WATER, ICE, AND METEOROLOGICAL MEASUREMENTS AT SOUTH CASCADE GLACIER, WASHINGTON, BALANCE YEAR 2002

Scientific Investigations Report 2004-5089

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Cover: Photograph showing view of South Cascade Glacier, Washington, from the northwest, October 26, 2002. (Photograph taken by William R. Bidlake, U.S. Geological Survey.)

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By William R. Bidlake, Edward G. Josberger, and Mark E. Savoca

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Suggested citation:
Bidlake, W.R., Josberger, E.G., and Savoca, M.E., 2004, Water, ice, and meteorological measurements at South Cascade Glacier, Washington, balance year 2002: U.S. Geological Survey Scientific Investigations Report 2004–5089, 38 p.

Contents

Figures

Tables

Conversion Factors, Vertical Datum, Symbols, and Abbreviations

Conversion Factors

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
meter per year (m/yr)	3.281	foot per year
kilometer (km)	0.6214	mile
square kilometer (km^2)	0.3861	square mile
kilogram (kg)	2.205	pound avoirdupois
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot
kilopascal (kPa)	0.01	bar
	0.1450	pound per square inch
meter per second (m/s)	2.237	mile per hour
watt (W)	0.2388	calorie per second
watt per square meter (W/m^2)	0.00002388	calorie per square centimeter per second

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=1.8 °C+32.

Vertical Datum

In this report “altitude” refers to height above the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Symbols Used in This Report

Symbol	Meaning
A_1 to A_6	Coefficients
$\dot{a}$	Ablation rate
b	Mass balance for a period of time beginning with time t_0 and ending with time t_1
$\dot{b}$	Balance rate
$\bar{b}_0$	Initial balance increment, the glacier balance between the time of the beginning of the water year and the beginning of the balance year
$\bar{b}_1$	Final balance increment, the glacier balance between the time of the end of the water year and the end of the balance year
b_a	Annual (water year) balance
$\bar{b}_a$	Glacier annual (water year) balance
b_n	Net balance
$\bar{b}_n$	Glacier net balance
b_s	Summer balance
$\bar{b}_s$	Glacier summer balance
b_w	Winter balance

Symbols Used in This Report—*Continued*

Symbol	Meaning
$b_{\mathrm{m}}(s)$	Measured winter snow balance
$\bar{b}_{\mathrm{m}}(s)$	Glacier measured winter snow balance
$b_{\mathrm{w}}(s)$	Maximum winter snow balance
$\bar{b}_{\mathrm{w}}(s)$	Glacier maximum winter snow balance
$b(Z_i)$	A relation that describes snow water equivalent or mass balance, in meters water equivalent, as either varies with glacier-surface altitude, evaluated at Z_i
$\dot{c}$	Accumulation rate
e	Atmospheric water-vapor pressure
e_s	Saturated atmospheric water-vapor pressure
h_r	Relative humidity, expressed as a decimal
n	Number of glacier DEM grid points
q	Stream discharge
S	Stream stage
T	Air temperature
X	Position in local coordinate system along the X-axis, which increases from west to east
Y	Position in local coordinate system along the Y-axis, which increases from south to north
Z	Altitude
Z_i	Altitude of a grid point in a glacier digital elevation model (DEM)

Abbreviations Used in This Report

Abbreviation	Meaning
DEM	Digital elevation model
PVC	Polyvinyl chloride
UTM	Universal Transverse Mercator

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Water, Ice, and Meteorological Measurements at South Cascade Glacier, Washington, Balance Year 2002

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Abstract

Winter snow accumulation and summer snow and ice ablation were measured at South Cascade Glacier, Washington, to estimate glacier mass balance quantities for balance year 2002. The 2002 glacier-average maximum winter snow balance was 4.02 meters, the second largest since 1959. The 2002 glacier summer, net, and annual (water year) balances were -3.47, 0.55, and 0.54 meters, respectively. The area of the glacier near the end of the balance year was 1.92 square kilometers, and the equilibrium-line altitude and the accumulation area ratio were 1,820 meters and 0.84, respectively. During September 20, 2001 to September 13, 2002, the terminus retreated 4 meters, and computed average ice speeds in the ablation area ranged from 7.8 to 20.7 meters per year. Runoff from the subbasin containing the glacier and from an adjacent non-glacierized basin were measured during part of the 2002 water year. Air temperature, precipitation, atmospheric water-vapor pressure, wind speed and incoming solar radiation were measured at selected locations near the glacier.

Introduction

Long-term investigation and monitoring of South Cascade Glacier, Washington, is an element of a larger U.S. Geological Survey (USGS) Glacier Monitoring Program that has the purpose of increasing understanding of the relation of glaciers to climate and of the effects of glaciers on water resources and hydrologic hazards (Fountain and others, 1997). A keystone of the USGS Glacier Monitoring Program is the system of Benchmark Glaciers, glaciers singled out for intensive study within distinct glacierized regions of the United States. Each Benchmark Glacier serves as an index site, the concerted investigation and monitoring of which is intended to provide a better understanding of the links between glaciers and climate (Hodge and others, 1998) and effects of glaciers on water resources within the home region of the Benchmark Glacier (Krimmel and Tangborn, 1974). Field-based measurements and analysis for Benchmark Glaciers include glacier mass balance and related glaciological, hydrologic, and meteorological phenomena. Glacier mass balance is the difference between annual accumulation and annual ablation of snow, firn, and ice averaged over the area of the glacier. South Cascade Glacier, the Benchmark Glacier for the extensively glacierized North Cascades region in Washington (Post and others, 1971), is a north-northwest-facing valley glacier that occupies approximately one-third of South Cascade Lake Basin near the crest of the Cascade Range (fig. 1). The USGS South Cascade Glacier data set now spans more than four decades. Glaciologists and climatologists from around the world have used these data extensively in a wide range of studies. Mass balance data for South Cascade Glacier and other selected glaciers around the world are compiled and published periodically by the World Glacier Monitoring Service (Haeberli and others, 2003). Two other Benchmark Glaciers, Gulkana Glacier and Wolverine Glacier, are in glacierized regions of Alaska (Kennedy, 1995; March, 1998, 2003).

Previous Work

The USGS began glaciological measurements on South Cascade Glacier during the late 1950's (Meier, 1958). Since that time, the USGS has monitored selected glaciological variables, including glacier mass balance and glacier area, as well as selected meteorological and hydrologic variables. Glacier mass balance and flow during 1957 to 1964 are described by Meier and Tangborn (1965). Glacier mass balance studies and some related work from 1965 to 1967 are described by Meier and others (1971) and by Tangborn and others (1977). Hydrologic and meteorological data for 1957 to 1967 are presented by Sullivan (1994). Glacier mass balance studies of South Cascade Glacier for the years 1958-85 are summarized in Krimmel (1989). Mass balance studies and related work for 1986-2001 are presented in detail in Krimmel (1993, 1994, 1995, 1996a, 1997, 1998, 1999, 2000, 2001, and 2002).

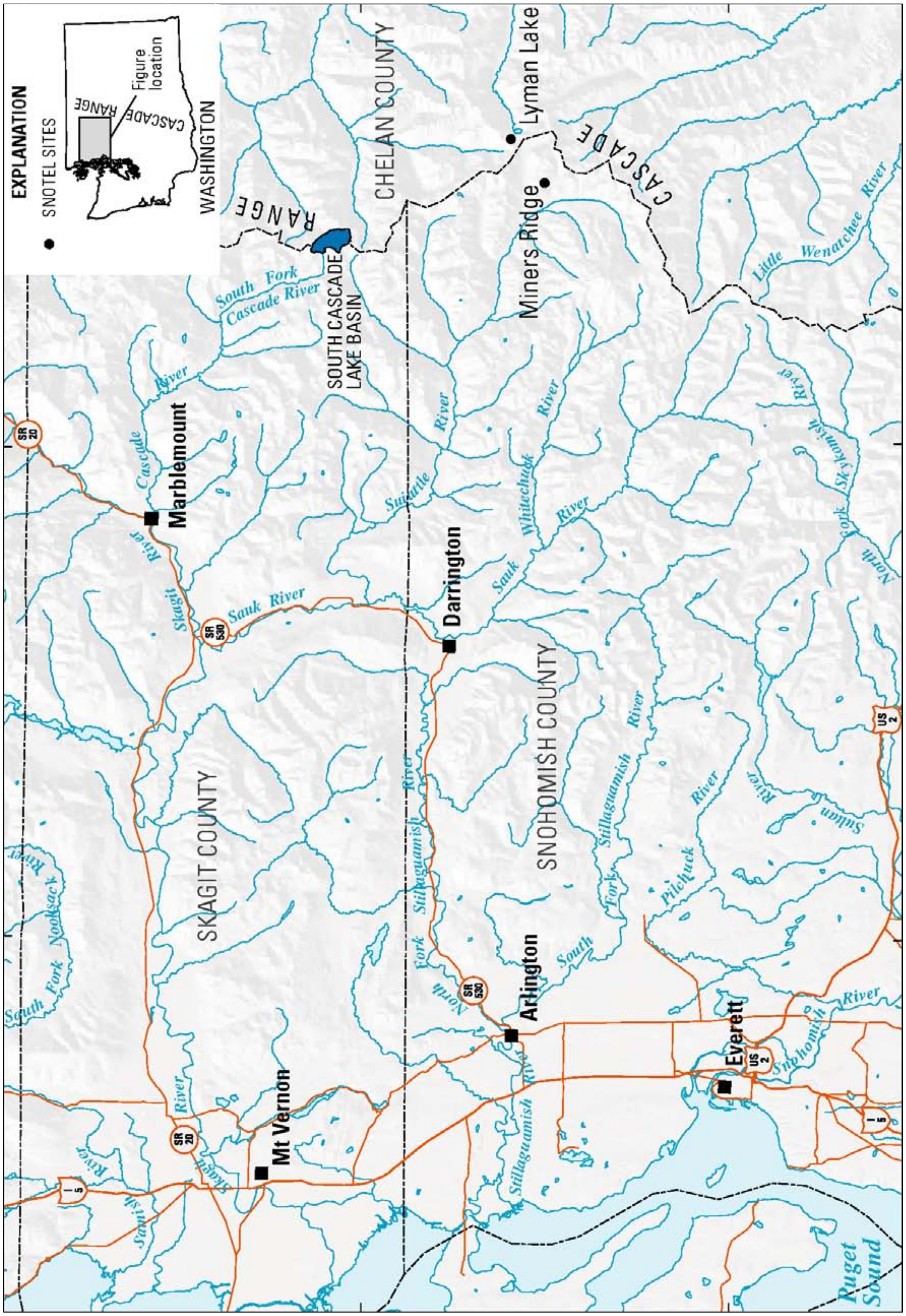

Figure 1. Location of study area, South Cascade Lake Basin, Washington.

Previous USGS work related to mass balance of South Cascade Glacier indicates the glacier has been losing mass and retreating up its confining valley for more than four decades. In 1958, the glacier was approximately 3.5 km long and occupied an area of 2.71 km^2 (Meier and Tangborn, 1965). Net balance of South Cascade Glacier, the mass balance from one annual glacier-mass minimum to the next, averaged –0.47 m water equivalent during 1959 to 2001, and years of negative net balance outnumbered years of positive net balance by a ratio of approximately 2 to 1 (Krimmel, 2000, 2002). By 2001, the terminus of the glacier had retreated approximately 0.6 km from its 1958 position (fig. 2) and the glacier had shrunk to an area of 1.92 km^2 (Krimmel, 2002).

Purpose and Scope

This report describes the glaciological, hydrologic, and meteorological measurements made at South Cascade Glacier during balance year 2002, and presents the data and selected glacier mass-balance quantities for 2002. Glaciological measurements included measurements of snow thickness and density, ablation of snow and ice, and photogrammetric measurements of the glacier perimeter, surface altitude, and horizontal displacement of selected glacier features between September 20, 2001, and September 13, 2002. Hydrologic measurements were made to compute runoff from the basin containing the South Cascade Glacier and runoff from a nearby, unglacierized basin. Meteorological measurements include those of precipitation, air temperature and relative humidity, incoming solar radiation, and wind speed.

Description and Climate of Study Area

South Cascade Glacier is at the head of the South Fork of the Cascade River, a tributary to the Skagit River, which flows into Puget Sound about 100 km to the west. The region is dominated by steep terrain, with local relief of more than 1,000 m. Areas within the basin not covered by glacier ice or water are thinly veneered bedrock. The bedrock either is mantled by a thin layer of soil and, in places, with stunted and shrubby conifers, heather, or other vegetation typical of the high North Cascade Range, or is covered by glacial moraine or outwash material.

South Cascade Lake Basin (fig. 2) has an area of 6.14 km^2, and ranges in altitude from 1,613 to 2,518 m. The area of this basin has been previously computed to be 6.02 km^2 and 6.11 km^2, owing to differing interpretations of the position of the drainage divide. A subbasin of the South Cascade Lake Basin is the 4.46-km^2 Middle Tarn Basin (unofficial name), which constitutes the southern two-thirds of the South Cascade Lake Basin. Virtually all ice melt within South Cascade Lake Basin takes place in Middle Tarn Basin.

Salix Creek Basin is an unglacierized basin adjacent to South Cascade Lake Basin. It has an area of approximately 0.22 km^2, but its drainage divides are poorly defined. Salix Creek Basin ranges in altitude from 1,587 to 2,140 m, and is predominantly south facing.

A local geographic coordinate system for South Cascade Lake Basin described by Krimmel (1994) is used in this report. The local Y-axis for the coordinate system is closely aligned with true north and the Y coordinate increases from south to north. The local X-axis is perpendicular to the local Y-axis, and the X coordinate increases from west to east. Distances are in meters, and the X and Y coordinates can be approximately converted to Universal Transverse Mercator (UTM) zone 10 coordinates by

$$\text{UTM easting} = X \times 0.99985 + 642{,}000\,, \tag{1}$$

and

$$\text{UTM northing} = Y \times 0.99985 + 5{,}355{,}000\,. \tag{2}$$

The climate of the region is maritime. Near the glacier, typical winter minimum air temperature is about -10°C, and typical maximum summer air temperature is about 20°C. Most of the precipitation, which commonly amounts to about 4.5 m annually (Meier and others, 1971), falls as snow in the period October to May.

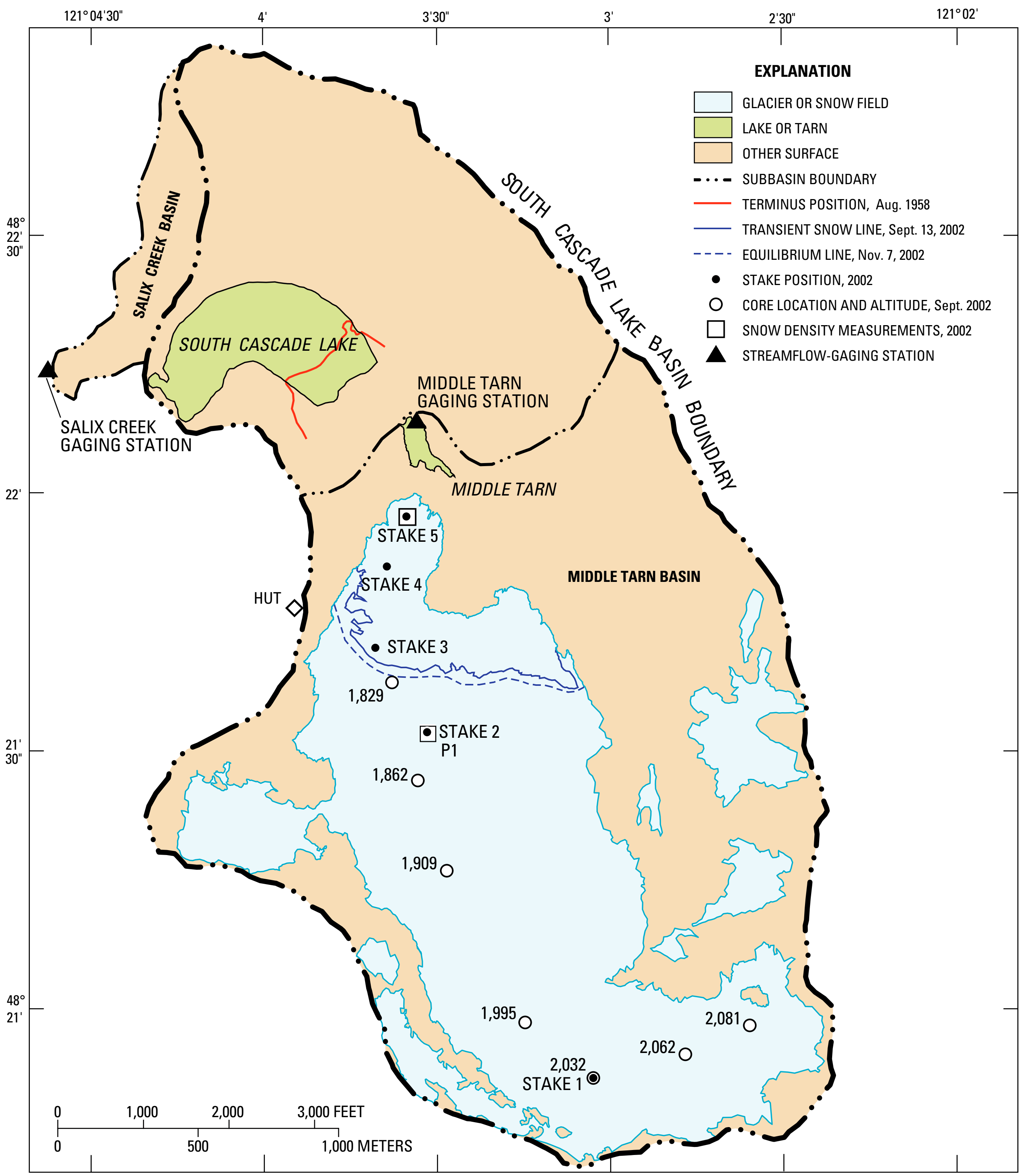

Figure 2. South Cascade Lake Basin and vicinity, Washington.

