WATER, ICE, AND METEOROLOGICAL MEASUREMENTS AT SOUTH CASCADE GLACIER, WASHINGTON, BALANCE YEAR 2003

Scientific Investigations Report 2005-5210

U.S. DEPARTMENT OF THE INTERIOR
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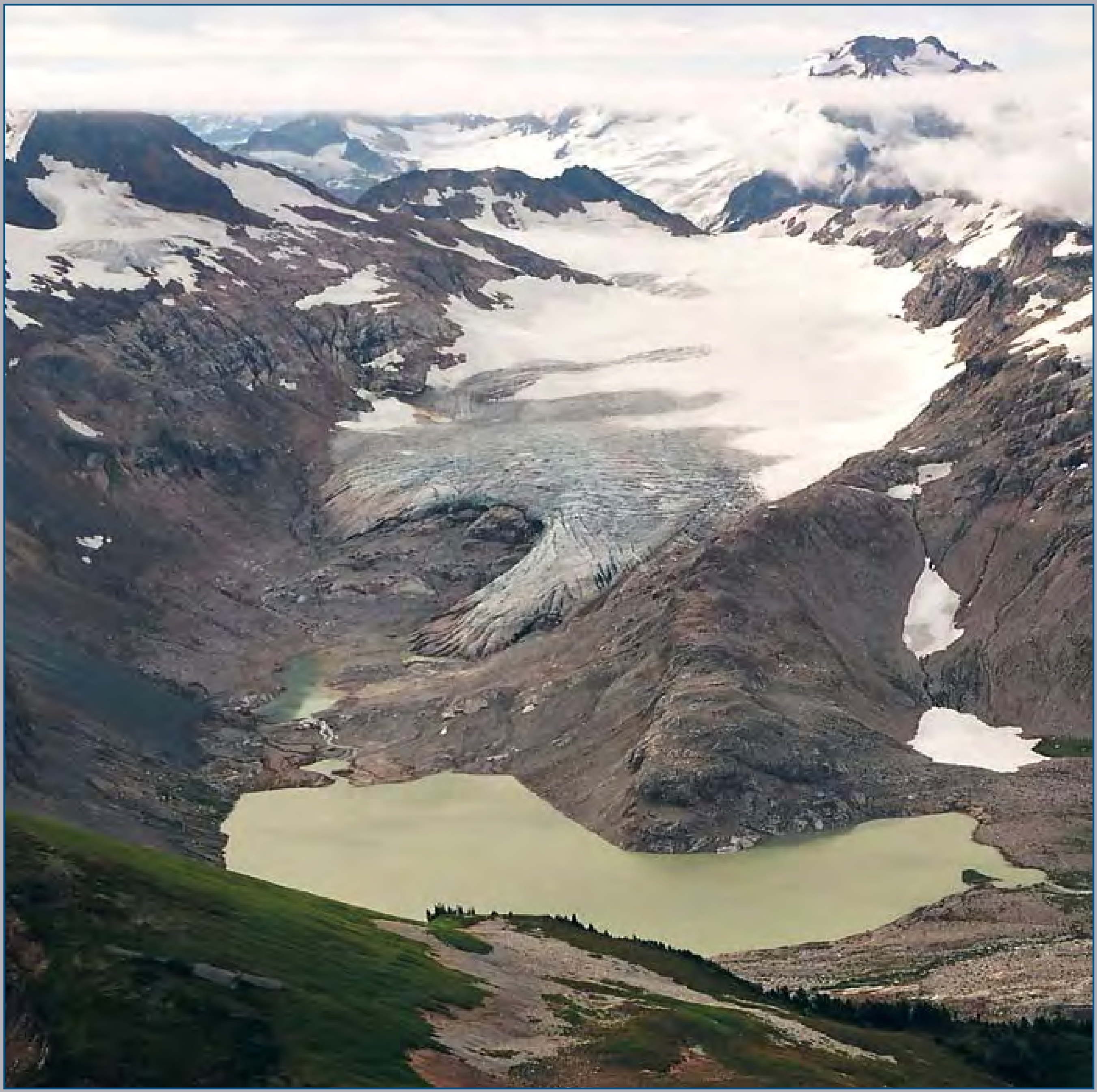

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Cover: Photograph of South Cascade Glacier, Washington, from the north-northwest, August 19, 2003 (photograph by Austin Post for the U.S. Geological Survey).

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

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U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2005

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Suggested citation:
Bidlake, W.R., Josberger, E.G., and Savoca, M.E., 2005, Water, ice, and meteorological measurements at South Cascade Glacier, Washington, Balance Year 2003: U.S. Geological Survey Scientific Investigations Report 2005-5210, 48 p.

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Conversion Factors

Multiply	By	To obtain
cubic meter per second (m^3/s)	35.31	cubic foot per second
kilogram (kg)	2.205	pound avoirdupois
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot
kilometer (km)	0.6214	mile
kilopascal (kPa)	0.01	bar
	0.1450	pound per square inch
meter (m)	3.281	foot
meter per second (m/s)	2.237	mile per hour
millimeter (mm)	0.03937	inch
square kilometer (km^2)	0.3861	square mile
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

Symbol	Meaning
$\dot{a}$	Ablation rate
b	Mass balance for a period of time beginning with time t_0, and ending with time t_1
$\overline{b}$	Glacier balance
$\overline{b}_0$	Glacier initial balance increment, the glacier balance between the time of the beginning of the water year and the beginning of the balance year
$\overline{b}_1$	Glacier 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
$\overline{b}_{\mathrm{a}}$	Glacier annual (water year) balance
b_{n}	Net balance
$\overline{b}_{\mathrm{n}}$	Glacier net balance
b_{s}	Summer balance
$\overline{b}_{\mathrm{s}}$	Glacier summer balance
b_{w}	Winter balance
$b_{\mathrm{m}}(\mathrm{s})$	Measured winter snow balance
$\overline{b}_{\mathrm{m}}(\mathrm{s})$	Glacier measured winter snow balance
$b_{\mathrm{w}}(\mathrm{s})$	Maximum winter snow balance
$\overline{b}_{\mathrm{w}}(\mathrm{s})$	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 altitude 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
m	Empirically determined constant
n	Number of glacier DEM grid points
p	Stream discharge when the quantity $(S - S_0)$ equals 0
q	Stream discharge
S	Water stage
S_0	Empirically determined constant equal to stage when q predicted from equation 5 equals 0
T	Air temperature
X	Position in local horizontal coordinate system along the X-axis, which increases from west to east
Y	Position in local horizontal 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

Abbreviations	Meaning
AAR	Accumulation area ratio
DEM	Digital elevation model
ELA	Equilibrium line altitude
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Water, Ice, and Meteorological Measurements at South Cascade Glacier, Washington, Balance Year 2003

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

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 2003. The 2003 glacier-average maximum winter snow balance was 2.66 meters water equivalent, which was about equal to the average of such balances for the glacier since balance year 1959. The 2003 glacier summer balance (-4.76 meters water equivalent) was the most negative reported for the glacier, and the 2003 net balance (-2.10 meters water equivalent), was the second-most negative reported. The glacier 2003 annual (water year) balance was -1.89 meters water equivalent.

The area of the glacier near the end of the balance year was 1.89 square kilometers, a decrease of 0.03 square kilometer from the previous year. The equilibrium-line altitude was higher than any part of the glacier; however, because snow remained along part of one side of the upper glacier, the accumulation-area ratio was 0.07. During September 13, 2002–September 13, 2003, the glacier terminus retreated at a rate of about 15 meters per year. Average speed of surface ice, computed using a series of vertical aerial photographs dating back to 2001, ranged from 2.2 to 21.8 meters per year.

Runoff from the subbasin containing the glacier and from an adjacent non-glacierized basin was gaged during part of water year 2003. Air temperature, precipitation, atmospheric water-vapor pressure, wind speed, and incoming solar radiation were measured at selected locations on and near the glacier. Summer 2003 at the glacier was among the warmest for which data are available.

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 with the objective of increasing understanding of the relation of glaciers to climate and 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; Rasmussen and Conway, 2004) 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 USGS Benchmark Glaciers, Gulkana Glacier and Wolverine Glacier, are in glacierized regions of Alaska (Kennedy, 1995; March, 1998, 2003).

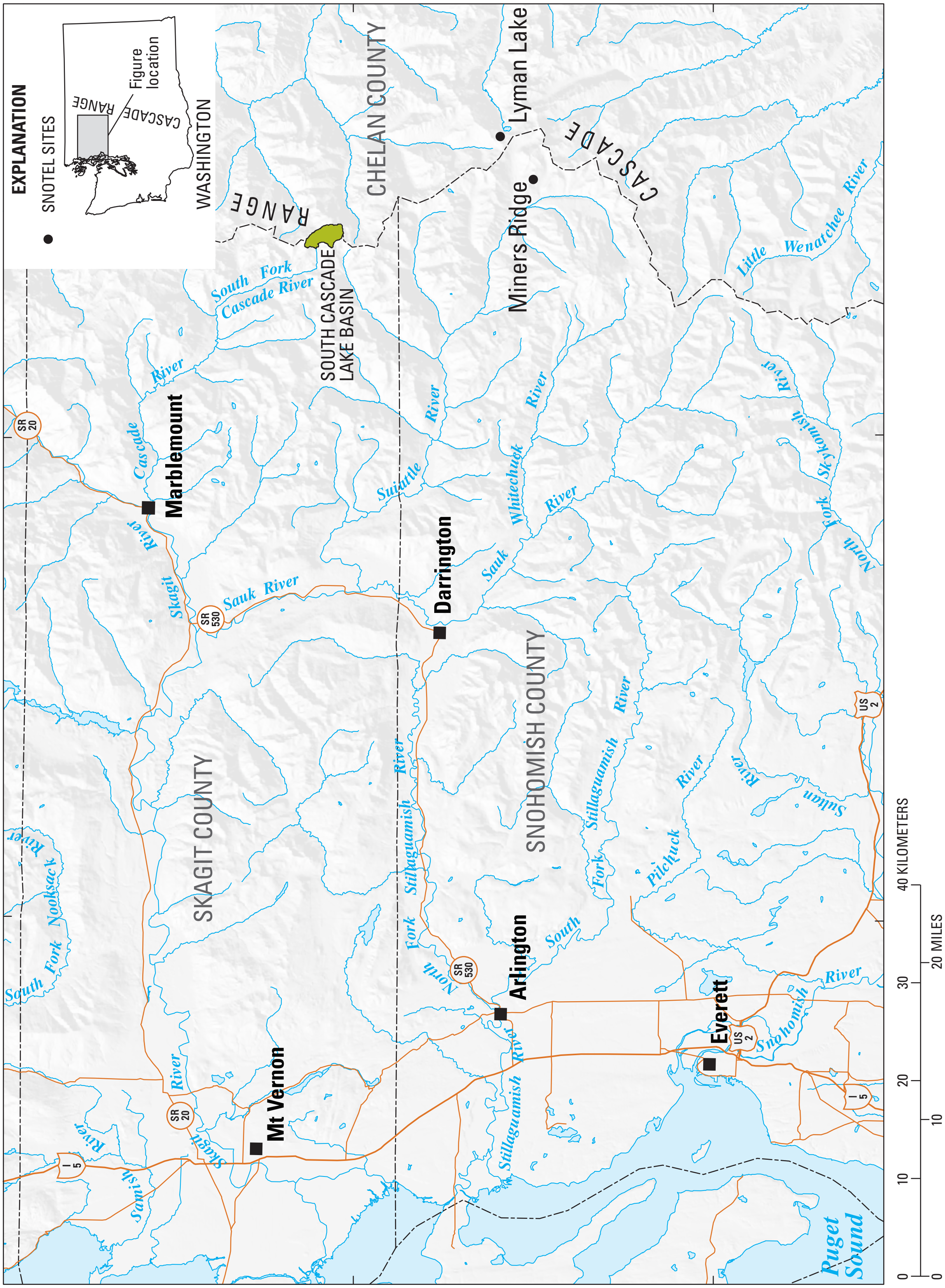

Figure 1. Location of the study area, South Cascade Lake Basin, Washington.

Previous Work

The USGS began intensive study of South Cascade Glacier in 1957 (Meier, 1958), and has since monitored selected glaciological variables, including glacier mass balance and glacier area, as well as selected meteorological and hydrologic variables. Photographs of the glacier taken in 1953 and 1955–1957 were used to estimate glacier mass balance for those balance years, and direct glaciological measurements were used to compute mass balance and flow during balance years 1958–1964 (Meier and Tangborn, 1965). The balance year is the time between successive annual minima of glacier mass. The annual minimum mass of South Cascade Glacier typically occurs in October. Glacier mass-balance studies and some related work for balance years 1965–1967 are described by Meier and others (1971) and by Tangborn and others (1977). Hydrologic and meteorological data for 1957–1967 are presented by Sullivan (1994). Glacier mass-balance studies of South Cascade Glacier for balance years 1959–1985 are summarized in Krimmel (1989). Mass-balance studies and related work for balance years 1986–2002 are presented in detail in Krimmel (1993, 1994, 1995, 1996a, 1997, 1998, 1999, 2000, 2001, and 2002) and Bidlake and others (2004).

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 kilometers (km) long and occupied an area of 2.71 square kilometers (km^2) (Meier and Tangborn, 1965). Net balance of South Cascade Glacier averaged –0.5 meter (m) water equivalent during balance years 1958–2002, and years of negative net balance outnumbered years of positive net balance by a ratio of approximately 2 to 1 (Bidlake and others, 2004). By 2002, 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 (Bidlake and others, 2004).

Purpose and Scope

This report describes glaciological, hydrologic, and meteorological measurements made at and near South Cascade Glacier during balance year 2003, and presents the data and selected glacier mass-balance quantities for balance year 2003. 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. Hydrologic measurements were made to compute runoff from the basin containing 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 the 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 during October to May.

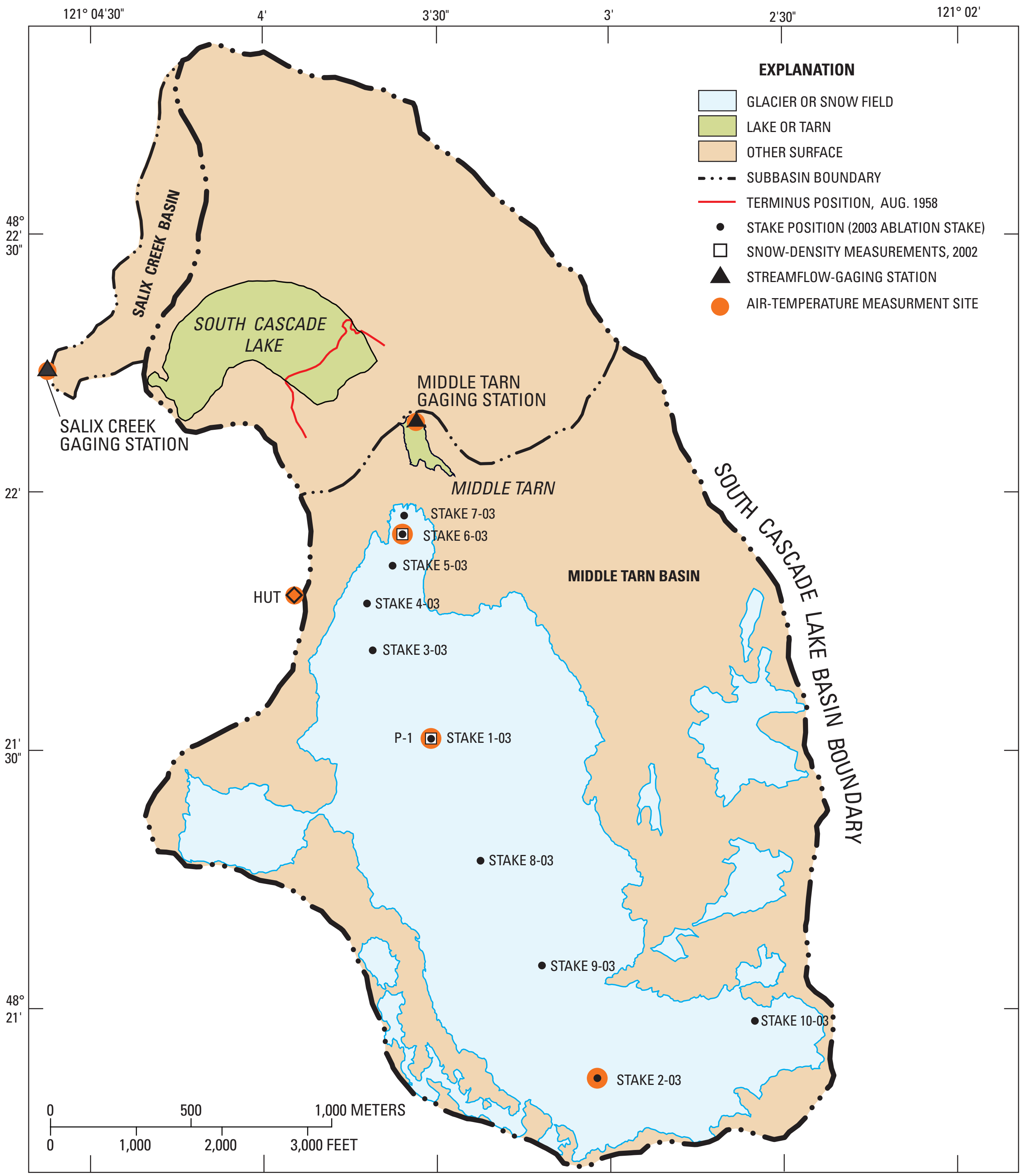

Figure 2. South Cascade Lake Basin and vicinity, Washington.

Study Methods

Methods of data collection and analysis followed in preparation of this report were similar to those of Bidlake and others (2004). 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 (PST). 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 2003. Speed and horizontal direction of surface ice movement were computed by measuring displacements of selected surface features in vertical aerial photography from 2001, 2002, and 2003.

Meteorological and Streamflow Measurements

Precipitation was measured at the Salix Creek gaging station (fig. 2) using an unheated tipping-bucket rain gage with a measurement resolution of each 0.254 millimeters (mm) (0.01 inch). Precipitation was totaled and recorded each hour. Because the gage was not heated or otherwise equipped to measure precipitation as snow, data are reliable only for periods when precipitation fell as rain at the Salix Creek gaging station.

Air temperature was measured with thermistor-based sensors at the Salix Creek and Middle Tarn gaging stations, at the Hut, and at selected locations over the glacier (fig. 2). The sensors were housed in passively ventilated radiation shields. A self-adjusting sensor mount was introduced in 2003 to maintain air-temperature sensors at a constant height (2 m) over the glacier surface as it lowered during the summer season (fig. 3). The mounts generally maintained sensor heights to within 0.2 m of the target height (2.0 m), except during periods of snow accumulation. Air temperature was sensed at a height of about 3.5 m above ground at the Salix

Figure 3. Self-adjusting mount for an air-temperature sensor over a glacier.

Creek gaging station and at about 3 m above ground at the Middle Tarn gaging station. Air temperature, relative humidity, and wind speed were measured over the roof of the Hut and at a height of about 5 m above ground. Air temperature at the gaging stations and at the Hut was measured every minute and averaged each hour. Air temperature over the glacier was measured and recorded every 10 minutes. Daily minimum and maximum air temperatures presented in this report were the daily extremes of hourly average temperature. Incoming solar radiation was measured at the Hut using a thermopile-based pyranometer. Wind speed at the Hut 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

$$e = e_s h_r , \qquad (3)$$

where

e is 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 varies with temperature and can be computed using an equation given by Monteith and Unsworth (1990):

$$e_s = 0.611 \times \mathrm{EXP}\left(17.27 \times T / [T + 237]\right), \qquad (4)$$

where

T is air temperature, in degrees Celsius.

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) over a mostly bedrock hydrologic control. The stage of Middle Tarn was monitored and recorded at the Middle Tarn gaging station (USGS station number 12181090) every 15 minutes using a submersible pressure transducer on the bed of the tarn. Stage of the tarn also was observed intermittently from a staff gage housed in a stilling well along the shore. Recorded stage was corrected as needed on the basis of the intermittent stage measurements.

Intermittent measurements of stage and discharge made with a current meter or by a volumetric technique were used to aid in developing a new rating curve describing the relation of stage to discharge for the Middle Tarn gaging station, and to check applicability of the rating curve used for many years for the Salix Creek gaging station (USGS station number 12181200). Two discharge measurements were made for the Middle Tarn gaging station during water year 2003 and three measurements were made for the Salix Creek gaging station.

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, streamflow quantities are presented in this report using SI units.

As in previous years, discharge of the river from Middle Tarn during water year 2003 was computed from the stage record by applying a rating curve that was developed using intermittent measurements of stage and discharge. A new rating curve was developed and used for 2003 that was more compatible with current USGS computer programs for streamflow computation than was the rating curve developed and used since establishment of the gaging station (1992) and until 2002 (Krimmel, 1994, 1995, 1996a, 1997, 1998, 1999, 2000, and 2001, and 2002; Bidlake and others, 2004). The new rating curve was based on techniques given by Rantz and others (1982), wherein a rating curve (or a segment of a rating curve) plots as a straight line on a logarithmic graph and can be described by the equation:

$$q = p(S - S_0)^m , \qquad (5)$$

where

q is stream discharge, in cubic feet per second;
p is discharge when the quantity ($S - S_0$) equals 1, in cubic feet per second;
$S - S_0$ is depth of water on the hydrologic control;

where
S is stage, in feet;
S_0 is equal to stage of effective zero flow, in feet; and

m is the slope of the rating-curve segment on a logarithmic plot.

A single rating curve can comprise multiple linear segments (on a logarithmic graph), where each segment describes a different subdomain in the observed relation of stage to discharge. Rating-curve segments typically are developed graphically and on the basis of subjective interpretations by the streamflow data analyst from intermittent stage and discharge measurements. A rating-curve segment also might be extrapolated beyond the range of measurements and to a limit judged to be reasonable in the mind of the analyst. USGS computer programs used to help analyze a rating curve produce a rating table that is based on all of the log-linear segments of the rating curve. The rating table becomes the primary tool used by the streamflow data analyst to describe and apply the rating curve to compute a record of discharge from a record of stage. A rating table was produced for the Middle Tarn using the new rating curve that was developed in 2003 (table 25, at back of report).

The outlet of Middle Tarn was covered with ice and snow during winter, and this potentially was the reason that the relation of stage to discharge differed from the relation that was developed for ice- and snow-free conditions. Because there were no wintertime measurements of discharge to use to adjust the rating curve for ice- and snow-covered conditions, discharge from Middle Tarn was not computed for periods when such conditions were thought to have existed.

