum of Measured Values	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	230.8	672.4	176.8	12.8	1098.4
Sum of Estimated Values	(30.0)	(17.0)	(12.6)	(10.2)	(8.4)	(6.9)	(4.6)	(5.7)	(21.4)	(0.0)	(0.0)	(20.4)	(137.4)
% Measured	16%	0%	0%	0%	0%	0%	0%	0%	92%	100%	100%	39%	89%

1992 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 quantities of internal accumulation. Indeed, many uncertainties must be estimated because there are an insufficient number of independent samples 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. Uncertain at this time is the error introduced by extrapolating from a few index-site values to glacier-wide and basin values. An independent assessment of long-term glacier volume change by means of profile surveying and photogrammetric mapping is under way to assess this error and, if necessary, revise the algorithm for extrapolating glacier-wide balance from index-site values. Error estimates are included in tabular data in this report.

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) and the stake, pit, probing, coring, and meteorological data (tables 6, 7, and 8; fig. 3).

One departure from the traditional methods is our application of stake geometry corrections that affect not only the stake position for motion ("Ice Motion Measurement and Errors" section), but also the height on the stake of the glacier surface, *b´* (table 6). After the position of the bottom of the stake is calculated using the stake's geometry, the height of the point on the glacier surface directly above the stake bottom is calculated and 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. These stake *b´* corrections typically change our balance determinations by about 5 cm, but occasionally up to 0.5 m.

Also a departure from traditional methods is our procedure for making and using multiple measurements of the height of a specific summer surface on a given stake to both understand and to reduce the balance errors at a single site. For example, we typically measure the snow depth and the stake height of the snow (glacier) surface in the fall after the formation of the summer surface and again during the winter or spring, giving us two measurements of the stake height of the same summer surface. If the measurements were made in the accumulation zone, a third measurement of this stake height of the summer surface can be made the following fall by subtracting the measured snow depth and firn depth from the stake height of the glacier surface. Because of measurement error, these successive measurements of the height of a specific summer surface on a given stake are usually different, yet, barring stake slip, the height of the summer surface on a given stake should not have changed. The interpretation that the differing stake measurements are the result of measurement error is reinforced by the observation that multiple measurements vary randomly, sometimes increasing and sometimes decreasing. 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 uses 20 snow-depth probings is given twice the weight of a measurement with 10 snow-depth probings. The weighted-average stake height of a specific summer surface is then used for all calculations of balance relative to that summer surface.

The temporal extrapolations between measurements necessary to determine estimated index-site balances, such as maximum winter balance and annual balance, are determined using a simple linear model that relates the recorded air temperature and precipitation-gage catch to glacier 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. Using the lapsed temperatures, the model estimates glacier ablation at the rate of about 5 mm water equivalent per degree Celsius above 0°C per day. Glacier accumulation is estimated by the model to be about 1.5 times the precipitation-gage catch when the temperature is below +1.8°C. The melt (or ablation) rate and the precipitation catch multipliers are not fixed, but are chosen to match measured balances on the glacier at the index sites.

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:

$$\bar{b} = 0.196\ (b_A) + 0.224\ (b_B) + 0.580\ (b_D)$$

where $\bar{b}$ is the glacier-averaged balance and b_A, b_B, and b_D are measured index-site balance values. The weighting factors, 0.196 for site A, 0.224 for site B, and 0.580 for site D, are derived by splitting the glacier into three sub-areas (index regions) at altitudes midway between the index sites (table 2). The percentage of total glacier area in each index region is the weighting factor for the index site within that region. For this method to be valid, the index-site balance value should equal the average balance in the index region.

This weighted, index-site method was used to reassess the 1966 and 1967 measured winter snow balance and annual firn-and-ice balance data published by Meier and others (1971) and by Tangborn and others (1977) (table 9). The annual firn and ice balance was

Table 6. Stake, snow depth, snow density, and snow temperature data for sites A, B, and D at Gulkana Glacier

[Stake name: two digits represent the year the stake was installed; letter (A, B, D) represents the site on the glacier; 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. Observed *b'*, the average stake height of the glacier surface within a 50-meter radius of the stake. *b**, stake height of surveyed point on the stake near *b'*. *b***, calculated height of the glacier surface directly above the stake bottom (i.e. as if the stake were vertical). *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. Stake *d*(s), snow depth as determined from the best *b'* and previous or subsequent determinations of the stake height of the summer surface. Pit *d*(s), snow depth measured in snow pit. McCall *d*(s), snow depth measured with a McCall snow sampler, a small-diameter sampler used to core the entire snowpack. Probe *d*(s), snow depth measured by probing to the summer surface with a metal rod. 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. Summer-surface temperature, observed with dial (±1.0°C) or digital (±0.1°C) thermometer, or estimated and the mean temperature. m, meter; kg/L, kilograms per liter]

			Stake Readings & Data							**Snow Depth**										**Snow Density**				**Summer Surf. Temp.**	
Date yy/mm/dd	**Stake Name**	**Surface Strata Type**	**Found /Left (m)**	**Obs. b' No Lean Correct. (m)**	**Surveyed *b** (m)**	**Surveyed *b*** (m)**	**Diff. *b*-b*** (m)**	**Total Stake Slip (m)**	**Best Stake *b'* (m)**	**Stake *d*(s) (m)**	**Pit *d*(s) (m)**	***n***	**McCall *d*(s) (m)**	***n***	**Probe *d*(s) (m)**	***n***	**Mean *d*(s) (m)**	**s.e. *d*(s) (m)**	***n***	**Pit (kg/L)**	**McCall (kg/L)**	**Est. (kg/L)**	**Mean (kg/L)**	**Obs. (degrees Celsius)**	**Est. (degrees Celsius)**
SITE A, 1372 m.																									
09/06/91	91-A	Ice/Dirt	6/6	2.52	2.51	2.51	0.00	0.00	2.52								0.00								
09/30/91	91-A	LSnow																				0.30	0.30		
10/07/91	91-A	Snow	9/9	2.80				0.00	2.80						0.44	26	0.44	0.02	26			0.30	0.30		
02/06/92	91-A	Snow	6/6	4.05				0.00	4.05	1.69							1.69					0.30	0.30		
03/26/92	91-A	Snow	6/3	3.95	3.93	3.95	0.02	0.00	3.97				1.63	2			1.63	0.00	2		0.32		0.32		
03/26/92	92-A	Snow	0/12	10.78	10.77	10.80	0.03	0.00	10.81				1.63	2			1.63	0.00	2		0.32		0.32		
05/19/92	92-A	Snow																							
07/22/92	92-A	Dirt/rock		7.24	8.18	8.15	0.03	0.00	7.21								0.00								
09/22/92	92-A	LSnow	9/10	6.59	8.18	8.15	0.03	0.00	6.56		0.17	2			0.27	20	0.26	0.03	22	0.30			0.30		
09/30/92	92-A	LSnow																				0.30	0.30		
03/31/93	92-A	Snow	10/9	7.49	6.60	6.58	0.02	0.00	7.47		1.58	1			1.45	15	1.46	0.08	16	0.37			0.37	- 4.3	
SITE B, 1684 m.																									
04/17/91	91-B2	Snow	0/9	10.48	10.47	10.49	0.02	0.00	10.50						3.31	20	3.31	0.04	20			0.42	0.42		
09/06/91	91-B2	Ice	12/12	6.88				0.00	6.88								0.00								
09/30/91	91-B2	LSnow																							
10/07/91	91-B2	Snow	12/12	7.78	7.80	7.82	0.02	0.00	7.80		0.97	1			0.89	21	0.90	0.02	22	0.32			0.32		
03/26/92	91-B2	Snow	12/9	9.47	9.52	9.57	0.05	0.00	9.52				2.46	2	2.35	10	2.37	0.01	12		0.37		0.37		
05/19/92	91-B2																								
07/18/92	91-B2	Snow		7.50				0.00	7.50	0.51							0.51					0.50	0.50		
07/22/92	91-B2	Snow	9/9	7.22	6.88	6.90	0.02	0.00	7.24	0.25							0.25		0			0.52	0.52		
09/22/92	91-B2	LSnow	(9/9)	7.11	7.11	7.13	0.02	0.00	7.13		0.66	1			0.68	17	0.68	0.02	18	0.27			0.27		
09/30/92	91-B2	LSnow																							
03/30/93	91-B2	Snow	11/11	8.64	8.63	8.67	0.04	0.00	8.68		2.31	1	2.40	3	2.29	20	2.30	0.03	24	0.37	0.37		0.37	- 3.2	