Study Methods

Methods of data collection and analysis followed in preparation of this report were similar to those of Krimmel (2002). Meteorological and streamflow data were collected using automated instrument systems with the intent of assembling continuous records. Time-series meteorological and streamflow data were registered to Pacific Standard Time. Daily summaries of time-series data were computed assuming that each day ended at midnight. Glaciological measurements for glacier mass balance were made manually during intermittent site visits. The glacier was mapped and a digital elevation model (DEM) of the glacier was produced using vertical aerial photography acquired in September 2002. Speed and horizontal direction of surface ice movement were computed by measuring displacements of selected surface features in vertical aerial photography from 2001 and 2002.

Meteorological and Streamflow Measurements

Precipitation was measured at the Salix Creek gaging station (fig. 2) using unheated tipping-bucket rain gages. The measurement resolution of each gage was 0.254 mm (0.01 in.). Precipitation was totaled and recorded each hour. Because the gages were not heated or otherwise equipped to measure precipitation as snow, data are reliable only for periods when air temperature remained above freezing at the Salix Creek gaging station. Air temperature was measured at the Salix Creek and Middle Tarn gaging stations, as well as at the Hut (fig. 2). Temperature sensors were thermistors in each case, housed in passively ventilated radiation shields. Air temperature at the Salix Creek and Middle Tarn gaging stations was measured and recorded each hour during 2001 and it was measured every minute and averaged each hour during 2002. At the Hut, air temperature was measured every minute and averaged each hour. Daily minimum and maximum air temperatures presented in this report were the daily extremes of hourly instantaneous or hourly average temperature. Incoming solar radiation was measured at the Hut using a thermopile-based pyranometer. Wind speed was measured using a cup anemometer, and relative humidity was measured using a capacitive relative humidity sensor. Incoming solar radiation, wind speed, and relative humidity were measured every minute and averaged each hour. Hourly average air temperature and relative humidity at the Hut were used to compute atmospheric water-vapor pressure (e) using the equation:

$$e = e_s h_r , \tag{3}$$

where

e is atmospheric water-vapor pressure, in kilopascals;

e_s is atmospheric water-vapor pressure at saturation, in kilopascals; and

h_r is relative humidity, expressed as a decimal, dimensionless.

Atmospheric water-vapor pressure at saturation was computed using the Lowe equation (Lowe, 1977):

$$e_s=(A_0+T(A_1+T(A_2+T(A_3+T(A_4+T(A_5+TA_6))))))/10, \tag{4}$$

where

T is air temperature, in degrees Celsius; and

the coefficients are

A_0: 6.107799961;

A_1: 4.436518521×10^{-1};

A_2: 1.428945805×10^{-2};

A_3: 2.650648471×10^{-4};

A_4: 3.031240396×10^{-6};

A_5: 2.034080948×10^{-8}; and

A_6: $6.136820929\times10^{-11}$.

Runoff from Middle Tarn Basin was computed from discharge of the South Fork of the Cascade River where it empties from Middle Tarn (fig. 2) through a channel defined by bedrock. The stage of Middle Tarn was monitored in a stilling well on the shore of the tarn, and discharge of the river from the tarn was computed using one of two rating curves that relate discharge to stage (Krimmel, 2001). For a stage equal to or less than 0.35 foot:

$$q = 25.123S^{1.809} , \tag{5}$$

and for a stage greater than 0.35 foot:

$$q = 2.064 - 3.673S + 24.770S^2 , \tag{6}$$

where

q is stream discharge, in cubic feet per second; and

S is stream stage, in feet.

Stage was measured with a submersible pressure transducer and recorded every 30 minutes during 2001 and every 15 minutes during 2002. Discharge from the tarn on September 21, 2003, computed from wading measurements made with a current meter (21.3 cubic feet per second), agreed to within 6 percent of the discharge computed from the measured stage (0.93 foot) and equation 6. Field measurements of stage and computations of discharge were made using English units to maintain compatibility with measuring equipment and for the convenience of the report author and data reviewers. Because the International System of Units (SI) is the primary system used in this report, however, the streamflow quantity, runoff, is reported in SI units. Daily average runoff from Middle Tarn Basin, in millimeters of water per day, was computed from daily average discharge divided by the area of the basin and the appropriate conversion factor.

Runoff from unglacierized Salix Creek Basin was computed in much the same manner as for Middle Tarn Basin. Salix Creek flows under the gaging station and is controlled by a weir set on bedrock. The rating curve for the gaging station that has been used for many years (Krimmel, 2002) and that was used for discharge computations in this report is:

$$q = 2.71S^{2.57}, \qquad (7)$$

where all terms have been defined previously.

Glacier Mass Balance Principles

The mass of a glacier, the combined masses of its snow and ice, is constantly changing through the operation of opposing processes of accumulation and ablation. Examples of accumulation processes important for South Cascade Glacier are precipitation in the form of snow, and avalanching or blowing of snow onto the glacier from surrounding terrain. Ablation is the loss of snow and ice from a glacier. The most important ablative processes at South Cascade Glacier likely operate at or very near the glacier surface: melting of surficial snow and ice, and evaporation. Other much less important ablative processes operate within and at the base of the glacier, such as melting at the contact between the basal glacier ice and the underlying geologic bed, and melt as a result of the kinetic energy of englacial and subglacial flowing water. As a result of the dominant importance of surficial accumulation and ablation processes for grounded, non-calving glaciers in temperate regions, such as the present-day South Cascade Glacier, mass balance can be investigated by studying snow and ice that lie very near the glacier surface.

The mass balance at a point on a glacier, b, for any period of time is given by the equation (Paterson, 1994):

$$b = \int_{t_0}^{t_1} (\dot{c} + \dot{a})\,dt, \qquad (8)$$

where

t_0 is beginning time of the period;

t_1 is ending time of the period;

$\dot{c}$ is accumulation rate at the point, in meters water equivalent divided by time; and

$\dot{a}$ is ablation rate at the point, in meters water equivalent divided by time.

Thus, increases in mass with time are indicated by positive b and decreases in mass with time by negative b. All mass balance terms in this report are presented as water-equivalent thickness, with the density of water assumed to equal 1.00×10^3 kilograms per cubic meter. Equation 8 is evaluated in practice by measuring changes in thickness of snow, firn, and ice during specified periods, and by measuring or estimating the density of material that has been gained or lost during each period. Firn is residual snow that has endured at least one melt season without being transformed into ice.

Time periods of most interest at South Cascade Glacier are defined either phenomenologically or by fixed dates. The balance year is the time between successive annual glacier mass minima, and the net balance (b_n) is the change in mass during the balance year (Anonymous, 1969). The beginning of the balance year is defined phenomenologically by the formation of the summer surface, the reference height that is used to compute accumulation and ablation all during the balance year. The balance year and b_n are components of a “stratigraphic” system of mass-balance measurement and reporting because they are defined with respect to snow, firn, and ice stratigraphic units (Mayo and others, 1972). The stratigraphic system is the primary system of measurement and reporting used in this report. At South Cascade Glacier, the balance year can be divided into winter and summer seasons. The winter season begins with the beginning of the balance year, typically in October or November, is dominated by accumulation, and ends at the time of the greatest annual glacier mass. The summer season follows the winter season, is dominated by ablation, and ends with the conclusion of the balance year. The net balance can thus be partitioned to the winter balance (b_w), the balance for the winter season, and the summer balance (b_s), the balance for the summer season (Anonymous, 1969). In this report, the winter balance is assumed to be equivalent to the maximum winter snow balance, b_w(s). The measured winter snow balance, b_m(s), is the winter snow balance computed from snow measurements made approximately at the end of the winter season (Mayo and others, 1972).

The fixed-dates system used in this report is based on the 365-day water year that begins October 1. The water-year mass balance is termed the annual balance (b_a) in this report.

The mass balance of the glacier for any time period is the average of b over the entire area of the glacier. Following the convention given by Mayo and others (1972), mass balances quantities for the entire glacier are indicated with an overbar in this report. For example, the glacier net balance is denoted $\bar{b}_{\mathrm{n}}$. Spatial averaging of local mass balance quantities to obtain glacier quantities is accomplished in this report by the grid-index technique (Krimmel, 1996b), which can be summarized using the equation:

$$\bar{b} = \frac{1}{n}\sum_{i=1}^{n} b(Z_i), \qquad (9)$$

where

Z_i is altitude of a grid point in a glacier digital elevation model (DEM), in meters;

$b(Z_i)$ is a relation that describes snow water equivalent or mass balance, in meters water equivalent, as either varies with glacier-surface altitude, evaluated at altitude Z_i; and

n is the number of glacier DEM grid points.

Snowpack measurements made on South Cascade Glacier near the time of maximum winter snow accumulation were used to develop a relation of snow water equivalent to altitude that could be used with equation 9 to compute the glacier measured winter snow balance ($\bar{b}_{\mathrm{m}}(\mathrm{s})$). The 2002 maximum winter snow balance ($\bar{b}_{\mathrm{w}}(\mathrm{s})$) was thought not to differ significantly from $\bar{b}_{\mathrm{m}}(\mathrm{s})$, based on ancillary data and observations from before and after the snowpack measurements. Mass balance measurements at selected points on the glacier late in the balance year were used to develop a relation of mass balance to altitude that could be used with equation 9 to compute the glacier net balance ($\bar{b}_{\mathrm{n}}$). The summer balance was then computed as $\bar{b}_{\mathrm{n}} - \bar{b}_{\mathrm{w}}(\mathrm{s})$. The annual balance ($\bar{b}_{\mathrm{a}}$) was computed from $\bar{b}_{\mathrm{n}}$ using the equation:

$$\bar{b}_{\mathrm{a}} = \bar{b}_{\mathrm{n}} + \bar{b}_0 - \bar{b}_1, \qquad (10)$$

where

$\bar{b}_0$ is the initial balance increment, the glacier balance between the time of the beginning of the water year and the beginning of the balance year, in meters water equivalent; and

$\bar{b}_1$ is the final balance increment, the glacier balance between the time of the end of the water year and the end of the balance year, in meters water equivalent; and

other terms are as previously defined.

Glaciological Measurements

Glaciological measurements included measurements of snow depth on the glacier near the time of the maximum winter snow accumulation, measurements of the lowering of the glacier surface due to melt during the summer season, measurements of snow depth near the time of the end of the balance year, and measurements of snow density. Snow depth near the time of the maximum snow accumulation was measured at selected locations using a flexible probe constructed from 10-mm diameter radio antenna sections. Measurements of surface lowering were made using ablation stakes installed in holes melted though the snow and ice. Stakes were constructed either from 21-mm diameter polyvinyl chloride (PVC) pipe or 32-mm diameter aluminum tubing. PVC stakes were assembled from 1.5-m sections and aluminum stakes were assembled from 2.0-m sections. The bottom of each stake was fitted with a wooden plug to reduce the amount by which the stake would sink into the glacier under the force of gravity. Lowering of the glacier surface at the stakes was determined from repeated measurements of the lengths of the stakes that were exposed during the summer season. Snow density at selected locations was computed from the mass of snow samples of known volume that were extracted from the snowpack on the glacier surface. Samples were obtained either with a coring auger with a 76.3 mm-diameter orifice, or with a sampling tube with a 72.3-mm-diameter orifice. Depth of residual snow near the end of the balance year was measured at selected locations by coring through the snowpack to find and measure the depth to the melt surface formed at the end of the previous balance year.

Photogrammetric Measurements

Color vertical aerial photographs of South Cascade Glacier were obtained on September 13, 2002. The photographs were taken with a 152-mm-focal-length lens. Film width was 230 mm. The camera was in an airplane that flew longitudinally along the glacier. The nominal scale of the photographs was 1:12,000. Diapositives from the photographs were analyzed using a stereo-digitizer system to produce stereo models of the surface of the glacier and of nearby terrain. Measurements made in the models with the stereo-digitizer system were used to delineate the glacier and adjacent snowfields, to produce a glacier DEM, and to locate selected features visible on the glacier surface in the local coordinate system described previously. Areas of features delineated by photogrammetric analysis were computed from the coordinates defining the delineations (Bouchard and Moffitt, 1972, p. 237) unless otherwise specified.

Horizontal positions of snow probing and coring sites, ablation stakes, and snow-density-measurement sites were estimated with a global positioning system (GPS) receiver. Horizontal coordinates in the local coordinate system were computed from UTM zone 10 northing and easting coordinates read from the GPS receiver. Surface altitude of each coordinate pair was then obtained using photogrammetric measurements. Positions of snow-probing and coring, and density-measurement sites that were associated with an ablation stake were assigned the position of the stake, even though the sites could have been as much as several meters from the stake.

Results and Discussion

The North Cascade Range accumulated a larger than normal snowpack during water year 2002. The maximum annual snow water equivalent reported for the Miners Ridge SNOTEL site (1.86 m; fig. 1) was the fourth largest on record for that site (years of record 1989 to 2003; National Water and Climate Center, 2003). The Miners Ridge site is west of the crest of the Cascade Range at altitude 1,890 m. The Lyman Lake SNOTEL site, which is east of the crest at altitude 1,798 m, received more precipitation during water year 2002 than did the Miners Ridge site. The 2002 maximum reported snow water equivalent at the Lyman Lake site (2.25 m) also was the fourth largest on record (years of record 1980, 1984 to 2003). Winter snow accumulation on South Cascade Glacier was exceptionally large, and snow persisted over most of the glacier late into the balance year (fig. 3).

Meteorological and Streamflow Data

The time series of hourly average air temperature at the Hut during water year 2002 is presented in figure 4, and daily maximum, minimum, and average air temperature is presented in table 1. The warmest day at the Hut was July 12, when daily average air temperature was 20.5°C and the coldest day was March 7, when daily average air temperature was -13.0°C (table 1). The warmest month at the Hut during the 2002 water year was July, when air temperature averaged 10.9°C, and the coldest month was March, when air temperature averaged -5.7°C.

The time series of hourly average atmospheric water-vapor pressure at the Hut during water year 2002 are presented in figure 4 and daily average atmospheric water-vapor pressure at the Hut is presented in table 2. Average monthly atmospheric water-vapor pressure at the Hut ranged from 0.33 kPa in February to 0.82 kPa in August.

The time series of hourly average wind speed at the Hut during water year 2002 is presented in figure 5 and daily average wind speed at the Hut is presented in table 3. The wind speed sensor probably was locked by ice during days for which average wind speed is tabulated as 0.2 m/s (table 3). If those days are omitted, monthly average wind speed ranged from 1.4 m/s in April 2002 to 6.2 m/s in December 2001. The windiest hour occurred January 1, 2002, when wind speed averaged 22.4 m/s.

The time series of hourly average incoming solar radiation measured at the Hut during water year 2002 is presented in figure 5 and daily average incoming solar radiation is presented in table 4. During winter months, the pyranometer could have been covered or partly covered with ice or snow at times, which would have caused the recorded solar radiation data to be in error. Monthly average measured incoming solar radiation ranged from 30 watts per square meter (W/m^2) in December 2001 to 244 W/m^2 in July 2002.

Infrastructure damage and power outages caused by the large winter snowfall, combined with equipment malfunctions and efforts to modify data collection systems at South Cascade Lake Basin during the brief summer field season, decimated the 2002 meteorological and streamflow records for the Salix Creek and Middle Tarn gaging stations. The available air-temperature data for the Salix Creek and Middle Tarn stations are presented in tables 5 and 6, and precipitation data for the Salix Creek station are presented in table 7. The available streamflow data for the Salix Creek and Middle Tarn gaging stations are summarized in terms of runoff averaged over the area of each respective basin in tables 8 and 9.

Figure 3. South Cascade Glacier, Washington, constructed from vertical aerial photographs, September 13, 2002.

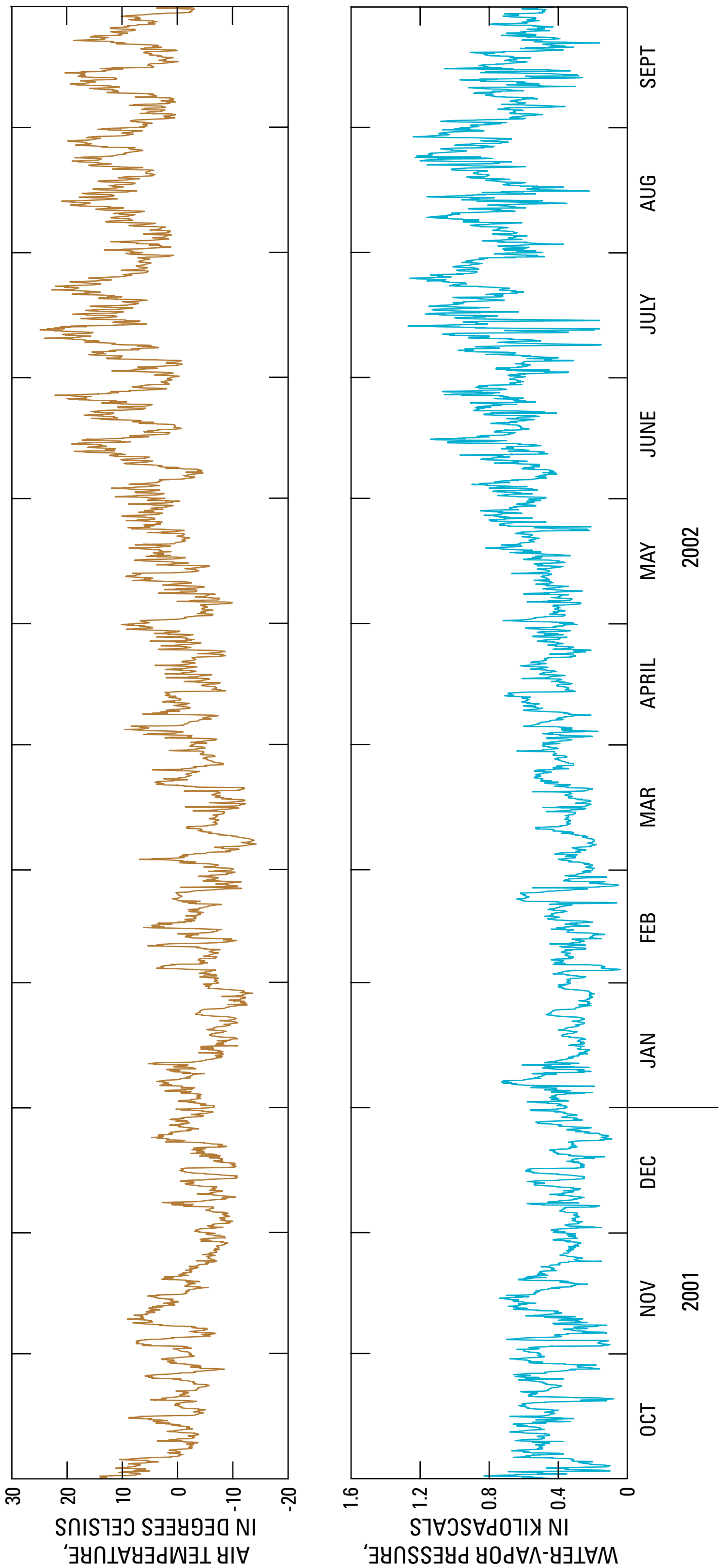

Figure 4. Hourly average air temperature and atmospheric water-vapor pressure at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, water year 2002.