The rating curve for the Middle Tarn gaging station for water year 2003 differed from the rating curve developed and used previously for that station. Analysis of the 2003 ice-free stage record indicated that average discharge computed using the old rating curve was 6 percent less than average discharge computed using the newly adopted 2003 rating curve. The standard deviation of the difference between average daily discharge amounted to 2 percent of the average daily discharge computed using the 2003 rating curve. The latest rating curve was drawn to plot close to most recent discharge measurements while maintaining the general shape of the previous rating curve. The difference between the old and new rating curves is thought to reflect slight changes in the hydrologic control.

Runoff from unglacierized Salix Creek Basin was computed in much the same manner as for Middle Tarn Basin, except the previously developed rating curve is compatible with current USGS computer programs and was retained. Salix Creek flows under the Salix Creek gaging station and is controlled by a weir set on bedrock. The rating curve used for many years (Krimmel, 2002) for the Salix Creek gaging station comprises a single log-linear segment that can be described by the power function

$$q = 2.71S^{2.57}\,, \qquad (6)$$

where all terms have been defined previously.

Glacier Mass Balance and Related Principles

The mass of a glacier, the combined masses of its snow and ice, is constantly changing through the opposing processes of accumulation and ablation. Examples of accumulation processes important at South Cascade Glacier are precipitation in the form of snow and avalanching or blowing of snow onto the glacier from surrounding terrain. Internal accumulation, caused by freezing of water derived from the current year's precipitation that has percolated into accumulations from previous years, is thought to be of small importance at South Cascade Glacier and is not considered in this report. 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, evaporation, and sublimation. 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. Because surficial accumulation and ablation processes are the dominant 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 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):

$$b = \int_{t_0}^{t_1} (\dot{c} + \dot{a})\; dt\,, \qquad (7)$$

where

- t_0 is beginning time of the period,
- t_1 is ending time of the period;
- $\dot{c}$ is accumulation rate, in meters water equivalent divided by time; and
- $\dot{a}$ is ablation rate, 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 x 10^3 kilograms per cubic meter. Equation 7 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 for at least one melt season without being transformed into ice.

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 balance 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 melt 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 at the beginning of the balance year, typically in October, 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 thus can 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). At South Cascade Glacier, b_w is assumed in this report to equal the maximum winter snow balance, $\bar{b}_w(s)$, the snow balance at the time of maximum snow accumulation during the balance year (Mayo and others 1972), because winter-season melting of ice and firn is thought to be negligibly small. At South Cascade Glacier, the hydrologic year is the same as the water year, which begins on October 1. The measured winter snow balance, $\bar{b}_m(s)$, 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 water year, which 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 period is the average of b over the entire area of the glacier. Following the convention given by Mayo and others (1972), mass-balance quantities for the entire glacier are indicated with an overbar in this report. For example, the glacier net balance is denoted $\bar{b}_n$. 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:

$$\bar{b} = \frac{1}{n}\sum_{i=1}^{n} b(Z_i)\,, \tag{8}$$

where

n is the number of glacier DEM grid points;

Z_i is the altitude of a grid point in a glacier DEM, in meters; and

$b(Z_i)$ is 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.

Snowpack measurements made on South Cascade Glacier near the time of maximum winter snow accumulation during 2003 were used to develop a relation of snow-water equivalent to altitude that could be used with equation 8 to compute the glacier-measured winter snow balance ($\bar{b}_m(s)$). The 2003 glacier maximum snow balance ($\bar{b}_w(s)$) was estimated on the basis of $\bar{b}_m(s)$ and observations made after the measurements for $\bar{b}_m(s)$.

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 8 to compute the glacier net balance ($\bar{b}_n$). The summer balance was then computed as $\bar{b}_n - \bar{b}_w(s)$. At South Cascade Glacier, the beginning of the water year usually coincides, within a few weeks, with the beginning on the balance year, and the annual balance ($\bar{b}_a$) can be computed from $\bar{b}_n$ and two small adjustments (termed “balance increments”) using the equation

$$\bar{b}_a = \bar{b}_n + \bar{b}_0 - \bar{b}_1\,, \tag{9}$$

where

$\bar{b}_0$ is the glacier 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;

$\bar{b}_1$ is the glacier 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 defined previously.

Two other glaciological quantities commonly reported in conjunction with mass-balance quantities are equilibrium-line altitude (ELA) and accumulation-area ratio (AAR). The surface of a classic mountain glacier can be divided into an accumulation area, where net balance is positive, and an ablation zone, where net balance is negative. The accumulation area of the classic mountain glacier occupies the uppermost expanses of the glacier and extends down slope to where it meets the ablation zone. The division between the accumulation and ablation areas is the equilibrium line, where net balance is zero, and the ELA is the altitude of the equilibrium line. The AAR is the ratio of the accumulation area to the area of the entire glacier. Many mountain glaciers differ substantially from the classic glacier in that more than one accumulation area and one ablation area can exist, or an accumulation area can be absent during any given year. The ELA typically cannot be specified for glaciers with multiple accumulation and ablation areas.

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, 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-millimeter (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 from 2.0-m-long sections of 32-mm-diameter aluminum tubing. The bottom of each stake was fitted with a wooden or Teflon 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 (fig. 2) was computed from the mass of snow samples of known volume that were extracted from the snowpack on the glacier surface. Samples were obtained using a coring auger with a 76.3-mm-diameter orifice, with a sampling tube with a 72.3-mm-diameter orifice, or with a specially designed snow corer that produced a 60.0-mm-diameter core (Philip Taylor, Seattle, Washington, written commun., May 2003)

Photogrammetric Measurements

Color vertical aerial photographs of South Cascade Glacier were obtained on September 13, 2003, using a lens with a 210-mm focal length and film with a width of 230 mm. The camera was mounted 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 horizontal coordinate system described previously. Areas of the 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. Local coordinates were computed from UTM zone10 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 in the vicinity of South Cascade Glacier accumulated a slightly smaller than normal snowpack during the 2003 water year. The maximum annual snow water equivalent reported for the Miners Ridge SNOTEL site (1.15 m; fig. 1) was the fourth smallest on record for that site (water years 1989 to 2003; National Water and Climate Center, 2004). The Miners Ridge site is west of the crest of the Cascades Range at an altitude of 1,890 m. The Lyman Lake SNOTEL site, which is east of the crest at an altitude of 1,798 m, received more precipitation during water year 2003 than did the Miners Ridge site. The maximum reported snow-water equivalent for 2003 at the Lyman Lake site (1.56 m) was the ninth smallest on record (water years 1980, 1984–2003). The accumulation of snow on South Cascade Glacier at the end of winter was the seventh smallest during 1989–2003, and almost all of the snow had melted by mid-September (fig. 4).

Meteorological and Streamflow Data

The time series of hourly average air temperature at the Hut during the water year 2003 is presented in figure 5, and daily maximum, minimum, and average air temperature is presented in table 1. The warmest days at the Hut for which data are available were July 29 and September 3, when daily average air temperature was 20.9°C, and the coldest day was February 23, when daily average air temperature was -10.9°C. March was the coldest month at the Hut, when air temperature there averaged -3.6°C.

The time series of hourly average air temperature during water year 2003 are also presented for the Middle Tarn and Salix Creek gaging stations (fig. 5). Daily maximum, minimum, and average air temperature during water year 2003 for the Middle Tarn gaging station is presented in table 2 and for the Salix Creek gaging station is presented in table 3. February was the coldest month at both gaging stations, when air temperature averaged -2.6°C and -2.1°C at the Middle Tarn and Salix Creek stations, respectively. July and August were the warmest months at the Middle Tarn gaging station, when air temperature averaged 11.2°C, and July was the warmest month at the Salix Creek gaging station, when air temperature averaged 14.1°C.

The time series of air temperature at three selected locations over South Cascade Glacier (fig. 2) during July 9 through September 30 is presented in figure 6, and daily maximum, minimum, and average air temperature at those locations is presented in tables 4, 5, and 6. Average air temperature at site P-1 during July 9 to September 30 (8.2°C) was similar to that at the site on the upper glacier (8.3°C), which was unexpected, given that the latter site was 188 m higher than site P-1. Average air temperature during July 9 to September 30 at the site near the glacier terminus was 10.9°C. The change of average temperature with altitude between the site near the terminus and site P-1was -0.016°C per meter (°C/m), and the change with altitude between the site near the terminus and the upper glacier site was -0.0072°C/m.

The time series of hourly average atmospheric water-vapor pressure measured at the Hut during water year 2003 is presented in figure 7, and daily average atmospheric water-vapor pressure measured at the Hut is presented in table 7. Monthly average atmospheric water-vapor pressure measured at the Hut ranged from 0.31 kilopascal (kPa) in February to 0.80 kPa in August, although averages were not computed for June and July because some of the data for those months are missing.

The time series of hourly average wind speed measured at the Hut during the water year 2003 is presented in figure 7 and daily average wind speed measured at the Hut is presented in table 8. The wind speed sensor probably was locked by ice during days for which average wind speed is tabulated as 0.2 meter per second (m/s), the starting threshold of the sensor, and data are not available for parts of June and July.

Figure 4. South Cascade Glacier, Washington, September 13, 2003.

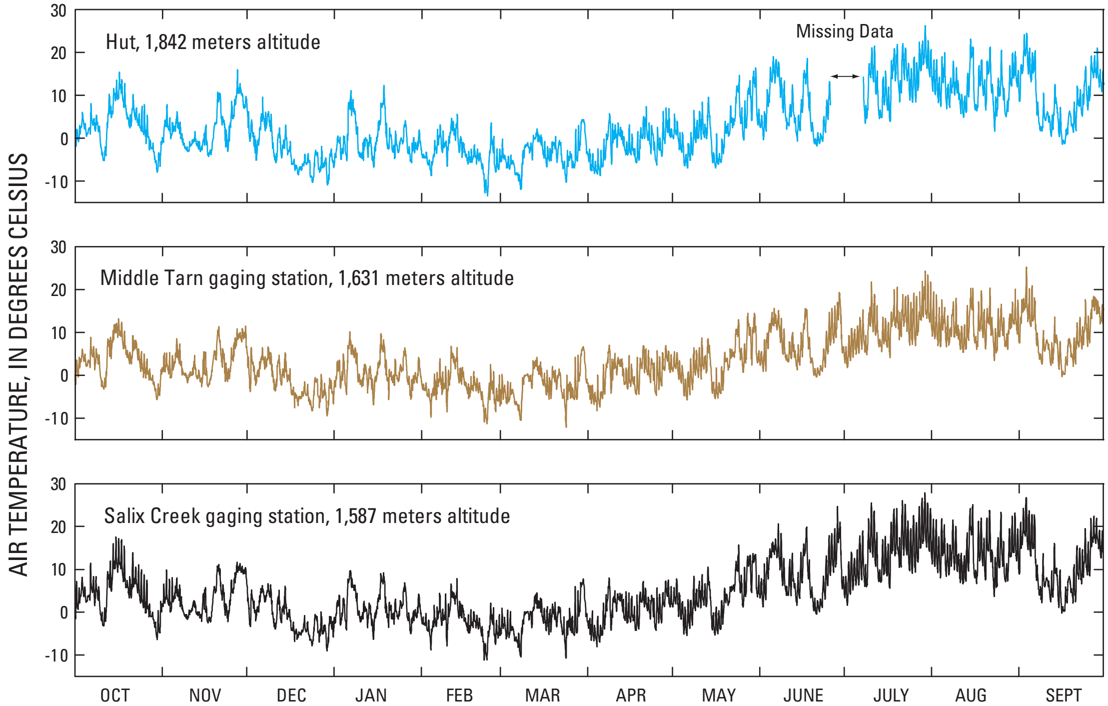

Figure 5. Hourly average air temperature at selected sites in and near South Cascade Lake Basin, Washington, water year 2003.
Daily summaries are presented in tables 1–3.

Table 1. Daily maximum, minimum, and average of hourly average air temperature at the Hut, 1,842 meters altitude, near South Cascade Lake Basin, Washington, water year 2003.

[**Abbreviations:** Max, maximum; Min, minimum; Avg, average; –, data missing]

Day	Daily air temperature, in degrees Celsius																	
	October			November			December			January			February			March		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	2.1	-1.8	0.1	4.3	-0.9	1.9	6.2	-0.7	2.7	0.0	-4.5	-2.9	-3.7	-4.6	-4.3	-0.2	-5.4	-3.6
2	3.0	-.8	1.3	7.9	2.2	4.2	4.3	.0	2.1	.6	-1.1	-.4	-3.2	-5.9	-4.4	-3.9	-6.5	-4.8
3	6.1	2.5	4.1	4.8	-.1	1.9	1.3	-3.4	-.8	-1.7	-4.9	-3.5	-5.0	-7.4	-6.1	-4.1	-6.9	-6.0
4	3.5	.5	2.1	3.7	.4	2.0	-.4	-5.1	-2.5	.6	-3.8	-1.4	-4.5	-8.7	-6.5	-3.9	-7.2	-5.8
5	2.5	.8	1.7	5.0	1.7	3.1	5.5	-.9	2.3	8.4	-5.2	-.1	-.5	-4.3	-2.8	-5.2	-8.4	-6.1
6	8.1	1.0	4.1	6.2	1.1	3.6	9.6	4.0	5.4	11.2	5.3	8.3	2.1	-3.5	-1.4	-8.0	-8.6	-8.3
7	4.6	2.1	3.5	3.8	-.9	1.2	6.1	1.8	3.2	9.1	5.4	7.1	3.2	-2.3	.4	-8.1	-11.6	-9.5
8	5.4	1.7	3.6	.0	-2.4	-1.4	6.2	3.4	5.0	6.4	1.0	3.7	1.8	-3.3	-1.8	-2.8	-11.9	-7.6
9	2.8	-1.6	1.1	-2.0	-3.1	-2.4	5.6	-1.7	2.4	2.7	-4.3	-2.3	-.6	-6.5	-2.5	-1.4	-4.5	-2.3
10	-1.9	-5.1	-3.5	-.8	-3.0	-2.0	-1.0	-5.5	-3.5	-2.9	-4.7	-4.0	1.4	-4.6	-1.1	-1.0	-2.2	-1.6
11	-.8	-5.2	-3.7	-.3	-1.6	-.9	.8	-5.7	-3.1	.2	-5.1	-1.5	4.7	1.0	2.7	-1.1	-3.6	-2.4
12	10.3	.0	4.4	1.6	-1.4	-.2	2.4	-3.4	.0	-.2	-4.4	-1.5	4.0	-.5	1.6	.7	-5.0	-1.4
13	9.8	4.8	6.9	-.6	-2.5	-1.6	-.4	-4.5	-2.7	.9	-2.0	-.8	5.6	-1.9	2.0	2.2	-.1	.8
14	11.6	5.7	8.7	-.7	-3.1	-2.3	3.1	-2.3	.3	-2.0	-6.7	-4.8	.4	-3.2	-1.5	1.4	-.9	-.2
15	13.6	8.8	10.4	1.2	-2.2	-.4	-.8	-3.8	-2.7	.2	-4.7	-1.9	-.9	-4.4	-2.2	.8	-3.6	-1.3
16	15.4	9.2	11.4	3.1	-3.9	-.1	-.7	-6.1	-4.0	4.1	.2	2.2	-2.5	-5.2	-3.8	-.7	-4.7	-3.4
17	13.7	8.6	11.1	-2.7	-4.2	-3.5	-4.9	-7.5	-6.0	8.2	3.2	6.6	-3.0	-6.0	-4.9	-1.9	-6.7	-4.8
18	12.8	6.7	8.7	.0	-3.8	-1.8	-6.2	-8.2	-7.1	12.4	5.8	8.7	-2.5	-5.6	-4.7	-2.3	-5.3	-4.1
19	6.2	3.5	4.9	3.8	.7	3.0	-6.6	-8.5	-7.4	4.0	-2.3	.2	-1.5	-4.7	-3.4	-.8	-3.4	-1.6
20	5.5	2.4	3.9	10.8	3.6	7.9	-5.9	-7.4	-6.6	2.4	-2.5	-.1	-2.5	-6.0	-4.1	.4	-5.6	-2.8
21	10.3	5.5	7.3	10.6	3.4	7.7	-3.7	-6.3	-5.3	.5	-3.2	-1.8	-3.4	-5.4	-4.6	-.5	-4.8	-2.0
22	7.1	3.8	5.5	5.1	2.6	3.9	-3.5	-6.1	-5.2	1.7	-4.7	-1.5	-5.6	-8.4	-7.0	-.9	-7.1	-3.8
23	5.8	2.6	4.0	2.5	-2.6	.0	-5.2	-9.8	-8.0	-.9	-3.3	-2.5	-8.3	-12.7	-10.9	-5.3	-9.5	-7.1
24	7.5	1.5	3.1	3.6	-3.0	.3	-3.9	-10.3	-8.1	.1	-1.7	-.5	-3.1	-13.4	-9.0	-2.8	-10.3	-7.0
25	7.9	.5	2.7	8.6	2.6	5.5	-2.8	-4.2	-3.5	3.6	-1.3	1.1	3.6	-3.4	-.4	-3.1	-5.2	-4.2
26	5.4	-1.2	1.3	9.8	4.7	7.3	-4.1	-7.9	-6.9	4.1	-3.3	.8	.5	-7.1	-3.6	-4.0	-6.9	-5.9
27	.4	-2.7	-1.3	16.0	9.3	11.5	-1.9	-7.4	-5.3	-1.9	-5.3	-3.6	-2.4	-7.9	-5.9	2.1	-6.8	-4.2
28	-1.1	-4.0	-2.5	12.8	10.1	11.2	-4.5	-6.7	-5.8	-.2	-5.7	-3.3	-2.5	-7.3	-5.3	3.0	-5.3	-2.1
29	-4.3	-7.9	-5.7	10.5	7.0	8.8	-6.3	-10.9	-9.4	.2	-3.4	-1.6				4.4	-1.7	2.3
30	-3.3	-7.8	-5.3	9.8	6.2	8.2	-2.5	-8.5	-4.2	2.0	-2.7	-1.1				4.4	.6	3.3
31	.2	-6.5	-2.0				-3.9	-6.8	-5.6	1.8	-3.8	-1.3				.4	-4.1	-2.6
Monthly average	5.5	.9	3.0	4.6	.6	2.6	-.6	-4.9	-2.9	2.4	-2.4	-.1	-1.0	-5.5	-3.4	-1.4	-5.6	-3.6

Table 1. Daily maximum, minimum, and average of hourly average air temperature at the Hut, 1,842 meters altitude, near South Cascade Lake Basin, Washington, water year 2003.—Continued

[**Abbreviations:** Max, maximum; Min, minimum; Avg, average; –, data missing]

Day	April			May			June			July			August			September		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	-2.5	-7.4	-5.2	5.6	-0.1	1.8	5.3	1.4	3.2	–	–	–	18.3	10.8	14.0	17.2	8.6	13.8
2	-3.5	-7.6	-6.0	4.0	-.2	1.8	6.2	-.3	2.8	–	–	–	18.3	9.9	13.7	24.2	15.1	18.8
3	-5.3	-8.2	-7.2	1.4	-2.7	-1.0	11.4	1.7	7.2	–	–	–	14.3	8.3	10.9	24.5	17.1	20.9
4	-2.4	-8.3	-6.6	1.4	-5.7	-1.8	16.6	8.4	12.5	–	–	–	19.1	7.4	13.2	21.0	14.3	17.3
5	-2.8	-8.7	-6.5	-3.7	-6.4	-5.3	19.1	13.1	15.6	–	–	–	20.0	8.7	14.5	20.0	13.2	16.4
6	-.2	-6.6	-4.1	-1.2	-6.9	-4.0	18.4	12.9	16.1	–	–	–	12.7	6.9	9.9	20.4	10.2	15.9
7	1.1	-4.5	-1.0	1.4	-5.1	-2.5	17.8	13.1	15.5	–	–	–	14.1	7.2	10.7	9.3	3.4	6.1
8	5.8	-1.0	3.3	6.5	-3.9	.8	14.2	7.1	11.2	7.7	3.5	5.2	18.0	10.4	13.6	3.5	1.7	2.4
9	3.4	-6.0	-1.6	4.2	-1.0	1.1	13.4	5.3	8.3	17.4	6.4	12.7	16.5	10.1	12.7	10.6	1.8	5.5
10	3.2	-.2	1.2	6.3	.1	2.7	5.0	2.1	3.8	21.1	14.2	17.3	13.5	7.7	10.7	6.2	4.1	5.0
11	3.6	-2.1	.8	8.5	-.2	3.4	7.9	2.9	5.2	21.5	10.7	16.3	10.3	5.8	7.8	6.0	1.8	4.5
12	2.6	-.3	1.0	3.3	.0	1.4	12.5	5.0	8.2	15.7	7.2	11.5	9.9	4.9	7.3	5.5	.5	2.4
13	1.7	-2.5	-.7	9.6	.0	5.3	5.3	.5	3.2	6.7	4.6	5.6	15.2	6.1	10.5	12.6	4.4	8.6
14	-.8	-3.9	-2.9	5.2	-4.3	.7	5.4	-.6	2.6	14.3	4.8	9.4	23.2	10.4	17.2	8.9	1.4	5.8
15	3.2	-3.7	-1.8	-3.3	-6.3	-4.9	9.1	1.8	5.7	15.7	7.8	10.9	21.3	8.8	17.5	7.2	.4	2.9
16	1.0	-3.8	-1.9	1.1	-6.9	-4.6	15.9	6.9	12.9	12.0	4.2	7.8	8.3	6.4	7.2	.0	-1.4	-.8
17	-2.3	-5.6	-4.0	-3.5	-6.1	-5.1	18.6	11.1	14.7	18.2	3.9	12.0	17.0	7.0	12.1	2.2	-1.2	.5
18	1.6	-5.7	-3.5	-.2	-5.6	-3.0	10.8	3.3	7.5	20.9	13.4	17.5	18.3	11.7	14.9	6.4	1.0	4.6
19	2.5	-5.1	-.7	4.0	-2.1	1.0	3.7	.3	2.1	21.9	13.3	17.5	13.7	7.2	10.8	5.8	2.0	3.7
20	5.1	.0	2.5	3.5	.5	1.8	.0	-1.4	-.7	13.5	8.5	11.6	18.0	6.6	13.6	8.5	1.4	4.3
21	7.4	.0	2.8	7.6	.9	3.9	1.3	-1.7	-.3	22.1	10.6	17.3	21.3	12.6	17.1	12.2	1.8	7.9
22	3.6	-1.4	.1	4.6	2.5	3.7	1.1	-1.2	.0	21.1	13.7	17.6	12.6	5.0	9.8	11.4	6.3	8.7
23	3.0	-3.6	.0	12.2	4.5	9.1	5.1	-.7	2.3	17.5	10.2	14.7	9.7	1.7	5.5	12.0	5.2	7.9
24	.8	-5.3	-2.5	14.7	4.4	10.0	8.9	1.4	5.1	16.3	8.9	12.1	14.0	6.4	10.3	16.8	9.6	13.5
25	2.6	-6.2	-2.4	7.1	.5	3.7	13.3	4.4	9.3	18.9	8.4	13.9	20.6	10.0	14.6	12.2	6.6	9.3
26	.1	-3.7	-1.9	8.8	-.4	3.2	–	–	–	17.7	8.5	13.0	12.4	5.6	9.5	19.2	9.6	15.4
27	6.3	-4.2	.0	11.7	2.4	7.6	–	–	–	22.4	11.8	17.0	8.7	5.0	6.4	19.3	14.2	16.3
28	7.1	-1.2	2.3	13.5	4.1	9.7	–	–	–	22.7	15.8	19.3	17.0	8.0	12.7	21.1	14.1	16.4
29	6.9	.6	2.5	15.7	4.2	11.3	–	–	–	26.3	17.6	20.9	19.9	12.2	15.3	16.1	12.0	14.0
30	2.2	.3	1.1	16.5	4.6	11.0	–	–	–	22.8	15.6	18.7	20.2	13.3	16.3	15.9	10.9	13.0
31				6.8	2.8	4.1				20.7	13.2	16.9	15.9	8.7	12.9			
Monthly average	1.8	-3.9	-1.4	5.6	-1.0	2.2	–	–	–	–	–	–	15.9	8.1	12.0	12.5	6.3	9.4

Table 2. Daily maximum, minimum, and average of hourly average air temperature at the Middle Tarn gaging station, 1,631 meters altitude, Middle Tarn Basin, Washington, water year 2003.