Table 6. Stake, snow depth, snow density, and snow temperature data for sites A, B, and D at Gulkana Glacier--Continued

			Stake Readings & Data							**Snow Depth**										**Snow Density**				**Summer Surf. Temp.**	
				Obs. b’				**Total**	**Best**																
		Surface	**Found**	**No Lean**	**Surveyed**		**Diff.**	**Stake**	**Stake**	**Stake**	**Pit**		**McCall**		**Probe**		**Mean**	**s.e.**		**Pit**	**McCall**	**Est.**	**Mean**	**Obs.**	**Est.**
Date	**Stake**	**Strata**	**/Left**	**Correct.**	***b****	***b*****	***b*-b*****	**Slip**	***b’***	***d*(s)**	***d*(s)**	***n***	***d*(s)**	***n***	***d*(s)**	***n***	***d*(s)**	***d*(s)**	***n***						
yy/mm/dd	**Name**	**Type**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**		**(m)**		**(m)**		**(m)**	**(m)**		**(kg/L)**	**(kg/L)**	**(kg/L)**	**(kg/L)**	**(degrees Celsius)**	
Site D, 1838 m.																									
04/17/91	91-D	Snow	0/9	7.09	7.09	7.10	0.01	0.00	7.10	3.68							3.68				0.40		0.40	- 4.0	
09/30/91	91-D	LSnow																							
10/07/91	91-D	Snow	9/11	6.37	6.38	6.37	0.01	-0.18	6.18		1.18	1					1.18		1	0.32			0.32		
03/26/92	91-D	Snow	11/11	8.50	8.48	8.53	0.05	-0.18	8.37				3.29	1	3.32	5	3.32	0.07	6		0.35		0.35	- 4.6	
05/19/92	91-D	Snow																							- 4.6
07/18/92	91-D	Snow	11/11	6.95				-0.50	6.45	1.36							1.36		0			0.50	0.50		0.0
09/22/92	91-D	LSnow	11/11	7.30	7.31	7.33	0.02	-0.50	6.82		0.84	1			0.87	5	0.86	0.02	6	0.24			0.24		0.0
09/30/92	91-D	LSnow																							
03/31/93	91-D	Snow	11/11	8.85	8.85	8.84	0.01	-0.50	8.34		2.36	1			2.53	8	2.51	0.06	9	0.36			0.36	- 4.8	
07/12/93	91-D	Snow	no change	7.34	7.35	7.38	0.03	-0.81	6.56	0.68							0.68					0.50	0.50		0.0
08/02/93	91-D	91 Firn	11/9	6.09	6.05	6.04	0.01	-0.85	5.23								0.00								0.0

Table 7. Continuation of stake data with firn depth, firn density, and ice data for sites A, B, and D at Gulkana Glacier

[Heights are above the bottom of the stake. Depths are measured from the glacier surface. Initial values are those at the beginning of the hydrologic year. Obs., observed values on a given date, generally the difference between the best stake *b'* and multiple snow or firn depth observations. b_0', initial average stake height of the glacier surface within a 50-meter radius of the stake, in meters. ss$_1$, first glacier summer surface down from the glacier surface (this is typically a bare ice surface in the ablation zone and a fin 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. Mean heights average stake heights of a given stratigraphic surface (summer surface) observed on different dates. *d*(nf), new firn depth, in meters. Mean depths average all pit, McCall, and probing depths for a given date. s.e. is standard error. *n*, number of observations. Diff., the difference between the observed value on a given date 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 meters. m, meter; kg/L, kilograms per liter]