Table 1. Daily maximum, minimum, and average of hourly average air temperature at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, water year 2002

	Air temperature, in degrees Celsius																	
	October			November			December			January			February			March		
Day	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**
1	14.1	7.4	11.7	-0.1	-2.3	-1.1	-3.1	-5.4	-3.8	-4.1	-6.7	-5.5	-6.6	-7.4	-6.9	-4.7	-10.1	-7.6
2	10.7	5.1	7.7	6.3	-2.5	.1	-5.4	-8.2	-6.5	-.1	-3.9	-2.0	-4.0	-7.4	-5.8	-.4	-7.4	-4.0
3	11.2	5.8	8.3	7.6	4.8	6.8	-6.5	-10.0	-8.6	-2.9	-4.2	-3.8	-3.9	-6.8	-5.4	6.9	-1.2	1.5
4	8.9	4.8	7.1	7.4	-.5	3.8	-7.6	-9.4	-8.4	.8	-4.3	-2.4	3.8	-6.9	.7	-.4	-5.0	-1.9
5	10.5	3.5	6.7	-1.3	-6.9	-5.0	-8.1	-9.3	-8.7	2.3	-3.1	-1.1	2.8	-5.4	-1.6	-5.2	-11.1	-8.4
6	6.6	-1.0	1.3	-2.2	-6.7	-4.1	-5.1	-7.8	-5.9	3.2	-.9	1.1	-3.7	-6.4	-4.3	-6.7	-12.4	-9.5
7	1.8	-.5	.5	3.3	-5.2	-2.1	.9	-6.5	-3.1	3.8	-.3	2.0	-4.7	-7.1	-6.1	-11.5	-14.2	-13.0
8	1.5	-2.7	-1.5	8.1	2.8	5.5	2.7	-5.6	-1.7	-.6	-2.7	-1.8	-5.7	-7.4	-6.5	-11.1	-13.9	-12.9
9	-1.6	-3.7	-2.7	9.1	4.7	6.4	-6.0	-10.5	-8.8	.8	-4.9	-1.7	2.9	-7.7	-3.9	-5.6	-10.9	-8.6
10	3.7	-2.7	-.1	7.9	5.2	6.3	-3.5	-8.3	-6.0	2.0	-3.3	-.7	5.4	-8.7	-.7	-3.7	-6.1	-4.7
11	-2.0	-3.8	-3.0	5.6	3.2	4.5	-5.8	-8.1	-7.0	5.3	-1.9	1.3	-2.9	-10.7	-8.8	-1.6	-6.2	-3.3
12	1.9	-3.7	-.7	5.3	.9	3.7	-1.5	-7.1	-4.4	3.7	-6.5	-3.5	.0	-3.8	-2.2	-6.4	-7.2	-6.8
13	-.5	-2.7	-1.7	2.5	-.2	1.0	-.5	-4.4	-2.0	-6.5	-8.1	-7.3	-.3	-7.2	-5.6	-5.8	-7.5	-6.8
14	3.9	-.5	1.5	4.2	.8	2.3	-5.0	-10.8	-9.1	-3.8	-8.3	-7.5	6.2	-8.0	.1	-6.4	-8.5	-7.4
15	8.8	1.8	4.7	5.4	-1.7	1.9	-1.3	-10.2	-5.4	-4.2	-7.7	-5.7	4.7	-1.5	1.8	-2.8	-9.2	-7.0
16	8.9	-3.8	2.1	-1.4	-3.0	-1.9	-.4	-4.5	-1.1	-4.2	-10.9	-7.4	-1.3	-3.3	-2.3	-1.4	-11.3	-8.7
17	-2.9	-4.8	-4.0	-1.3	-5.6	-3.0	-6.2	-10.7	-9.9	-7.2	-10.6	-8.9	-1.5	-4.1	-3.1	-5.8	-12.3	-10.4
18	-.1	-5.1	-1.7	-1.6	-4.0	-2.6	-6.5	-10.3	-8.2	-5.8	-10.9	-8.1	-2.0	-4.7	-3.3	-6.8	-12.2	-9.4
19	.6	-2.8	-.4	2.9	-1.7	.9	-4.0	-8.1	-6.9	-5.8	-8.8	-7.4	-1.9	-5.8	-4.4	-6.2	-7.7	-7.1
20	4.9	-3.4	1.2	1.3	-2.0	-.8	-2.4	-7.7	-5.1	-5.3	-7.9	-6.5	-.9	-7.9	-4.3	-1.2	-12.1	-8.6
21	1.9	-2.2	-.5	-1.5	-2.8	-2.3	-2.6	-5.1	-3.9	-8.0	-10.9	-9.3	1.0	-4.1	-.3	2.7	-12.1	-4.6
22	.3	-3.4	-1.7	-2.1	-3.9	-3.3	-3.6	-8.9	-7.4	-7.6	-10.8	-9.7	.1	-.8	-.4	4.1	.6	3.0
23	-3.4	-5.6	-4.2	-3.4	-7.1	-5.4	2.2	-5.9	-1.7	-3.9	-10.6	-7.7	.3	-6.9	-2.5	2.5	-1.8	-.4
24	-2.7	-5.7	-3.8	-4.7	-6.8	-5.9	4.7	1.5	2.8	-3.2	-4.2	-3.8	-.5	-11.6	-8.9	-1.5	-2.6	-2.0
25	4.7	-2.7	.3	-4.5	-6.8	-5.9	3.5	-.4	1.5	-4.2	-9.5	-7.1	-6.9	-11.5	-9.2	4.6	-4.0	-.9
26	5.9	.3	4.1	-6.5	-7.6	-7.0	-.3	-3.8	-2.1	-9.1	-12.6	-11.4	-4.6	-8.2	-6.6	-2.3	-8.3	-4.4
27	-.1	-7.3	-3.7	-6.9	-8.5	-7.5	1.5	-1.7	-.3	-9.3	-12.1	-11.1	-3.8	-9.1	-6.7	-5.8	-8.3	-7.1
28	-2.3	-8.5	-4.6	-4.2	-9.1	-7.7	1.4	-2.1	-.9	-8.0	-12.3	-11.3	-5.6	-10.4	-8.9	-4.6	-6.6	-5.3
29	1.8	-3.8	-.3	-4.1	-8.7	-6.4	1.0	-4.7	-2.0	-11.3	-13.6	-12.2				-4.1	-6.8	-5.2
30	2.9	-.1	1.4	-5.0	-8.1	-6.3	-2.5	-6.4	-4.7	-5.3	-11.0	-7.1				1.5	-4.7	-2.7
31	-.5	-3.0	-2.2				.3	-6.4	-3.1	-4.7	-7.4	-6.1				-2.2	-5.0	-3.4
Monthly Average	3.2	-1.8	0.7	0.9	-3.0	-1.2	-2.2	-6.7	-4.6	-3.3	-7.4	-5.6	-1.2	-6.8	-4.1	-3.0	-7.9	-5.7

Table 1. Daily maximum, minimum, and average of hourly average air temperature at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, water year 2002—*Continued*

	Air temperature, in degrees Celsius																	
	April			May			June			July			August			September		
Day	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**
1	-2.4	-6.0	-4.2	6.8	0.8	5.2	11.3	2.9	6.5	4.2	-0.3	1.8	13.4	5.3	9.1	6.8	4.6	5.8
2	2.3	-7.1	-3.4	.2	-6.2	-2.3	7.7	2.4	5.1	11.9	.8	6.5	5.1	1.2	3.1	8.5	4.8	6.9
3	6.2	-2.6	1.1	-3.6	-6.4	-5.1	12.0	3.2	7.5	7.2	.3	4.1	12.1	3.5	7.9	3.9	.5	1.6
4	9.6	-1.0	4.5	-4.4	-6.4	-5.2	8.8	3.3	5.2	2.1	-.8	.3	4.5	1.6	2.8	6.8	.4	3.5
5	8.4	-1.3	3.4	-4.2	-9.6	-5.9	3.6	-1.9	1.7	12.9	-.7	7.2	6.2	1.1	3.2	6.5	2.2	4.0
6	-1.3	-3.8	-2.5	.1	-9.9	-6.2	-1.0	-3.1	-2.2	16.1	10.0	13.1	5.0	1.3	2.8	8.7	1.4	4.6
7	-3.8	-6.8	-5.3	-3.2	-7.6	-5.7	-1.5	-4.6	-3.8	15.5	6.9	11.7	8.8	2.2	5.6	3.0	.4	1.4
8	6.3	-7.4	-.1	3.5	-6.8	-2.2	3.5	-4.0	.1	8.4	3.5	5.4	13.0	4.0	9.2	7.7	.7	3.6
9	3.0	-2.2	.4	2.4	-4.9	-2.2	9.7	2.8	6.6	16.8	8.9	13.2	12.1	8.4	10.1	12.8	4.4	8.9
10	.7	-2.3	-1.0	2.7	-4.8	-.9	10.3	4.5	7.4	24.1	14.8	18.8	11.6	6.7	9.0	15.9	10.5	12.7
11	2.7	-2.1	.3	8.2	-2.5	3.0	12.3	5.1	9.4	20.8	15.7	18.0	14.8	6.0	10.7	19.4	11.3	15.7
12	1.6	-.6	.3	9.4	4.5	7.2	18.7	10.1	13.9	24.9	15.3	20.5	19.4	9.9	15.7	17.6	11.1	14.7
13	2.3	1.0	1.8	8.2	-3.8	2.4	16.3	11.2	13.6	22.4	10.2	18.2	21.0	13.8	17.8	18.0	11.0	15.4
14	.1	-8.7	-6.4	-1.3	-5.0	-3.1	19.2	8.5	14.9	11.7	5.6	8.7	17.8	10.9	13.8	20.4	13.0	16.8
15	-4.3	-7.0	-5.7	3.8	-5.8	-1.2	17.3	8.7	12.9	17.5	7.5	13.0	17.3	9.0	13.6	13.9	4.3	10.2
16	-1.2	-7.7	-4.8	7.8	-2.0	3.6	8.9	1.7	5.6	19.0	10.9	14.3	15.4	7.4	11.6	5.4	1.7	4.3
17	2.1	-5.8	-3.2	5.7	-1.4	1.7	6.1	1.4	3.8	16.7	9.7	12.9	12.4	7.8	10.3	3.4	-.1	1.9
18	2.3	-6.2	-2.4	4.4	1.2	3.1	2.5	-.7	.4	15.8	8.1	11.3	14.4	7.7	10.9	5.1	.8	2.8
19	2.2	-3.3	-1.0	8.8	2.9	5.2	8.2	.5	4.0	10.0	6.5	8.1	10.7	4.5	8.1	6.2	.0	4.5
20	4.1	-3.5	-.9	7.7	.3	2.3	15.6	6.6	10.6	14.3	5.5	10.5	5.8	4.1	5.0	6.7	.2	3.9
21	-.8	-3.2	-2.1	.3	-1.5	-.9	16.9	11.3	13.6	19.1	11.5	15.2	11.8	4.3	7.3	11.6	3.5	7.0
22	-2.6	-8.7	-4.5	.1	-2.2	-1.1	15.7	8.1	12.8	22.8	14.0	17.8	16.1	6.3	13.1	18.8	11.6	14.4
23	-3.6	-8.7	-7.1	5.5	-1.2	.8	10.9	5.3	7.5	22.1	14.7	18.7	19.1	13.3	16.0	15.8	10.1	13.0
24	3.5	-8.6	-2.4	9.0	-1.2	4.7	13.7	4.6	9.3	19.5	13.7	16.3	18.6	11.3	14.4	12.1	8.3	10.2
25	3.0	-3.5	-.8	6.1	3.1	4.2	20.1	11.0	16.1	16.1	10.0	13.2	11.2	7.5	9.5	12.2	7.7	9.9
26	5.0	-4.2	-1.4	9.3	2.8	5.1	22.2	12.2	17.3	9.9	5.6	8.3	10.3	6.3	7.8	9.1	4.1	6.1
27	3.8	-2.2	-.3	10.1	4.1	6.8	12.8	3.1	9.2	10.2	5.3	6.7	18.5	12.7	15.9	8.8	3.7	6.1
28	4.2	-2.8	.6	7.1	2.7	4.7	8.2	2.0	5.6	7.5	5.4	6.5	19.9	15.2	17.5	10.2	5.4	7.7
29	9.3	-.4	5.1	5.4	1.4	3.5	5.9	1.5	2.9	7.1	4.8	6.0	16.5	9.3	13.9	5.0	-2.7	-.5
30	10.2	4.6	7.4	8.9	.7	3.7	2.2	1.0	1.6	7.2	1.8	5.2	10.1	7.3	8.6	3.8	-3.1	-1.5
31				5.5	-.4	2.7				9.4	.7	5.6	14.4	6.4	10.7			
Monthly Average	2.4	-4.1	-1.2	4.2	-2.1	0.9	10.6	4.0	7.3	14.3	7.3	10.9	13.1	7.0	10.2	10.1	4.4	7.2

Table 2. Daily average atmospheric water-vapor pressure at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, water year 2002

	Atmospheric water-vapor pressure, in kilopascals											
Day	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
1	0.61	0.56	0.41	0.37	0.34	0.21	0.43	0.49	0.6	0.64	0.61	0.86
2	.50	.51	.29	.44	.29	.24	.37	.51	.67	.51	.66	.90
3	.29	.14	.30	.43	.38	.36	.38	.40	.65	.65	.61	.64
4	.17	.45	.30	.35	.12	.34	.33	.40	.79	.60	.68	.60
5	.29	.41	.30	.41	.28	.31	.46	.38	.66	.45	.68	.68
6	.53	.24	.37	.53	.40	.27	.49	.37	.49	.61	.72	.53
7	.51	.27	.29	.68	.34	.20	.39	.38	.43	.82	.81	.63
8	.54	.31	.44	.53	.36	.20	.31	.45	.53	.81	.81	.66
9	.49	.33	.30	.43	.30	.27	.51	.39	.60	.48	1.02	.82
10	.55	.46	.37	.35	.32	.38	.55	.43	.72	.67	1.02	.76
11	.48	.45	.31	.40	.27	.47	.57	.47	.78	.94	.78	.55
12	.57	.64	.42	.40	.20	.34	.59	.48	.54	.50	.71	.74
13	.52	.60	.52	.32	.28	.35	.67	.50	.66	.84	.56	.49
14	.59	.68	.29	.26	.37	.33	.36	.46	.67	.91	.93	.55
15	.44	.60	.40	.25	.29	.34	.38	.47	.97	.68	.79	.68
16	.50	.52	.56	.29	.35	.29	.37	.44	.83	.96	.54	.79
17	.44	.38	.27	.27	.43	.24	.45	.51	.71	.95	.57	.65
18	.53	.32	.30	.31	.40	.28	.45	.53	.61	1.00	.70	.68
19	.59	.54	.25	.33	.42	.34	.48	.68	.69	.97	.82	.79
20	.22	.52	.36	.36	.28	.31	.54	.65	.62	.84	.85	.48
21	.46	.47	.41	.28	.58	.32	.51	.56	.65	.74	.93	.41
22	.53	.45	.31	.27	.59	.43	.42	.56	.69	.66	.87	.47
23	.43	.37	.30	.33	.50	.50	.34	.59	.85	.83	.91	.53
24	.45	.28	.13	.45	.26	.51	.31	.37	.77	1.00	1.04	.61
25	.54	.36	.17	.34	.13	.48	.39	.64	.64	1.13	1.13	.51
26	.59	.34	.29	.23	.30	.38	.45	.70	.80	1.04	1.00	.63
27	.46	.32	.34	.24	.26	.34	.44	.71	.88	.91	.88	.56
28	.26	.30	.45	.21	.24	.39	.46	.73	.80	.94	.77	.62
29	.39	.35	.32	.21		.40	.45	.70	.69	.90	.92	.56
30	.60	.32	.34	.34		.48	.39	.59	.65	.81	1.06	.51
31	.51		.45	.37		.45		.55		.63	.94	
Monthly Average	0.47	0.42	0.34	0.35	0.33	0.35	0.44	0.52	0.69	0.79	0.82	0.63

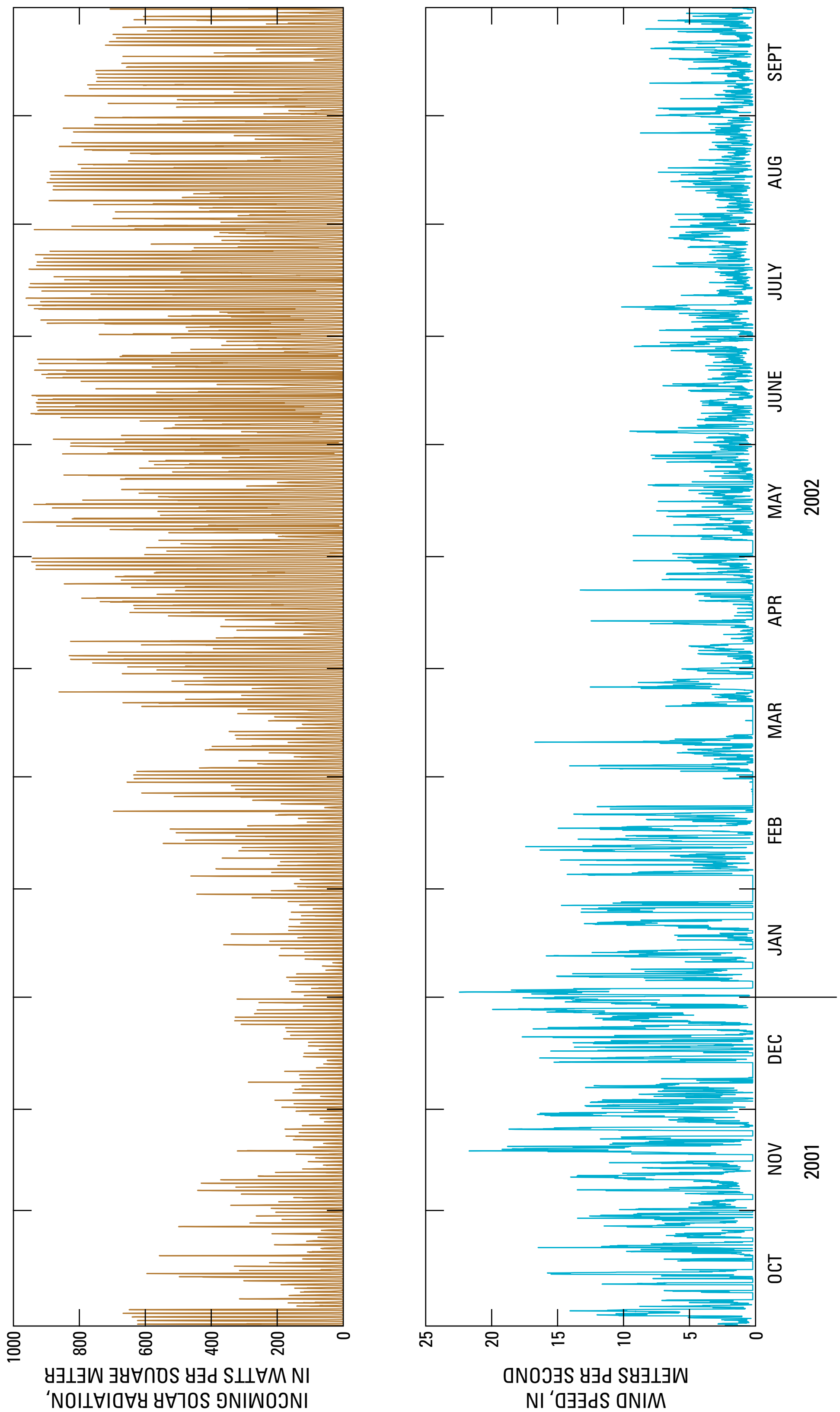

Figure 5. Hourly average incoming solar radiation and wind speed at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, water year 2002.