[**Abbreviations:** Max, maximum; Min, minimum; Avg, average]

Day	Daily air temperature, in degrees Celsius																	
	October			November			December			January			February			March		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	3.6	-2.2	0.6	5.2	0.8	2.4	5.5	-3.1	2.2	2.8	-2.7	-1.0	-2.0	-3.5	-2.8	0.2	-6.7	-3.4
2	4.2	-.4	2.2	5.2	1.3	2.6	6.5	-3.8	1.6	3.5	.8	2.2	-1.8	-4.7	-3.1	-2.3	-5.3	-3.8
3	6.1	3.1	4.6	5.3	-.6	1.3	3.1	-1.2	1.2	.9	-3.0	-1.4	-3.2	-5.9	-4.7	-1.4	-6.7	-4.9
4	4.9	2.1	3.5	4.6	-.6	1.6	1.1	-2.3	-.4	5.0	-2.4	1.4	-3.3	-9.8	-6.1	-1.7	-5.9	-4.1
5	3.6	2.2	2.9	7.0	2.2	3.9	3.9	-.4	1.8	6.9	-4.5	.4	.3	-4.8	-2.7	-3.3	-6.4	-4.3
6	8.9	1.8	5.0	8.5	2.8	5.4	6.4	3.6	4.4	10.1	5.4	7.6	.7	-5.7	-2.6	-6.1	-6.9	-6.6
7	6.7	1.9	4.8	7.3	.1	3.5	4.3	1.4	2.5	7.1	4.8	5.8	3.9	-2.2	-.3	-6.8	-10.3	-8.2
8	6.2	1.3	4.1	1.6	.0	.6	6.6	2.8	4.6	6.4	2.6	4.5	.8	-4.5	-2.4	-.5	-10.5	-6.3
9	4.8	-.1	2.8	.5	-1.8	-.4	5.3	-.3	3.2	5.1	-1.6	.3	2.1	-8.5	-2.7	.0	-2.1	-.4
10	-.3	-2.8	-1.8	.8	-1.1	-.2	1.1	-3.7	-1.4	-1.0	-2.7	-1.8	1.2	-8.0	-2.4	.4	-.4	.0
11	-.6	-3.2	-2.3	1.7	.0	.4	3.0	-3.6	-.9	2.5	-2.4	.4	6.8	-1.0	3.1	.0	-2.2	-.8
12	8.5	-.3	4.9	4.6	.0	2.0	4.7	-1.2	2.2	2.2	-4.1	-.2	4.9	1.5	3.5	3.4	-3.1	.6
13	8.9	3.9	6.4	1.2	-.8	-.1	1.5	-2.3	-.5	2.1	-2.3	.3	6.5	.0	3.2	4.2	2.1	3.1
14	11.8	6.2	9.2	.8	-2.7	-.8	5.2	-.5	2.3	.0	-6.9	-3.3	1.7	-1.8	.0	3.6	.2	1.7
15	12.1	9.8	11.0	5.5	-2.0	2.2	1.3	-1.5	-.4	-.1	-5.4	-1.8	1.9	-2.1	.2	3.1	-1.5	.4
16	13.2	8.9	10.7	5.4	-2.4	2.1	1.6	-4.6	-2.1	3.4	-.6	1.5	-.8	-3.2	-1.9	.5	-2.6	-1.6
17	12.4	7.0	9.8	-.8	-2.7	-2.0	-2.8	-7.6	-4.4	9.7	2.3	6.2	-2.0	-5.5	-3.6	1.2	-4.6	-2.7
18	10.3	6.2	7.4	3.4	-1.1	.8	-4.1	-6.1	-5.1	8.3	4.9	6.2	-.3	-5.1	-3.0	-.5	-5.6	-3.2
19	5.8	4.0	4.9	5.7	3.6	4.8	-4.9	-7.1	-5.6	3.6	-1.3	.7	.9	-3.7	-1.7	2.1	-4.5	-.2
20	5.4	2.7	3.9	10.9	3.6	8.1	-3.8	-5.4	-4.7	1.4	-5.7	-1.1	-.7	-3.7	-2.2	1.2	-3.3	-1.0
21	9.2	2.7	6.4	11.3	3.1	7.0	-1.5	-4.7	-3.5	.8	-1.7	-.4	-1.7	-4.1	-3.1	1.5	-2.4	-.2
22	8.2	6.1	7.1	6.2	1.9	4.3	-2.1	-6.1	-4.3	3.7	-2.3	.5	-3.8	-7.2	-5.5	.6	-5.3	-2.3
23	6.2	3.0	4.7	2.8	-1.4	1.0	-5.6	-8.0	-6.6	.6	-1.5	-.7	-7.3	-10.9	-9.2	-3.3	-8.2	-5.3
24	5.5	.9	2.6	1.5	-1.4	.0	-1.6	-8.3	-6.0	2.5	-.5	1.3	-1.9	-11.3	-7.4	.0	-12.1	-6.2
25	5.0	-.5	1.7	6.4	.9	3.7	-.5	-1.6	-1.1	5.9	1.1	3.5	2.5	-5.7	-2.1	-1.6	-5.4	-2.9
26	3.8	-.7	1.2	8.7	3.3	6.1	-1.8	-7.6	-5.0	6.4	-1.5	2.9	.9	-6.6	-3.6	-2.4	-5.4	-4.1
27	1.5	-1.1	.0	10.8	6.7	8.6	.2	-6.2	-3.1	-.2	-4.7	-2.2	-3.1	-8.5	-5.8	4.2	-5.7	-3.0
28	.0	-2.2	-1.2	10.0	8.4	9.2	-1.9	-5.1	-3.9	-.9	-5.6	-3.2	.0	-7.2	-4.7	4.7	-5.6	-1.4
29	-1.9	-5.6	-3.6	10.9	7.8	9.4	-4.8	-9.5	-7.6	.6	-1.8	-.4				6.0	-.1	3.4
30	-2.0	-5.7	-4.0	11.5	5.6	8.8	-.7	-5.3	-2.2	4.2	-1.8	.4				6.6	2.7	5.4
31	1.8	-4.7	-.4				-2.8	-6.7	-4.3	3.8	-1.6	.8				2.5	-1.9	-.6
Monthly average	5.6	1.4	3.5	5.5	1.1	3.2	.7	-3.7	-1.5	3.5	-1.5	.9	.1	-5.1	-2.6	.5	-4.4	-2.0

Table 2. Daily maximum, minimum, and average of hourly average air temperature at the Middle Tarn gaging station, 1,631 meters altitude, Middle Tarn Basin, Washington, water year 2003.—Continued

[**Abbreviations:** Max, maximum; Min, minimum; Avg, average]

Day	Daily air temperature, in degrees Celsius																	
	April			May			June			July			August			September		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	-2.3	-5.6	-3.3	5.5	0.9	2.5	5.5	2.3	3.6	6.7	2.1	4.3	19.5	9.1	13.2	17.6	7.5	11.6
2	-2.3	-6.6	-4.3	5.3	1.0	3.1	8.3	.9	3.7	9.2	1.8	5.3	18.8	8.5	11.7	17.9	14.7	16.3
3	-4.0	-6.8	-5.5	3.4	-1.3	.6	9.8	1.0	6.5	10.9	3.4	7.1	15.8	6.9	10.6	25.2	14.8	18.4
4	.1	-8.3	-4.9	2.3	-3.7	-.4	12.1	7.0	10.7	10.7	4.2	7.5	17.6	6.7	11.2	20.2	12.0	14.7
5	-3.8	-7.4	-5.4	-.9	-5.1	-3.3	14.7	10.9	12.8	11.5	4.9	7.8	15.8	8.3	12.5	20.9	11.4	14.6
6	2.5	-5.5	-2.5	.8	-5.8	-2.4	15.6	11.3	13.4	13.5	5.1	9.4	13.9	6.6	9.7	18.1	10.5	14.4
7	3.3	-3.2	1.1	3.9	-4.6	-.7	15.1	10.6	12.5	15.3	6.0	9.8	11.1	7.0	9.2	10.5	5.3	7.9
8	7.0	.5	5.0	6.4	-3.4	1.6	13.3	6.4	9.8	9.3	4.8	6.7	17.2	9.0	13.3	5.1	3.1	4.2
9	3.8	-4.2	-.1	5.8	.1	2.1	10.8	4.9	7.0	15.9	5.3	10.6	18.0	8.9	11.8	10.4	2.6	6.3
10	5.1	1.5	2.7	6.4	-.5	2.6	4.8	3.2	4.1	21.8	11.4	14.9	11.7	7.1	9.7	8.3	5.6	7.0
11	4.2	.1	2.4	8.7	-.9	3.5	7.8	3.1	5.3	18.9	9.7	13.8	11.4	6.0	8.4	7.6	3.8	6.3
12	3.7	2.1	2.8	4.6	.6	2.7	10.0	3.9	6.9	16.3	9.3	11.3	11.8	5.4	7.9	7.6	2.3	4.0
13	3.8	-2.1	.6	8.5	.6	5.0	7.1	2.2	4.6	9.0	6.6	7.5	16.3	6.1	10.1	13.6	3.1	7.9
14	1.7	-3.0	-1.0	7.0	-2.8	2.6	7.1	1.3	3.8	13.6	5.5	8.9	20.3	8.1	14.0	9.4	2.9	7.1
15	4.6	-3.2	-.6	-1.6	-5.0	-3.5	10.0	2.4	5.7	13.3	7.1	9.6	20.3	9.1	15.8	7.9	1.4	4.3
16	2.6	-2.6	-.5	1.7	-5.5	-3.4	14.1	4.3	9.7	12.3	5.8	8.6	9.3	6.0	7.9	2.2	-.3	.5
17	-.3	-4.2	-2.3	-1.7	-5.3	-3.6	15.5	9.9	14.0	14.8	4.1	9.8	17.2	6.7	10.6	4.3	.2	2.0
18	4.2	-4.5	-1.9	2.0	-4.3	-1.8	9.2	3.8	7.0	20.0	11.6	14.3	19.7	10.3	13.5	8.5	2.3	6.7
19	4.0	-4.4	.5	5.4	-2.1	2.5	4.0	1.6	3.1	20.6	11.1	14.2	15.4	6.5	11.2	8.1	3.9	5.5
20	6.9	1.6	4.6	4.0	1.2	2.8	1.6	-.2	.5	15.1	8.3	11.8	15.6	6.1	11.2	8.7	2.1	5.2
21	6.2	.6	2.6	6.2	1.9	4.0	1.7	-.4	.6	18.8	9.0	13.5	20.4	10.8	14.4	12.2	2.6	7.7
22	5.8	-.2	1.3	6.0	4.2	5.0	2.2	.0	1.2	18.4	11.4	14.4	13.5	7.1	10.0	13.5	6.6	9.6
23	3.9	-1.7	1.6	10.7	4.7	8.5	6.2	.9	3.5	18.7	8.7	13.7	10.9	3.4	6.5	11.3	6.1	8.1
24	2.9	-4.1	-.4	13.0	5.5	9.4	10.3	1.9	5.9	17.0	7.0	11.4	15.5	5.7	9.9	17.6	10.0	12.6
25	5.7	-4.7	-.6	6.3	1.3	4.1	14.7	5.0	9.1	19.2	7.2	12.6	16.6	9.0	12.4	13.8	6.7	9.9
26	4.3	-3.4	-.4	7.3	.7	3.8	15.6	7.0	11.2	18.4	6.9	11.4	13.4	6.8	10.4	17.5	7.5	13.1
27	5.3	-2.5	1.3	14.5	3.0	9.2	16.2	7.5	11.0	19.5	10.2	13.0	9.7	6.0	7.7	18.4	15.1	16.9
28	6.9	1.1	3.8	12.1	3.9	9.6	17.0	8.9	13.3	21.9	12.8	15.8	14.3	6.2	11.2	17.8	14.3	16.3
29	5.6	1.3	3.6	13.4	2.4	8.7	19.3	8.5	15.9	24.3	13.6	18.0	17.1	11.2	13.5	16.9	12.0	14.6
30	4.8	.7	2.2	14.5	4.0	10.1	9.4	4.5	6.1	23.4	13.3	16.7	20.1	11.9	14.0	16.5	12.0	13.9
31				5.7	2.9	3.9				21.8	11.2	14.8	17.5	7.9	12.4			
Monthly average	3.2	-2.6	.1	6.0	-.4	2.9	10.3	4.5	7.4	16.1	7.7	11.2	15.7	7.6	11.2	12.9	6.7	9.6

Table 3. Daily maximum, minimum, and average of hourly average air temperature at the Salix Creek gaging station, 1,587 meters altitude, Salix Creek Basin, Washington, water year 2003.

[**Abbreviations:** Max, maximum; Min, minimum; Avg, average]

Day	Daily air temperature, in degrees Celsius																	
	October			November			December			January			February			March		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	7.2	-1.5	1.9	6.6	1.3	3.1	6.3	-2.8	2.4	2.2	-2.6	-1.2	-1.1	-2.9	-2.3	0.9	-5.1	-2.8
2	5.7	.6	3.0	9.9	2.4	4.4	5.2	-3.3	1.1	4.0	1.3	2.3	-.3	-4.2	-2.4	-1.2	-4.7	-3.2
3	8.2	3.7	5.6	7.7	.0	2.6	3.1	-.1	1.5	.3	-3.0	-1.6	-1.8	-5.5	-3.8	.5	-6.2	-4.1
4	5.9	2.3	4.0	8.1	.2	3.0	1.3	-2.0	-.1	3.2	-2.0	1.2	-2.9	-8.8	-5.6	.2	-5.9	-3.8
5	4.0	2.4	3.2	6.1	2.9	4.3	5.5	.0	2.5	7.7	-4.1	1.0	1.6	-3.4	-1.8	-3.3	-6.6	-4.2
6	11.5	2.8	6.0	8.0	2.7	5.2	6.2	4.4	5.2	9.7	6.9	8.4	1.2	-3.3	-1.4	-5.7	-6.9	-6.4
7	8.3	2.0	5.4	6.4	.8	3.3	4.1	2.4	3.3	8.1	5.7	6.5	4.4	-1.7	.8	-4.9	-9.6	-7.3
8	8.3	1.5	4.9	1.7	-.9	.1	6.7	3.8	5.1	6.4	2.6	4.7	.7	-3.0	-1.6	-1.8	-10.4	-6.2
9	5.9	-.1	3.2	-.6	-1.7	-1.0	6.4	.4	3.7	4.4	-1.3	.6	4.3	-6.8	-1.4	.1	-2.7	-.9
10	.0	-3.0	-1.4	.5	-1.4	-.4	.0	-3.8	-1.8	-.8	-2.3	-1.6	2.0	-7.9	-1.6	.2	-.4	.0
11	1.0	-3.2	-1.7	1.9	.0	.7	3.0	-3.9	-1.3	2.6	-1.5	.5	6.6	.3	3.5	.2	-1.8	-.6
12	9.5	.0	5.6	2.7	.0	1.7	5.1	-1.5	2.0	1.0	-3.6	-.5	4.7	1.9	3.5	1.4	-3.6	-.5
13	12.0	4.9	7.8	.1	-.8	-.3	1.3	-2.4	-.6	2.1	-1.5	.5	7.9	.2	3.5	4.5	1.9	3.3
14	16.0	5.2	10.6	.1	-2.1	-.7	6.1	-.4	2.5	-.3	-6.3	-3.1	2.6	-1.4	.4	4.3	.9	2.1
15	17.6	10.1	12.3	4.4	-1.5	2.3	1.2	-1.7	-.5	.5	-5.0	-1.4	1.7	-1.3	.2	3.3	-1.1	1.0
16	17.2	9.4	12.4	5.8	-2.1	2.0	.6	-4.2	-2.1	4.1	.0	2.2	-.4	-3.1	-1.9	.9	-2.6	-1.2
17	16.9	8.3	11.9	-1.2	-2.5	-1.8	-2.3	-6.8	-4.1	9.0	3.0	6.3	-.6	-4.8	-3.5	1.3	-4.3	-2.1
18	15.4	7.0	9.3	3.1	-2.3	-.2	-3.9	-6.3	-4.9	9.2	6.5	7.5	.6	-4.8	-2.7	.7	-5.2	-2.7
19	7.4	4.6	6.1	6.0	3.5	5.1	-4.6	-5.9	-5.1	3.5	-1.3	.8	.1	-3.5	-1.6	1.9	-3.7	.0
20	8.3	3.3	5.1	10.8	4.9	8.5	-4.1	-5.3	-4.6	2.3	-3.5	-.3	-.7	-3.7	-2.2	2.3	-3.4	-.9
21	13.9	3.3	8.0	11.2	4.1	7.9	-.8	-4.4	-3.1	1.7	-1.6	-.3	-1.4	-3.9	-3.0	1.3	-3.2	-.4
22	10.6	6.4	7.9	6.4	2.8	4.6	-2.2	-5.2	-4.0	3.1	-2.8	.3	-3.3	-6.9	-5.1	1.1	-5.2	-1.8
23	11.1	3.7	6.1	2.2	-.7	.8	-5.2	-7.0	-6.1	.3	-1.6	-.7	-6.9	-11.2	-9.0	-1.1	-7.9	-4.7
24	9.9	2.1	4.3	2.8	-2.2	-.1	-2.4	-7.8	-5.9	2.7	-.8	1.3	-4.4	-11.1	-7.5	-2.1	-10.7	-6.0
25	8.8	1.1	3.4	7.5	1.7	4.8	-.5	-2.0	-1.2	6.1	1.3	3.6	2.1	-4.2	-1.4	.9	-4.2	-2.0
26	7.5	-.2	2.5	9.2	4.4	6.7	-1.9	-7.0	-4.7	6.9	-1.3	3.4	1.1	-5.6	-2.7	-.9	-5.0	-3.3
27	2.0	-1.1	.2	11.7	8.1	10.1	.1	-5.4	-3.3	-.1	-4.3	-1.9	-1.9	-7.5	-5.0	6.0	-5.4	-2.1
28	.0	-1.8	-1.0	11.4	9.4	10.3	-3.0	-5.0	-3.8	-.7	-5.0	-2.8	-.6	-6.0	-4.2	5.0	-4.8	-.7
29	-2.1	-5.6	-3.5	10.7	8.9	9.7	-4.7	-9.0	-7.3	.6	-2.0	-.3				7.0	-.1	4.2
30	.4	-6.4	-3.6	10.4	6.6	9.1	-1.0	-5.9	-2.4	4.2	-1.3	.4				7.8	2.8	6.1
31	2.6	-4.8	-.3				-2.1	-5.8	-3.9	4.1	-1.4	1.1				2.6	-2.2	-.3
Monthly average	8.1	1.8	4.5	5.7	1.6	3.5	.8	-3.4	-1.3	3.5	-1.1	1.2	.5	-4.4	-2.1	1.1	-4.1	-1.7

Table 3. Daily maximum, minimum, and average of hourly average air temperature at the Salix Creek gaging station, 1,587 meters altitude, Salix Creek Basin, Washington, water year 2003.—Continued

[**Abbreviations:** Max, maximum; Min, minimum; Avg, average]