			Height of Top of 1st Firn				Depth to Bottom of 1st Firn Layer										Firn Density			Height of 1st Firn Bottom				Height of Top of Ice			
Date yy/mm/dd	Stake Name	Surface Strata Type	Initial b_0'ss$_1$ (meters)	Obs. b'ss$_1$	Mean b'ss$_1$	ss$_1$ Diff.	Stake d(nf) (m)	Pit d(nf) (m)	n	McCall d(nf) (m)	n	Probe d(nf) (m)	n	Mean d(nf) (m)	s.e. d(nf) (m)	n	Pit (kg/L)	Est. (kg/L)	Mean (kg/L)	Initial b_0'ss$_2$ (meters)	Obs. b'ss$_2$	Mean b'ss$_2$	diff. ss$_2$ Diff.	Initial b_0'ss$_1$ (meters)	Obs. b'ss$_1$	Mean b'ss$_1$	ss$_1$ Diff.
SITE A, 1372 m.																											
91/09/06	91-A	Ice/Dirt																						6.16	2.52	2.52	0.00
91/09/30	91-A	LSnow																						6.16		2.36	
91/10/07	91-A	Snow																						2.36	2.36	2.36	0.00
92/02/06	91-A	Snow																						2.36			
92/03/26	91-A	Snow																						2.36	2.34	2.36	0.02
92/03/26	92-A	Snow																						9.18	9.18	9.18	
92/05/19	92-A	Snow																									
92/07/22	92-A	Dirt/rock																						9.18	7.21	7.21	
92/09/22	92-A	LSnow																						9.18	6.30	6.18	0.12
92/09/30	92-A	LSnow																						9.18		6.18	
93/03/31	92-A	Snow																						6.18	6.01	6.18	0.17
SITE B, 1684 m.																											
91/04/17	91-B2	Snow																						7.19	7.19	7.19	
91/09/06	91-B2	Ice																						7.19	6.88	6.99	0.11
91/09/30	91-B2	LSnow																						7.19		6.99	
91/10/07	91-B2	Snow																						6.99	6.90	6.99	0.09
92/03/26	91-B2	Snow																						6.99	7.15	6.99	0.16
92/05/19	91-B2																										
92/07/18	91-B2	Snow																						6.99		6.99	
92/07/22	91-B2	Snow																						6.99		6.99	
92/09/22	91-B2	LSnow																						6.99	6.45	6.41	0.04
92/09/30	91-B2	LSnow																						6.99		6.41	
93/03/30	91-B2	Snow																						6.41	6.38	6.41	0.03
Site D, 1838 m.																											
91/04/17	91-D	Snow	3.42	3.42	3.42					4.01	1	4.00	13	4.00	0.05	14				3.10	3.10	3.10	0.00				
91/09/30	91-D	LSnow	3.42		5.04														0.51	3.10		3.42					
91/10/07	91-D	Snow	5.09	5.00	5.09	0.09		2.59	1			2.78	12	2.76	0.09	13	0.51		0.51	3.42	3.42	3.42	0.00				
92/03/26	91-D	Snow	5.09	5.05	5.09	0.04																					
92/05/19	91-D	Snow	5.09		5.09																						
92/07/18	91-D	Snow	5.09		5.09																						
92/09/22	91-D	LSnow	5.09	5.96	5.88			1.58	1			1.74	2	1.68	0.06	3	0.54		0.54	3.42	5.14	5.09	0.05				
92/09/30	91-D	LSnow	5.09		5.88													0.54	0.54	3.42		5.09					
93/03/31	91-D	Snow	5.88	5.83	5.88															5.09							
93/07/12	91-D	Snow	5.88	5.88	5.88													0.61	0.61	5.09							
93/08/02	91-D	91 Firn	5.88	5.23	5.23												0.61		0.61	5.09							

Table 8. Continuation of stake data with mass-balance calculations for sites A, B, and D at Gulkana Glacier

[b_0(s), initial snow balance; b_0(i), initial ice balance; b(s), snow balance; b_1(i), late ice balance; b_1(ls), late snow balance; b(f), firn balance; b(k), internal accumulation; b(i), ice balance; b_n, net balance; b_a, annual balance; m_{we}, meters water equivalent (See Mayo and others (1972) for detailed explanation of this terminology)]

			Water Equivalent Balances										
Date yy/mm/dd	**Stake Name**	**Surface Strata Type**	**Init. Snow b_o(s) (m_{we})**	**Init. Ice b_o(i) (m_{we})**	**Snow b(s) (m_{we})**	**Late Ice b_1(i) (m_{we})**	**Late Snow b_1(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})**	**Special Notes**
SITE A, 1372 m.													
91/09/06	91-A	Ice/Dirt		0.00	0.00	0.00	0.00	0.00	0.00	- 3.28	-3.28		Stake in edge of moraine, but not at high point; ablation does not appear to be significantly different right at stake.
91/09/30	91-A	LSnow		0.00	0.04	0.00	0.04	0.00	0.00	- 3.42	0.04		Est. annual balance
91/10/07	91-A	Snow	0.04	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.13	0.09	
92/02/06	91-A	Snow	0.04	0.00	0.51	0.00	0.00	0.00	0.00	- 2.12	-1.61	-1.65	
92/03/26	91-A	Snow	0.04	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0.52	0.48	
92/03/26	92-A	Snow	0.04	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0.52	0.48	
92/05/19	92-A	Snow	0.04	0.00	0.58	0.00	0.00	0.00	0.00	0.00	0.58	0.54	Est. maximum winter snow balance
92/07/22	92-A	Dirt/rock	0.04	0.00	0.00	0.00	0.00	0.00	0.00	- 1.77	-1.77	-1.81	
92/09/22	92-A	LSnow	0.04	0.00	0.08	0.00	0.08	0.00	0.00	- 2.70	0.08	-2.66	
92/09/30	92-A	LSnow	0.04	0.00	0.08	0.00	0.08	0.00	0.00	- 2.70	0.08	-2.66	Est. annual balance
93/03/31	92-A	Snow	0.08	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.54	0.46	
SITE B, 1684 m.													
91/04/17	91-B2	Snow		0.00	1.39	0.00	0.00	0.00	0.00	0.00	1.39		
91/09/06	91-B2	Ice		0.00	0.00	0.00	0.00	0.00	0.00	- 0.18	-0.18		
91/09/30	91-B2	LSnow		0.00	0.00	0.00	0.22	0.00	0.00	- 0.18	0.00		Est. annual balance
91/10/07	91-B2	Snow	0.22	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.29	0.07	
92/03/26	91-B2	Snow	0.22	0.00	0.88	0.00	0.00	0.00	0.00	0.00	0.88	0.66	
92/05/19	91-B2		0.22	0.00	0.96	0.00	0.00	0.00	0.00	0.00	0.96	0.74	Est. maximum winter snow balance
92/07/18	91-B2	Snow	0.22	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.26	0.04	
92/07/22	91-B2	Snow	0.22	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.13	-0.09	
92/09/22	91-B2	LSnow	0.22	0.00	0.19	0.00	0.19	0.00	0.00	- 0.52	0.19	-0.55	
92/09/30	91-B2	LSnow	0.22	0.00	0.19	0.00	0.19	0.00	0.00	- 0.52	0.19	-0.55	Est. annual balance
93/03/30	91-B2	Snow	0.19	0.00	0.85	0.00	0.00	0.00	0.00	0.00	0.85	0.66	
Site D, 1838 m.													
91/04/17	91-D	Snow		0.00	1.47	0.00	0.00	0.00	0.00	0.00	1.47		
91/09/30	91-D	LSnow		0.00		0.00	0.30	0.83	0.16	0.00	0.99		Est. annual balance
91/10/07	91-D	Snow	0.30	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.35	0.05	
92/03/26	91-D	Snow	0.30	0.00	1.15	0.00	0.00	0.00	0.00	0.00	1.15	0.85	
92/05/19	91-D	Snow	0.30	0.00	1.25	0.00	0.00	0.00	0.00	0.00	1.25	0.95	Est. maximum winter snow balance
92/07/18	91-D	Snow	0.30	0.00	0.68	0.00	0.00	0.00	0.18	0.00	0.86	0.56	
92/09/22	91-D	LSnow	0.30	0.00	**0.22**	0.00	0.22	0.43	0.18	0.00	**0.83**	0.53	
92/09/30	91-D	LSnow	0.30	0.00	**0.22**	0.00	0.22	0.43	0.18	0.00	**0.83**	0.53	Est. annual balance
93/03/31	91-D	Snow	0.22	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.89	0.67	
93/07/12	91-D	Snow	0.22	0.00	0.34	0.00	0.00	0.00	0.19	0.00	0.53	0.31	
93/08/02	91-D	91 Firn	0.22	0.00	0.00	0.00	0.00	0.00	0.19	- 0.40	-0.21	-0.43	91 & '92 summer surface sawdust patches exposed