Table 3. Daily average wind speed at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, water year 2002

[Days for which the tabulated wind speed is 0.2 meter per second, when the wind speed sensor probably was locked by ice, were not used in computing the monthly averages]

	Wind speed, in meters per second											
Day	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
1	1.7	2.9	7.7	16.6	0.2	0.5	0.9	2.7	1.9	2.2	3.6	4.3
2	1.2	5.0	5.8	6.2	2.9	.3	.5	2.2	1.7	.7	2.1	3.0
3	4.1	2.9	4.1	.2	7.2	.8	.5	.2	1.6	2.7	2.6	2.2
4	8.1	2.8	4.3	2.0	2.1	4.1	1.3	.2	1.3	1.8	3.1	.9
5	7.2	.2	4.4	8.0	4.1	4.4	1.6	.2	4.8	1.4	1.0	1.5
6	3.2	1.8	8.0	4.4	4.9	.7	2.7	1.4	2.3	1.9	1.3	1.5
7	2.0	6.3	2.3	4.2	3.6	1.1	2.6	3.5	2.0	2.8	1.1	1.1
8	1.7	2.8	1.8	.2	3.6	3.3	.3	.7	1.7	2.1	1.3	.9
9	.2	2.1	.2	.9	10.0	2.6	.6	1.3	2.0	5.8	1.9	1.5
10	2.5	6.6	.2	2.1	7.4	1.5	.5	2.6	1.5	4.8	2.1	2.7
11	.2	10.6	.2	8.4	2.2	6.7	.4	1.4	1.3	1.0	2.0	1.0
12	4.8	3.4	.8	7.5	8.0	2.5	.8	2.9	1.9	.7	2.1	1.7
13	.2	3.7	6.2	1.5	5.4	.9	3.7	3.0	2.9	2.3	3.5	1.4
14	2.9	2.5	7.0	.3	1.0	.2	2.6	2.0	2.1	2.1	2.4	1.9
15	10.3	3.9	.8	.9	8.7	.2	.3	1.2	.8	.9	2.4	1.7
16	1.8	.2	5.3	1.7	4.4	.2	.4	1.8	2.1	1.1	2.2	3.3
17	.2	3.2	5.0	1.6	1.7	.2	.3	2.0	1.4	1.1	2.4	1.6
18	.4	14.2	8.3	1.1	4.1	.2	.4	2.1	4.3	1.3	1.3	1.9
19	2.5	12.1	4.6	4.8	6.8	.2	1.3	2.5	1.3	1.8	1.9	5.0
20	.5	6.1	5.5	10.0	.7	.2	1.1	1.4	2.0	1.2	1.7	1.4
21	3.7	5.6	.9	2.8	5.1	2.1	2.2	3.9	1.5	3.6	1.1	3.8
22	6.1	4.9	10.5	.2	.2	2.7	2.6	.7	1.6	3.4	1.3	.8
23	7.3	.2	3.7	5.7	.2	.9	.2	.6	1.3	1.4	1.9	1.2
24	.8	12.6	7.9	8.2	.2	1.9	.5	1.0	1.1	1.6	1.3	3.3
25	2.6	1.1	9.4	4.4	.2	.4	2.2	1.5	1.5	1.7	1.4	1.8
26	3.7	3.5	10.0	3.1	.2	5.1	.8	1.0	2.0	2.4	1.2	2.1
27	.8	5.4	14.5	.2	.2	5.0	3.5	1.0	2.1	1.6	2.8	3.0
28	6.0	13.1	3.2	.2	.2	6.2	1.6	2.4	2.2	3.6	1.9	2.0
29	4.0	6.1	10.9	.2		.8	1.5	4.3	5.2	4.3	1.9	1.2
30	5.8	6.5	13.1	.2		.8	3.3	3.0	3.2	4.1	1.1	.5
31	7.8		8.5	.2		3.5		1.7		1.5	2.3	
Monthly Average	3.8	5.6	6.2	4.6	4.7	2.5	1.4	2.0	2.1	2.2	1.9	2.0

Table 4. Daily average incoming solar radiation at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, water year 2002

	Daily average incoming solar radiation, in watts per square meter											
Day	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
1	158	37	30	31	30	170	166	330	266	174	247	61
2	168	46	38	20	92	168	230	156	206	202	124	39
3	177	72	13	28	49	168	259	156	277	154	219	109
4	184	37	30	34	85	108	265	189	179	143	97	176
5	179	34	30	35	48	75	142	140	99	293	181	128
6	31	57	25	23	43	68	109	134	202	287	115	218
7	35	84	49	10	64	39	169	64	177	168	193	74
8	70	66	24	10	43	49	240	125	185	142	303	148
9	44	78	27	6	69	110	111	237	244	312	146	201
10	29	72	30	25	61	90	36	220	286	355	133	227
11	39	52	12	35	92	46	70	345	295	346	298	234
12	51	33	13	26	108	94	89	281	290	353	305	235
13	75	26	12	38	74	88	62	135	302	225	309	235
14	108	13	24	56	120	74	111	200	322	228	305	215
15	132	18	21	43	122	36	153	223	303	350	300	178
16	38	18	14	33	62	32	168	281	185	346	305	30
17	70	25	21	55	25	59	123	185	197	257	230	140
18	53	62	21	34	36	59	208	180	111	247	273	86
19	30	19	31	36	54	85	237	198	262	181	174	50
20	116	14	25	31	153	61	224	183	291	349	78	218
21	31	33	36	32	15	157	177	89	291	338	212	211
22	19	35	27	25	45	187	160	74	297	333	254	206
23	47	29	45	36	70	129	204	199	204	321	273	202
24	30	38	47	20	117	89	258	281	298	337	202	165
25	17	24	47	28	150	241	208	142	337	238	68	196
26	49	12	47	33	89	86	221	172	230	109	88	54
27	16	15	36	57	80	141	190	189	114	150	269	140
28	108	21	24	80	154	137	269	152	114	105	263	156
29	70	31	45	49		121	321	120	103	95	234	46
30	40	35	48	32		164	328	249	101	138	116	104
31	44		25	29		149		211		284	241	
Monthly Average	73	38	30	33	77	106	184	188	226	244	211	149

Table 5. Daily maximum, minimum, and average air temperature at the Salix Creek gaging station, 1,587 meters altitude, Salix Creek Basin, Washington, water year 2002

[Data were not obtained November 2001 through August 2002 or as indicated by –. Values for 2001 and 2002 were computed from hourly instantaneous temperature and hourly average temperature, respectively]

Day	October 2001			September 2002		
	Max	Min	Avg	Max	Min	Avg
1	20.1	7.9	13.3	–	–	–
2	16.8	5.8	10.0	–	–	–
3	18.2	6.2	10.8	–	–	–
4	12.4	6.3	9.4	–	–	–
5	13.7	6.5	9.4	–	–	–
6	7.9	-.2	3.4	–	–	–
7	4.2	.5	2.6	–	–	–
8	4.0	-.5	1.0	–	–	–
9	3.3	-1.2	.0	–	–	–
10	6.3	-1.0	2.3	–	–	–
11	1.0	-1.5	-.5	–	–	–
12	3.5	-1.2	1.5	–	–	–
13	2.9	-.2	1.0	–	–	–
14	9.9	1.0	3.8	–	–	–
15	10.1	4.2	7.1	–	–	–
16	10.0	-1.8	3.7	–	–	–
17	.6	-3.0	-1.7	–	–	–
18	2.2	-2.7	.4	7.2	2.5	5.2
19	3.8	-.9	1.6	10.1	1.6	6.7
20	6.9	-2.9	1.9	–	–	–
21	3.9	.1	1.5	22.3	10.6	14.5
22	3.6	-1.3	.5	21.7	10.4	14.5
23	-.7	-3.6	-1.9	17.5	9.4	12.5
24	.0	-3.5	-1.4	19.6	7.5	12.0
25	6.1	-.7	2.4	10.4	5.3	7.8
26	8.5	1.5	5.9	13.1	4.1	8.4
27	1.2	-5.5	-1.8	–	–	–
28	–	–	–	–	–	–
29	–	–	–	7.7	-.7	2.0
30	–	–	–	7.8	-1.1	1.5
31	–	–	–			
Monthly Average	–	–	–	–	–	–

Table 6. Daily maximum, minimum, and average air temperature at the Middle Tarn gaging station, 1,631 meters altitude, South Cascade Lake Basin, Washington, water year 2002

[Data were not obtained November 2001 through August 2002 or as indicated by –. Values for 2001 and 2002 were computed from hourly instantaneous temperature and hourly average temperature, respectively]

Day	October 2001			September 2002		
	Max	Min	Avg	Max	Min	Avg
1	16.4	6.3	10.9	–	–	–
2	13.7	4.8	7.8	–	–	–
3	11.6	4.6	8.8	–	–	–
4	10.8	5.9	8.6	–	–	–
5	11.4	5.6	7.8	–	–	–
6	7.5	.0	2.9	–	–	–
7	3.9	-.2	1.9	–	–	–
8	3.7	-1.2	.2	–	–	–
9	1.2	-2.6	-1.1	–	–	–
10	6.7	-1.5	2.2	–	–	–
11	-.5	-2.2	-1.4	–	–	–
12	3.7	-1.8	1.3	–	–	–
13	2.1	-.8	.4	–	–	–
14	6.4	.4	2.8	–	–	–
15	8.8	2.8	6.0	–	–	–
16	8.6	-2.3	2.8	–	–	–
17	-1.1	-3.6	-2.5	–	–	–
18	1.9	-3.5	-.2	–	–	–
19	3.0	-.8	1.2	–	–	–
20	5.8	-3.8	.7	–	–	–
21	3.3	-.5	1.1	–	–	–
22	3.6	-1.8	.2	13.7	9.4	11.2
23	-1.6	-4.0	-2.5	16.3	8.9	11.8
24	-.8	-3.9	-2.0	12.7	8.0	10.4
25	6.4	-1.3	2.2	11.7	6.2	8.7
26	7.8	1.0	5.6	8.8	5.0	6.5
27	.8	-6.6	-2.4	9.2	3.6	6.5
28	–	–	–	11.0	6.5	8.4
29	–	–	–	7.0	-1.3	1.2
30	–	–	–	1.3	-2.3	-.8
31	–	–	–			
Monthly Average	–	–	–	–	–	–

Table 7. Daily precipitation at the Salix Creek gaging station, 1,587 meters altitude, Salix Creek Basin, Washington, water year 2002

[Data were not obtained November 2001 through August 2002 or as indicated by –]

Day	Daily precipitation, in millimeters — October 2001	September 2002
1	0.0	–
2	.0	–
3	.0	–
4	.0	–
5	.0	–
6	.0	–
7	.0	–
8	.5	–
9	.8	–
10	.8	–
11	.0	–
12	9.4	–
13	.8	–
14	4.6	–
15	.0	–
16	.0	–
17	.0	–
18	.3	–
19	1.0	–
20	.0	–
21	6.1	–
22	7.6	–
23	.0	–
24	.0	–
25	10.4	–
26	8.4	–
27	.0	–
28	–	–
29	–	5.3
30	–	10.9
31	–	
Total	–	–

Table 8. Daily average runoff from the Salix Creek Basin, Washington, water year 2002

[Daily average runoff is averaged over the area of the basin (0.22 square kilometer). Data were not obtained November 2001 through August 2002 or as indicated by –]

Day	Daily average runoff, in millimeters — October 2001	September 2002
1	0.22	–
2	.22	–
3	.22	–
4	.22	–
5	.11	1.3
6	.22	1.2
7	.22	1.4
8	.78	1.3
9	1.0	1.2
10	8.6	1.0
11	4.4	.89
12	9.6	.78
13	8.2	.67
14	9.6	.56
15	6.0	.56
16	8.7	1.6
17	4.6	1.1
18	2.8	.78
19	8.1	1.6
20	4.1	1.2
21	2.8	.78
22	3.9	.44
23	4.1	.44
24	3.0	.33
25	2.1	.33
26	6.7	.33
27	11	.22
28	–	.22
29	–	.89
30	–	2.0
31	–	
Monthly Average	–	–

Table 9. Daily average runoff from Middle Tarn Basin, Washington, water year 2002

[Daily average runoff is in millimeters averaged over the area of the basin (4.46 square kilometers). Data were not obtained November 2001 through August 2002 or as indicated by –]

Day	Daily average runoff, in millimeters	
	October 2001	September 2002
1	11	–
2	8.2	–
3	7.1	–
4	5.4	–
5	4.9	12
6	4.0	9.3
7	2.7	8.8
8	2.8	8.2
9	2.0	9.9
10	3.3	13
11	2.9	14
12	3.0	15
13	3.8	15
14	3.1	15
15	2.6	15
16	3.6	21
17	2.5	18
18	1.6	11
19	1.8	15
20	1.5	16
21	1.3	–
22	1.3	9.3
23	1.4	9.9
24	1.1	9.9
25	.93	8.8
26	1.7	8.2
27	3.1	7.1
28	–	7.1
29	–	7.7
30	–	6.6
31	–	
Monthly Average	–	–

Winter Balance

Depth of snow on South Cascade Glacier at site P1 (fig. 6) on May 1, 2002 was measured by digging and coring through the snow to the underlying ice that was the 2001 summer surface (Krimmel, 2002). Snow-depth measurements by probing at site P1 agreed with snow depth determined by digging and coring. Down-glacier from P1, ice that formed the 2001 summer surface also provided a reliable reference to determine snow depths by probing (fig. 6, table 10). Snow depth was probed progressively up-glacier from site P1 generally along the glacier's longitudinal axis until it was no longer possible to reliably detect the position of the 2001 summer surface. Snow up-glacier (southeasterly) from site P1was largely underlain by firn that made detection of the 2001 summer surface by probing unreliable in some places. Firn typically is denser and more consolidated than is most of the snow in the pack, and sometimes the base of a snowpack lying on firn can be detected by noting a substantial increase in the resistance to probe penetration as the probe tip encounters the firn. However, the snowpack of glaciers in a maritime climate, such as South Cascade Glacier, can contain layers of ice and hard, buried snow crusts. Penetration resistance of these features can be similar to that of firn, which can make detection of the real interface between snow and firn difficult, if not impossible.

On May 1, 2002, an ablation stake (stake 1, fig. 2) was set near the upper end of the glacier in an area where several probing measurements indicated that snow depth could have been approximately 7.9 m. On the basis of this indicated depth, the stake was set in a hole melted through the snow and into what was suspected to be underlying firn. Coring measurements made late in the balance year 2002 to detect the depth of residual snow indicated the snow at stake 1 had been deeper than was indicated by probing on May 1 and also that the base of the stake set on that date was seated in snow rather than firn. The estimated depth of snow at stake 1 on May 1, 2002 was revised to 9.26 m, based on the depth of residual snow (3.33 m) and measurements of surface lowering at the stake during the summer season.

Density of snow on South Cascade Glacier at site P1 and near the terminus (fig. 2) was determined on May 1, 2002. Density of the uppermost 1.22 m of snow at site P1 was determined from samples taken in the wall of a pit and density of the remaining snow profile was determined from samples extracted with the coring auger (table 11). The profile-average snow density at site P1 was 0.51. Density of snow near the terminus was determined from samples taken in the wall of a pit dug to the underlying ice (table 12). The profile-average snow density at the site near the terminus was 0.46.