Day	Daily air temperature, in degrees Celsius																	
	April			May			June			July			August			September		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	-1.4	-5.1	-3.2	5.8	1.2	3.1	7.9	3.0	4.9	8.4	2.6	5.4	21.7	11.3	15.8	21.0	8.9	14.8
2	.3	-6.5	-3.5	7.8	1.9	4.2	11.3	1.3	5.1	11.8	1.6	6.6	21.6	10.7	15.2	24.2	15.8	19.4
3	-3.0	-6.7	-5.2	4.5	-1.2	1.4	12.7	2.9	8.1	14.0	4.2	8.9	17.6	9.2	12.9	26.8	16.4	21.1
4	-.9	-8.0	-4.8	2.5	-3.7	-.1	14.8	7.7	12.2	12.6	5.2	9.0	21.8	8.0	14.7	23.7	14.3	18.0
5	-3.0	-7.0	-5.2	1.2	-5.1	-2.5	16.4	12.7	14.7	14.6	6.3	9.6	20.4	9.8	15.2	22.8	13.1	17.2
6	2.1	-5.3	-2.6	2.9	-5.4	-1.9	17.1	13.5	15.2	17.8	6.4	12.4	16.0	8.4	11.9	22.7	11.5	17.0
7	4.1	-3.1	.8	2.8	-3.8	-.5	20.6	12.7	14.9	19.0	7.6	12.3	15.7	8.7	12.1	11.2	5.3	8.3
8	8.0	.5	5.2	8.4	-3.0	2.3	18.4	7.8	12.7	11.2	5.9	7.7	21.5	10.9	15.7	6.0	3.0	4.5
9	3.1	-4.2	-1.1	5.4	.4	2.5	12.6	6.0	8.7	21.8	6.2	14.0	20.0	9.9	14.3	13.7	2.2	7.4
10	5.0	2.1	3.0	7.2	1.2	3.7	6.1	3.9	5.1	25.5	14.0	18.7	13.6	7.9	11.0	8.1	5.9	7.0
11	4.3	.2	2.6	8.8	1.0	4.3	12.4	3.9	7.5	23.6	11.8	17.2	13.8	6.9	10.1	7.5	3.7	6.4
12	4.4	2.6	3.2	6.7	1.5	3.5	13.8	3.8	9.0	18.6	9.5	13.4	13.2	6.7	9.6	9.7	2.4	4.8
13	4.2	-1.4	.9	10.6	1.3	5.9	7.4	2.5	5.4	9.9	7.0	8.2	18.5	7.3	12.4	16.1	3.5	9.7
14	4.8	-2.5	.0	7.1	-2.7	3.1	9.3	1.6	5.0	17.0	7.2	11.4	24.2	9.6	17.4	10.3	2.6	7.8
15	4.5	-2.4	-.5	-.1	-4.8	-3.0	14.0	3.2	8.2	17.7	8.8	12.5	25.1	10.3	18.8	9.9	1.1	5.0
16	3.7	-2.3	-.1	1.2	-5.3	-2.5	15.9	6.9	12.3	15.9	6.1	10.9	9.8	6.7	8.6	2.2	-.2	.7
17	1.4	-4.2	-2.0	.3	-5.0	-2.6	19.9	11.3	16.1	21.0	5.6	13.6	21.2	7.6	13.9	5.9	.2	2.4
18	4.0	-4.2	-1.5	2.7	-4.0	-.9	12.2	4.7	8.7	24.1	13.4	18.3	22.0	12.0	16.1	8.4	2.2	6.5
19	4.7	-3.9	1.1	5.6	-1.8	2.6	5.9	2.1	3.9	24.2	13.2	17.9	17.3	8.3	12.8	7.9	3.9	5.6
20	7.2	2.2	4.2	4.2	1.6	3.1	3.2	-.2	1.1	17.4	10.5	13.9	22.0	7.6	14.7	11.1	2.1	6.2
21	5.6	1.1	2.9	5.9	2.2	4.3	2.7	-.4	1.1	26.0	10.6	17.8	23.8	12.9	17.6	15.5	2.4	9.1
22	3.5	-.1	1.3	6.4	5.0	5.7	3.1	.1	1.7	25.2	13.3	18.5	14.5	7.1	11.7	15.0	7.6	10.9
23	4.0	-1.6	1.7	11.9	4.9	9.1	8.4	1.1	4.7	21.3	10.9	16.4	12.8	3.7	7.7	14.6	6.6	9.7
24	3.2	-3.8	-.3	15.7	6.4	10.5	13.2	3.0	7.6	19.5	9.7	14.0	17.4	6.1	11.7	19.5	10.4	13.9
25	5.7	-4.2	-.1	8.6	1.6	5.2	17.9	6.2	11.4	22.6	9.1	15.8	23.3	10.4	16.1	16.4	8.7	11.6
26	4.2	-2.5	.4	10.5	1.2	4.8	18.3	8.6	13.4	20.9	9.4	14.7	16.5	7.6	11.8	21.9	8.5	15.2
27	4.6	-2.5	1.1	13.1	3.7	9.0	19.5	9.3	13.7	24.7	11.7	17.6	11.3	7.1	8.8	22.4	16.3	18.4
28	7.3	1.3	4.2	13.3	5.0	10.8	24.7	11.3	16.6	26.6	15.0	19.7	19.4	7.5	13.7	21.9	16.1	18.0
29	7.5	1.9	4.3	13.7	4.6	10.3	21.0	10.4	17.1	27.9	16.6	21.5	22.4	13.0	16.6	19.1	13.4	16.2
30	6.0	1.2	2.8	13.5	4.9	10.9	9.9	4.7	6.7	25.5	15.2	19.6	23.2	13.2	17.2	19.0	12.7	15.0
31				8.6	3.6	5.0				24.2	13.2	18.1	19.4	9.7	14.5			
Monthly average	3.6	-2.3	.3	7.0	.2	3.6	13.0	5.5	9.1	19.7	9.3	14.1	18.7	8.9	13.6	15.2	7.4	10.9

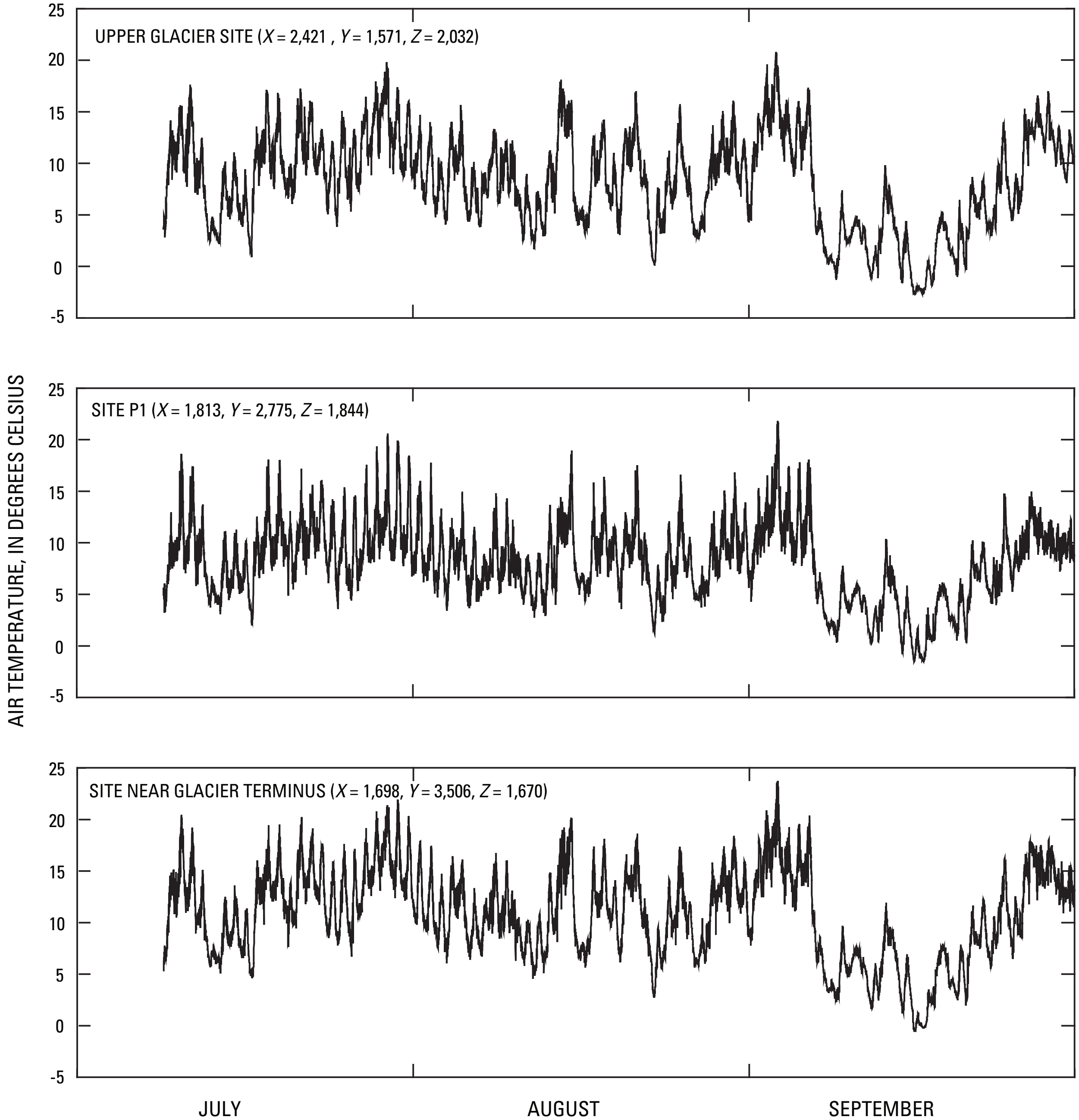

Figure 6. Air temperature at three sites at South Cascade Glacier, Washington, July 9–September 30, 2003. Daily summaries are presented in tables 4–6. Locations are given by X and Y coordinates in a local horizontal coordinate system, in meters, and altitude, Z, in meters, and sites are shown on figure 2.

Table 4. Daily maximum, minimum, and average air temperature over South Cascade Glacier, Washington, at site P-1, altitude 1,844 meters, during July through September of water year 2003.

[Location of site on figure 2; **Abbreviations:** Max, maximum; Min, minimum; Avg, average; –, data missing]

Day	Daily air temperature, in degrees Celsius								
	July			August			September		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	–	–	–	16.0	6.2	10.6	15.3	4.3	9.2
2	–	–	–	17.8	5.8	9.2	16.5	8.6	11.7
3	–	–	–	13.3	4.7	8.1	21.8	9.2	15.3
4	–	–	–	12.4	3.4	8.2	17.5	8.2	12.2
5	–	–	–	15.0	5.2	9.1	17.8	7.8	11.5
6	–	–	–	11.6	3.7	7.1	18.1	6.9	12.3
7	–	–	–	8.9	4.3	6.5	8.1	2.9	5.3
8	–	–	–	14.8	5.0	9.2	3.1	1.1	2.1
9	13.0	3.2	7.3	14.3	5.1	8.7	7.8	.3	4.1
10	18.6	7.4	11.4	12.2	5.5	8.0	6.1	3.2	4.6
11	17.4	6.3	11.3	8.9	3.9	6.2	5.9	1.6	4.2
12	13.7	5.8	9.0	9.1	2.7	5.8	3.9	.3	1.8
13	6.8	3.7	5.0	13.7	2.9	7.3	10.4	1.4	5.8
14	11.1	3.1	6.6	14.4	4.0	10.2	7.8	.9	4.9
15	11.3	4.4	7.2	19.0	7.3	12.1	5.9	-.8	2.1
16	10.2	3.4	6.6	8.1	4.3	6.2	1.8	-1.5	-.5
17	12.5	2.0	7.3	15.9	4.8	8.5	3.7	-1.4	.6
18	18.0	7.0	10.9	16.4	6.7	10.7	6.2	.5	4.3
19	18.0	7.3	11.3	11.6	5.6	9.0	5.7	1.6	3.4
20	13.1	4.9	9.4	13.0	3.6	8.7	6.6	.4	3.2
21	17.2	6.2	10.3	17.5	7.9	11.1	10.2	.3	6.0
22	15.6	6.9	11.1	11.0	3.9	7.6	10.1	5.6	7.6
23	16.1	8.0	11.8	7.9	1.4	4.0	8.6	3.9	5.7
24	14.2	4.7	9.5	12.1	2.4	7.2	14.8	4.8	9.4
25	15.4	3.6	9.1	16.6	5.5	9.9	10.8	5.2	7.9
26	14.6	4.4	8.3	10.6	4.5	7.6	14.5	7.8	10.5
27	17.6	6.3	10.2	7.8	3.7	5.3	15.0	8.8	12.0
28	19.4	8.0	11.2	13.1	4.8	8.1	12.3	8.5	10.3
29	20.6	8.3	12.6	15.1	6.5	9.9	11.9	7.2	9.5
30	19.9	8.2	12.7	16.8	7.3	11.0	12.3	8.1	9.7
31	18.5	6.7	11.4	13.9	5.6	9.9			
Monthly average	–	–	–	13.2	4.8	8.4	10.4	3.9	6.9

Table 5. Daily maximum, minimum, and average air temperature over South Cascade Glacier, Washington, near the glacier terminus, altitude 1,670 meters, during July through September of water year 2003.

[Location of site on figure 2; **Abbreviations:** Max, maximum; Min, minimum; Avg, average; –, data missing]

Day	Daily air temperature, in degrees Celsius								
	July			August			September		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	–	–	–	17.9	9.8	12.9	18.1	7.8	12.6
2	–	–	–	17.5	9.1	11.9	20.9	12.5	16.6
3	–	–	–	14.7	7.1	10.1	23.8	13.4	18.8
4	–	–	–	16.4	6.0	11.5	19.3	11.8	15.6
5	–	–	–	16.1	8.2	12.3	19.6	11.1	14.9
6	–	–	–	13.3	6.4	9.2	20.4	9.6	15.2
7	–	–	–	12.4	6.7	9.5	9.9	4.5	7.0
8	–	–	–	16.7	8.4	12.3	4.7	2.6	3.6
9	15.2	5.4	10.7	16.0	8.7	11.5	9.7	2.3	5.6
10	20.5	10.5	15.0	13.1	6.3	9.8	7.8	4.7	6.3
11	19.2	8.9	13.9	10.3	5.8	7.9	7.5	3.2	5.7
12	15.1	8.1	10.9	10.9	4.5	7.5	6.1	1.7	3.4
13	8.4	5.7	6.7	14.9	5.1	9.7	11.9	3.2	7.9
14	12.5	5.1	8.4	19.2	8.1	14.2	9.5	2.7	6.6
15	13.6	7.7	9.7	20.2	7.7	15.4	6.9	1.2	3.7
16	11.4	5.1	8.0	8.8	5.6	7.3	1.8	-.6	.2
17	16.0	4.6	10.2	17.4	6.8	11.0	3.7	-.3	1.5
18	19.5	9.8	14.4	18.1	10.4	13.4	8.0	1.7	5.9
19	19.5	12.1	14.5	14.1	6.9	10.9	7.6	3.1	5.0
20	14.3	7.6	11.4	16.6	6.1	11.7	7.9	2.0	4.8
21	20.2	9.4	14.6	18.6	11.7	14.7	11.7	2.4	7.7
22	19.1	11.8	15.1	12.4	6.0	9.5	12.3	7.0	9.3
23	17.7	9.7	13.8	9.6	2.7	5.7	11.5	5.5	7.9
24	15.9	8.3	11.3	14.2	6.1	9.6	16.2	8.9	12.5
25	17.6	7.8	12.2	17.4	7.8	12.6	12.5	6.5	9.5
26	17.1	6.7	11.5	12.6	5.6	9.8	17.9	8.6	14.0
27	19.2	10.5	14.2	10.4	5.7	7.0	17.7	12.2	16.1
28	20.8	12.6	16.2	15.8	6.3	11.3	18.1	13.3	15.5
29	21.4	14.5	17.9	17.4	11.1	13.9	16.7	10.9	14.0
30	21.9	12.4	16.3	18.4	9.9	14.5	15.6	11.1	13.2
31	20.3	12.1	14.8	15.9	8.6	12.4			
Monthly average	_	_	_	15.1	7.3	11.0	12.5	6.2	9.4

Table 6. Daily maximum, minimum, and average air temperature over South Cascade Glacier, Washington, near the upper end of the glacier, altitude 2,032 meters, during July through September of water year 2003.

[Location of site on figure 2; **Abbreviations:** Max, maximum; Min, minimum; Avg, average; –, data missing]

Day	Daily air temperature, in degrees Celsius								
	July			August			September		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
1	–	–	–	14.7	6.5	10.0	14.9	4.4	9.9
2	–	–	–	14.0	6.0	9.3	19.6	11.3	14.8
3	–	–	–	10.6	4.5	7.3	20.8	12.3	16.7
4	–	–	–	14.0	4.1	9.4	16.2	9.9	13.1
5	–	–	–	15.7	5.5	10.1	16.0	8.7	12.2
6	–	–	–	10.1	4.3	6.6	17.3	7.2	12.6
7	–	–	–	9.6	3.8	6.7	7.1	1.2	3.8
8	–	–	–	13.3	6.1	10.0	2.0	-.6	.7
9	14.2	2.8	8.8	12.2	6.1	9.2	7.4	-1.3	2.8
10	15.6	9.0	12.1	12.2	4.6	8.0	4.9	2.2	3.4
11	17.6	7.1	12.6	9.0	2.4	5.0	4.5	.4	2.9
12	12.5	4.8	8.5	7.3	1.7	4.5	2.6	-1.1	.2
13	5.2	2.4	3.5	11.3	2.9	7.2	9.8	1.2	5.6
14	10.2	2.2	6.0	18.1	5.1	13.2	6.9	-.1	3.7
15	11.1	4.6	7.3	16.1	5.3	12.6	4.4	-1.6	1.0
16	9.4	1.9	5.1	6.3	3.1	4.8	-1.4	-2.7	-2.2
17	13.6	.9	8.2	12.7	3.6	7.9	.6	-2.7	-1.2
18	17.1	8.5	12.5	14.3	7.0	10.4	5.3	-1.3	3.0
19	16.9	7.5	12.1	11.0	3.2	7.0	4.4	.4	2.2
20	10.2	6.1	8.1	13.4	3.1	9.5	6.5	-1.0	2.0
21	17.2	6.6	12.4	17.0	9.2	12.5	8.7	-.4	5.5
22	16.1	8.8	12.5	10.4	2.3	6.9	8.6	3.6	6.0
23	13.3	8.5	10.7	7.7	.1	3.0	9.5	2.9	4.9
24	12.2	3.8	8.2	11.2	3.2	7.0	14.0	6.4	9.8
25	15.1	3.8	10.0	15.7	6.1	10.6	9.0	4.4	6.4
26	13.3	5.3	9.1	10.1	3.0	7.0	15.3	5.9	11.4
27	16.5	7.2	12.1	6.6	2.6	3.8	16.6	12.3	14.0
28	18.0	8.9	13.6	13.7	6.2	9.1	17.0	11.0	13.5
29	19.8	9.5	15.8	15.1	8.1	11.2	13.7	9.7	11.6
30	17.4	9.0	12.9	16.1	8.2	11.5	13.3	8.1	10.4
31	16.0	8.7	11.7	12.4	4.3	9.0			
Monthly average	–	–	–	12.3	4.6	8.4	9.9	3.7	6.7

The available data nonetheless indicate wind speed was substantially greater during winter than summer. Average hourly wind speed exceeded 20 m/s on January 3 and February 23.

The time series of hourly average incoming solar radiation measured at the Hut during water year 2003 is presented in figure 7, and daily average incoming solar radiation is presented in table 9. 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 underestimate actual solar radiation.

The time series of hourly measured precipitation measured at the Salix Creek gaging station during water year 2003 is presented in figure 8, and daily total measured precipitation is presented in table 10. Although the time series is complete, measured precipitation likely is an underestimate of precipitation at the Salix Creek gaging station, owing to precipitation catch deficiency, snow, and freezing of the precipitation gage during winter. Precipitation catch deficiency can result from the interaction of the gage with wind. Snow can fill the gage and slough away before it melts and is metered by the tipping-bucket mechanism. Ice can lock the tipping mechanism and cause it to not function. The primary uses of the precipitation record are for detecting the onset of storms in the vicinity of South Cascade Glacier and for describing general precipitation trends.

The time series of instantaneous stage recorded at the Middle Tarn and Salix Creek gaging stations during water year 2003 are presented in figure 8. Both Middle Tarn and Salix Creek gaging stations were visited on February 5, 2003, when Middle Tarn was covered with snow and ice and the stilling well along the shore was frozen. It is believed the Middle Tarn stage record was adversely affected by ice in the tarn from early December through early June; thus, computed discharge for that period is considered unreliable and is not included in this report. The Salix Creek gaging station on February 5 was free of ice that would have interfered with accurate measurement of stage and computation of discharge. The stage recorder at the Salix Creek station lost power sometime after February 5, resulting in the loss of all of the data after that date until a new recorder was started on July 9. Intermittent discharge measurements made during 2003 with a current meter or by using a volumetric discharge measurement technique are presented in table 11. Daily average runoff from Middle Tarn Basin and Salix Creek Basin is presented in tables 12 and 13.

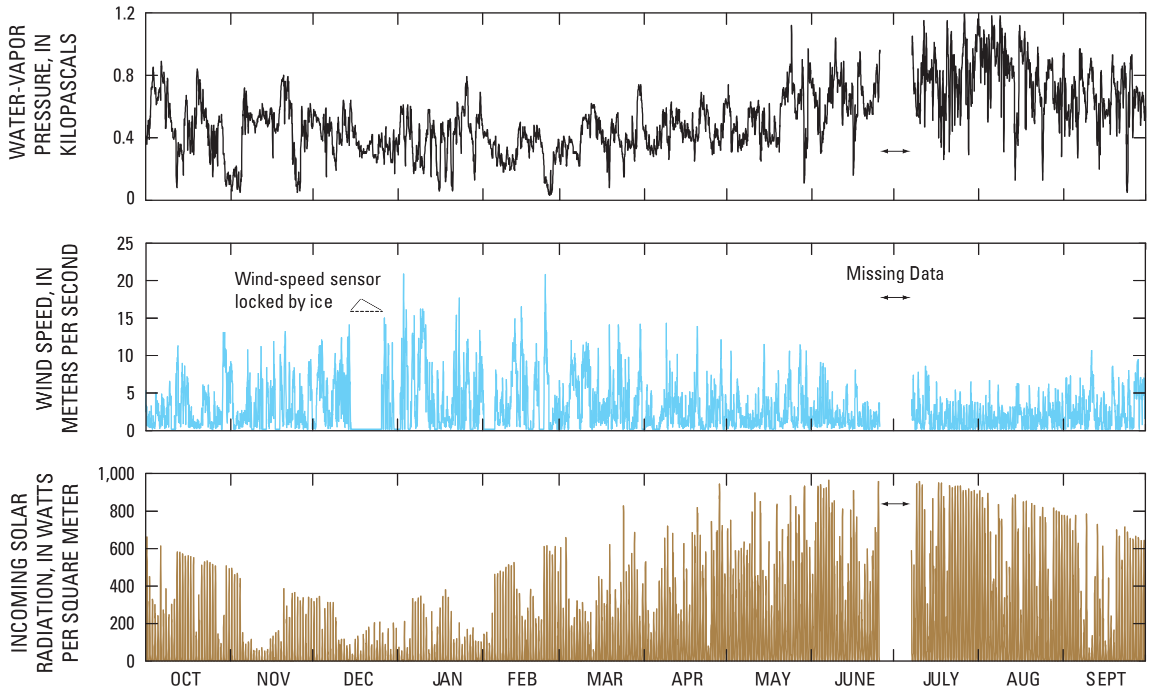

Figure 7. Hourly average atmospheric water-vapor pressure, wind speed, and incoming solar radiation at the Hut, 1,842 meters altitude, near South Cascade Lake Basin, Washington, water year 2003. Daily summaries are presented in tables 7–9.

Table 7. Daily average atmospheric water-vapor pressure at the Hut, 1,842 meters altitude, near South Cascade Lake Basin, Washington, water year 2003.