Table 9. Mapped and weighted index-site balances for 1966 and 1967

[Mapped values for 1966 from Meier and others (1971) and for 1967 from Tangborn and others (1977)]

Glacier averaged balance quantity & method	**1966 balance (meters)**	**1967 balance (meters)**
b_m(s), Measured winter snow balance		
Mapped value	1.00 ± 0.15	1.05 ± 0.12
Weighted index-site value	1.13 ± 0.33	1.08 ± 0.33
b_a(fi), Annual firn & ice balance		
Mapped value	-0.21 ± 0.10	-0.28 ± 0.14
Weighted index-site value	-0.01 ± 0.46	-0.29 ± 0.46

used for the comparison because it is similar to the net balance, whereas insufficient net-balance data were published for 1966 and 1967 to allow a direct net-balance comparison. The errors associated with the weighted index-site values are large because the current index-site locations were not measured in 1966 or 1967. Hence, the index-site values were picked by interpolating from 1966 and 1967 balance contour maps. The errors are larger for the annual firn-and-ice balance because the contour interval on those maps is greater. The results of the comparison show that the weighted index-site values are consistently high, but within the estimated errors. Figures 8 and 9 show a detailed comparison for 1966 and 1967 of the estimated index-site balances, the mapped balances with altitude, and the average balances for the regions associated with each index site. Only index site B seems to consistently bias the data by overestimating the balance for its region. Given the variability of balance gradients we have observed, it is not justified to adjust the weighting factors on the basis of only 2 years of detailed data. The weighted, index-site method should be verified and (or) adjusted from an independent assessment of glacier mass balance for many years or from a long-term photogrammetric or surveyed volume change of the entire glacier. Until this has been done, it is not possible to determine the error in glacier-averaged balances, as determined by the weighted, index-site method. From the 1966 and 1967 data, we estimate that glacier-averaged balance values have an error of ±0.2 m.

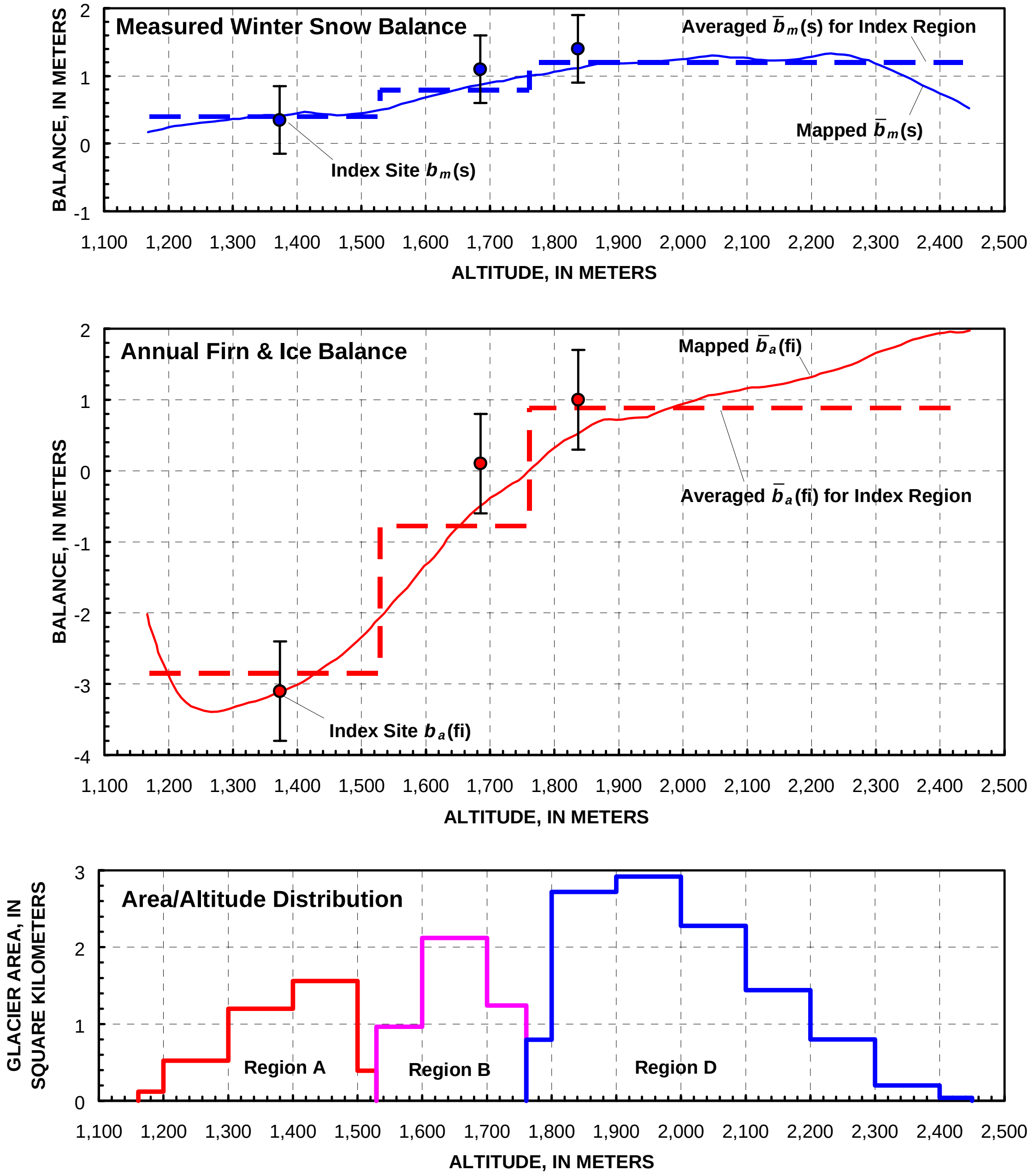

Figure 8. Altitude distribution of measured winter snow balance, b_m(s), annual firn and ice balance, b_a(fi), and glacier area of Gulkana Glacier for 1966 (data from Meier and others, 1971). (Index-site values and error bars are estimated from balance contour maps by Meier and others (1971). Average balance values for index regions are calculated by integrating the balance curve with the area/altitude curve for the region of each index site.)