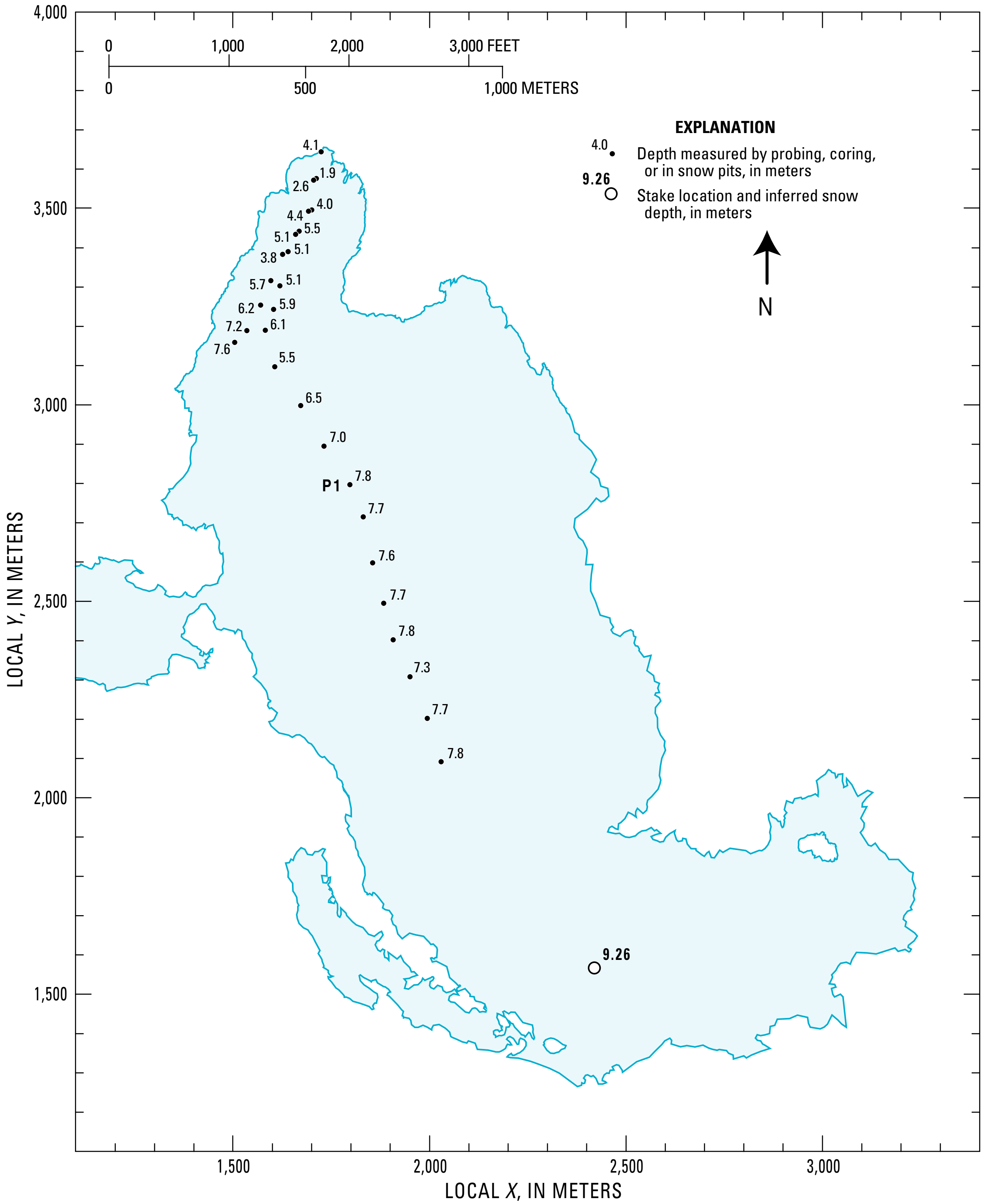

Figure 6. Snow depth at South Cascade Glacier, Washington, on May 1, 2002, determined on that date by probing, coring, or in snow pits, and inferred from ablation stake and coring measurements made late in the balance year.

Data are presented in table 10.

Table 10. Snow depth on South Cascade Glacier, Washington, 2002

[*X* and *Y* are easting and northing coordinates in the local coordinate system, meters; *Z*, altitude, meters]

X	Y	Z	Snow depth (meters)
May 1			
2,420	1,567	2,032	9.26
2,030	2,092	1,944	7.8
1,995	2,202	1,933	7.7
1,951	2,308	1,921	7.3
1,908	2,402	1,897	7.8
1,884	2,495	1,876	7.7
1,856	2,598	1,862	7.6
1,832	2,715	1,852	7.7
1,798	2,797	1,846	7.8
1,732	2,895	1,842	7.0
1,673	2,998	1,827	6.5
1,607	3,097	1,806	5.5
1,583	3,190	1,775	6.1
1,604	3,243	1,754	5.9
1,620	3,303	1,736	5.1
1,641	3,390	1,714	5.1
1,669	3,442	1,696	5.5
1,701	3,496	1,677	4.0
1,706	3,572	1,650	1.9
1,725	3,644	1,633	4.1
1,713	3,576	1,647	2.6
1,693	3,493	1,679	4.4
1,660	3,434	1,699	5.1
1,627	3,383	1,714	3.8
1,597	3,316	1,734	5.7
1,571	3,254	1,751	6.2
1,536	3,189	1,776	7.2
1,505	3,159	1,791	7.6
September 21			
1,769	2,623	1,862	1.59
September 22			
1,880	2,301	1,909	1.33
2,172	1,761	1,995	3.50
2,420	1,567	2,032	3.33
1,669	2,973	1,829	.64
September 27			
2,973	1,770	2,081	1.35
2,746	1,661	2,062	2.07

Table 11. Snow density on South Cascade Glacier near site P1, South Cascade Glacier, Washington, May 1, 2002

[Location of site P1 is shown on figure 2. **Snow density** to a depth of 1.220 m was computed from 0.0723-meter-diameter samples taken with a sampling tube from the wall of a pit. Snow density throughout the remaining snow depth was computed from 0.0763-meter-diameter samples taken with a coring auger; location *X* = 1,798, *Y* = 2,797, where *X* and *Y* are easting and northing coordinates in a local coordinate system, meters; altitude 1,846 meters. Density, fraction of the density of water, where the latter is assumed to equal 1,000 kilograms per cubic meter]

Snow sample			Snow density
Bottom depth (meters)	Length (meters)	Mass (kilograms)	
0.465	0.465	0.80	0.42
.890	.425	.66	.38
1.220	.330	.59	.44
1.640	.420	.91	.47
2.110	.470	1.03	.48
2.620	.430	1.01	.51
3.220	.610	1.44	.52
3.330	.110	.27	.54
3.410	.090	.20	.49
3.920	.480	1.26	.57
4.290	.400	1.03	.56
5.060	.770	1.92	.55
5.330	.280	.76	.59
5.540	.150	.39	.57
5.900	.360	.89	.54
6.080	.190	.43	.49
6.840	.780	1.81	.51
6.890	.055	.17	.68
7.870	.910	2.20	.53
		Average	.51

Table 12. Snow density near the terminus of South Cascade Glacier, Washington, May 1, 2002

[**Snow density** was computed from 0.0723-meter-diameter samples taken with a sampling tube from the wall of a pit dug through the entire snow depth; location X = 1,706, Y = 3,572, where X and Y are easting and northing coordinates in a local coordinate system, in meters; altitude 1,650 meters. Density, fraction of the density of water, where the latter is assumed to equal 1,000 kilograms per cubic meter]

Snow sample			Snow density
Bottom depth (meters)	Length (meters)	Mass (kilograms)	
0.460	0.460	0.83	0.44
.770	.310	.61	.48
1.110	.340	.62	.44
1.420	.310	.59	.46
1.890	.470	.93	.48
		Average.........	.46

Profile-average snow densities measured near the terminus and at site P1 on May 1 were used to estimate snow density over the entire glacier. Snow density was assumed to vary linearly with altitude between the values measured near the glacier terminus and at site P1. Snow density at sites of lower altitude than the density-measurement site near the terminus was assumed to equal that at the density-measurement site, and snow density at sites of higher altitude than site P1 was assumed to equal the snow density at site P1.

Snow water equivalent was computed for each site where snow depth on May 1, 2002 was measured or estimated by multiplying snow depth by snow density. Snow water equivalent was plotted as a function of altitude and a curve was fitted to the data by eye (fig. 7). Points digitized on the curve were used to populate an interpolation table (table 13) that can be used to estimate the May 1, 2002 snow water equivalent for any point of known altitude on South Cascade Glacier. The interpolation table assumed the role of the relation $b(Z)$ in equation 9 for the purpose of computing the measured winter snow balance $\bar{b}_m(s)$ of South Cascade Glacier.

The DEM needed to compute the glacier measured winter snow balance ($\bar{b}_m(s)$) with equation 9 was assembled using the September 13, 2002 vertical aerial photography described previously and the 2001 South Cascade Glacier DEM reported by Krimmel (2002). Stereo photogrammetric analysis of featureless snow surfaces generally is not reliable, and DEM grid points that in 2002 fell in featureless snow-covered regions of the glacier were assumed to be equal to the respective 2001 DEM grid points reported by Krimmel (2002). The nominal horizontal grid spacing of the resulting composite DEM (fig. 8, table 14) is 100 m.

Table 13. Altitude and snow water equivalent values defining a curve used to estimate snow water equivalent as it varied with altitude at South Cascade Glacier, Washington, on May 1, 2002

[Snow water equivalent as it varied with altitude is shown in figure 7]

Altitude (meters)	Snow water equivalent (meters)
1,633	0.56
1,637	.88
1,640	1.21
1,649	1.52
1,664	1.83
1,686	2.14
1,709	2.42
1,735	2.71
1,764	2.99
1,795	3.27
1,825	3.53
1,859	3.79
1,895	4.04
1,932	4.26
1,973	4.45
2,016	4.63
2,068	4.78
2,127	4.87

The May 1, 2002 measured winter snow balance of South Cascade Glacier ($\bar{b}_m(s)$) was the second largest on record for the glacier (4.02 m, table 15). Measurements used to compute $\bar{b}_m(s)$ likely were appropriately timed to reliably estimate $\bar{b}_w(s)$, and the two glacier balances were assumed to be equal. Although snow water equivalent was not monitored daily at South Cascade Glacier, examination of data reported for two nearby automated SNOTEL sites yields evidence that the 2002 winter-balance measurements were made at approximately the right time. The maximum snow water equivalent reported for the Lyman Lake SNOTEL site (fig. 1) for the 2002 winter season was 2.25 m during April 28 to 30 and again on May 10 (fig. 9) (National Water and Climate Center, 2003); whereas, snow water equivalent May 1 was only 0.01 m less than the winter season maximum. The Lyman Lake SNOTEL site (1,798 m) is approximately 170 m higher than the South Cascade Glacier terminus. Snow water equivalent reported for the Miners Ridge site (fig. 1) on May 1 was 1.82 m, and the maximum 2002 snow water equivalent of 1.86 m occurred during May 9 to 11 as a result of a cold spring storm that swept into the North Cascade Range during the first week of that month (fig. 9). Approximately 60 percent of the area of South

Cascade Glacier is at an altitude greater than that of the Miners Ridge SNOTEL site (1,890 m) (fig. 10). The date of maximum snow water equivalent at SNOTEL sites in the North Cascade Range tends to be later at higher altitudes; therefore, the date of maximum snow water equivalent of South Cascade Glacier up-glacier from site P1 could have been later than the date of maximum snow water equivalent at Miners Ridge. However, snow water equivalent tends to change very slowly near the date of the maximum (National Water and Climate Center, 2003). Thus, measured winter snow balance at South Cascade Glacier on May 1, 2002 is believed to closely approximate the 2002 maximum. The 2002 winter season at South Cascade Glacier is estimated to have ended on May 10, 2002.

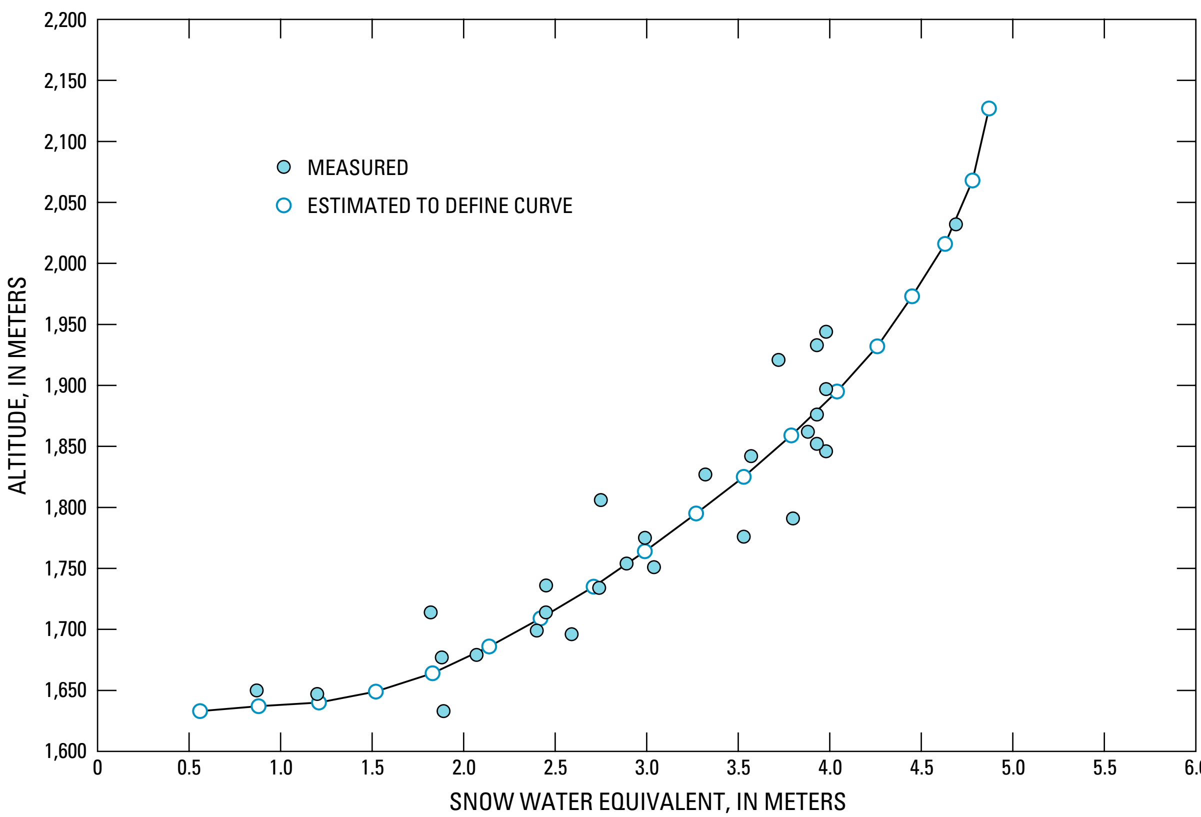

Figure 7. Snow water equivalent as it varied with altitude at South Cascade Glacier, Washington, May 1, 2002. Estimated values for points defining the curve are presented in table 13.

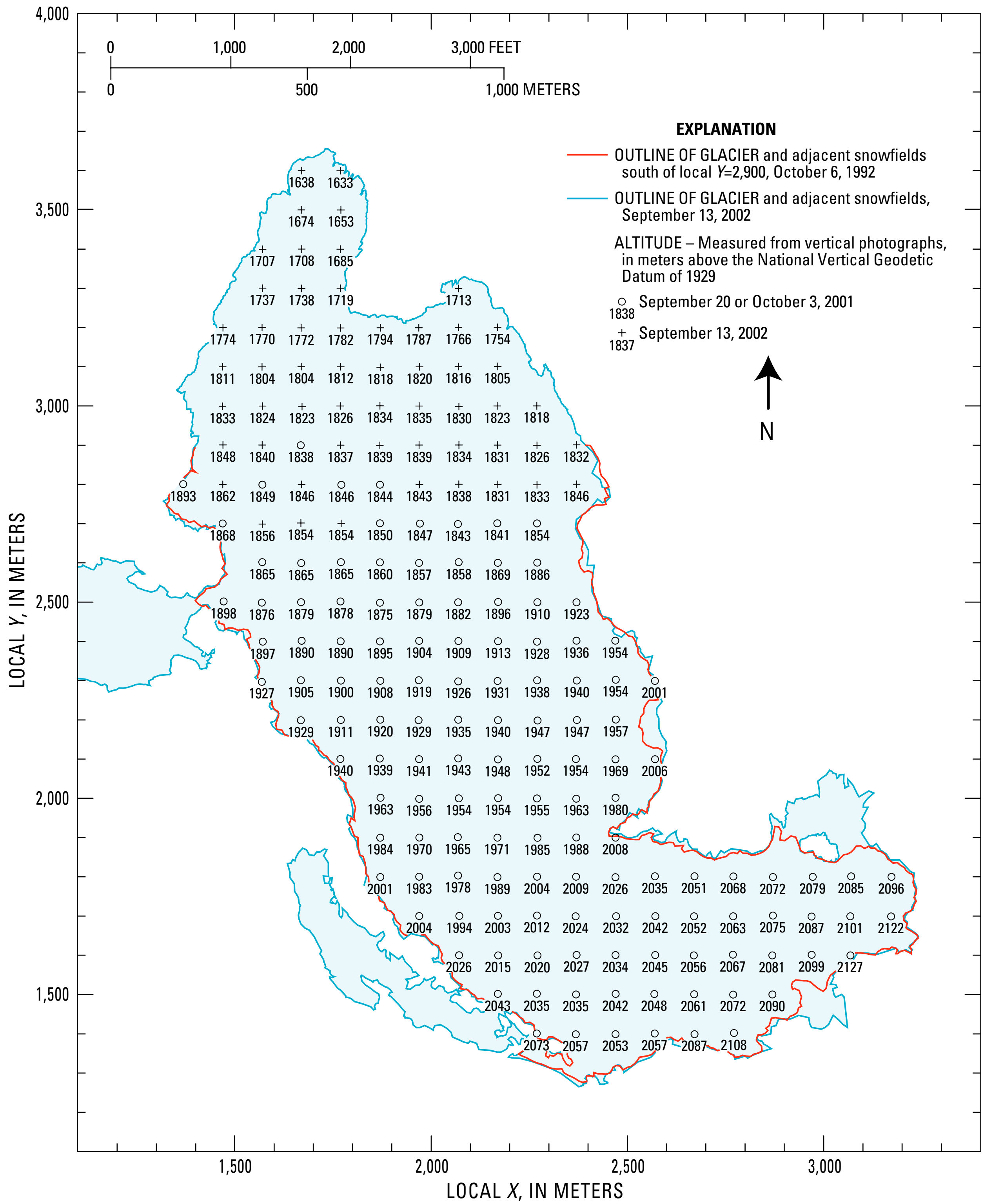

Figure 8. Altitude grid for South Cascade Glacier, Washington, measured from vertical photographs taken on September 20 or October 3, 2001, and September 13, 2002.
Data for grid are presented in table 14.