[–, data missing]

Day	Daily average atmospheric water-vapor pressure, in kilopascals											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1	0.43	0.11	0.55	0.44	0.42	0.30	0.39	0.63	0.71	–	0.99	0.68
2	.56	.19	.52	.58	.42	.37	.35	.46	.63	–	.95	.54
3	.78	.12	.47	.38	.36	.30	.32	.45	.55	–	.93	.54
4	.67	.13	.45	.52	.32	.37	.33	.48	.37	–	.82	.68
5	.68	.58	.42	.48	.34	.37	.35	.36	.48	–	.86	.58
6	.78	.58	.46	.27	.29	.31	.39	.37	.55	–	1.03	.62
7	.74	.52	.46	.26	.26	.27	.48	.41	.70	–	.95	.84
8	.64	.53	.30	.37	.22	.33	.53	.44	.73	.73	.97	.69
9	.58	.49	.32	.25	.27	.50	.37	.58	.89	.64	.96	.63
10	.45	.50	.43	.25	.24	.53	.51	.54	.78	.63	.80	.83
11	.40	.54	.45	.44	.24	.50	.49	.51	.78	.88	.87	.80
12	.23	.56	.56	.49	.24	.54	.52	.57	.64	.84	.85	.64
13	.33	.53	.43	.41	.34	.59	.53	.37	.68	.80	.82	.45
14	.30	.50	.54	.40	.43	.47	.44	.52	.60	.81	.36	.61
15	.60	.56	.45	.14	.41	.48	.44	.40	.68	.80	.68	.59
16	.44	.46	.42	.29	.42	.41	.45	.41	.38	.85	.98	.55
17	.40	.46	.35	.43	.35	.35	.41	.39	.59	.66	.94	.57
18	.42	.52	.31	.22	.37	.30	.43	.45	.85	.60	.79	.75
19	.69	.74	.31	.47	.39	.34	.38	.37	.68	.52	.84	.76
20	.71	.71	.32	.21	.43	.45	.42	.51	.57	.92	.68	.62
21	.58	.71	.36	.42	.42	.48	.61	.68	.58	.74	.63	.60
22	.55	.62	.36	.51	.34	.44	.59	.68	.60	.82	.83	.76
23	.45	.40	.28	.45	.17	.33	.54	.77	.65	.76	.65	.72
24	.34	.20	.29	.56	.09	.25	.48	.86	.77	.70	.40	.34
25	.34	.11	.38	.64	.07	.38	.35	.70	.79	.70	.74	.83
26	.37	.32	.32	.62	.18	.36	.39	.56	–	1.06	.85	.60
27	.46	.44	.38	.44	.28	.40	.42	.66	–	.88	.86	.68
28	.49	.41	.35	.28	.34	.34	.37	.74	–	.66	.66	.64
29	.25	.55	.27	.43		.63	.49	.32	–	.74	.64	.61
30	.13	.51	.34	.54		.69	.61	.58	–	.90	.63	.59
31	.13		.36	.53		.49		.78		1.07	.71	
Monthly average	.48	.45	.39	.41	.31	.42	.45	.53	–	–	.80	.64

Table 8. Daily average wind speed at the Hut, 1,842 meters altitude, near South Cascade Lake Basin, Washington, water year 2003.

[**Wind speed**: wind-speed sensor probably was locked by ice during days for which tabulated wind speed is 0.2; –, data missing or average not computed due to probable sensor icing]

Day	Daily average wind speed, in meters per second											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1	1.8	6.1	0.7	0.5	1.6	2.0	1.5	1.2	1.9	–	1.6	1.5
2	1.4	.6	4.8	5.3	.2	2.4	1.6	3.5	1.5	–	1.2	4.2
3	.9	1.3	8.3	9.8	.2	2.1	2.1	1.7	2.1	–	1.6	2.7
4	2.3	1.2	7.8	7.1	.2	2.7	.6	2.1	3.6	–	1.3	1.4
5	2.7	1.5	2.4	.7	2.8	8.4	.2	3.9	3.9	–	2.4	1.9
6	1.7	2.2	2.7	10.2	2.4	8.0	.7	1.5	3.8	–	1.2	2.2
7	2.4	5.4	1.6	3.1	2.2	5.3	2.2	1.3	2.6	–	1.0	2.1
8	1.7	2.0	5.1	6.6	3.1	2.3	3.1	2.3	2.0	3.4	2.8	3.2
9	3.8	1.1	4.5	12.0	2.3	6.6	4.3	1.1	1.3	1.9	1.5	1.3
10	1.4	2.4	5.0	13.8	2.0	9.4	3.8	.9	1.9	3.4	1.1	3.4
11	.8	4.0	7.0	7.7	6.2	8.5	2.3	1.8	1.4	1.3	1.5	7.0
12	7.0	3.1	3.9	2.1	11.4	2.8	4.7	2.1	1.2	2.9	1.3	2.2
13	1.9	.2	5.8	3.4	5.9	2.9	2.5	1.2	2.5	5.0	1.2	1.5
14	5.2	4.4	5.0	1.7	4.2	3.4	2.8	5.7	2.1	1.3	2.2	1.9
15	4.9	3.1	.2	3.0	10.4	3.9	.8	1.8	1.1	.7	3.6	1.8
16	4.0	5.2	.2	.9	3.7	1.8	1.4	2.1	1.6	2.5	2.2	1.4
17	1.3	1.5	.2	3.8	3.2	2.5	2.4	1.6	4.9	.8	1.3	.9
18	.9	.4	.2	1.4	.3	2.3	1.7	1.3	1.3	1.8	1.6	3.1
19	.8	6.3	.2	1.7	2.4	5.8	2.8	4.2	1.8	1.0	2.5	5.0
20	.7	6.3	.2	1.4	7.5	3.4	6.4	1.6	1.4	2.1	1.1	.9
21	1.8	2.9	.2	5.1	3.4	1.8	1.3	1.0	1.5	1.3	1.1	1.7
22	4.7	3.5	.2	6.0	.2	6.9	.5	2.4	1.3	1.4	1.8	3.2
23	3.8	3.8	.2	4.7	8.6	6.2	1.9	4.3	1.0	2.1	1.8	2.2
24	1.5	3.4	.2	2.0	9.4	1.8	1.9	4.7	1.7	1.6	1.5	3.6
25	1.0	1.4	.2	3.4	1.2	3.5	3.0	1.3	1.7	2.2	1.5	2.4
26	1.4	3.4	4.2	8.9	1.1	3.1	3.6	.9	–	1.3	2.9	1.8
27	1.9	1.7	7.8	1.9	2.1	.4	2.0	6.5	–	1.2	2.2	5.8
28	1.4	.8	5.0	1.6	1.7	1.6	4.6	4.5	–	1.1	1.9	6.1
29	10.2	5.8	1.8	4.4		3.2	4.4	2.7	–	2.7	2.7	5.1
30	5.9	5.0	3.0	3.7		8.8	2.1	4.2	–	1.6	2.6	5.5
31	6.1		.2	8.4		.9		1.5		1.6	1.9	
Monthly average	2.8	–	–	4.7	–	4.0	–	2.5	–	–	1.8	2.9

Table 9. Daily average incoming solar radiation at the Hut, 1,842 meters altitude, near South Cascade Lake Basin, Washington, water year 2003.

[–, data missing]

Day	Daily average incoming solar radiation, in watts per square meter											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1	167	93	48	17	31	151	162	228	142	–	328	238
2	95	85	51	12	34	67	80	202	212	–	295	249
3	74	87	50	32	23	185	46	160	326	–	247	242
4	66	87	27	15	39	81	76	150	312	–	297	195
5	61	33	42	20	79	49	66	185	341	–	204	248
6	155	17	48	51	87	61	139	195	330	–	174	179
7	67	23	48	48	90	82	122	197	348	–	174	72
8	87	24	47	51	90	74	177	214	268	135	260	50
9	60	14	41	55	102	73	190	177	236	352	251	228
10	68	13	27	49	99	70	132	195	124	358	99	20
11	71	13	21	44	102	59	187	209	220	327	131	34
12	156	13	19	13	112	55	125	170	223	193	148	131
13	154	12	18	44	82	16	74	294	90	76	301	229
14	150	13	17	17	68	83	91	126	176	199	305	70
15	144	22	8	38	56	98	157	149	235	220	244	141
16	144	25	23	50	57	108	148	175	337	198	81	27
17	142	33	27	60	70	89	95	90	290	351	291	74
18	138	35	11	61	82	120	160	154	137	347	288	62
19	37	22	30	64	80	133	215	275	107	297	187	39
20	81	65	27	44	58	68	217	176	138	140	284	178
21	125	51	33	25	51	94	178	180	144	345	277	203
22	129	50	19	21	51	74	152	121	116	337	103	159
23	128	66	32	35	153	104	185	243	208	337	205	169
24	123	59	23	20	156	182	28	240	215	336	258	198
25	120	60	33	20	147	126	145	156	352	340	252	183
26	117	51	32	23	139	139	171	206	–	317	120	190
27	32	52	19	32	148	143	221	295	–	330	96	195
28	21	41	32	37	77	191	309	186	–	329	267	189
29	59	53	11	24		111	215	305	–	327	259	183
30	104	51	32	21		70	140	177	–	324	248	168
31	95		26	21		128		178		315	247	
Monthly average	102	42	30	34	84	99	147	194	–	–	223	151

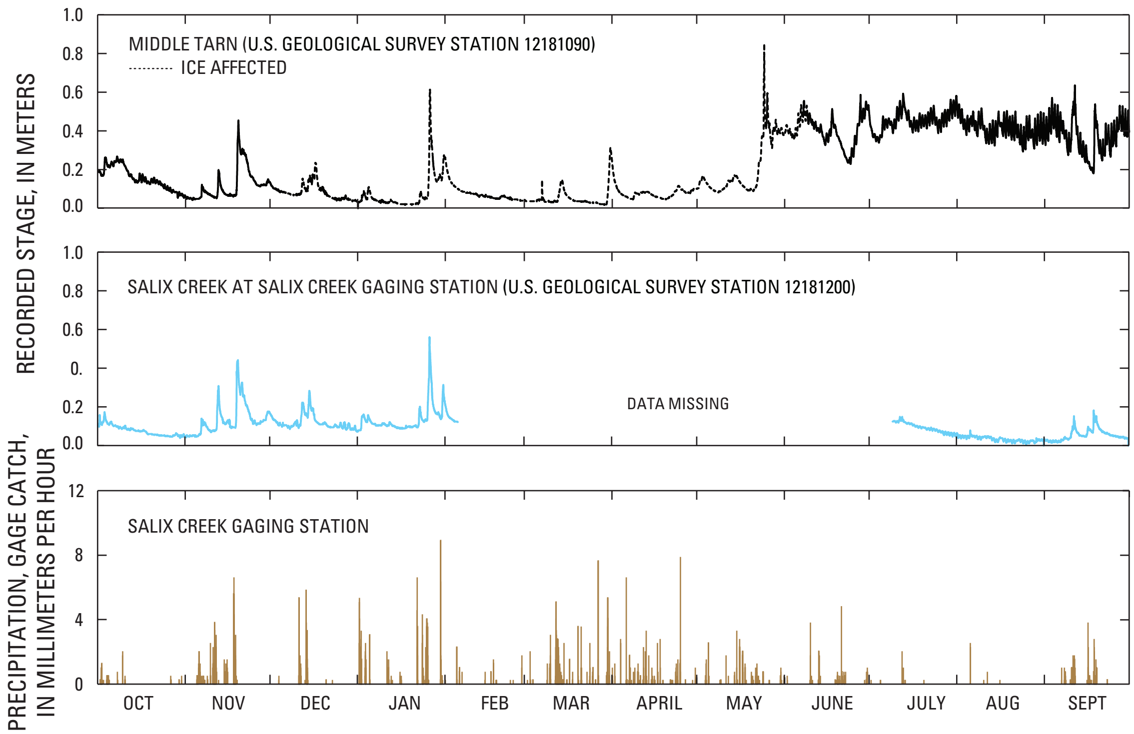

Figure 8. Recorded stage of Middle Tarn, South Cascade Lake Basin, Washington, and recorded stage of Salix Creek and hourly precipitation (gage catch) at the Salix Creek gaging station, Salix Creek Basin, Washington, water year 2003.
Daily summaries of precipitation are presented in table 10.

Table 10. Daily total precipitation (gage catch) at the Salix Creek gaging station, Salix Creek Basin, Washington, 1,587 meters altitude, water year 2003.

Day	Daily precipitation, in millimeters											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1	0.0	0.0	0.0	0.0	0.3	0.0	2.8	0.3	1.0	0.3	0.0	0.0
2	1.3	.0	.0	39.4	.0	.3	1.8	.0	.8	.0	.0	.0
3	7.9	.0	.0	.3	.0	2.3	.0	.0	.0	.0	.0	.0
4	.5	.0	.8	14.2	.0	.5	5.3	4.8	.0	.0	.0	.0
5	5.3	.8	.0	3.3	2.5	.0	.0	3.6	.0	.5	4.8	.0
6	.0	11.4	.0	.0	2.5	.0	7.4	.0	.0	.0	.0	.0
7	.0	2.8	.0	.0	.8	.0	6.9	.0	.0	.0	.0	1.3
8	1.3	3.0	.0	.0	.0	.0	1.3	.0	.0	.0	.0	5.6
9	.0	1.0	.0	.0	.0	1.8	2.0	.8	.0	.0	.0	.0
10	3.8	3.0	.0	.0	.0	9.7	3.3	.0	6.6	.0	.3	7.4
11	1.3	9.1	9.9	3.3	.0	.0	1.0	1.8	.3	.0	.8	15.2
12	.0	37.1	9.9	6.1	.0	32.5	4.1	.5	.0	3.0	.0	.0
13	.0	.3	.0	1.0	.0	36.6	10.7	.0	7.4	1.8	.0	.0
14	.0	.0	29.7	.0	.0	3.6	1.8	1.5	.0	.0	.0	.0
15	.0	6.1	.3	.0	1.0	3.6	2.5	4.8	.0	.0	.0	.0
16	.0	8.4	.0	3.3	.0	.8	1.3	7.4	.0	.0	.3	10.7
17	.0	.0	.0	.8	.8	1.5	3.8	7.6	.0	.0	.0	1.5
18	.0	26.2	.0	.0	3.0	1.0	4.1	2.8	.0	.0	.0	11.7
19	.0	29.0	.0	.0	1.0	.0	.5	.0	2.8	.0	.0	5.6
20	.0	.3	.0	.0	.0	4.6	.0	3.6	3.3	.3	.0	.0
21	.0	.0	.3	.0	.0	6.9	.3	1.8	8.9	.0	.0	.0
22	.0	.0	.0	22.6	.0	.0	1.5	8.9	4.8	.0	.0	.0
23	.0	.0	.3	.0	.0	.8	2.0	1.5	.0	.0	.0	.5
24	.0	.0	.0	14.7	.3	4.3	5.8	2.3	.0	.0	.0	.0
25	.0	.0	.0	19.3	.3	3.3	12.7	.0	.0	.0	.0	.0
26	.0	.0	.0	31.8	.0	.3	.0	.5	.0	.0	.0	.0
27	1.0	.0	.0	.0	.0	11.2	.3	.0	.0	.0	.0	.0
28	.0	.0	.0	.0	2.8	.0	.0	.0	.0	.0	.0	.0
29	.0	.0	.0	.0		.0	.3	.0	.3	.0	.0	.0
30	.3	.0	.0	27.4		20.1	1.3	1.3	4.6	.0	.0	.0
31	1.0		.0	4.6		9.4		2.5		.0	.0	
Monthly total	23.7	138.5	51.2	192.1	15.3	155.1	84.8	58.3	40.8	5.9	6.2	59.5

Table 11. Miscellaneous stream discharge measurements made in and near South Cascade Lake Basin, Washington, water year 2003.

[**Abbreviations**: m, meter; m^3/s, cubic meter per second]

Date	Stream measurement		Type of measurement
	Stage (m)	Discharge (m^3/s)	
South Fork of Cascade River at Middle Tarn outlet			
07-09-03	0.421	1.36	Current meter
07-27-03	.503	1.81	Current meter
09-21-03	.308	.72	Current meter
Salix Creek near Salix Creek gaging station			
07-09-03	0.128	0.0079	Current meter
07-27-03	.067	.0017	Volumetric
08-29-03	.040	.0003	Volumetric

Table 12. Daily average runoff from Middle Tarn Basin, Washington, water year 2003.

[Daily average runoff is averaged over the area of the basin (4.46 square kilometers); –, data not available or not reliable due to likely presence of ice]

Day	Daily average runoff, in millimeters						
	2002			2003			
	October	November	December	June	July	August	September
1	6.3	1.2	3.0	–	26.0	36.1	22.4
2	5.4	1.2	2.6	–	20.8	31.9	26.2
3	9.5	1.1	2.3	–	19.2	27.5	30.9
4	8.1	1.1	2.1	–	18.9	26.1	30.6
5	8.5	1.1	2.0	–	24.2	27.2	27.7
6	8.8	1.9	–	–	27.3	30.1	25.2
7	10.1	2.3	–	–	27.9	26.0	24.6
8	9.7	1.9	–	–	27.5	27.1	20.8
9	9.6	1.6	–	31.0	25.6	30.3	15.8
10	8.0	1.4	–	28.9	30.7	24.5	22.4
11	6.3	1.3	–	26.6	35.3	20.2	39.9
12	5.3	4.0	–	24.6	36.7	21.1	23.7
13	4.5	3.0	–	24.2	38.9	22.2	15.9
14	3.9	1.9	–	20.7	32.4	21.7	14.0
15	4.7	1.6	–	18.4	27.8	26.8	11.9
16	4.7	1.5	–	20.0	26.1	26.5	9.2
17	4.4	1.5	–	27.3	26.4	26.5	7.2
18	3.8	1.6	–	26.7	27.9	26.8	17.6
19	3.8	17.1	–	21.7	28.8	25.7	26.3
20	4.2	13.6	–	18.1	28.8	24.4	15.5
21	3.9	13.1	–	14.5	29.4	25.6	13.2
22	3.8	10.5	–	11.4	31.8	22.9	17.1
23	3.3	6.3	–	9.6	32.9	20.2	20.3
24	2.9	4.9	–	11.4	29.4	17.6	17.3
25	2.5	3.9	–	14.9	26.2	21.8	20.7
26	2.3	3.2	–	21.1	28.1	23.1	22.1
27	2.1	3.1	–	32.3	30.7	21.8	29.8
28	2.0	3.3	–	32.5	31.4	20.9	29.7
29	1.7	3.4	–	35.9	35.8	23.1	26.5
30	1.7	3.9	–	37.1	36.9	24.8	25.3
31	1.4		–		38.9	23.6	
Monthly average	5.1	3.9	–	–	29.3	25.0	21.7

Table 13. Daily average runoff from Salix Creek Basin at Salix Creek gaging station, Washington, water year 2003.

[Daily average runoff is averaged over the area of the basin (0.22 square kilometer); –, no data]

Day	Daily average runoff, in millimeters							
	2002			2003				
	October	November	December	January	February	July	August	September
1	2.7	0.3	5.1	0.9	8.0	–	0.4	0.1
2	2.5	.3	3.6	3.7	4.6	–	.3	.1
3	4.6	.3	2.7	4.3	3.7	–	.3	.0
4	2.5	.3	2.1	3.9	3.1	–	.3	.0
5	2.6	.3	2.0	3.3	–	–	.4	.0
6	2.0	1.3	2.0	2.4	–	–	.5	.0
7	1.7	2.5	1.6	2.0	–	–	.4	.1
8	1.5	1.7	1.6	2.0	–	–	.3	.1
9	1.3	1.0	2.3	2.1	–	–	.2	.1
10	1.5	.9	2.6	2.3	–	3.0	.3	.3
11	1.1	1.0	2.2	1.9	–	3.2	.3	2.0
12	1.1	16.4	10.6	2.4	–	3.8	.4	1.1
13	1.1	6.6	6.2	1.9	–	3.1	.3	.4
14	.9	3.0	11.9	1.6	–	2.5	.2	.3
15	.8	2.7	11.4	1.4	–	2.4	.1	.3
16	.9	2.8	6.1	1.3	–	2.2	.3	.9
17	.9	1.5	2.9	1.3	–	1.8	.2	1.0
18	.5	1.9	2.3	1.5	–	1.6	.2	2.6
19	.5	53.2	2.3	1.6	–	1.5	.2	3.4
20	.4	27.6	2.4	1.6	–	1.5	.1	1.6
21	.4	22.6	1.7	1.8	–	1.2	.1	.9
22	.3	12.0	1.5	3.7	–	1.2	.2	.6
23	.3	7.1	1.6	5.6	–	1.2	.2	.5
24	.3	3.5	1.8	3.2	–	1.0	.2	.4
25	.3	2.7	1.9	6.3	–	.9	.1	.3
26	.3	2.4	1.6	72.1	–	.8	.1	.3
27	.3	2.6	1.9	20.9	–	.5	.2	.2
28	.4	3.2	1.8	7.3	–	.6	.2	.2
29	.3	4.5	1.3	6.2		.5	.1	.2
30	.3	7.0	1.2	5.1		.5	.1	.1
31	.3		1.0	20.1		.5	.1	
Monthly average	1.1	6.4	3.3	6.3	–	–	.2	.6

Winter Balance

Snow depth on South Cascade Glacier measured by probing during May 7 to 11, 2003, ranged from 0.87 m near the terminus to 5.90 m near the upper end of the glacier (table 14, fig. 9). Over more than 80 percent of the glacier area, the summer melt surface under the snowpack was firn formed from snow that fell during 2002 (Bidlake and others, 2004). Probing the depth of snow that lay atop of firn relied on detecting the firn at depth by an increase in penetration resistance as the probe encountered 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 that exhibit penetration resistances similar to that of firn, which can make detection of the interface between snow and firn difficult, if not impossible. Snow depth measured by probing on May 7 or 8 was checked at site P-1 and at stake 2-03 (fig. 2) using independent measurements of snow and firn thicknesses and surface lowering made at those sites during 2002 and 2003.

The 2002 ELA was estimated to be 1,820, and depth of residual snow at site P-1 (altitude 1,846 m) late in balance year 2002 (October 26, 2002) was 1.26 m (Bidlake and others, 2004). The residual snow became the firn under the 2003 snowpack. On July 28, 2003, coring through the combined thicknesses of remaining 2003 snow and firn formed at the end of balance year 2002 indicated that 1.86 m of snow and firn remained at that time. Surface lowering at ablation stake 1-03 during May 7-July 28 was 4.20 m. Assuming that firn thickness on May 7, 2003, remained 1.26 m, snow depth at site P-1 on May 7 was computed to have been 4.80 m, which differed by less than 2 percent from snow depth measured by probing (4.72 m).

The 2002 summer melt surface near stake 1-02 (Bidlake and others, 2004) had been marked on October 26, 2002. On May 8, 2003, ablation stake 2-03 was placed within about 10 m of the site of the surface marking. On August 28, 2003, the surface marking was found beneath 0.12 m of residual snow from the previous winter. Surface lowering at stake 2-03 during May 8 to August 28 was 5.66 m, thus the May 8 snow depth was computed to have been 5.78 m, which was about 2 percent less than snow depth measured by probing on May 8 (5.90 m).

On the basis of the independent checks and experience gained in previous years, snow depths measurements made on South Cascade Glacier during early May 2003 are thought to be generally reliable. One probed snow-depth measurement made on the lower glacier (local X = 1,624, local Y = 3,338), a measurement that appeared abnormally large at the time it was taken, was rejected when analysis of vertical aerial photographs taken late in the balance year indicated that the probing measurement likely was made over a large crevasse, where snow depth probably was not representative of the average depth to nearby ice.

