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Authors: Lillquist, Karl, and Walker, Karen

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Historical Glacier and Climate Fluctuations at Mount Hood, Oregon

Karl Lillquist and*
Karen Walker†

*Geography and Land Studies Department,
Central Washington University,
Ellensburg, WA 98926, U.S.A.
lillquis@cwu.edu
†3568 Tilden Trail,
New Braunfels, TX 78132, U.S.A.

Abstract

Terminus fluctuations of five glaciers and the correspondence of these fluctuations to temperature and precipitation patterns were assessed at Oregon's Mount Hood over the period 1901–2001. Historical photographs, descriptions, and climate data, combined with contemporary GPS measurements and GIS analysis, revealed that each glacier experienced overall retreat, ranging from −62 m at the Newton Clark Glacier to −1102 m at the Ladd Glacier. Within this overall trend, Mount Hood's glaciers experienced two periods each of retreat and advance. Glaciers retreated between 1901 and 1946 in response to rising temperatures and declining precipitation. A mid-century cool, wet period led to glacier advances. Glaciers retreated from the late 1970s to the mid-1990s as a result of rising temperatures and generally declining precipitation. High precipitation in the late 1990s caused slight advances in 2000 and 2001. The general correspondence of Mount Hood's glacier terminus fluctuations with glaciers in Washington and Oregon suggests that regional, decadal-scale weather and climate events, driven by the Pacific Decadal Oscillation, play a key role in shaping atmosphere-cryosphere interactions in Pacific Northwest mountains. Deviations from the general glacier fluctuation pattern may arise from local differences in glacier aspect, altitude, size, and steepness as well as volcanic and geothermal activity, topography, and debris cover.

Introduction

Glaciers thicken and advance when accumulation (e.g., snowfall and avalanches) exceeds ablation (e.g., snowmelt and calving); conversely, glaciers thin and retreat under negative mass balance conditions. The termini of small alpine glaciers are especially sensitive indicators of climate change (Menzies, 2002). Ablation season temperature changes of as little as 0.5°C or accumulation season precipitation changes of 10% may be sufficient to alter glacier mass balance (Tangborn, 1980) and ultimately shift termini. Measurable alpine glacier size changes may occur in as few as 1–5 years (Burbank, 1982) to a more decadal scale (Johannesson, 1989; Pelto and Hedlund, 2001; Kovanen, 2003) following climate forcing (Burbank, 1982). Glacier termini measurements have long been used to assess glacier response to climate (Nesje and Dahl, 2000). While lacking the accuracy of mass balance determinations, termini measurements provide a spatially and temporally comparable and economical way to assess glacier-climate relationships (Harper, 1993). Alpine glacier termini may thus be important tools for determining the direction, frequency, and magnitude of past climate change.

North America's Pacific Northwest glaciers have generally receded during the past century, a period characterized by a region-wide temperature rise of ~0.8°C and precipitation increase of approximately 7 cm (JISAO/SMA Climate Impacts Group, 1999). Most such glacier change has been attributed to climate fluctuations; however, glacier aspect, altitude, size, and steepness as well as volcanic and geothermal activity, accumulation area, topography, and debris cover can complicate a direct response to climate forcing.

Glaciers on Oregon's Mount Hood (Fig. 1) have been studied since the late 19th century when Hague (1871) recorded the character and extent of the White River, Sandy, and Reid glaciers. Reid (1905, 1906) described the Coe, Eliot, Ladd, Newton Clark, and White River glacier termini in 1901. His termini photographs are a remarkable baseline for 20th century glacier studies at Mount Hood. Gannett (1903) and Sylvester (1908a) further described Mount Hood's early 20th century glaciers. The Mazamas, a Portland, Oregon-based mountaineering organization, began measurements from fixed points to the termini of the Eliot, Ladd, and Coe glaciers in the 1920s (Mazamas Research Committee, 1925, 1927, 1928), and the White River and Newton Clark glaciers in the 1930s (Phillips, 1935). Termini measurements continued until 1946 (Phillips, 1946). The Mazamas Research Committee (MRC) also contracted for oblique aerial photographs of Mount Hood's glaciers in 1935, 1938, 1946 and 1956 (Mazamas Research Committee, 1935, 1938, 1946, 1956). Ice volume mapping (Driedger and Kennard, 1986), cross-section and mass balance measurements (Mason, 1954, 1955, 1957; Handewith, 1959; Dodge, 1964, 1971, 1987), superglacial debris analysis (Lundstrom, 1992, 1993), and moraine mapping and dating (Lawrence, 1948; Lillquist, 1988) have shed further light on Mount Hood's post-Pleistocene glaciers.

This paper addresses two questions: (1) how did Coe, Eliot, Ladd, Newton Clark, and White River glacier termini fluctuate between 1901 and 2001; and (2) how did these fluctuations correspond to Mount Hood's temperature and precipitation patterns?

Study Area

Mount Hood, at 3426 m, is the highest summit in Oregon and the fourth highest mountain in the Cascade Range. Quaternary andesite and dacite lavas and interbedded pyroclastic debris compose this stratovolcano (Wise, 1969; White, 1980). Collapsing lava domes formed pyroclastic flows on Mount Hood's south flanks, ash plumes that drifted downwind, and lahars that extended far down valleys radiating from the mountain (Crandell, 1980; Cameron and Pringle, 1986, 1987). Crater Rock (Fig. 1) has been the focus of historic geothermal and minor eruptive activity (Sylvester, 1908a; Phillips and Collins, 1935).