Table 14. Altitude grid for South Cascade Glacier, Washington, 2002

[Year, Calendar year of aerial photography; *X*, easting coordinate in local coordinate system, meters; *Y*, northing coordinate in local coordinate system, meters; *Z*, altitude, meters]

Year	X	Y	Z
2002	1,769	3,599	1,633
2002	1,671	3,600	1,638
2002	1,771	3,500	1,653
2002	1,670	3,500	1,674
2002	1,769	3,400	1,685
2002	1,671	3,400	1,708
2002	1,571	3,399	1,707
2002	2,070	3,299	1,713
2002	1,770	3,300	1,719
2002	1,670	3,299	1,738
2002	1,571	3,301	1,737
2002	2,170	3,201	1,754
2002	2,070	3,201	1,766
2002	1,969	3,199	1,787
2002	1,871	3,200	1,794
2002	1,770	3,199	1,782
2002	1,670	3,199	1,772
2002	1,570	3,200	1,770
2002	1,470	3,200	1,774
2002	2,170	3,101	1,805
2002	2,070	3,100	1,816
2002	1,971	3,100	1,820
2002	1,871	3,099	1,818
2002	1,770	3,100	1,812
2002	1,670	3,100	1,804
2002	1,570	3,100	1,804
2002	1,470	3,100	1,811
2002	2,270	3,000	1,818
2002	2,169	3,000	1,823
2002	2,071	2,998	1,830
2002	1,970	3,000	1,835
2002	1,870	3,001	1,834
2002	1,769	3,000	1,826
2002	1,671	2,999	1,823
2002	1,571	3,000	1,824
2002	1,469	2,999	1,833
2002	2,371	2,901	1,832
2002	2,270	2,900	1,826
2002	2,170	2,900	1,831
2002	2,071	2,901	1,834
2002	1,970	2,900	1,839
2002	1,870	2,900	1,839
2002	1,770	2,900	1,837
2001	1,669	2,900	1,838
2002	1,570	2,900	1,840
2002	1,470	2,901	1,848
2002	2,371	2,801	1,846
2002	2,270	2,799	1,833
2002	2,170	2,800	1,831
2002	2,071	2,800	1,838
2002	1,971	2,800	1,843
2001	1,870	2,799	1,844
2001	1,772	2,799	1,846
2002	1,671	2,800	1,846
2001	1,571	2,800	1,849
2002	1,470	2,800	1,862
2001	1,369	2,801	1,893
2001	2,270	2,701	1,854
2001	2,169	2,701	1,841
2001	2,069	2,699	1,843
2001	1,972	2,700	1,847
2001	1,870	2,701	1,850
2002	1,771	2,701	1,854
2002	1,669	2,702	1,854
2002	1,571	2,699	1,856
2001	1,470	2,700	1,868
2001	2,271	2,601	1,886
2001	2,170	2,600	1,869
2001	2,071	2,602	1,858
2001	1,970	2,600	1,857
2001	1,870	2,601	1,860
2001	1,771	2,602	1,865
2001	1,670	2,600	1,865
2001	1,570	2,602	1,865
2001	2,371	2,499	1,923
2001	2,271	2,500	1,910
2001	2,171	2,500	1,896
2001	2,069	2,500	1,882
2001	1,970	2,499	1,879
2001	1,870	2,498	1,875
2001	1,770	2,502	1,878
2001	1,669	2,500	1,879
2001	1,569	2,499	1,876
2001	1,472	2,502	1,898
2001	2,469	2,402	1,954
2001	2,371	2,402	1,936
2001	2,270	2,399	1,928
2001	2,171	2,400	1,913
2001	2,070	2,401	1,909
2001	1,970	2,401	1,904
2001	1,870	2,400	1,895
2001	1,770	2,400	1,890
2001	1,671	2,401	1,890
2001	1,572	2,399	1,897
2001	2,571	2,299	2,001
2001	2,471	2,302	1,954
2001	2,371	2,300	1,940
2001	2,270	2,301	1,938
2001	2,170	2,299	1,931
2001	2,070	2,298	1,926
2001	1,969	2,301	1,919
2001	1,871	2,300	1,908
2001	1,771	2,300	1,900
2001	1,669	2,301	1,905
2001	1,569	2,297	1,927
2001	2,471	2,201	1,957
2001	2,372	2,200	1,947
2001	2,272	2,198	1,947
2001	2,171	2,199	1,940
2001	2,070	2,200	1,935
2001	1,969	2,199	1,929
2001	1,871	2,200	1,920
2001	1,771	2,199	1,911
2001	1,669	2,199	1,929
2001	2,571	2,099	2,006
2001	2,470	2,099	1,969
2001	2,369	2,100	1,954
2001	2,271	2,100	1,952
2001	2,171	2,099	1,948
2001	2,069	2,101	1,943
2001	1,970	2,100	1,941
2001	1,870	2,101	1,939
2001	1,769	2,100	1,940
2001	2,470	2,001	1,980
2001	2,370	1,999	1,963
2001	2,270	2,000	1,955
2001	2,171	2,000	1,954
2001	2,071	2,000	1,954
2001	1,970	1,998	1,956
2001	1,872	2,001	1,963
2001	2,470	1,900	2,008
2001	2,370	1,900	1,988
2001	2,271	1,899	1,985
2001	2,169	1,900	1,971
2001	2,069	1,901	1,965
2001	1,970	1,900	1,970
2001	1,871	1,899	1,984
2001	3,173	1,800	2,096
2001	3,070	1,801	2,085
2001	2,972	1,800	2,079
2001	2,871	1,799	2,072
2001	2,770	1,801	2,068
2001	2,671	1,801	2,051
2001	2,571	1,801	2,035
2001	2,470	1,799	2,026
2001	2,370	1,800	2,009
2001	2,270	1,800	2,004
2001	2,169	1,799	1,989
2001	2,069	1,803	1,978
2001	1,970	1,800	1,983
2001	1,871	1,799	2,001
2001	3,172	1,699	2,122
2001	3,068	1,699	2,101
2001	2,969	1,698	2,087
2001	2,871	1,701	2,075
2001	2,770	1,699	2,063
2001	2,670	1,699	2,052
2001	2,572	1,700	2,042
2001	2,471	1,700	2,032
2001	2,369	1,699	2,024
2001	2,270	1,701	2,012
2001	2,171	1,701	2,003
2001	2,072	1,700	1,994
2001	1,970	1,700	2,004
2001	3,068	1,600	2,127
2001	2,970	1,601	2,099
2001	2,869	1,600	2,081
2001	2,769	1,601	2,067
2001	2,669	1,600	2,056
2001	2,571	1,600	2,045
2001	2,470	1,600	2,034
2001	2,371	1,601	2,027
2001	2,271	1,600	2,020
2001	2,171	1,600	2,015
2001	2,072	1,600	2,026
2001	2,870	1,500	2,090
2001	2,770	1,500	2,072
2001	2,670	1,501	2,061
2001	2,569	1,501	2,048
2001	2,470	1,501	2,042
2001	2,369	1,500	2,035
2001	2,270	1,502	2,035
2001	2,170	1,502	2,043
2001	2,772	1,402	2,108
2001	2,671	1,399	2,087
2001	2,570	1,400	2,057
2001	2,470	1,399	2,053
2001	2,369	1,399	2,057
2001	2,269	1,401	2,073

Table 15. Winter, summer, and net balances of South Cascade Glacier, Washington, balance years 1959 to 2002

[$\bar{b}_m(s)$, glacier measured winter snow balance; $\bar{b}_s$, glacier summer balance; $\bar{b}_n$, glacier net balance; balances are in meters water equivalent; data for 1959 to 1985 and 1992 to 2001 are from Krimmel (2002); data for 1986 to 1991 are from Krimmel (2000)]

Balance year	$\bar{b}_m(s)$	$\bar{b}_s$	$\bar{b}_n$
1959	3.28	-2.58	0.70
1960	2.21	-2.71	-.50
1961	2.40	-3.50	-1.10
1962	2.50	-2.30	.20
1963	2.23	-3.53	-1.30
1964	3.25	-2.05	1.20
1965	3.48	-3.65	-.17
1966	2.47	-3.50	-1.03
1967	3.29	-3.92	-.63
1968	3.00	-2.99	.01
1969	3.17	-3.90	-.73
1970	2.41	-3.61	-1.20
1971	3.51	-2.91	.60
1972	4.27	-2.84	1.43
1973	2.21	-3.25	-1.04
1974	3.65	-2.63	1.02
1975	3.06	-3.11	-.05
1976	3.53	-2.58	.95
1977	1.57	-2.87	-1.30
1978	2.49	-2.87	-.38
1979	2.18	-3.74	-1.56
1980	1.83	-2.85	-1.02
1981	2.28	-3.12	-.84
1982	3.11	-3.03	.08
1983	1.91	-2.68	-.77
1984	2.38	-2.26	0.12
1985	2.18	-3.38	-1.20
1986	2.45	-3.06	-.61
1987	2.04	-4.10	-2.06
1988	2.44	-3.78	-1.34
1989	2.43	-3.34	-.91
1990	2.60	-2.71	-.11
1991	3.54	-3.47	.07
1992	1.91	-3.92	-2.01
1993	1.98	-3.21	-1.23
1994	2.39	-3.99	-1.60
1995	2.86	-3.55	-.69
1996	2.94	-2.84	.10
1997	3.71	-3.08	.63
1998	2.76	-4.62	-1.86
1999	3.59	-2.57	1.02
2000	3.32	-2.94	.38
2001	1.90	-3.47	-1.57
2002	4.02	-3.47	.55
MEAN 1959 to 2002	2.74	-3.19	-0.45
MEDIAN 1959 to 2002	2.50	-3.12	-0.62
2002 RANK	2	28	9

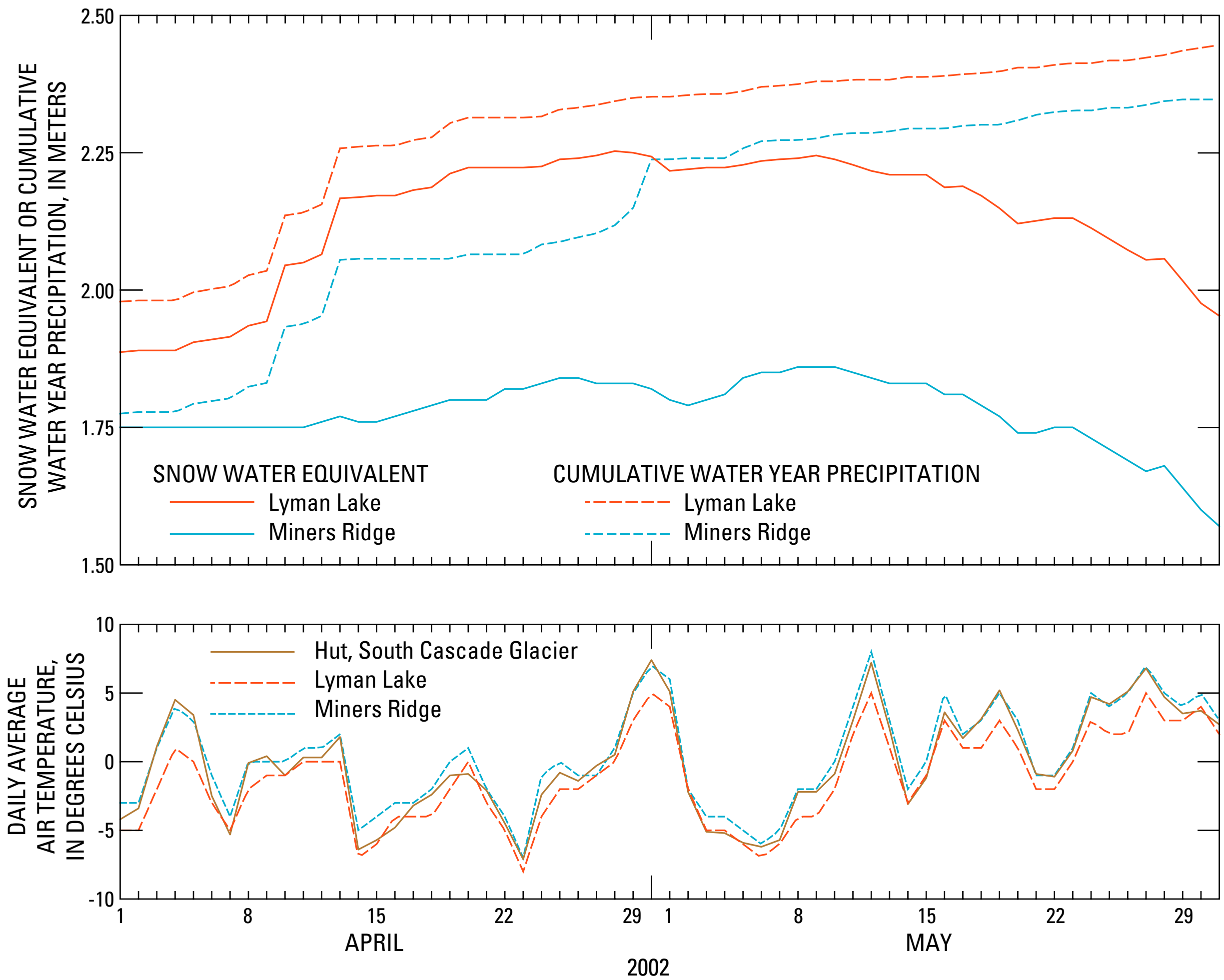

Figure 9. Snow water equivalent and cumulative water year precipitation and average daily air temperature at the Lyman Lake SNOTEL site, 1,798 meters altitude, and Miners Ridge SNOTEL site, 1,890 meters altitude, and daily average air temperature at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, April and May 2002.

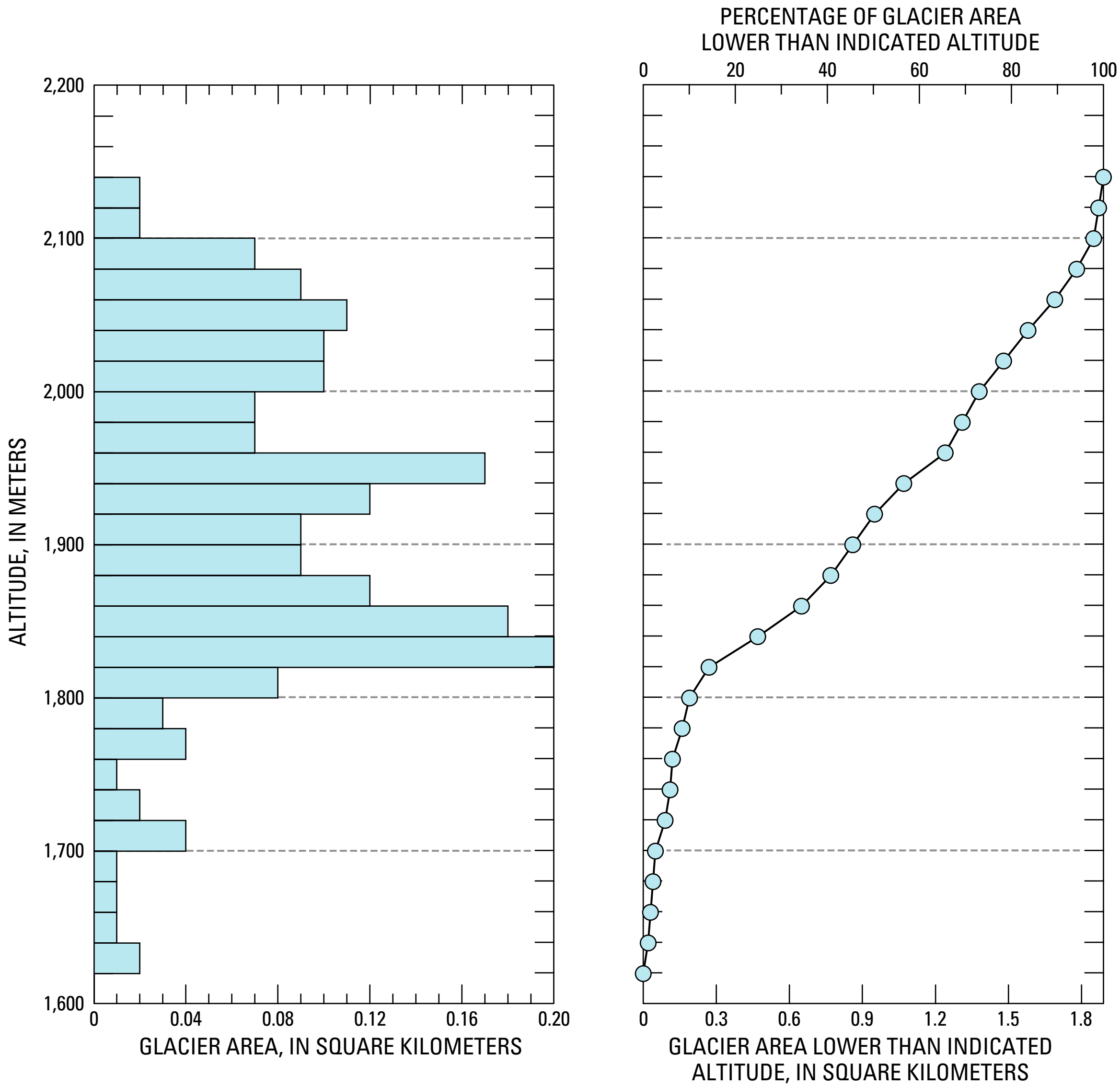

Figure 10. South Cascade Glacier area-altitude distribution and cumulative-area-altitude distribution, based on the 2002 South Cascade Glacier, Washington, altitude grid (fig. 8).

Net Balance

The 2002 net balance of South Cascade Glacier was estimated by using measurements of snow accumulation and ice ablation, and an estimate of the altitude of the glacier equilibrium line, where the net balance is 0. Height of the snow or ice surface on ablation stakes set May 1, 2002 (fig. 2) was measured intermittently during May 1 to October 26, 2002 (table 16). Thickness of residual snow was measured September 21, 22, or 27, 2002 at selected sites in the altitude range of 1,829 to 2,081 m (fig. 2) by coring through the snow to measure the depth to the underlying melt surface formed at the end of the 2001 balance year. Measured thickness of the residual snow ranged from 0.64 to 3.50 m (table 10).