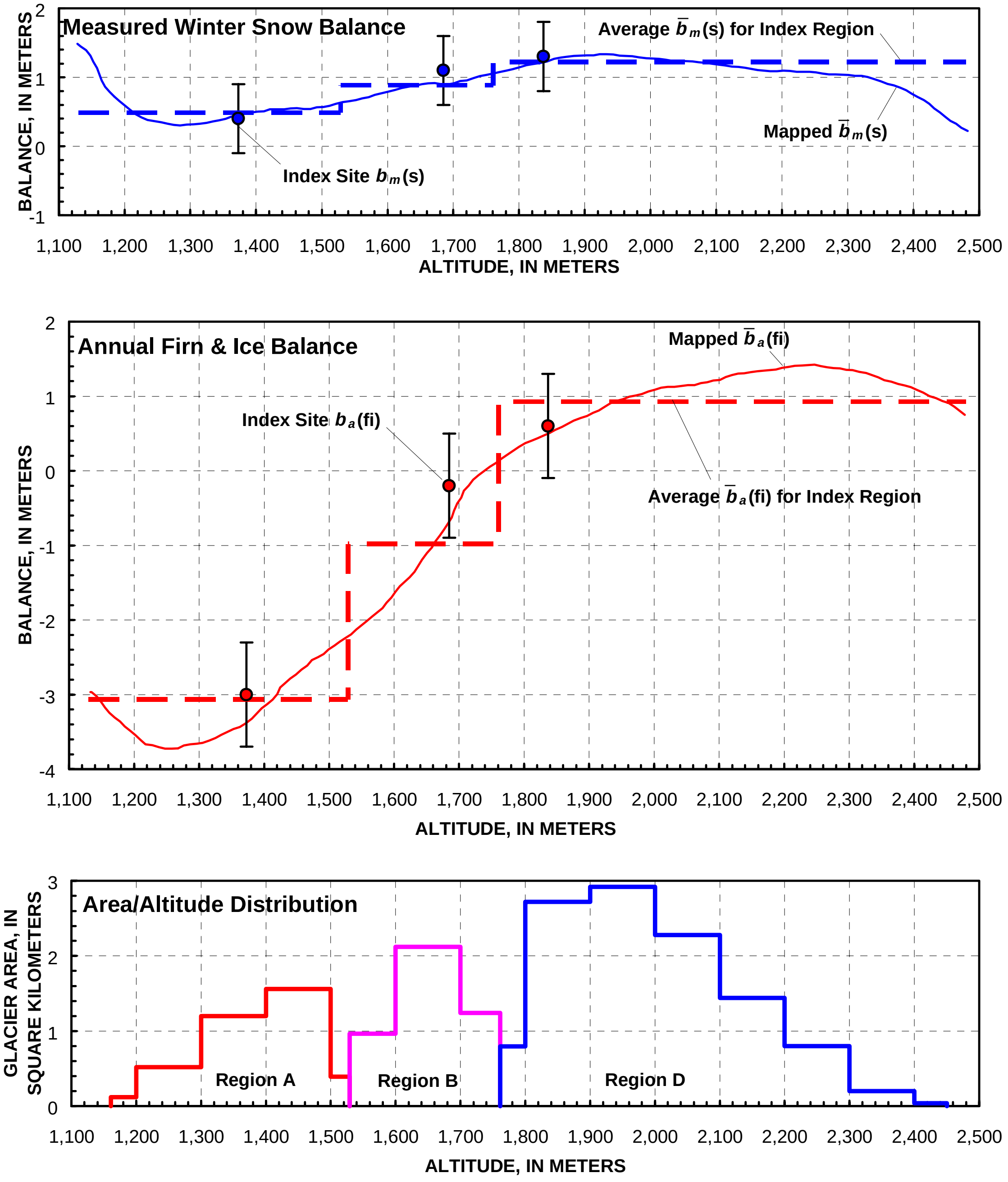

Figure 9. Altitude distribution of measured winter snow balance, b_m(s), annual firn and ice balance, b_a(fi), and glacier area of Gulkana Glacier for 1967 (data from Tangborn and others, 1977). (Index-site values and error bars are estimated from balance contour maps by Tangborn and others (1977). Average balance values for index regions are calculated by integrating the balance curve with the area/altitude curve for the region of each index site.)

Weather in 1991-1992

The 1992 net balance year began on September 6, 1991, when below-freezing temperatures and snow accumulation started on the upper part of the glacier. The seasonal stream runoff recession began during late September 1991. The last day of open-water stage at the stream-gaging station at 1,125 m altitude was recorded on October 3, 1991. The lowest daily-mean winter air temperature was -27°C on February 27, 1992. Winter (October 1 to April 30) precipitation-gage catch totaled 308 mm. As is typical, no surface melt occurred on the glacier from about October 1 to mid-April. The 1992 mass balance maximum occurred about May 19 after surface melting on the lower part of the glacier and the seasonal rise in runoff had presumably begun. The final mass balance minimum occurred about August 17, 1992, when the entire glacier was observed covered by fresh snow that did not melt; the seasonal runoff recession began after August 25, 1992, when the season's last precipitation-caused runoff peak ended. The last day of open-water stage was recorded on September 9, 1992. The total runoff for the 1992 water year was 65 percent of the mean for the period of record (1966-78 and 1989-current).

Measured and Maximum Winter Snow Balances[1]

The glacier-average measured winter snow balance, $\bar{b}_m$(s), is the balance measured to the summer surface in late winter or spring (Mayo and others, 1972). It was 0.97 m on March 26, 1992 (table 10). This value was derived by using the weighted index-site method and the March field visit data (tables 6, 7, and 8). 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 and is determined by estimating the balance increment at each index site between the time of the measured winter snow balance and the time of the maximum winter snow balance. The 1992 glacier-average maximum winter snow balance of 1.05 m occurred about May 19, 1992 (table 10).

Net Balance

Net balance is the change in snow, firn, and ice storage between times of minimum glacier mass (Mayo and others, 1972). The net balance, b_n, at each index site is calculated directly from balance-motion stake, pit, and probing data. Field measurements made near the end of the balance year are confirmed with measurements during the next balance year before final values are assigned (tables 6, 7, and 8). The 1992 net balance year began on about September 8, 1991, and ended on about August 17, 1992; the glacier-average net balance was -0.29 m (table 10).

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[1] Mayo and others (1972) define three "winter" balance values in the stratigraphic system: the measured winter snow balance, $\bar{b}_m$(s); the maximum winter snow balance, $\bar{b}_w$(s); and the winter balance, $\bar{b}_w$. The World Glacier Monitoring Service (WGMS) publishes a winter balance that is not rigorously any of these, but is most closely related to the measured winter snow balance, $\bar{b}_m$(s).