Table 14. Snow depth on South Cascade Glacier, Washington, May 2003.

[***X*** and ***Y*** are easting and northing coordinates in the local coordinate system, meters; ***Z***, altitude, meters. Data and probing locations are shown in figure 9]

X	*Y*	*Z*	Snow depth (meters)
May 7			
1,813	2,775	1,844	4.72
1,830	2,678	1,852	4.97
1,861	2,591	1,861	4.97
1,882	2,509	1,872	4.92
1,901	2,424	1,895	5.17
1,910	2,327	1,911	5.07
1,951	2,245	1,924	4.87
2,007	2,175	1,934	5.02
2,074	2,085	1,945	5.17
2,130	1,972	1,956	5.07
2,184	1,872	1,978	5.32
2,273	1,767	2,008	5.68
May 8			
1,548	3,201	1,768	4.27
1,569	3,136	1,790	3.86
1,628	3,035	1,815	4.47
1,679	2,969	1,826	4.58
1,742	2,880	1,837	4.78
2,028	2,085	1,944	4.83
2,077	1,985	1,955	5.14
2,137	1,865	1,974	5.64
2,210	1,752	2,001	5.70
2,335	1,705	2,019	5.90
2,311	1,652	2,019	5.70
2,430	1,561	2,032	5.64
2,428	1,565	2,032	5.90
2,540	1,608	2,041	5.90
2,647	1,648	2,051	5.80
2,751	1,692	2,063	5.29
2,876	1,732	2,073	4.83
2,989	1,782	2,078	5.09
3,102	1,832	2,084	5.19
May 9			
1,686	3,450	1,690	2.80
1,664	3,394	1,707	3.41
1,587	3,269	1,743	3.70
1,576	3,257	1,747	3.94
1,599	3,089	1,804	4.08
May 11			
1,705	3,588	1,639	1.00
1,702	3,574	1,644	.87
1,707	3,545	1,655	1.25
1,698	3,506	1,670	2.61
May 19			
1,813	2,775	1,844	4.98

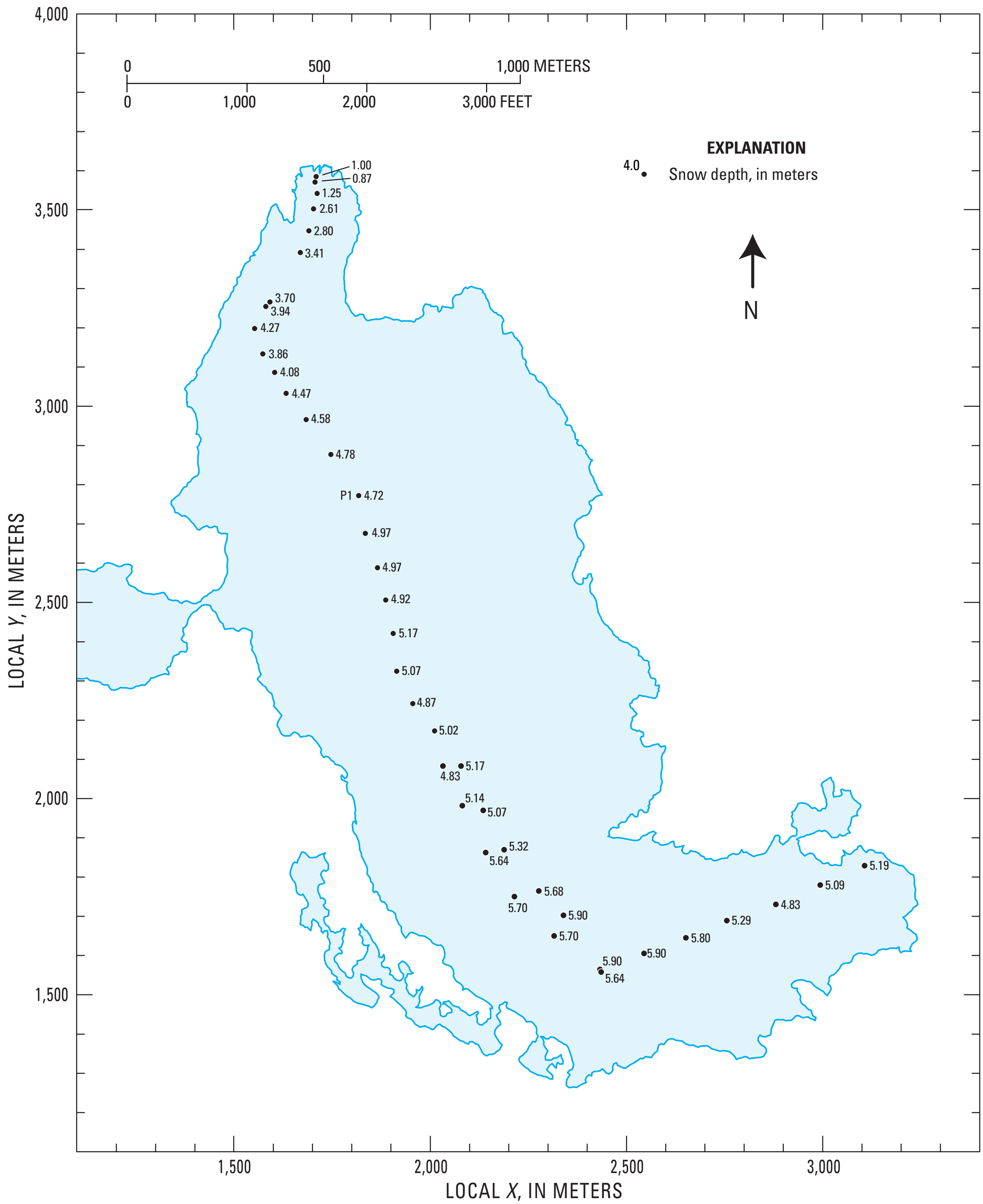

Figure 9. Snow depth at South Cascade Glacier, Washington, May 7–11, 2003. Data are presented in table 14.

Density of the snowpack on South Cascade Glacier on May 7 was estimated on the basis of density measurements made during May. A partial snowpack density profile was obtained at site P-1 on May 7 from samples taken in the wall of a pit and from cores extracted with a coring auger (table 15). The sampling crew was unable to extract cores from a depth greater than 2.867 m using the coring auger, therefore snow below that depth was not sampled on May 7. Site P-1 was revisited on May 19 when a nearly complete snow-density profile was obtained with a specially designed snow corer (Philip Taylor, Seattle, Washington, written commun., May 2003) (table 16). Snow depth at the site was greater than on May 7, due to one or more storms, and it was assumed that the density of snow stratigraphically below the pit from May 7 had remained unchanged since that date. Average density of the entire snow profile at site P-1 on May 7 (0.52) was computed by combining density measurements made from the pit wall on May 7 with those made below the level of the pit on May 19.

Density of the entire snow profile near the glacier terminus was measured on May 9 using samples taken from the wall of a pit (fig. 2, table 17). Average density of the snow profile was 0.47. Snow density on May 9 was assumed equal to the density on May 7.

Table 15. Snow density measured at site P-1 on South Cascade Glacier, Washington, May 7, 2003.

[Site P-1 is located at *X* = 1,813, *Y* = 2,775, where *X* and *Y* are easting and northing coordinates in a local coordinate system, meters; 1,844 meters altitude **Snow density** expressed as a fraction of the density of water; snow density to a depth of 1.007 meters was computed from 72.3-millimeter-diameter samples taken with a sampling tube from the wall of a pit; snow density between depths of 1.007 and 2.867 meters was computed from 76.3-millimeter-diameter samples taken with a coring auger.]

Snow sample			Snow density
Bottom (meters)	Length (meters)	Mass (kilograms)	
0.456	0.456	0.68	0.36
.934	.498	.92	.45
1.007	.073	.18	.60
1.567	.480	1.00	.46
1.722	.190	.45	.52
1.997	.280	.55	.43
2.867	.875	2.00	.50

An altitude-based interpolation scheme was used to estimate snow density at each snow-depth probing location. Snow density on May 7 was assumed to vary linearly with altitude between the density-measurement site near the terminus and site P-1. Snow density at locations lower in altitude than the density-measurement site near the terminus was assumed to equal that at the density-measurement site. Snow density at altitudes greater than site P-1 was assumed to equal the density at site P-1.

Table 16. Snow density measured at site P-1 on South Cascade Glacier, Washington, May 19, 2003.

[Site P-1 is located at *X* = 1,813, *Y* = 2,775, where *X* and *Y* are easting and northing coordinates in a local coordinate system, meters; altitude 1,844 meters **Snow density** expressed as a fraction of the density of water; snow density was computed from 60.0-millimeter-diameter samples taken with a snow corer.]

Snow sample			Snow density
Bottom (meters)	Length (meters)	Mass (kilograms)	
1.280	1.280	1.26	0.35
2.830	1.550	2.28	.52
3.380	.550	.87	.56
3.820	.440	.76	.61
4.620	.800	1.17	.52
4.920	.300	.53	.62

Table 17. Snow density measured near the terminus of South Cascade Glacier, Washington, May 9, 2003.

[Site is located at *X* = 1,698, *Y* = 3,506, where *X* and *Y* are easting and northing coordinates in a local coordinate system, meters; altitude 1,670 meters **Snow density** expressed as a fraction of the density of water; snow density was computed from 72.3-millimeter-diameter samples taken with a sampling tube from the wall of a pit]

Snow sample			Snow density
Bottom (meters)	Length (meters)	Mass (kilograms)	
0.330	0.330	0.58	0.43
.655	.325	.65	.49
.995	.340	.66	.47
1.320	.325	.60	.45
1.675	.355	.72	.49
1.999	.324	.63	.47
2.314	.315	.65	.50

Snow water equivalent on May 7 was computed for each depth-measurement site by multiplying snow depth by snow density. No snow fell during May 7–11, and it was assumed that snow depth on May 8 and 9 was equal to depth on May 7. Snow depth on May 11 was adjusted to May 9 on the basis of surface lowering at ablation stake 6-03. Snow water equivalent was plotted as a function of altitude and a curve was fitted to the data by eye (fig. 10). Points digitized on the curve were used to create an interpolation table (table 18) that can be used to estimate the snow-water equivalent for May 7, 2003, for any point of known altitude on South Cascade Glacier. The interpolation table assumed the role of the relation $\bar{b}(Z_i)$ in equation 8 for the purpose of computing the measured winter snow balance ($\bar{b}_{\mathrm{m}}(\mathrm{s})$) of South Cascade Glacier.

Table 18. Altitude and snow water equivalent values defining a curve used to estimate snow water equivalent as it varied with altitude on South Cascade Glacier, Washington, on May 7, 2003.

[Snow water equivalent as it varied with altitude is shown in figure 10]

Altitude (meters)	Snow water equivalent (meters)	Altitude (meters)	Snow water equivalent (meters)
1,630	0.33	1,794	2.17
1,645	.62	1,842	2.36
1,658	.90	1,895	2.53
1,672	1.18	1,951	2.68
1,689	1.45	2,009	2.81
1,715	1.71	2,069	2.93
1,750	1.95	2,131	3.04

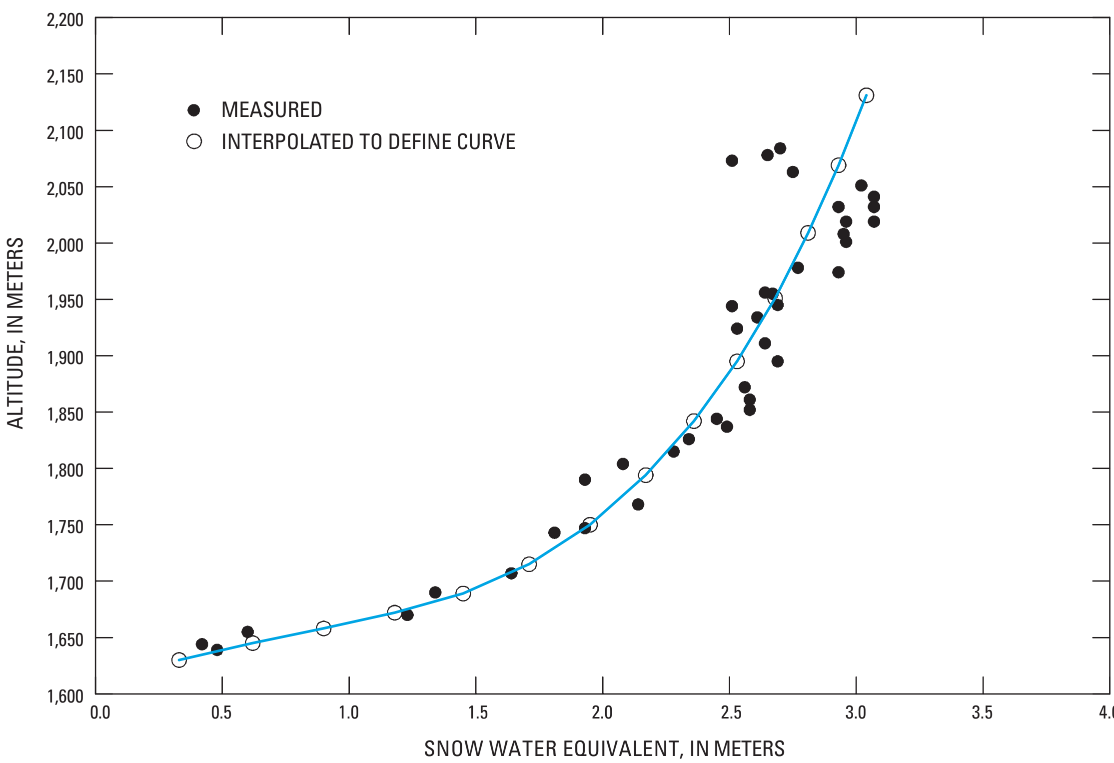

Figure 10. Snow-water equivalent as it varied with altitude on South Cascade Glacier, Washington, May 2003. Estimated values for points defining the curve are presented in table 18.

The DEM needed to compute the glacier-measured winter snow balance ($\bar{b}_{\mathrm{m}}(\mathrm{s})$) with equation 8 was assembled using the vertical aerial photography from September 13, 2003, described previously, and the 2001 and 2002 South Cascade Glacier DEMs reported by Krimmel (2002) and Bidlake and others (2004). Stereo photogrammetric analysis of featureless snow surfaces generally is not reliable, and DEM grid points that in 2003 fell in regions of the glacier where altitude could not be determined photogrammetrically were assumed to have the same altitude as in the 2001 or 2002 DEM, whichever was most recently measured. The nominal horizontal grid spacing of the resulting composite DEM (fig. 11, table 19) is 100 m. The 2003 South Cascade Glacier altitude grid comprises 186 grid points, of which 51 were from the 2001 or 2002 DEM. Eighty percent of the 2001 and 2002 grid points substituted into the 2003 DEM were at altitudes greater than 1,900 m, where year-to-year variations of measured altitude are generally within the margin of measurement error (about 2 m). Therefore, error in the 2003 grid-average glacier altitude (1,920 m) due to the substitutions is probably at most a few percent of the average altitude. Due to glacier shrinkage, the 2003 DEM has three fewer grid points than the 2002 altitude grid reported by Bidlake and others (2004).

The May 7, 2003, glacier measured winter snow balance ($\bar{b}_{\mathrm{m}}(\mathrm{s})$) of South Cascade Glacier of 2.53 m was slightly smaller than the glacier maximum winter snow balance ($\bar{b}_{\mathrm{w}}(\mathrm{s})$), due to one or more storms that swept into the North Cascade Range during May 14–18. Depth of snow at site P-1 increased by 0.26 m during May 7–19. Air temperature at the Middle Tarn gaging station and at the Hut generally remained below freezing during the storms, and it is assumed the change in snow depth at site P-1 equaled that over the entire glacier. If it is further assumed that the density of the fresh snow was 0.50, the increase in snow-water equivalent during May 7–19 can be computed to be 0.13 m. Thus, the glacier maximum winter snow balance was 2.66 m and the date of the end of the winter season was May 18. The first year for which glacier winter balance is available for South Cascade Glacier is 1959, and the 2003 glacier maximum winter snow balance was about equal to the mean for 1959–2003 (2.74 m, table 20).

Net Balance

The roughly average 2003 winter snow accumulation, combined with a warmer-than-normal 2003 summer (fig. 12), left the surface of South Cascade Glacier almost bare of snow by late summer (fig. 4). At the time of the aerial photography of the glacier, September 13, only about 7 percent of the glacier surface remained covered by snow deposited during balance year 2003 (fig. 11). Balance year 2003 ended about 6 weeks after the photography, when the percentage of glacier surface area remaining snow-covered probably was smaller than on September 13.

USGS personnel were not present at South Cascade Glacier at the conclusion of balance year 2003 in late October. The balance year end date and glacier surface height at ablation stakes were estimated using meteorological and streamflow data recorded by the previously described gaging and meteorological stations near the glacier, and from measurements at ablation stakes made after the balance year had ended. The glacier balance year most likely ended October 22 as snow fell over the entire glacier after it had been scoured free of snow by an intense deluge of rain October 20. The Salix Creek gaging station recorded 136 mm of precipitation October 20, most likely an underestimate of the precipitation total anywhere on the glacier on that date. Air temperature at the Hut indicated that the October 20 precipitation fell as rain over the entire glacier, and that temperature remained too high for snow to accumulate until October 22, the ending date of balance year 2003.

Recently fallen snow covered the entire 2003 summer melt surface of South Cascade Glacier on October 24, and height of the summer melt surface on ablation stakes was measured by digging through the snow cover (table 21). Net balance at ablation stakes was plotted against altitude to develop a net balance-altitude function (fig. 13).

Points digitized on the curve were used to create an interpolation table (table 22) that can be used to estimate the 2003 net-balance equivalent for any point of known altitude on South Cascade Glacier. Application of the grid-index technique with the net balance-altitude interpolation table and the 2003 South Cascade Glacier DEM yielded a 2003 glacier net balance of -2.10 m.

The computed 2003 net balance of South Cascade Glacier was the most negative since 1958, although it was probably within the margin of uncertainty of the net balances reported for 1987, 1992, and 1998 (table 20). The exceptionally negative 2003 glacier mass balance was the result of the average 2003 winter balance and an exceptionally negative summer balance.

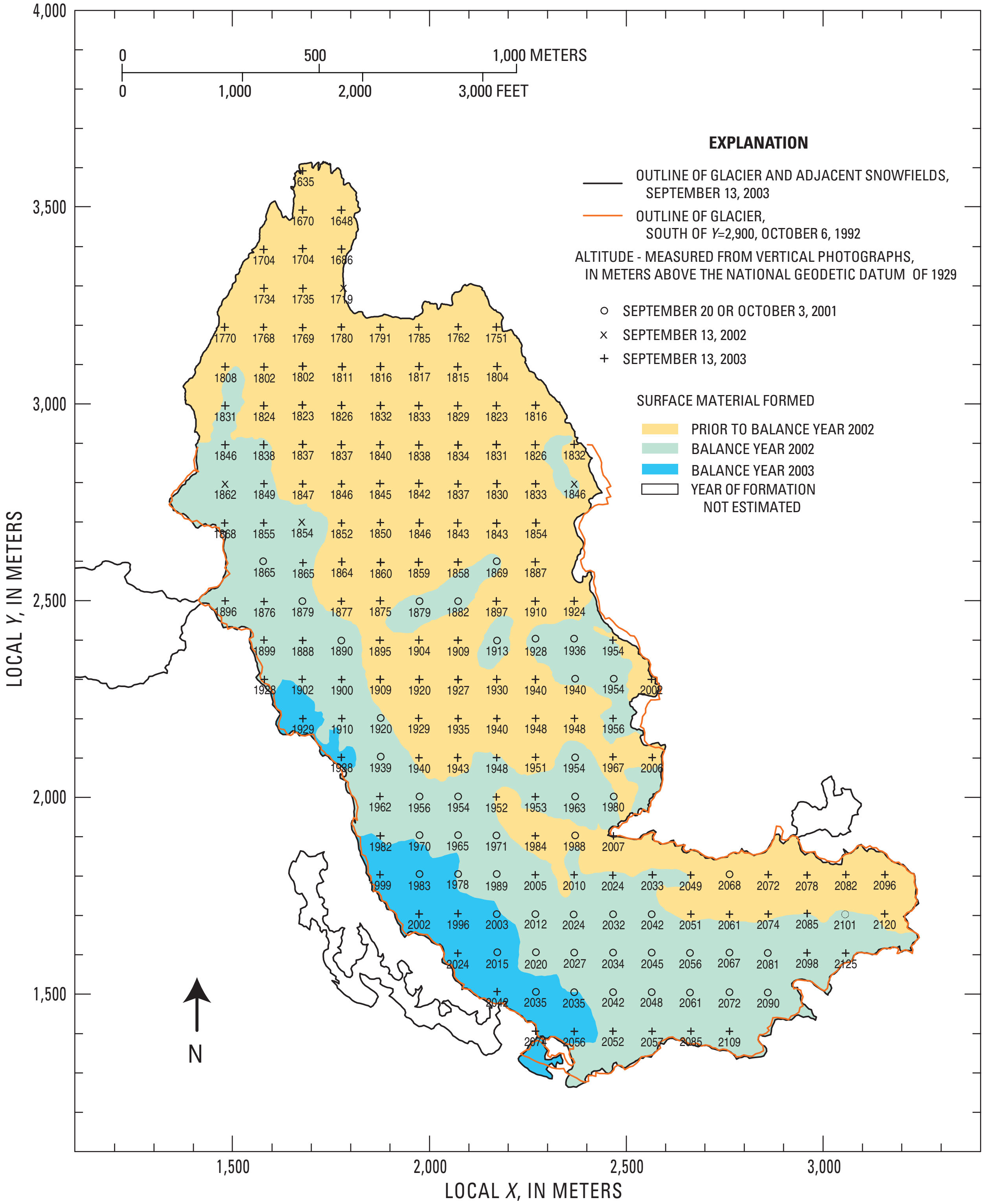

Figure 11. Altitude grid for South Cascade Glacier, Washington, 2003, measured from variously dated vertical aerial photographs.
Grid data are presented in table 19.

Table 19. Altitude grid for South Cascade Glacier, Washington, 2003.