Measured stake height and snow thickness were converted to balances using measured snow density and estimated ice density, or more commonly, estimated snow and ice densities. Measured density of residual snow at site P1 September 27, 2002 was 0.56 (table 17), and density of all snow remaining on the glacier on that date was assumed to equal the density at site P1. During May 1 to September 27, the density of any remaining snow at the density-measurement site near the glacier terminus and at site P1 was assumed to vary linearly with time between the value obtained May 1 and the value from site P1 measured September 27. Density of snow anywhere on the glacier during May 1 to September 27 was estimated using the same altitude-based scheme as described previously for computing the winter balance. After September 27, snow density was assumed to be spatially invariable and to change linearly with time from 0.56 on September 27 to 0.58 on October 26. Density of ice was assumed to be 0.90.

Stake 1 likely was reliable for gaging ablation during the 2002 summer season, despite having been seated in snow rather than firn or ice, although seating in firn or ice has been the practice at South Cascade Glacier in the past and is suggested by Østrem and Brugman (1991) to reduce the amount of sinking of the stake into the glacier. The ratio of computed ablation at stake 1 to that at stake 2 during May 1 to September 27, 2002 was 0.90 (table 16). During May 15 to September 12, 1995, when stakes 1-95 and 2-95 were close to the 2002 locations of stakes 1 and 2, respectively, the ratio of ablation at stake 1-95 to that stake 2-95 was 0.88 (Krimmel, 1996a). In general, the ratio of ablation between any two sites on the glacier with predominantly the same surface type tends to remain relatively constant from time to time. Had the 2002 stake 1 sunk into the snow at its base, the above-reported ratio (0.90) likely would have been unexpectedly small, which it was not.

Table 16. Ablation stake measurements at South Cascade Glacier, Washington, balance year 2002

[**Date**: Date of measurement. **Surface height**: Height of glacier surface above the 2001 melt horizon, in meters. **Density**: Measured or estimated density of material between the surface and the 2001 melt horizon, expressed as a fraction of the density of water. **Balance**: Gain of glacier mass per unit area since time of formation of the 2001 melt horizon, in meters water equivalent; e, balance estimated without surface height measurement; *X* and *Y* are easting and northing coordinates in a local coordinate system, meters; *Z*, altitude, meters; –, no data]

Date	Surface material	Surface height	Density	Balance
Stake 1 [*X*=2,420, *Y*=1,567, *Z*=2,032]				
May 1	snow	9.26	0.51	4.72
July 2	snow	7.59	.53	4.02
Sept. 20	snow	3.36	.56	1.88
Sept. 22	snow	3.33	.56	1.86
Sept. 27	snow	3.28	.56	1.84
Oct. 26	snow	3.36	.58	1.95
Stake 2 [*X*=1,798, *Y*=2,797, *Z*=1,846] Site P1				
May 1	snow	7.80	.51	3.98
July 2	snow	5.84	.53	3.10
Sept. 20	snow	1.56	.56	.87
Sept. 27	snow	1.39	.56	.78
Oct. 26	snow	1.26	.58	.73
Stake 3 [*X*=1,607, *Y*=3,097, *Z*=1,806]				
May 1	snow	5.50	.50	2.75
July 2	snow	3.54	.52	1.84
Sept. 21	ice	-1.43	.90	-1.29
Sept. 27	ice	–	–	-1.40e
Oct. 26	ice	–	–	-1.67e
Stake 4 [*X*=1,641, *Y*=3,390, *Z*=1,714]				
May 1	snow	5.10	.48	2.45
July 2	snow	2.97	.51	1.51
Sept. 21	ice	-2.01	.90	-1.81
Sept. 27	ice	–	–	-1.92e
Oct. 26	ice	–	–	-2.21e
Stake 5 [*X*=1,706, *Y*=3,572, *Z*=1,650]				
May 1	snow	1.90	.46	.87
July 2	ice	-.42	.90	-.38
Aug. 19	ice	-3.64	.90	-3.28
Sept. 21	ice	-5.45	.90	-4.91
Sept. 27	ice	–	–	-5.06e
Oct. 26	ice	-6.07	.90	-5.46

Table 17. Snow density on South Cascade Glacier near site P1, South Cascade Glacier, Washington, September 27, 2002

[Location of site P1 is shown on figure 2. **Snow density** was computed from 0.0763-m-diameter samples taken through the entire snow thickness with a coring auger; location *X* = 1,798, *Y* = 2,797, where *X* and *Y* are easting and northing coordinates in a local coordinate system, meters; altitude 1,846 meters; density, fraction of the density of water, where the latter is assumed to equal 1,000 kilograms per cubic meter]

Snow sample			Snow density
Bottom depth (meters)	Length (meters)	Mass (kilograms)	
0.380	0.335	0.87	0.57
.930	.540	1.35	.55
1.500	.495	1.29	.57
		Average	.56

A snow storm that struck South Cascade Glacier September 29, 2002 likely blanketed the entire glacier. The storm was followed by one more cold spell during the second week of October, and then by unseasonably warm and mostly dry weather that persisted until late October (fig. 11). When the glacier was visited October 26, 2002, 0.08 m of well-consolidated snow from the late September storm was present at the highest-altitude ablation stake (stake 1, fig. 2), whereas no such snow was present at site P1 or lower down the glacier. Balance year 2002 is believed to have ended on November 7, 2002, when a series of storms began to arrive in the North Cascade Range, accompanied by freezing or near-freezing air temperatures at the Hut and at the Lyman Lake and Miners Ridge SNOTEL sites (fig. 11).

The transient snow line was mapped using vertical aerial photography obtained September 13, 2002 (fig. 2). The approximate 2002 equilibrium line was mapped by adjusting the September 13 transient snow line for the change in snow cover between September 13 and that observed in oblique 35-mm aerial photographs that were taken October 26.

The glacier balance was computed for October 26, 2002, which necessitated the extension of balance records by estimation for some sites. Balance records at ablation stakes not visited on October 26 (stakes 3 and 4) were extended to that date by assuming the ratio of the balance rate ($\dot{b}$, in meters water equivalent per day) at a stake not measured on October 26 to computed for a stake measured then was the same as the ratio during previous periods, when balances rates for both stakes were computed from direct measurements. Balance records at residual-snow coring sites were extended to October 26 by assuming that $\dot{b}$ varied linearly with altitude. The altitude dependence of $\dot{b}$ was computed using balance data from stakes 1 and 2 during September 20 to October 26.

Measured and estimated October 26, 2002 point balances from the ablation stakes and coring sites were used to develop a balance-to-altitude relation that was used with equation 9 and the 2002 glacier DEM to compute the glacier balance on that date. Point balances were plotted as a function of altitude, along with a point representing the estimated 2002 glacier equilibrium altitude (1,820 m). A curve was fitted to the data by eye (fig. 12). Points digitized on the curve were used to populate an interpolation table (table 18) that served as the relation of net balance to altitude ($b(Z)$) in equation 9. Any changes in glacier balance during October 26 to November 7, 2002 likely were negligibly small because the days were short, sun elevation angles were small, and daily average air temperature generally was close to 0°C (fig. 11). Balance year 2001 likely ended on or about October 12, 2001 (Krimmel, 2002), making balance year 2002 391 days in duration. The computed 2002 net balance of South Cascade Glacier ($\bar{b}_n$) was the ninth largest since 1959 (table 15).

Table 18. Altitude and net balance values defining a curve used to estimate net balance as it varied with altitude at South Cascade Glacier, Washington, balance year 2002

[Net balance as it varied with altitude is shown in figure 12]

Altitude (meters)	Net balance
1,633	-6.09
1,647	-5.61
1,660	-5.14
1,674	-4.66
1,687	-4.19
1,701	-3.71
1,714	-3.23
1,727	-2.75
1,741	-2.27
1,755	-1.79
1,768	-1.32
1,782	-.85
1,801	-.39
1,826	.04
1,857	.42
1,893	.74
1,933	1.02
1,975	1.26
2,015	1.46
2,059	1.65
2,106	1.83
2,146	1.98

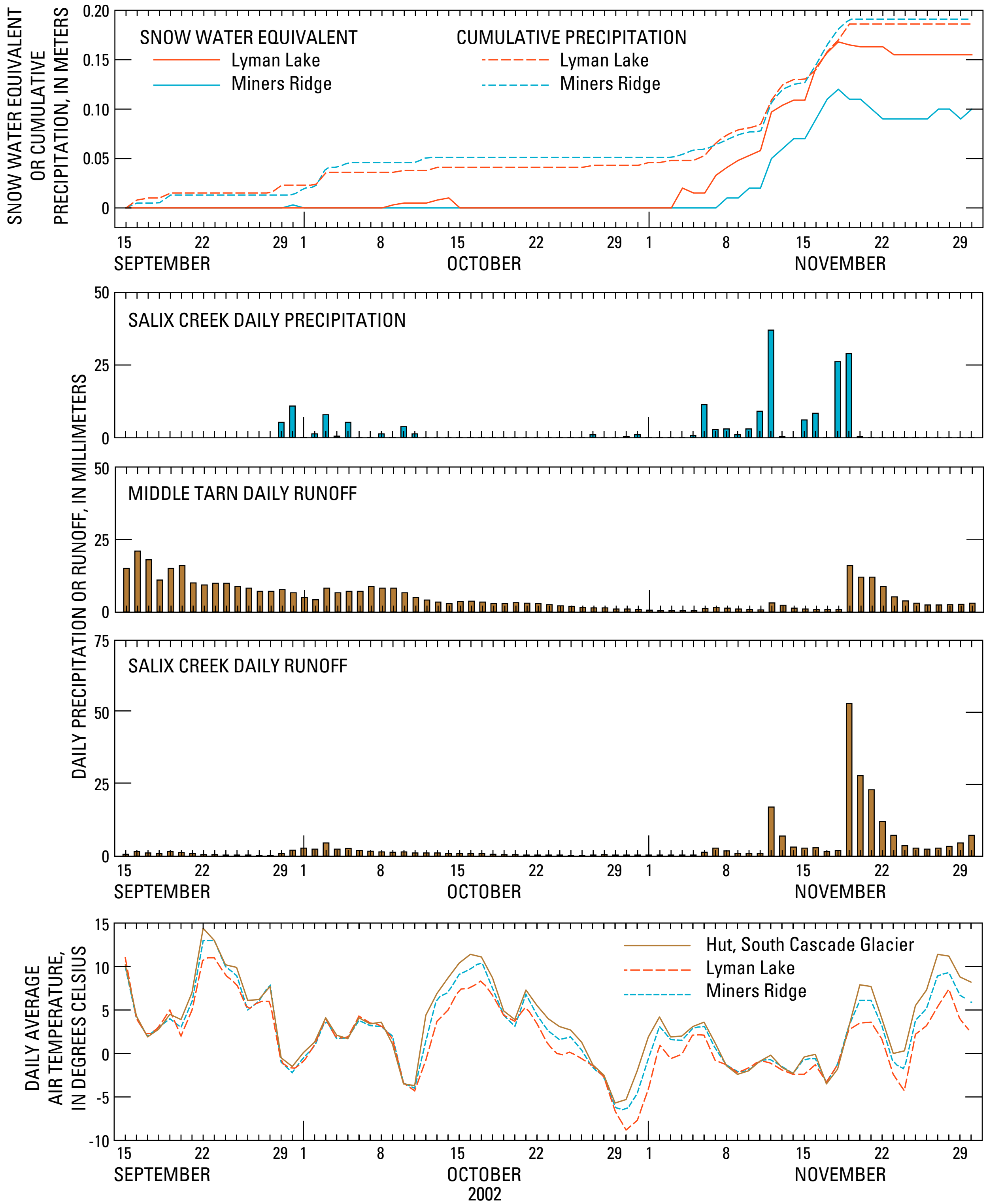

Figure 11. Snow water equivalent, cumulative precipitation beginning September 15, 2002, and daily average air temperature at the Lyman Lake and Miners Ridge SNOTEL sites, daily precipitation and runoff at the Salix Creek gaging station, daily runoff at the Middle Tarn gaging station, and daily average air temperature at the Hut, near South Cascade Glacier, Washington, during part of September, October, and November 2002.

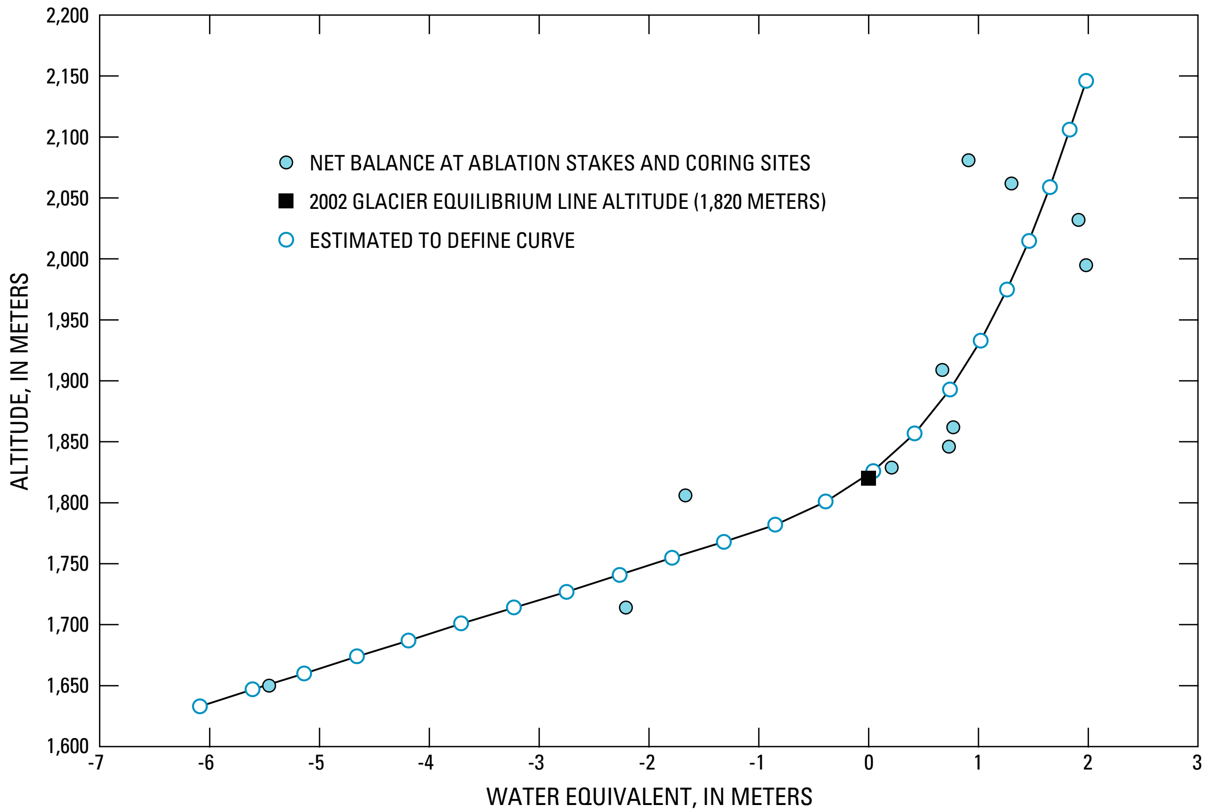

Figure 12. Net balance as it varied with altitude at South Cascade Glacier, Washington, balance year 2002. Estimated values for points defining the curve are presented in table 18.

Summer and Annual Balances

The computed 2002 summer balance of South Cascade Glacier ($\bar{b}_s$) was -3.47 m, which was 9 percent more negative that the average summer balance during 1959 to 2002. Larger than normal ablation during the 2002 summer season partly offset the exceptionally large 2002 winter balance to result in the unexceptional, but positive, 2002 net balance. Available data for 1960 to 2002 indicate $\bar{b}_s$ is negatively correlated with average air temperature at the Hut during June through September (the glacier tends to lose more mass as average June-through-September temperature increases), and the computed 2002 $\bar{b}_s$ is consistent with that relation (fig. 13).

Personnel were not present at South Cascade Glacier on either the beginning or ending days of water year 2002, and the 2002 annual balance of the glacier ($\bar{b}_a$) was computed based on estimates of the initial and final balance increments ($\bar{b}_0$ and $\bar{b}_1$). Krimmel (2002) estimated $\bar{b}_1$ for water year 2001 to be -0.05 m, and the 2001 $\bar{b}_1$ is equivalent to the 2002 $\bar{b}_0$. The 2002 final balance increment was estimated using three steps. First, glacier balance relative to the 2001 summer surface was computed by the grid index technique for September 27, 2002 using the previously described ablation stake and coring measurements. Balance records for sites not measured on September 27 were extended to that date using procedures similar to those described for the net balance. Glacier balance on September 27 was 0.57 m. Second, glacier balance on September 30 was computed by summing the September 27 glacier balance with water equivalent depth of snow that fell on the glacier during September 29 and 30 (0.02 m), where the latter was computed by assuming that precipitation measured at the Salix gaging station (table 7) also fell as snow upon the glacier (no precipitation fell at South Cascade Lake Basin on September 28, 2002). Finally, $\bar{b}_1$ was computed as $\bar{b}_n$ minus the balance on September 30. The estimated value for $\bar{b}_1$ was -0.04 m, and the estimated 2002 annual balance ($\bar{b}_a$) was 0.54 m.