Table 10. Area-integrated measured winter snow, maximum winter snow, annual, and net balance quantities for Gulkana Glacier and Gulkana Glacier basin

Balance quantity and site or area	**Balance (meters)**
b_m(s), Measured winter snow balance on March 26, 1992	
Site A, 1373 m.	0.52
Site B, 1685 m.	0.88
Site D, 1837 m.	1.15
Glacier Average	0.97
b_w(s), Maximum winter snow balance on May 19, 1992	
Site A, 1373 m.	0.58
Site B, 1685 m.	0.96
Site D, 1837 m.	1.25
Glacier Average	1.05
b_a, Annual balance, October 1, 1991 - September 30, 1992	
Site A, 1373 m.	-2.65
Site B, 1685 m.	-0.74
Site D, 1837 m.	0.53
Glacier Average	-0.38
b_n, Net balance, September 8, 1991 - August 17, 1992	
Site A, 1373 m.	-2.70
Site B, 1685 m.	-0.52
Site D, 1837 m.	0.61
Glacier Average	-0.29

Summer Balance

The summer balance, $\bar{b}_s$, was not defined by Mayo and others (1972); we follow the definition by United Nations Educational, Scientific, and Cultural Organization/ International Association of Scientific Hydrology (1970) which says it is the algebraic difference between the winter balance and the net balance, $\bar{b}_n$. Following their definition of winter balance, we use the corresponding term from Mayo and others (1972), $\bar{b}_w$(s), so that:

$$\bar{b}_s = \bar{b}_n - \bar{b}_w(s) = -1.34 \text{ m}$$

Annual Mass Balance

Annual mass balance is the change in snow, firn, and ice storage between the beginning (October 1, 1991) and end (September 30, 1992) of the hydrologic year. Evaluation of the 1992 annual balance required estimating two adjustment quantities. At the beginning of the hydrologic year, the initial snow balance at each index site, b_0(s), was estimated using field data from the balance-motion stakes and air temperature and precipitation data. At the end of the hydrologic year, the final late snow balance at each index site, b_1(ls), was estimated using field data from the balance-motion stakes and air temperature and precipitation data. The 1992 annual balance at each index site, b_a, is derived from the net balance and adjustment quantities: $b_a = b_n - b_0(\mathrm{s}) + b_1(\mathrm{ls})$ (table 8). The index-site annual balances are combined using the weighted index-site method to yield the 1992 annual balance of -0.38 m (table 10).

Accumulation Area Ratio and Equilibrium Line Altitude

The accumulation area ratio (AAR) is the area of new firn, superimposed ice, and any area where internal accumulation exceeds old firn loss, i.e. the accumulation area, divided by the total glacier area. The 1992 AAR was 0.59, based on a glacier surface area of 19.3 km^2, which was reported for 1967 by Tangborn and others (1977).

The equilibrium line altitude (ELA), the average altitude where snow ablation equals snow accumulation, seldom crosses a glacier at a single altitude. The Gulkana Glacier ELA can be extremely complicated and would require well-timed vertical or high-angle oblique aerial photography to define accurately. Obtaining this kind of photography near the time of formation of the ELA on a consistent basis year after year was judged impractical. Therefore, it was decided that calculating the ELA by linear interpolation from the balance-altitude curve for the three index sites would be a more consistent and meaningful method in the long term. The 1992 ELA for Gulkana Glacier was 1,755 m. The Gulkana Glacier terminus position was not measured during 1992.

The surface area of Gulkana Glacier and other small glaciers in the Gulkana Glacier basin has not been determined since 1967. Therefore, the reported areas and area ratios will change when a reassessment is made because obvious retreat of the terminus and thinning have occurred since 1967.

ICE MOTION MEASUREMENT AND ERRORS

Surface ice displacements near the fixed index sites are measured during each field visit by optical surveying. Balance-motion stakes are installed at a location equivalent to about one year's flow displacement upstream 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 (typically 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 11) are the average velocities derived from the linear displacement of the bottom of the stake divided by the measurement period. 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. Movement of the bottom of the stake is believed to be the most representative of the motion of the glacier 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 at 1 or 2 m higher on the stake) and then calculating the location of the stake bottom using a linear (lean), bent, or bowed stake geometry. In the long history of field observations at Gulkana Glacier, it has been rare to

Table 11. Stake locations, stake lean corrections, and ice motion determined from optical surveys

[Stake name: two digits represent the year the stake was installed; letter (A, B, D) represents the site on the glacier; 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; bow, treats the stake as a combination of linear and arc segments. *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 (i.e. as if the stake were vertical). Stake slip is distance the stake bottom has moved into the glacier; it is generally assumed that the stake bottom is fixed in the glacier. *dXYZ* is the total three-dimensional displacement of the stake bottom between measurements. Annual velocity is the stake displacement divided by the period between measurements. Horizontal displacement angle is measured positive counter-clockwise, zero is east. Vertical displacement angle is measured positive up from horizontal. m, meters; m/yr, meters per year]