[**Year**, calendar year of aerial photography; *X* and *Y* are easting and northing coordinates in the local coordinate system, meters; *Z* is altitude, meters; data are presented in figure 11]

Year	X	Y	Z
2003	1,670	3,600	1,635
2003	1,670	3,500	1,670
2003	1,770	3,500	1,648
2003	1,570	3,399	1,704
2003	1,670	3,401	1,704
2003	1,770	3,400	1,686
2003	1,571	3,300	1,734
2003	1,670	3,300	1,735
2002	1,770	3,300	1,719
2003	1,469	3,200	1,770
2003	1,569	3,200	1,768
2003	1,670	3,199	1,769
2003	1,770	3,201	1,780
2003	1,870	3,200	1,791
2003	1,970	3,200	1,785
2003	2,071	3,201	1,762
2003	2,170	3,201	1,751
2003	1,470	3,099	1,808
2003	1,571	3,099	1,802
2003	1,670	3,100	1,802
2003	1,772	3,099	1,811
2003	1,871	3,100	1,816
2003	1,970	3,100	1,817
2003	2,070	3,099	1,815
2003	2,171	3,100	1,804
2003	1,470	3,000	1,831
2003	1,570	3,000	1,824
2003	1,669	3,001	1,823
2003	1,770	3,000	1,826
2003	1,871	3,000	1,832
2003	1,970	3,000	1,833
2003	2,070	3,000	1,829
2003	2,169	3,000	1,823
2003	2,270	3,001	1,816
2003	1,470	2,900	1,846
2003	1,569	2,900	1,838
2003	1,670	2,901	1,837
2003	1,770	2,900	1,837
2003	1,870	2,900	1,840
2003	1,970	2,899	1,838
2003	2,071	2,899	1,834
2003	2,169	2,900	1,831
2003	2,270	2,900	1,826
2003	2,370	2,901	1,832
2002	1,470	2,800	1,862
2003	1,570	2,800	1,849
2003	1,670	2,800	1,847
2003	1,770	2,800	1,846
2003	1,870	2,800	1,845
2003	1,970	2,800	1,842
2003	2,070	2,800	1,837
2003	2,170	2,800	1,830
2003	2,270	2,800	1,833
2002	2,371	2,801	1,846
2003	1,469	2,700	1,868
2003	1,570	2,700	1,855
2002	1,669	2,702	1,854
2003	1,770	2,700	1,852
2003	1,870	2,701	1,850
2003	1,971	2,700	1,846
2003	2,070	2,700	1,843
2003	2,170	2,699	1,843
2003	2,271	2,700	1,854
2001	1,570	2,602	1,865
2003	1,671	2,598	1,865
2003	1,771	2,600	1,864
2003	1,871	2,599	1,860
2003	1,969	2,599	1,859
2003	2,070	2,600	1,858
2001	2,170	2,600	1,869
2003	2,270	2,600	1,887
2003	1,470	2,500	1,896
2003	1,571	2,499	1,876
2001	1,669	2,500	1,879
2003	1,770	2,500	1,877
2003	1,870	2,501	1,875
2001	1,970	2,499	1,879
2001	2,069	2,500	1,882
2003	2,169	2,500	1,897
2003	2,270	2,500	1,910
2003	2,370	2,500	1,924
2003	1,570	2,401	1,899
2003	1,670	2,399	1,888
2001	1,770	2,400	1,890
2003	1,869	2,400	1,895
2003	1,970	2,400	1,904
2003	2,070	2,400	1,909
2001	2,171	2,400	1,913
2001	2,270	2,399	1,928
2001	2,371	2,402	1,936
2003	2,470	2,400	1,954
2003	1,571	2,300	1,928
2003	1,669	2,300	1,902
2003	1,771	2,300	1,900
2003	1,870	2,300	1,909
2003	1,970	2,300	1,920
2003	2,071	2,300	1,927
2003	2,170	2,300	1,930
2003	2,270	2,300	1,940
2001	2,371	2,300	1,940
2001	2,471	2,302	1,954
2003	2,569	2,300	2,002
2003	1,670	2,199	1,929
2003	1,771	2,200	1,910
2001	1,871	2,200	1,920
2003	1,969	2,200	1,929
2003	2,071	2,200	1,935
2003	2,171	2,200	1,940
2003	2,270	2,200	1,948
2003	2,370	2,200	1,948
2003	2,470	2,200	1,956
2003	1,770	2,100	1,938
2001	1,870	2,101	1,939
2003	1,970	2,099	1,940
2003	2,069	2,100	1,943
2003	2,170	2,100	1,948
2003	2,270	2,101	1,951
2001	2,369	2,100	1,954
2003	2,470	2,101	1,967
2003	2,571	2,100	2,006
2003	1,869	2,001	1,962
2001	1,970	1,998	1,956
2001	2,071	2,000	1,954
2003	2,169	1,999	1,952
2003	2,270	1,999	1,953
2001	2,370	1,999	1,963
2001	2,470	2,001	1,980
2003	1,870	1,900	1,982
2001	1,970	1,900	1,970
2001	2,069	1,901	1,965
2001	2,169	1,900	1,971
2003	2,269	1,900	1,984
2001	2,370	1,900	1,988
2003	2,471	1,899	2,007
2003	1,869	1,800	1,999
2001	1,970	1,800	1,983
2001	2,069	1,803	1,978
2001	2,169	1,799	1,989
2003	2,270	1,800	2,005
2003	2,370	1,800	2,010
2003	2,469	1,799	2,024
2003	2,571	1,800	2,033
2003	2,670	1,799	2,049
2001	2,770	1,801	2,068
2003	2,870	1,800	2,072
2003	2,970	1,799	2,078
2003	3,070	1,800	2,082
2003	3,170	1,800	2,096
2003	1,970	1,700	2,002
2003	2,070	1,701	1,996
2001	2,171	1,701	2,003
2001	2,270	1,701	2,012
2001	2,369	1,699	2,024
2001	2,471	1,700	2,032
2001	2,572	1,700	2,042
2003	2,670	1,700	2,051
2003	2,770	1,699	2,061
2003	2,870	1,700	2,074
2003	2,970	1,701	2,085
2001	3,068	1,699	2,101
2003	3,170	1,700	2,120
2003	2,070	1,599	2,024
2001	2,171	1,600	2,015
2001	2,271	1,600	2,020
2001	2,371	1,601	2,027
2001	2,470	1,600	2,034
2001	2,571	1,600	2,045
2001	2,669	1,600	2,056
2001	2,769	1,601	2,067
2001	2,869	1,600	2,081
2003	2,970	1,601	2,098
2003	3,069	1,600	2,125
2003	2,171	1,501	2,042
2001	2,270	1,502	2,035
2001	2,369	1,500	2,035
2001	2,470	1,501	2,042
2001	2,569	1,501	2,048
2001	2,670	1,501	2,061
2001	2,770	1,500	2,072
2001	2,870	1,500	2,090
2003	2,270	1,400	2,074
2003	2,370	1,400	2,056
2003	2,470	1,400	2,052
2003	2,570	1,400	2,057
2003	2,671	1,400	2,085
2003	2,770	1,400	2,109

Table 20. Winter, summer, and net balances of South Cascade Glacier, Washington, balance years 1953–2003.

[$\bar{b}_{\mathrm{m}}(\mathrm{s})$, glacier measured winter snow balance; $\bar{b}_{\mathrm{w}}(\mathrm{s})$, glacier maximum winter snow balance; $\bar{b}_{\mathrm{s}}$, glacier summer balance; $\bar{b}_{\mathrm{n}}$, glacier net balance. Balances are in meters water equivalent; data for 1953 and 1955–58 are from Meier and Tangborn (1965); data for 1958–85 and 1992–2001 are from mass-balance summaries and original work presented by Krimmel (2002); data for 1986–91 are from Krimmel (2000), and data for 2002 are from Bidlake and others (2004). Glacier maximum winter snow balance $\bar{b}_{\mathrm{w}}(\mathrm{s})$, if available, is given in preference to $\bar{b}_{\mathrm{m}}(\mathrm{s})$, and in any case, the value given under the heading $\bar{b}_{\mathrm{m}}(\mathrm{s})$ or $\bar{b}_{\mathrm{w}}(\mathrm{s})$ is the best available estimate of the glacier winter balance; **Abbreviations:** –, no data]

Balance year	$\bar{b}_{\mathrm{m}}(\mathrm{s})$ or $\bar{b}_{\mathrm{w}}(\mathrm{s})$	$\bar{b}_{\mathrm{s}}$	$\bar{b}_{\mathrm{n}}$
1953	–	–	-0.6
1954	–	–	–
1955	–	–	.3
1956	–	–	.2
1957	–	–	-.2
1958	–	–	-3.3
1959	3.28	-2.58	.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	-0.84
1982	3.11	-3.03	.08
1983	1.91	-2.68	-.77
1984	2.38	-2.26	.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
2003	2.66	-4.76	-2.10
MEAN 1959–2003	2.74	-3.23	-0.49
MEDIAN 1959–2003	2.50	-3.12	-0.63

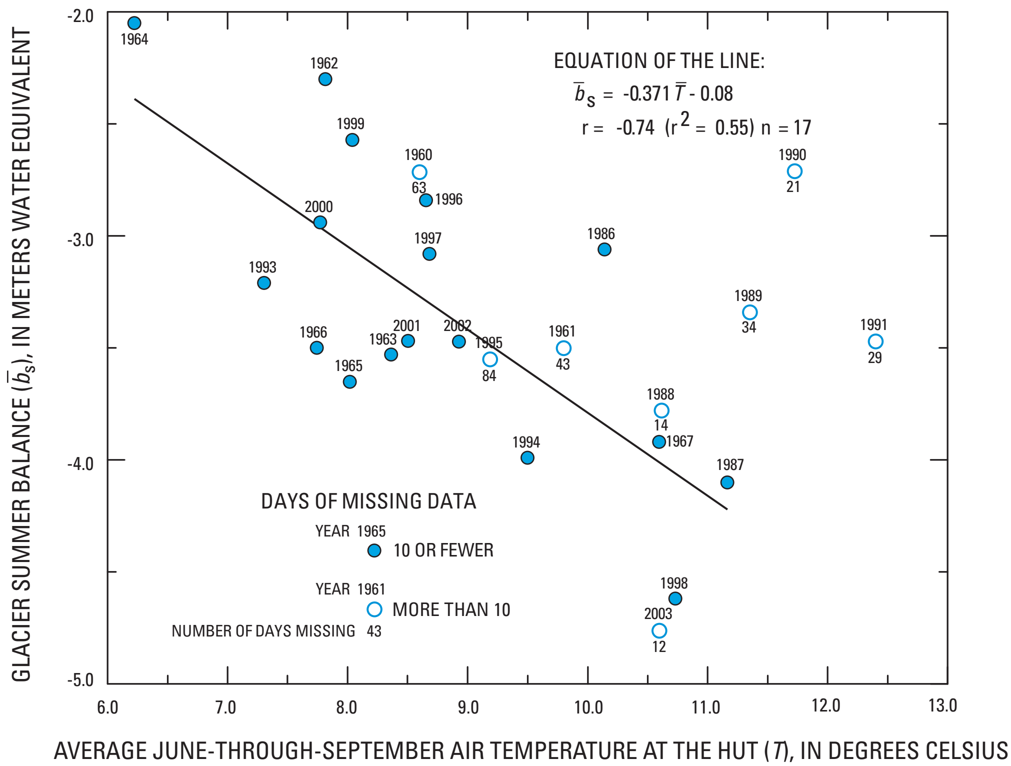

Figure 12. Summer balance of South Cascade Glacier, Washington, as it varied with average air temperature at the Hut, 1,842 meters altitude, near South Cascade Lake Basin, June through September.
Data presented are for years for which numerical data have been published (1960–67, Sullivan, 1994; 1986–91, Krimmel, 2000; and 1993–2001, Krimmel, 1994, 1995, 1996a, 1997, 1998, 1999, 2001, 2002; 2002, Bidlake and others, 2004). Regression line and equation are fitted to data from years with 10 or fewer days of missing data.

Table 21. Ablation stake measurements at South Cascade Glacier, Washington, balance year 2003.

[**Surface material**: Snow, snow accumulated on the 2002 summer melt surface; Firn, metamorphosed, old snow that has endured at least one summer season; Lsnow (late snow), snow accumulated on the 2003 summer surface. **Surface height**, height of glacier surface above 2002 summer melt surface, meters. **Balance components**, specific cryologic materials gained or lost since the beginning of balance year 2003, with thickness of material gained (loss expressed as negative gain), meters, and density of material, expressed as a fraction of the density of water; **Balance**, combined gain or loss of all balance components since beginning of balance year 2003, meters water equivalent; ***X*** and ***Y*** are easting and northing coordinates in a local coordinate system, meters; ***Z***, altitude, meters; e, estimated or inferred; **Abbreviations**: m, meter]

Date	Surface material	Surface height (m)	Balance components								Balance (m)
			Snow		Firn		Ice		Lsnow		
			Thickness gain (m)	Density	Thickness gain (m)	Density	Thickness gain (m)	Density	Thickness gain (m)	Density	
Stake 1-03 [*X* = 1,813, *Y* = 2,775, *Z* = 1,844] Site P-1											
05-07-03	SNOW	4.72	4.72	0.52							2.45
07-08-03	SNOW	1.97	1.97	.56e							1.10
07-25-03	SNOW	.66	.66	.57e							.38
07-28-03	SNOW	.52	.52	.57e							.30
08-27-03	ICE	-1.60			-1.26	0.60e	-0.34	0.90e			-1.06
09-20-03	ICE	-2.49			-1.26	.60e	-1.23	.90e			-1.86
10-22-03	ICEe	-3.36e			-1.26	.60e	-2.10e	.90e			-2.65e
10-24-03	LSNOW	-3.09			-1.26	.60e	-2.10	.90e	0.27	0.50e	-2.51
Stake 2-03 [*X* = 2,421, *Y* = 1,571, *Z* = 2,032]											
05-08-03	SNOW	5.90	5.90	0.52e							3.07
07-08-03	SNOW	3.38	3.38	.56e							1.89
07-25-03	SNOW	2.26	2.26	.57e							1.29
08-28-03	SNOW	.24	.24	.57e							.14
09-20-03	FIRN	-.40			-0.40	0.60e					-.24
10-22-03	FIRNe	-1.13e			-1.13e	.60e					-.68e
10-24-03	LSNOW	-.67			-1.13	.60e			0.46	0.50e	-.45
Stake 3-03 [*X* = 1,599, *Y* = 3,089, *Z* = 1,804]											
05-09-03	SNOW	4.08	4.08	0.51e							2.08
07-08-03	SNOW	1.18	1.18	.55e							.65
Stake 4-03 [*X* = 1,576, *Y* = 3,257, *Z* = 1,747]											
05-09-03	SNOW	3.94	3.94	0.47e							1.85
07-08-03	SNOW	.84	.84	.55e							.46
07-26-03	ICE	-.72					-0.72	0.90e			-.65
08-27-03	ICE	-3.08					-3.08	.90e			-2.77
09-20-03	ICE	-4.17					-4.17	.90e			-3.75
10-22-03	ICEe						-5.26e	.90e			-4.73e
Stake 5-03 [*X* = 1,664, *Y* = 3,394, *Z* = 1,707]											
05-09-03	SNOW	3.41	3.41	0.48e							1.64
07-08-03	SNOW	.17	.17	.54e							.09
07-26-03	ICE	-1.25					-1.25	0.90e			-1.13
08-27-03	ICE	-3.54					-3.54	.90e			-3.19
09-20-03	ICE	-4.63					-4.63	.90e			-4.17
10-22-03	ICEe	-5.81e					-5.81e	.90e			-5.23e
10-24-03	LSNOW	-5.52					-5.81	.90e	0.29	0.50e	-5.08

Table 21. Ablation stake measurements at South Cascade Glacier, Washington, balance year 2003.—Continued

[**Surface material**: Snow, snow accumulated on the 2002 summer melt surface; Firn, metamorphosed, old snow that has endured at least one summer season; Lsnow (late snow), snow accumulated on the 2003 summer surface. **Surface height**, height of glacier surface above 2002 summer melt surface, meters. **Balance components**, specific cryologic materials gained or lost since the beginning of balance year 2003, with thickness of material gained (loss expressed as negative gain), meters, and density of material, expressed as a fraction of the density of water; **Balance**, combined gain or loss of all balance components since beginning of balance year 2003, meters water equivalent; ***X*** and ***Y*** are easting and northing coordinates in a local coordinate system, meters; ***Z***, altitude, meters; e, estimated or inferred; **Abbreviations**: m, meter]

Date	Surface material	Surface height (m)	Balance components								Balance (m)
			Snow		Firn		Ice		Lsnow		
			Thickness gain (m)	Density	Thickness gain (m)	Density	Thickness gain (m)	Density	Thickness gain (m)	Density	
Stake 6-03 [*X* = 1,698, *Y* = 3,506, *Z* = 1,670]											
05-09-03	SNOW	2.61	2.61	0.47							1.23
05-11-03	SNOW	2.59	2.59	.47e							1.22
07-08-03	ICE	-.69					-0.69	0.90e			-.62
07-26-03	ICE	-2.13					-2.13	.90e			-1.92
08-28-03	ICE	-4.72					-4.72	.90e			-4.25
09-20-03	ICE	-5.89					-5.89	.90e			-5.30
10-22-03	ICEe	-7.50e					-7.50e	.90e			-6.75e
10-24-03	LSNOW	-7.45					-7.50	.90e	0.05e	0.50e	-6.73
Stake 7-03 [*X* = 1,705, *Y* = 3,574, *Z* = 1,644]											
05-09-03	SNOW	0.89e	0.89e	0.47e							0.42
05-11-03	SNOW	.87	.87	.47e							.41
07-08-03	ICE	-2.53					-2.53	0.90e			-2.28
07-26-03	ICE	-4.30					-4.30	.90e			-3.87
08-28-03	ICE	-6.67					-6.67	.90e			-6.00
09-20-03	ICE	-7.82					-7.82	.90e			-7.04
10-22-03	ICEe	-9.33e					-9.33e	.90e			-8.40e
10-24-03	LSNOW	-9.28					-9.33	.90e	0.05e	0.50e	-8.37
Stake 8-03 [*X* = 1,997, *Y* = 2,339, *Z* = 1,918]											
07-25-03	SNOW	2.15	2.15	0.57e							1.23
Stake 9-03 [*X* = 2,224, *Y* = 1,892, *Z* = 1,978]											
07-25-03	SNOW	2.10	2.10	0.57e							1.20
08-28-03	FIRN	-.07			-0.07	0.60e					-.04
09-20-03	FIRN	-.85			-.85	.60e					-.51
10-22-03	FIRNe	-1.74e			-1.74e	.60e					-1.04e
10-24-03	LSNOW	-1.34			-1.74	.60e			0.40	0.50e	-.84
Stake 10-03 [*X* = 2,987, *Y* = 1,780, *Z* = 2,077]											
07-25-03	SNOW	2.30	2.30	0.57e							1.31
08-28-03	SLUSH	-.01									
09-20-03	ICE	-.84			-0.40	0.60e	-0.44	0.90e			-.64
10-22-03	ICEe	-1.63e			-.40	.60e	-1.23e	.90e			-1.35e
10-24-03	LSNOW	-1.45			-.40	.60e	-1.23	.90e	0.18	0.50e	-1.26

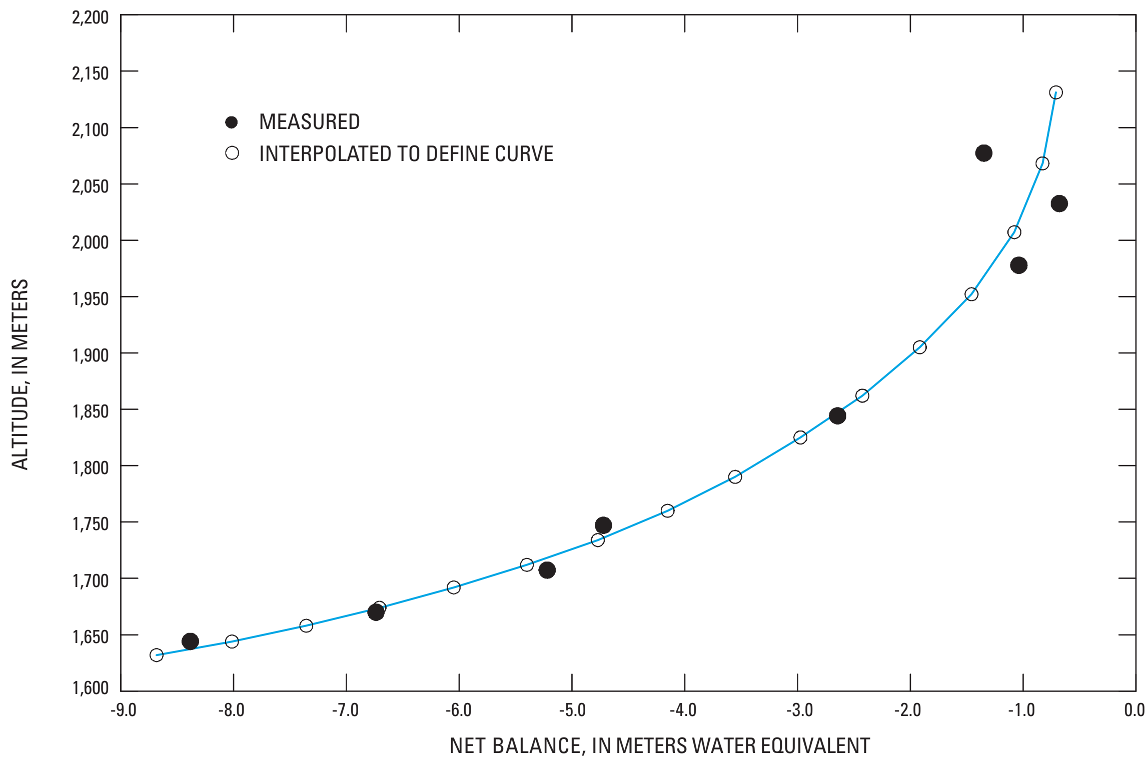

Figure 13. Net balance as it varied with altitude on South Cascade Glacier, Washington, balance year 2003. Data are presented in tables 21 and 22.

Table 22. 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 2003.

[Net balance as it varied with altitude is shown in figure 13]

Altitude (meters)	Net balance (meters water equivalent)	Altitude (meters)	Net balance (meters water equivalent)
1,632	-8.70	1,790	-3.56
1,644	-8.03	1,825	-2.98
1,658	-7.37	1,862	-2.43
1,674	-6.72	1,905	-1.92
1,692	-6.06	1,952	-1.46
1,712	-5.41	2,007	-1.08
1,734	-4.78	2,068	-.83
1,760	-4.16	2,131	-.71

Summer and Annual Balances

The computed 2003 glacier summer balance ($\bar{b}_s$) was -4.76 m, which was the most negative of such balances available for the glacier (table 20). The computed $\bar{b}_s$ for 2003 was about 3 percent more negative than that for 1998, the next most negative since 1959, although the difference was likely within the margin of uncertainty. Available data for 1960–2003 indicate that $\bar{b}_s$ was 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) (fig. 12), which is consistent with findings of Rasmussen and Conway (2003), who examined relations between upper-air conditions and summer balance of South Cascade Glacier. As was the case in 1998, the 2003 summer mass loss was greater than predicted by the relation in figure 12. Variations of summer snowfall amounts introduces an additional source of variability to $\bar{b}_s$ (Rasmussen and Conway, 2003) and might explain some of the departures of measured $\bar{b}_s$ from that predicted on the basis of air temperature alone.