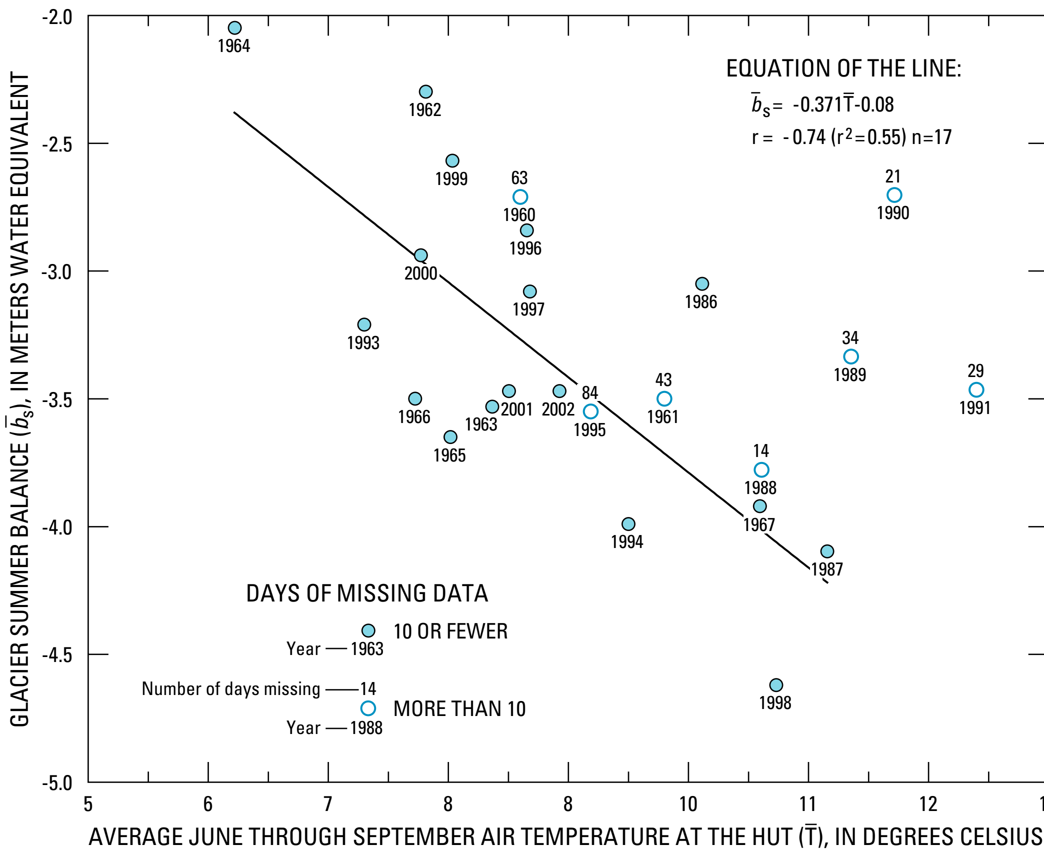

Figure 13. Summer balance of South Cascade Glacier as it varied with average air temperature at the Hut, 1,842 meters altitude, South Cascade Lake Basin, Washington, during June through September.

Data presented are for years for which numerical data have been published (1960–67, Sullivan, 1994; 1986–91, Krimmel, 2000; and 1993–2001, Krimmel, 1994, 1995, 1996a, 1997, 1998, 1999, 2001, 2002). Regression line and equation are fitted to data from years with 10 or fewer days of missing data.

Some Sources of Mass Balance Errors

Glacier mass-balance quantities in this report were subject to numerous measurement and sampling errors. Among the potentially most significant measurement errors were errors in depth of snow measured by probing (due to false detection of the base of the snowpack in areas where the snow was underlain by firn), errors in volumes of snow samples used to compute snow bulk density (due to sample disturbance caused by sampling equipment), and errors in computed surface lowering due to sinking of ablation stakes.

Sampling errors, both in time and in space, probably contributed more uncertainty in the mass-balance estimates than did measurement errors. Sampling errors in time were due to the impracticality of monitoring the glacier daily, which required that conclusion dates of the winter season and balance year be estimated, and also that balance records for individual sites or for the entire glacier be extended to the concluding dates. As a result, errors of estimation likely accompanied the extensions of the balance records. Each of the glaciological measurements that were made for computing mass balance (snow depth and density and surface lowering) was subject to spatial sampling errors caused by spatial variations of the measured properties that were not accounted for. Sampling errors in space with the grid-index method are apparent in the failure of altitude, as the single explanatory variable, to account for all of the observed variation of snow water equivalent (fig. 7) and net balance (fig. 12). Another potential source of sampling error was the spatial variation of profile-average snow density not accounted for by the three measured profiles (tables 11, 12, and 17) or by the density estimation schemes described previously. The total error in each of the glacier mass-balance quantities in this report ($\bar{b}_{\mathrm{w}}(\mathrm{s})$, $\bar{b}_{\mathrm{s}}$, $\bar{b}_{\mathrm{n}}$, and $\bar{b}_{\mathrm{a}}$) due to measurement and sampling errors is not objectively known but probably is a few tenths of a meter water equivalent, which would be consistent with errors reported by Krimmel (2002) for past South Cascade Glacier mass balances. Mass-balance errors due to neglect of internal ablation and accumulation and basal melting were likely much smaller than those due to measurement and sampling errors.

Terminus Retreat, Glacier Area, and Equilibrium Line

The unusually large snowpack of 2002 shielded the terminus ice of South Cascade Glacier from the elements until later in the summer season than has been usual in recent years. As a result, retreat of the terminus during balance year 2002 was less than usual. Retreat of the terminus during September 20, 2001 to September 13, 2002, was estimated to be 4 m, with an uncertainty of about 2 m (fig. 14).

The area of South Cascade Glacier was determined using a composite map of the glacier outline derived from vertical aerial photographs taken October 6, 1992 (Krimmel, 1993) and September 13, 2002. The area of the glacier south of $Y = 2{,}900$ likely does not change much from year to year, but the combined area of the glacier and contiguous snowfields does vary, depending on how much snow falls each winter. Balance year 1992 was the second most negative for South Cascade Glacier since 1959 (table 15). The October 6, 1992 glacier outline south of $Y = 2{,}900$ (fig. 8) therefore includes a relatively small area of contiguous snowfields and is an appropriate base for computing changes in total glacier area from year to year. The total area of South Cascade Glacier on September 13, 2002 computed from the 2002 glacier outline for areas north of $Y = 2{,}900$ and the 1992 outline for areas south of $Y = 2{,}900$ was 1.92 km^2. The area of the glacier north of $Y = 2{,}900$ was 0.41 km^2. The area of South Cascade Glacier computed using the DEM grid by assuming each grid point represented 0.01 km^2 of glacier area was 1.89 km^2. The area of the glacier computed from the glacier outlines is probably more accurate than the area computed using the DEM grid. The average altitude of the 2002 equilibrium line was 1,820 m and the accumulation area ratio was 0.84.

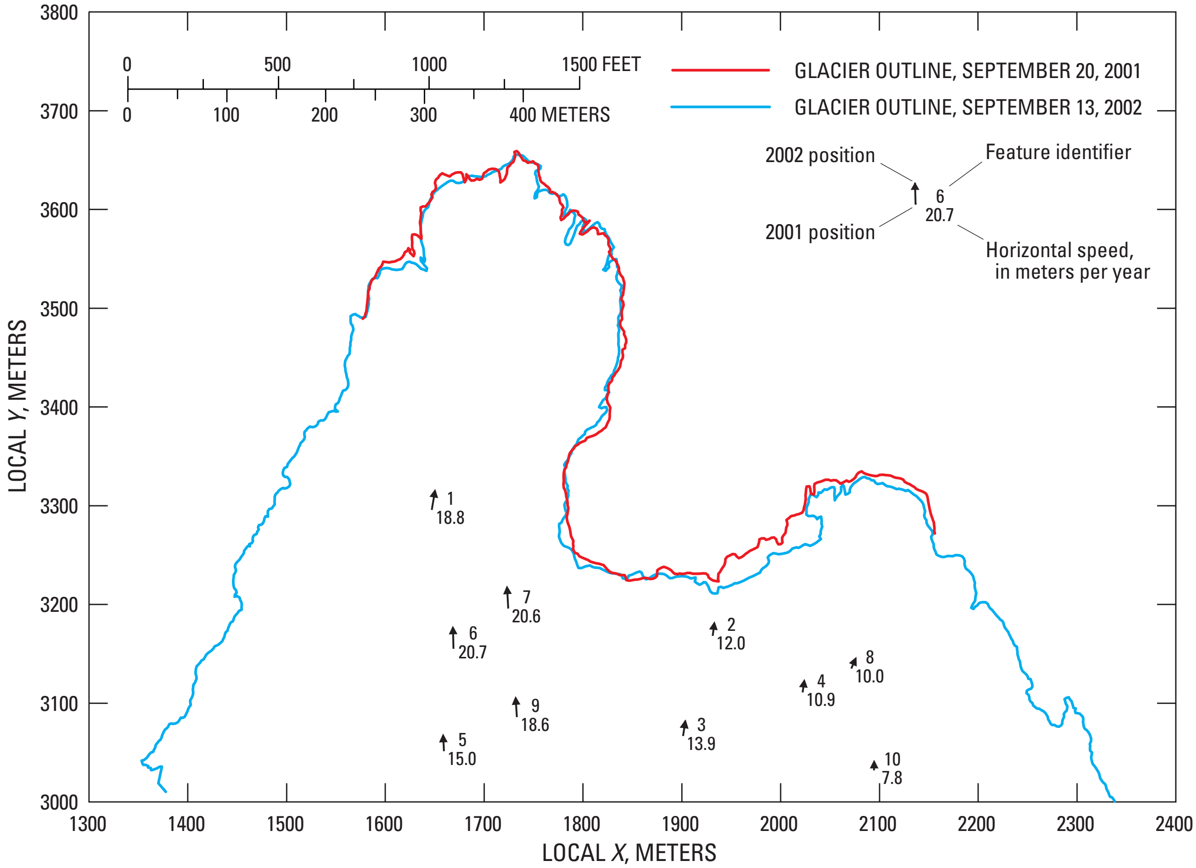

Figure 14. Position of the terminus of South Cascade Glacier, Washington, on September 20, 2001, and September 13, 2002, and average annual speed and direction of surficial ice as computed from the displacement of selected features identified in vertical photographs from September 20, 2001 and September 13, 2002.

Ice Movement

Average horizontal speed and direction of movement of surficial glacier ice were computed by measuring displacement of selected surface features, typically crevasses, identified in vertical aerial photographs taken September 20, 2001 and September 13, 2002. Most of the glacier was still covered in snow at the time of the 2002 photographs, and photogrammetric measurements for ice movement were confined to the lower glacier (fig. 14). The 2001 and 2002 positions of surface features used for ice movement studies are presented in table 19. Average ice speed ranged from 7.8 to 20.7 m per year, and there was a marked diversion of the ice flow around the involution of the terminal ice margin caused by a bedrock promontory. Uncertainty in the feature positions was about 2 m.

Table 19. Positions of selected South Cascade Glacier, Washington, surface features used to estimate horizontal speed and direction of ice movement during September 20, 2001 to September 13, 2002

[Locations of features are shown in figure 14; ***X***, easting coordinate in local coordinate system, meters; ***Y***, northing coordinate in local coordinate system, meters; ***Z***, altitude, meters]

Feature Identifier	September 20, 2001			September 13, 2002		
	X	***Y***	***Z***	***X***	***Y***	***Z***
1	1647.1	3296.7	1739.5	1650.1	3314.9	1732.4
2	1931.4	3169.2	1806.7	1932.8	3180.9	1800.1
3	1901.3	3067.8	1828.1	1903.4	3081.3	1821.3
4	2022.5	3111.9	1817.1	2023.9	3122.5	1813.1
5	1659.1	3052.4	1815.1	1658.5	3067.0	1810.8
6	1668.8	3156.1	1788.0	1668.3	3176.4	1780.7
7	1724.3	3196.9	1783.2	1723.1	3217.1	1774.8
8	2071.9	3136.0	1807.8	2075.8	3144.9	1800.9
9	1733.1	3086.8	1812.5	1731.9	3105.1	1807.0
10	2094.6	3032.9	1824.8	2094.7	3040.6	1821.7

Summary and Conclusions

Long-term monitoring of South Cascade Glacier was continued through the end of the 2002 balance year, during which selected glaciological, meteorological, and hydrologic data were collected and analyzed. Selected glaciological quantities and dates for balance year 2002 are given in table 20. Snow accumulation during the 2002 winter resulted in an exceptionally large glacier winter snow balance. The large snow accumulation was offset somewhat by larger than average summer ablation, but the positive 2002 glacier net balance was the ninth largest since 1959. Analysis of glaciological and meteorological data for 2002 and those published for previous years indicated glacier summer balance was negatively correlated with the average June-through-September air temperature at the Hut.

Table 20. Selected glaciological quantities and dates for South Cascade Glacier, Washington, balance year 2002

[Glacier balances expressed in meters water equivalent; m, meter; km^2, square kilometer]

Glaciological quantity or date	Value
Beginning date of balance year 2002	October 12, 2001
2002 glacier measured winter snow balance ($\bar{b}_m(s)$)	4.02 m
Ending date of winter season	May 10, 2002
2002 glacier summer balance ($\bar{b}_s$)	-3.47 m
Ending date of balance year 2002	November 7, 2002
2002 glacier net balance ($\bar{b}_n$)	0.55 m
2002 glacier annual (water year) balance ($\bar{b}_a$)	0.54 m
Terminus retreat during September 20, 2001 to September 13, 2002	4 m
Glacier area on September 13, 2002	1.92 km^2
Average 2002 equilibrium line altitude	1,820 m
2002 accumulation area ratio	0.84

The large 2002 winter snowpack damaged the stream gaging stations and otherwise contributed to loss of much of the meteorological and hydrologic data normally collected by automated equipment at those sites. Efforts during 2002 and 2003 to reduce susceptibility of the gaging stations to damage from snow, combined with a comparatively small 2003 winter snowpack, resulted in much improved performance of the stations during 2003. The practical difficulties of measuring precipitation in the form of snow and gaging stream flow when the subject water bodies are snow- or ice-covered will for the present time continue to limit the amount and continuity of precipitation and runoff data from South Cascade Lake Basin.

Positive net balance of South Cascade Glacier for balance year 2002 provides more evidence that a shift in the general mass-balance trend occurred during the mid-1990's and continued to 2002 (fig. 15). The average net balance during 1995 to 2002 (-0.18 m) was substantially less negative than the average net balance during 1977 to 1994 (-0.93 m), indicating the glacier has been losing mass at a slower rate, on average, during the past several years. The glacier terminus retreated during balance year 2002, as it has during every year of measurement except 1972 (Krimmel, 2002), but the computed retreat rate during balance year 2002 was only 4 m/yr.

The position of the South Cascade Glacier terminus responds to the variations of long-term average glacier mass balance and to variations of the mass balance from year to year. The average glacier mass balance over many years strongly influences the thickness, surface slope, and flow regime of the glacier, which in turn controls the rate at which ice is delivered to the terminus. During the decades South Cascade Glacier has been monitored, the long-term average mass balance has been too small to induce sufficient flow of ice to the glacier region near the terminus to replace the ice lost by ablation. The result has been the long-term terminus retreat described by Krimmel (2002). Year-to-year variations of mass balance in the vicinity of the terminus, particularly variations of the winter balance, have partly controlled the amount of terminal ice that has been lost by ablation. As a result, terminus retreat rate during years with an unusually large winter balance, such as 1999 [$\bar{b}_m(s) = 3.59$ m, retreat rate about 5 m/yr; Krimmel, 2001] and 2002, has tended to be less than retreat rate during years with a smaller winter balance, such as 1998 [$\bar{b}_m(s) = 2.76$ m, retreat rate about 20 m/yr; Krimmel, 1999] and 2001 [$\bar{b}_m(s) = 1.90$ m, retreat rate about 30 m/yr; Krimmel, 2002].

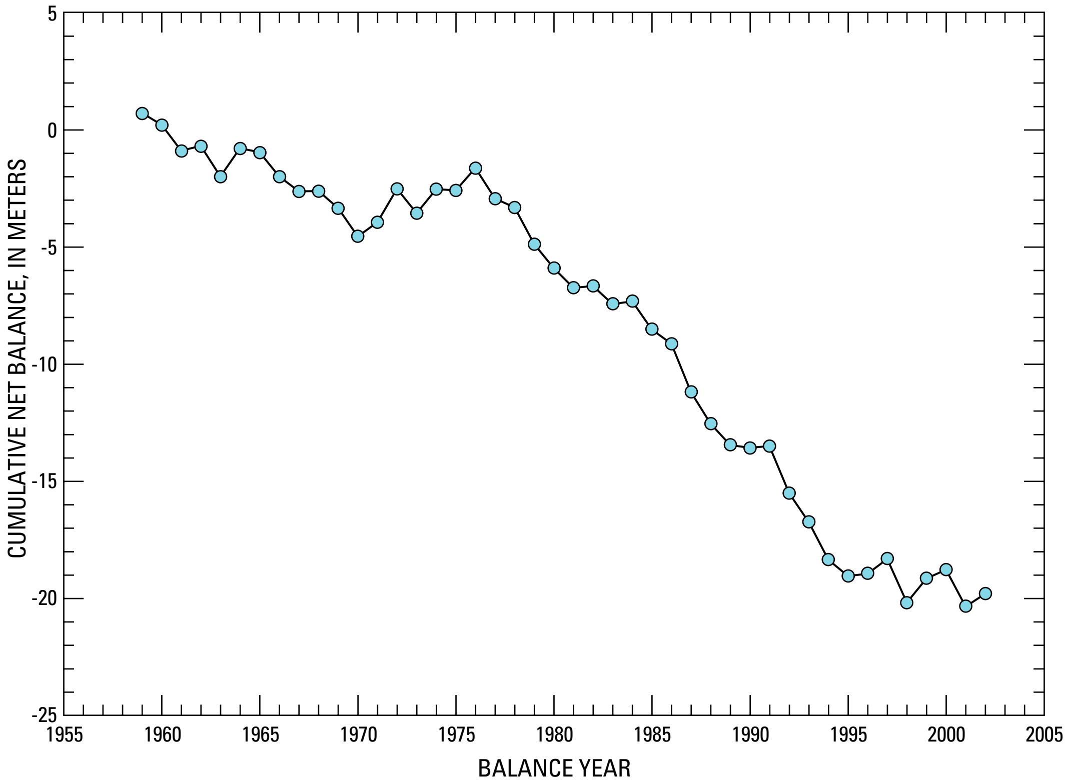

Figure 15. Cumulative net balance of South Cascade Glacier, Washington, balance years 1959 to 2002.

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This report on South Cascade Glacier is the first of its kind since the retirement of Robert M. Krimmel, Research Hydrologist, who worked on and published studies of South Cascade Glacier and other glaciers for more than 30 years. Bob recognized the critical importance of glacier mass-balance data for bettering our understanding of glaciers and the roles they play in our world. Glaciers, however, are challenging places to work, and reliable mass-balance data are hard-won. Among Bob's contributions to glaciology are the measurement and analysis techniques he developed or adapted that help to maximize the amount of information that can be gained from a trip onto a glacier. Many of those techniques are used in this report.

Manuscript approved for publication, May 27, 2004

Prepared by the Publishing Group, U.S. Geological Survey,
Washington Water Science Center, Tacoma, Washington

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