			Stake, Lower Target			**Stake, Upper Target**				**Glacier Surface**		**Solution**	**Stake Angles**		**Stake Bottom**					**Stake**		**Annual**	**Displ. Angles**	
	Date	**Stake**	**X_g**	**Y_g**	**Z_g**	**X_t**	**Y_t**	**Z_t**	**H_t**	θ	ϕ	**Type**	θ	ϕ	**X_s**	**Y_s**	**Z_s**	***b****	***b*****	**Slip**	***d*XYZ**	**Velocity**	**Horiz.**	**Vert.**
	yy/mm/dd	**Name**	(meters)			(meters)				(grad)			(grad)		(meters)			(meters)			(m)	(m/yr)	(grad)	
Site A	91/04/18	91-A	3,821.58	4,463.64	1,376.79	3,821.46	4,463.67	1,378.89	10.00	-159.76	-7.46	lean	- 15.60	-96.25	3,822.03	4,463.53	1,368.90	7.90	7.92					
	91/09/06	91-A	3,814.81	4,455.62	1,371.39	3,814.78	4,455.60	1,373.38	4.50	-166.31	-6.81	lean	37.43	-98.85	3,814.85	4,455.65	1,368.88	2.51	2.51		10.66	27.60	-147.05	- 0.14
	92/03/26	91-A	3,808.02	4,448.29	1,373.13	3,807.87	4,448.28	1,375.19	6.00	-151.11	-7.55	lean	4.24	-95.36	3,808.31	4,448.31	1,369.21	3.93	3.95		9.84	17.78	-146.36	2.14
	92/03/26	92-A	3,818.69	4,460.43	1,375.05	3,818.62	4,460.44	1,376.28	12.00	-151.11	-7.55	lean	- 9.03	-96.34	3,819.30	4,460.34	1,364.30	10.77	10.80					
	92/07/22	92-A	3,813.26	4,453.81	1,373.10	3,813.19	4,453.86	1,373.92	9.00	-151.45	-6.86	lean	- 39.49	-93.35	3,813.95	4,453.31	1,364.96	8.18	8.15		8.86	27.41	-141.40	4.80
	92/09/22	92-A	3,811.00	4,451.40	1,371.18	3,810.78	4,451.51	1,373.57	9.00	-136.16	-9.97	lean	- 29.52	-93.47	3,811.60	4,451.10	1,364.61	6.60	6.58		3.25	19.13	-151.87	- 6.87
Site B	91/09/06	91-B2				4,764.86	7,439.53	1,692.44	9.00			lean			4,764.86	7,439.53	1,683.44				22.36	57.47	-131.56	- 6.03
	91/10/07	91-B2	4,762.56	7,435.54	1,690.81	4,762.54	7,435.45	1,693.01	10.00	-127.83	-6.31	lean	86.08	-97.33	4,762.63	7,435.86	1,683.02	7.80	7.82		4.32	50.86	-134.74	- 6.25
	92/03/26	91-B2	4,752.59	7,416.45	1,690.81	4,752.53	7,416.33	1,692.28	11.00	-130.41	-6.22	lean	70.48	-94.21	4,752.98	7,417.22	1,681.33	9.52	9.57		21.05	44.93	-130.43	- 5.11
	92/07/22	91-B2	4,744.38	7,399.58	1,686.44	4,744.42	7,399.46	1,688.56	9.00	-129.84	-6.35	lean	120.48	-96.21	4,744.25	7,399.97	1,679.57	6.88	6.90		19.42	60.07	-129.81	- 5.77
	92/09/22	91-B2	4,740.74	7,391.58	1,685.49	4,740.72	7,391.52	1,687.38	9.00	-131.05	-6.27	lean	79.52	-97.87	4,740.82	7,391.81	1,678.38	7.11	7.13		8.94	52.63	-125.36	- 8.49
	93/03/30	91-B2	4,731.22	7,371.53	1,685.15	4,731.15	7,371.40	1,687.01	10.50	-122.31	-5.99	lean	68.55	-94.96	4,731.54	7,372.13	1,676.55	8.63	8.67		21.83	42.16	-128.04	- 5.36
Site D	91/04/17	90-D2	6,012.02	7,354.21	1,840.47	6,011.76	7,354.71	1,841.94	7.00	174.07	-7.06	lean	- 69.47	-76.69	6,012.92	7,352.49	1,835.40	5.43	5.24	- 0.41	10.13	49.30	168.11	- 6.39
	91/10/07	90-D2	5,987.15	7,368.24	1,836.11	5,987.07	7,368.40	1,837.79	6.00	173.60	-6.75	lean	- 70.48	-93.25	5,987.35	7,367.83	1,831.82	4.31	4.32	- 0.41	30.03	63.36	165.58	- 7.60
	91/04/17	91-D	6,059.91	7,324.84	1,846.66	6,059.87	7,324.84	1,848.57	9.00	174.07	-7.06	lean		-98.67	6,060.06	7,324.84	1,839.57	7.09	7.10					
	91/10/07	91-D	6,034.50	7,339.70	1,841.95	6,034.52	7,339.66	1,844.07	8.50	173.60	-6.75	lean	129.52	-98.66	6,034.44	7,339.82	1,835.57	6.38	6.37		29.95	63.19	166.31	- 8.53
	92/03/26	91-D	6,011.32	7,353.14	1,841.02	6,011.07	7,353.33	1,843.02	10.50	140.53	-7.90	lean	- 41.37	-90.09	6,012.37	7,352.34	1,832.64	8.48	8.53		25.55	54.54	167.14	- 7.31
	92/09/22	91-D	5,984.48	7,368.66	1,835.61	5,984.37	7,368.67	1,837.30	9.00	159.02	-6.12	lean	- 5.77	-95.85	5,984.95	7,368.62	1,828.32	7.31	7.33		32.17	65.23	165.90	- 8.59
	93/03/31	91-D	5,959.80	7,382.52	1,834.33	5,959.44	7,382.65	1,836.45	11.00	147.92	-6.01	lean	- 22.06	-88.63	5,961.28	7,381.99	1,825.62	8.85	8.84		27.32	52.48	167.28	- 6.29

find melted-out stakes bent or bowed, so a "lean" geometry is generally assumed unless the stake is severely tilted. Occasionally, when a stake is severely tilted, it is partly excavated to determine if it is bent or bowed, and where. Bent or bowed geometries, when they do occur, generally occur at or above the most recent summer surface.

Determining and measuring the stake geometry is an imprecise process. Stake connectors, which join multiple 3-m stakes to make taller stakes, allow stake tilt of about ±1.5 grad at connectors. This translates into horizontal errors of ±0.15 m at the bottom of the typical stake that extends about 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. The bottom of the stake (X_sY_s in table 11) is typically offset horizontally 0.3-1.5 m from the surveyed target on the stake at the glacier surface (X_gY_g in table 11). Therefore, the geometric corrections are significant and would typically lead to motion errors of 5-20 percent in the Gulkana data if not corrected.

Location uncertainty is largely a result of the survey control net errors (GPS for horizontal and optical surveying for vertical) and resection[2] survey errors. Combined, these yield position errors of about ±0.15 m in the horizontal and ±0.05 m in the vertical. Additionally, ice motion errors include the error in assuming a stake geometry and extrapolating from surveyed points on the stake to the bottom of the stake. Measuring this error would require digging up a statistically significant number of stakes, an unreasonable task. We estimate the error of extrapolating to the bottom of the stake to be ±0.15 m, giving a total horizontal error for stake bottom positions of ±0.2 m. Vertical errors are significantly less, about ±0.05 m. Hence, reported displacements have errors of about ±0.3 m.

GLACIER SURFACE ALTITUDE MEASUREMENT AND ERRORS

Seasonal changes of the glacier surface altitude at each index site are measured during each field visit (tables 12-13). 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 to 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 net errors and resection errors. Additionally there is the possibility that the locations used to define the plane of the glacier surface are not representative of the average glacier surface and hence extrapolating along this plane to the index site introduces 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

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[2] Resection surveys are conducted with redundancy to allow estimation of their error. Typically, four or five backsight targets are surveyed for each resection.

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 tables 12-13.