USGS personnel were not present at South Cascade Glacier on either the beginning or ending days of water year 2003, and the 2003 annual balance of the glacier ($\bar{b}_a$) was computed on the basis of $\bar{b}_n$ and estimates of the initial and final balance increments ($\bar{b}_0$ and $\bar{b}_1$). Bidlake and others (2004) estimated $\bar{b}_1$ for water year 2002 to be -0.04 m, and the 2002 $\bar{b}_1$ is equivalent to the 2003 $\bar{b}_0$. The 2003 final balance increment was estimated using three steps. First, balance at ablation stakes measured on September 20 was extended to September 30 using a simple melt and accumulation computation. Daily melt was computed from air temperature over the glacier using a degree-day approach. Accumulation was estimated on the basis of precipitation measured at the Salix Creek gaging station. Precipitation was assumed to have fallen as snow on the glacier when air temperature there was 2°C or less. Melt factors during September 20–30 were computed on the basis of observed melt during late August to September 20. Second, computed balances at the ablation stakes on September 30 were employed with the grid index technique to estimate the glacier balance relative to the 2002 summer melt surface. Finally, the glacier balance on September 30 (-1.85 m) was subtracted from the 2003 glacier net balance ($\bar{b}_n$, -2.10 m) to obtain $\bar{b}_1$ (-0.25 m). The computed 2003 glacier annual balance (b_a) was -1.89 m.

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 (because of 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 (because sampling equipment disturbed the sample), and errors in computed surface lowering due to sinking of ablation stakes.

Sampling errors in both time and space probably contributed more uncertainty in the mass-balance estimates than did measurement errors. Sampling errors in time were caused by 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. Extending the balance records probably resulted in errors of estimation. Each glaciological measurement that was 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 using 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. 10) and net balance (fig. 13). Another potential source of sampling error was the spatial variation of profile-average snow density not accounted for by the measured profiles (tables 15-17) or by the density estimation schemes described previously. The total error in each of the glacier mass-balance quantities in this report ($\bar{b}_w(s)$, $\bar{b}_s$, $\bar{b}_n$, and $\bar{b}_a$) 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 accumulation and ablation and basal melting are thought to have been much smaller than those due to measurement and sampling errors.

Terminus Retreat, Glacier Area, and Equilibrium Line

The smaller 2003 winter snow accumulation afforded terminal ice less protection from the elements during summer than was the case during 2002, a year of exceptionally large winter snow accumulation (Bidlake and others, 2004). Partly as a result of the smaller snow accumulation, the terminus retreated a greater distance during balance year 2003 than during the previous year. Average retreat rate computed from vertical aerial photographs for September 13, 2002, and September 13, 2003, was about 15 m per year, with an uncertainty of about 2 m per year (fig. 14).

The glacier terminus retreated during 2003, as it has during every year of measurement except 1972 (Krimmel, 2002), and the computed retreat rate was about 15 m per year. Accompanying the terminus retreat during 2003 was a reduction in glacier area to 1.89 km^2, which was 0.03 km^2 smaller than a year earlier.

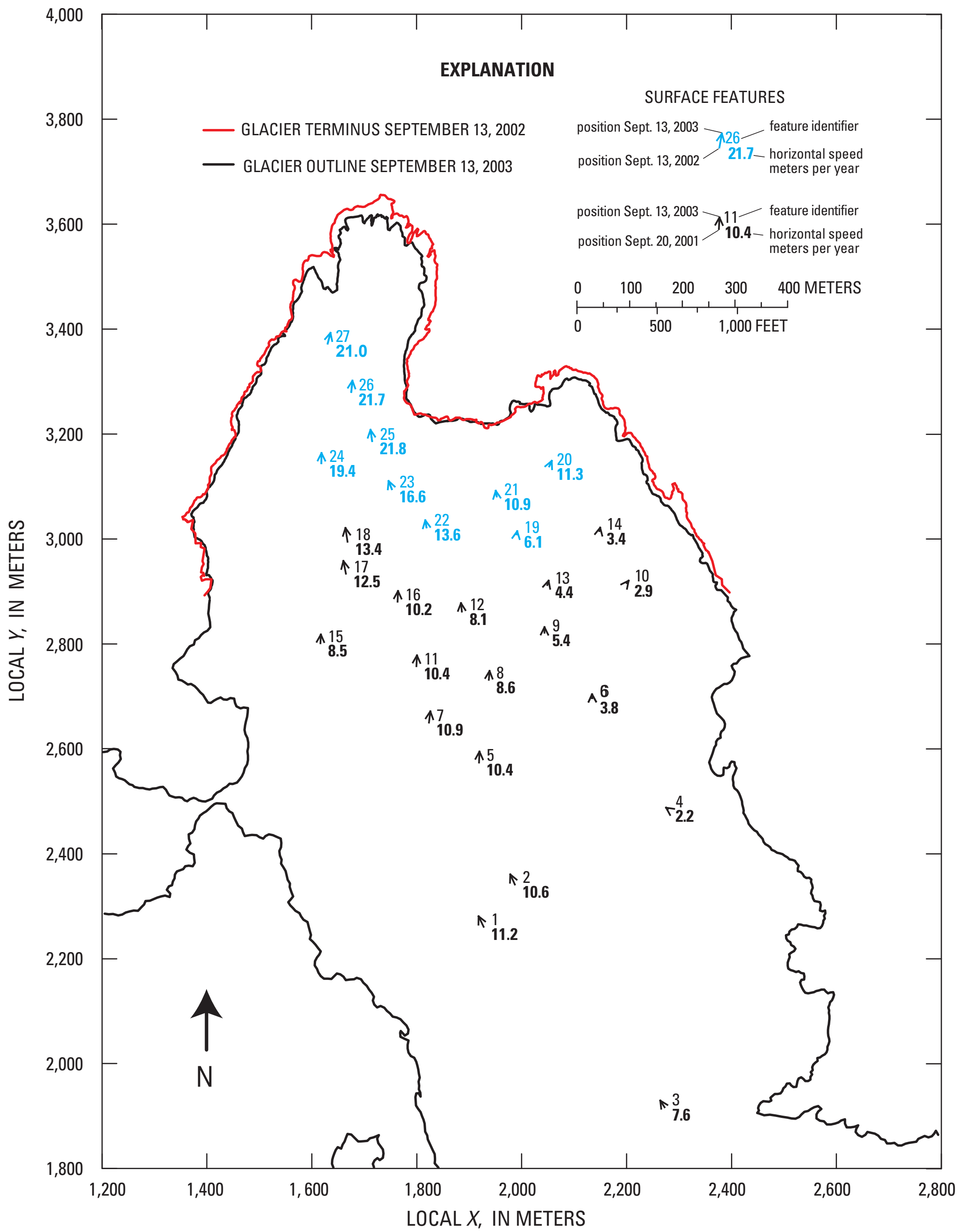

Figure 14. Outline of part of South Cascade Glacier, Washington, and adjacent snow fields on September 13, 2003, position of the terminus September 13, 2002, and average speed and direction of surficial ice movement.

Ice movement was computed from the displacement of selected features identified in vertical photographs from September 20, 2001, September 13, 2002, and September 13, 2003. Data for position of surface features are given in table 23.

The continued retreat and loss of mass by South Cascade Glacier during 2003 was consistent with overall trends since 1953 (fig. 15). These overall trends of decreasing glacier extent and mass indicate that South Cascade Glacier has been responding to climate conditions that will not support the glacier in its recent size and position on the landscape (Rasmusen and Conway, 2001).

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, 2003. 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. The 1992 balance year was the fourth most negative for South Cascade Glacier during balance years 1958–2003, and the glacier net balance was negative during 6 of the 7 preceding years (table 20). The glacier outline south of $Y = 2{,}900$ for October 6, 1992 (fig. 11) 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, 2003, computed from the 2003 glacier outline for areas north of $Y = 2{,}900$ and the 1992 outline for areas south of $Y = 2{,}900$, was 1.89 km^2, which was 0.03 km^2 smaller than the area of the glacier on September 13, 2002 (Bidlake and others, 2004). The area of the glacier north of $Y = 2{,}900$ was 0.38 km^2.

The 2003 ELA was higher than the top of the glacier (greater than 2,125 m), despite the presence of residual snow from winter 2003 on the southwest edges of the glacier on September 13, 2003 (fig. 11). The accumulations of residual snow were thought not to represent any glacier-wide balance-altitude condition represented by the ELA.

The accumulations of residual snow were accounted for in computation of the AAR, because the AAR does not imply any overall glacier balance-altitude condition. The best estimate of the 2003 South Cascade Glacier AAR, derived from the September 13 aerial photography, was 0.07.

Ice Movement

Average horizontal speed and direction of movement of surficial glacier ice were computed by measuring displacement of selected surface features, typically crevasses or ice seams, identified in vertical aerial photographs taken September 20, 2001, September 13, 2002, and September 13, 2003 (fig. 14). Photogrammetric measurements of ice movement on the upper glacier were made using 2001 and 2003 photography because those regions were mostly covered by snow at the time of the 2002 photography. Ice-movement studies for the glacier region near the terminus were made using 2002 and 2003 photography because surface features there are less persistent than they are on the upper glacier, and use of the more recent photography made repeated identification of the features more reliable.

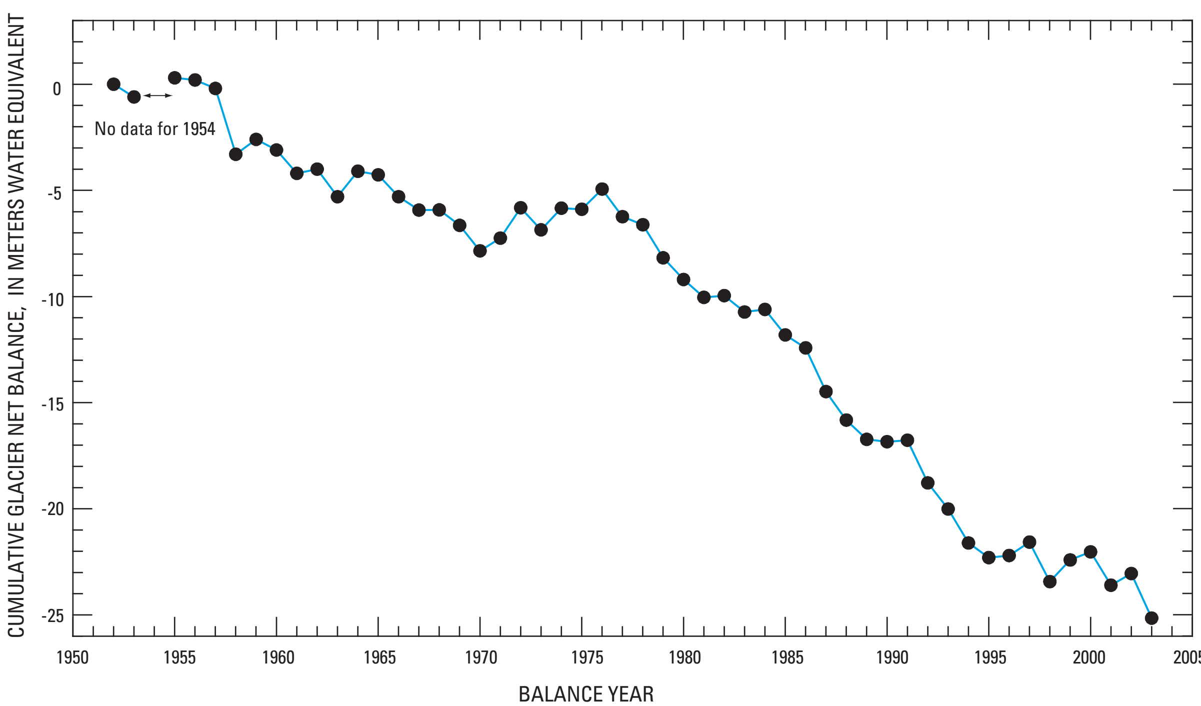

Figure 15. Cumulative net balance of South Cascade Glacier, Washington, balance years 1953–2003.

The 2001, 2002, and 2003 positions of surface features used for ice-movement studies are presented in table 23. Average ice speed ranged from 2.2 to 21.8 m per year, with the largest speeds in the vicinity of the terminus, 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 23. Positions of selected surface features at South Cascade Glacier, Washington, used to estimate horizontal speed and direction of ice movement during September 20, 2001–September 13, 2003, or September 13, 2002–September 13, 2003.

[Locations of features are shown in figure 14; ***X*** and ***Y***, easting and northing coordinates in local coordinate system, meters; ***Z***, altitude, meters; –, not measured]

Feature identifier	September 20, 2001			September 13, 2002			September 13, 2003		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
1	1,928.0	2,258.2	1,920.8	–	–	–	1,918.4	2,278.1	1,917.0
2	1,987.6	2,338.9	1,918.4	–	–	–	1,978.8	2,358.0	1,915.9
3	2,272.9	1,914.3	1,980.3	–	–	–	2,264.8	1,927.0	1,976.5
4	2,279.2	2,482.5	1,915.9	–	–	–	2,275.6	2,485.0	1,916.7
5	1,919.2	2,571.2	1,863.9	–	–	–	1,920.1	2,591.9	1,860.5
6	2,134.9	2,693.7	1,843.1	–	–	–	2,134.7	2,701.3	1,843.2
7	1,823.9	2,647.3	1,857.4	–	–	–	1,826.3	2,668.7	1,854.6
8	1,937.8	2,728.7	1,848.2	–	–	–	1,939.2	2,745.7	1,847.2
9	2,044.0	2,818.4	1,839.6	–	–	–	2,044.1	2,829.1	1,838.9
10	2,200.8	2,913.1	1,831.1	–	–	–	2,204.3	2,917.7	1,829.8
11	1,799.8	2,754.8	1,850.1	–	–	–	1,801.0	2,775.4	1,848.5
12	1,886.5	2,858.9	1,842.5	–	–	–	1,884.9	2,874.8	1,840.4
13	2,049.5	2,909.4	1,838.2	–	–	–	2,051.9	2,917.9	1,835.1
14	2,148.6	3,012.2	1,823.9	–	–	–	2,150.0	3,018.8	1,821.8
15	1,617.0	2,798.3	1,848.1	–	–	–	1,617.8	2,815.1	1,845.3
16	1,764.2	2,877.8	1,841.1	–	–	–	1,765.0	2,898.1	1,838.6
17	1,665.7	2,930.9	1,836.2	–	–	–	1,660.9	2,955.1	1,832.2
18	1,668.7	2,992.0	1,827.9	–	–	–	1,664.7	3,018.3	1,821.3
19	–	–	–	1,991.0	3,006.0	1,833.3	1,992.1	3,012.0	1,830.5
20	–	–	–	2,053.1	3,135.5	1,807.6	2,057.7	3,145.8	1,801.1
21	–	–	–	1,952.8	3,078.1	1,824.4	1,951.2	3,088.9	1,822.1
22	–	–	–	1,819.2	3,019.4	1,829.5	1,816.9	3,032.8	1,827.2
23	–	–	–	1,753.0	3,092.2	1,812.7	1,746.8	3,107.5	1,807.2
24	–	–	–	1,618.8	3,141.4	1,792.5	1,619.1	3,160.8	1,784.0
25	–	–	–	1,715.4	3,183.6	1,784.7	1,712.3	3,205.2	1,774.3
26	–	–	–	1,675.7	3,277.3	1,746.0	1,678.0	3,298.9	1,736.2
27	–	–	–	1,630.8	3,369.6	1,720.0	1,636.4	3,389.9	1,709.9

Summary and Conclusions

The long-term U.S. Geological Survey monitoring of South Cascade Glacier, Washington, a benchmark glacier for the extensively glacierized North Cascade Range, is part of the larger USGS Glacier Monitoring Program. Meteorological, hydrologic, and glaciological monitoring of South Cascade Glacier has been carried out for more than four decades, and this report is intended to present results of the 2003 monitoring to all interested parties.

Meteorological and hydrologic data-collection efforts yielded more complete records than was the case during balance year 2002, owing to improvements in the data-collection systems during 2002 and to a much smaller and less damaging winter snow accumulation during 2003. A new type of sensor mount was developed during 2003 at South Cascade Glacier to maintain the height of air-temperature sensors above the glacier surface constant as that surface lowers during the summer melt season.

Selected glaciological quantities and dates for balance year 2003 are given in table 24. Glacier maximum winter snow accumulation during 2003 (2.66 m) was about equal to the average glacier maximum or measured snow accumulation during balance years 1959 to 2003. That near-normal winter snow accumulation, combined with the most negative glacier summer balance recorded during balance years 1959 to 2003 (-4.76 m), yielded an exceptionally negative glacier net balance (-2.10 m). Balance year 2003 mass loss contributed to the long-term trend of decreasing mass of South Cascade Glacier since 1953.

Analysis of glaciological and meteorological data for 2003 and those published for previous years indicated glacier summer balance was negatively correlated with the average June-through-September air temperature at the Hut, and the exceptionally negative 2003 summer balance was accompanied by one of the warmest summers at the Hut for which meteorological data are available.

The glacier terminus retreated during 2003, as it has during every year of measurement except 1972, and the computed retreat rate was about 15 m per year. Accompanying the terminus retreat during was a reduction in glacier area to 1.89 km^2, which was 0.03 km^2 smaller than a year earlier.

The continued retreat and loss of mass by South Cascade Glacier during 2003 was consistent with overall trends since 1953. These overall trends of decreasing glacier extent and mass indicate that South Cascade Glacier has been responding to climate conditions that will not support the glacier in its recent size and position on the landscape.

Table 24. Selected glaciological quantities and dates for South Cascade Glacier, balance year 2003.

[Glacier balances expressed in meters water equivalent; **Abbreviations**: m, meter; m/y, meter per year; km^2, square kilometer; >, greater than]

Glaciological quantity or date	Value
2003 glacier maximum winter snow balance ($\bar{b}_w(s)$)	2.66 m
Ending date of winter season	May 18, 2003
2003 glacier summer balance ($\bar{b}_s$)	-4.76 m
Ending date of summer season	October 22, 2003
2003 glacier net balance ($\bar{b}_n$)	-2.10 m
2003 glacier initial balance increment ($\bar{b}_0$)	-.04 m
2003 glacier final balance increment ($\bar{b}_1$)	-.25 m
2003 glacier annual (water year) balance ($\bar{b}_a$)	-1.89 m
Terminus retreat rate during September 13, 2002–September 13, 2003	15 m/y
Glacier area on September 13, 2003	1.89 km^2
Average 2003 equilibrium line altitude	> 2,125 m
2003 accumulation area ratio	.07

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Table 25. Rating table for the Middle Tarn gaging station (U.S. Geological Survey station number 12181090), South Cascade Lake Basin, Washington, water year 2003.

[Example of reading the table: a stage of 1.75 feet corresponds to a discharge of 72.14 cubic feet per second. **Abbreviations:** –, no data]

Stage, in feet	Discharge, in cubic feet per second, for stage extended to hundredths of feet									
	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	–	–	–	–	–	0.94	1.02	1.11	1.19	1.29
.1	1.38	1.48	1.58	1.69	1.80	1.91	2.03	2.15	2.28	2.40
.2	2.54	2.67	2.81	2.96	3.10	3.25	3.41	3.57	3.73	3.89
.3	4.06	4.24	4.41	4.60	4.78	4.97	5.16	5.36	5.56	5.76
.4	5.97	6.19	6.40	6.62	6.85	7.07	7.31	7.54	7.78	8.03
.5	8.27	8.53	8.78	9.04	9.30	9.57	9.84	10.12	10.40	10.68
.6	10.97	11.26	11.56	11.86	12.16	12.47	12.78	13.10	13.42	13.74
.7	14.07	14.40	14.74	15.08	15.43	15.78	16.13	16.49	16.85	17.21
.8	17.58	17.96	18.33	18.71	19.10	19.49	19.89	20.28	20.69	21.09
.9	21.51	21.92	22.34	22.76	23.19	23.62	24.06	24.50	24.94	25.39
1.0	25.85	26.30	26.77	27.23	27.70	28.18	28.66	29.14	29.63	30.12
1.1	30.61	31.11	31.62	32.13	32.64	33.16	33.68	34.20	34.73	35.27
1.2	35.81	36.35	36.90	37.45	38.00	38.56	39.13	39.70	40.27	40.85
1.3	41.43	42.01	42.61	43.20	43.80	44.40	45.01	45.62	46.24	46.86
1.4	47.49	48.12	48.75	49.39	50.03	50.68	51.33	51.98	52.65	53.31
1.5	53.98	54.65	55.33	56.01	56.70	57.39	58.09	58.79	59.49	60.20
1.6	60.91	61.63	62.35	63.08	63.81	64.55	65.29	66.03	66.78	67.53
1.7	68.29	69.05	69.82	70.59	71.36	72.14	72.93	73.72	74.51	75.31
1.8	76.11	76.92	77.73	78.55	79.37	80.19	81.02	81.85	82.69	83.53
1.9	84.38	85.23	86.09	86.95	87.82	88.69	89.56	90.44	91.32	92.21
2.0	93.10	94.00	94.90	95.81	96.72	97.63	98.55	99.48	100.41	101.34
2.1	102.28	103.22	104.17	105.12	106.07	107.03	108.00	108.98	109.96	110.94
2.2	111.93	112.93	113.93	114.93	115.94	116.96	117.98	119.00	120.03	121.06
2.3	122.10	123.14	124.19	125.24	126.29	127.35	128.42	129.49	130.57	131.64
2.4	132.73	133.82	134.91	136.01	137.11	138.22	139.34	140.45	141.57	142.70
2.5	143.83	144.97	146.11	147.26	148.41	149.56	150.72	151.89	153.06	154.23
2.6	155.41	156.60	157.78	158.98	160.18	161.38	162.59	163.80	165.02	166.24
2.7	167.47	168.70	169.93	171.18	172.42	173.67	174.93	176.19	177.45	178.72
2.8	180.00	–	–	–	–	–	–	–	–	–

Manuscript approved for publication, September 16, 2005

Prepared by the U.S. Geological Survey publishing staff,
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Upper photograph: Hiker viewing upper South Cascade Glacier from a ridge on the west side of the glacier about 1938 (photograph taken by Dwight Watson). Lower photograph: Similar vantage in 1985 (photograph by Robert M. Krimmel U.S. Geological Survey).

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SIR 2005-5210

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