Table 12. Glacier surface and summer-surface altitude measurements and analysis at index sites

[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 down-dip direction of the glacier surface, with zero east and positive counterclockwise; ϕ is the dip angle of the glacier surface with positive angles up from horizontal. "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 from combining the resection errors with the error in extrapolating the glacier surface altitude from the closest point to the index site assuming the glacier surface slope to be linear]

		P			**Q**			**R**			**Index Site**			**Glacier Surface Slope**		**Dist. to Closest Point**	**Z_i Error**
	Date	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X_i**	**Y_i**	**Z_i**	θ	ϕ		
	yy/mm/dd		(meters)			(meters)			(meters)			(meters)		(grad)		(meters)	
Site A	91/09/06	3,814.81	4,455.62	1,371.39	3,804.40	4,463.27	1,370.84	3,787.83	4,442.69	1,368.19	3,825.10	4,447.27	1,371.89	-166.31	-6.81	13.25	0.11
	92/03/26	3,824.54	4,445.63	1,374.33	3,808.02	4,448.29	1,373.13	3,818.69	4,460.43	1,375.05	3,825.10	4,447.27	1,374.51	-151.11	-7.55	1.73	0.19
	92/07/22	3,840.10	4,464.55	1,375.04	3,816.52	4,411.83	1,369.26	3,813.26	4,453.81	1,372.14	3,825.10	4,447.27	1,372.58	-151.45	-6.86	13.53	0.22
	92/09/22	3,797.89	4,443.92	1,369.07	3,811.00	4,451.40	1,371.18	3,821.16	4,447.77	1,371.56	3,825.10	4,447.27	1,371.83	-136.16	-9.97	3.97	0.03
	93/03/31	3,830.33	4,441.34	1,373.96	3,804.50	4,444.38	1,372.22	3,820.25	4,449.24	1,373.78	3,825.10	4,447.27	1,374.01	-150.57	-6.77	5.24	0.05
Site B	91/09/06	4,767.29	7,437.99	1,690.37	4,764.86	7,439.53	1,690.32	4,740.45	7,386.37	1,685.45	4,728.61	7,391.17	1,685.03	-148.68	-5.60	12.78	0.14
	91/10/07	4,751.43	7,428.94	1,689.75	4,762.56	7,435.54	1,690.81	4,740.45	7,386.37	1,685.45	4,728.61	7,391.17	1,685.38	-127.83	-6.31	12.78	0.10
	92/03/26	4,735.64	7,422.97	1,690.52	4,765.85	7,412.04	1,690.93	4,742.18	7,388.45	1,687.81	4,728.61	7,391.17	1,687.44	-130.41	-6.22	13.84	0.11
	92/07/18	4,665.30	7,361.52	1,679.62	4,774.92	7,370.67	1,685.39	4,727.68	7,417.12	1,687.40	4,728.61	7,391.17	1,685.13	-129.84	-6.35	25.97	0.20
	92/09/22	4,741.79	7,376.12	1,684.19	4,740.74	7,391.58	1,685.49	4,725.60	7,377.14	1,683.53	4,728.61	7,391.17	1,684.89	-131.05	-6.27	12.14	0.10
	93/03/30	4,731.98	7,391.00	1,686.90	4,731.22	7,371.53	1,685.15	4,738.00	7,382.62	1,686.35	4,728.61	7,391.17	1,686.81	-122.31	-5.99	3.37	0.03
Site D	91/04/17	6,061.49	7,323.74	1,846.87	6,059.91	7,324.84	1,846.66	6,012.02	7,354.21	1,840.47	5,999.01	7,353.57	1,839.17	174.07	-7.06	13.03	0.11
	91/10/07	5,996.74	7,349.40	1,837.85	5,987.15	7,368.24	1,836.11	6,034.50	7,339.70	1,841.95	5,999.01	7,353.57	1,837.90	173.60	-6.75	4.74	0.05
	92/03/26	5,970.60	7,364.10	1,836.90	6,011.32	7,353.14	1,841.02	6,011.82	7,363.68	1,840.00	5,999.01	7,353.57	1,840.06	140.53	-7.90	12.32	0.11
	92/07/18												1,837.49				
	92/09/22	5,992.53	7,355.91	1,836.97	5,984.48	7,368.66	1,835.61	6,008.16	7,360.11	1,837.93	5,999.01	7,353.57	1,837.60	159.02	-6.12	6.90	0.06
	93/03/31	6,017.02	7,362.13	1,839.44	6,007.48	7,349.97	1,839.66	5,959.80	7,382.52	1,834.33	5,999.01	7,353.57	1,838.87	147.92	-6.01	9.20	0.07
	Average															9.69	0.10

Table 13. Continuation of glacier surface and summer-surface altitude measurements and analysis at index sites

[Stake naming convention is described in headnote for table 11. Best *b'* is the height of the glacier surface directly above the stake bottom. Change in *b'* is the change from the previous measurement to the current measurement. Emergence is the change in Z_i minus the change in *b'* divided by the time in years. Snow depth is the depth from the glacier surface to the summer surface (see table 6). *Z* summer surface is Z_i - snow depth. m/yr, meters per year]

		Stake 1			**Stake 2**			**Stake 3**					
	Date	**Name**	**Best b'**	**Change b'**	**Name**	**Best b'**	**Change b'**	**Name**	**Best b'**	**Change b'**	**Emerg.**	**Snow Depth**	**Z Summer Surface**
	yy/mm/dd		(meters)			(meters)			(meters)		(m/yr)	(meters)	
Site A	91/09/06	90-A2	- 0.36	-5.25	91-A	2.52	-5.40				2.39		1,371.89
	92/03/26				91-A	3.97	1.45	92-A	10.81		2.11	1.63	1,372.88
	92/07/22							92-A	7.21	-3.60	5.17		1,372.58
	92/09/22							92-A	6.56	-0.65	-0.59	0.26	1,371.57
	93/03/31	93-A	10.49		93-A2	10.43		92-A	7.47	0.91	2.44	1.46	1,372.55
Site B	91/09/06							91-B2	6.88	- 3.62	1.41		1,685.03
	91/10/07							91-B2	7.80	0.92	-6.71	0.90	1,684.48
	92/03/26							91-B2	9.52	1.72	0.73	2.37	1,685.07
	92/07/18							91-B2	7.24	- 2.28	-0.10	0.25	1,684.88
	92/09/22							91-B2	7.13	- 0.11	-0.72	0.68	1,684.21
	93/03/30							91-B2	8.68	1.55	0.71	2.30	1,684.51
Site D	91/04/17				90-D2	4.86	0.71	91-D	7.10		1.07		1,839.17
	91/10/07				90-D2	3.94	- 0.92	91-D	6.18	- 0.92	-0.74	1.18	1,836.72
	92/03/26							91-D	8.37	2.19	-0.06	3.32	1,836.74
	92/07/18							91-D	6.45	- 1.92	-2.08	1.36	1,836.13
	92/09/22				90-D2	4.58		91-D	6.82	- 1.55	-1.85	0.86	1,836.74
	93/03/31	93-D	8.84					91-D	8.34	1.52	-0.48	2.51	1,836.36

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