Mount Hood's mid-latitude location atop the north-trending Cascade Range, approximately 160 km inland of the Pacific Ocean and the Coast Range, plays a strong role in its climate patterns. Temperatures are generally lower and precipitation is typically higher

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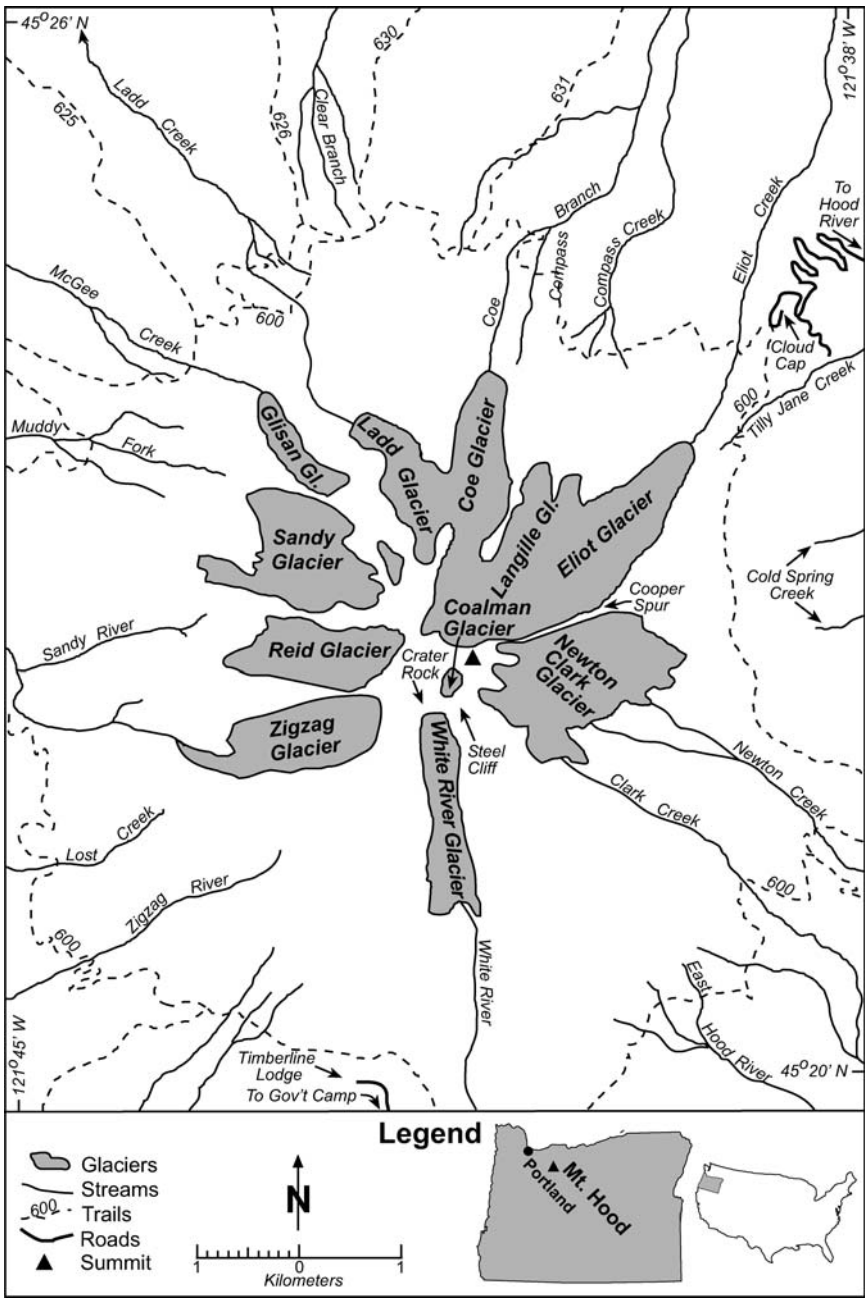


FIGURE 1. Mount Hood, Oregon. Glacier outlines generalized from Mount Hood National Forest, U.S. Department of Agriculture–Forest Service airphotos (Project ID: 616060D), September 1989.

at the mountain than in adjacent lowlands. Eastward-moving midlatitude cyclones bring more precipitation to west-facing slopes than east-facing slopes. Pacific Northwest (PNW) summers are generally dry because of the influence of the North Pacific High, while winters are generally wet because of the influence of the Aleutian Low (Walters and Meier, 1989). Deviations from "normal" climatic conditions result from changing intensities in the pressure systems (Miller et al., 2004) associated with the coupled atmosphere/ocean system (e.g., Arctic Oscillation—Thompson and Wallace, 1998; El Nino/Southern Oscillation (ENSO)—Walters and Meier, 1989; Pacific Decadal Oscillation (PDO)—Mantua et al., 1997; and Pacific North America pattern—Wallace and Gutzler, 1981). During 1971–2000, Government Camp (1213 m elevation) (Fig. 1) averaged 6°C temperature and 225 cm precipitation annually with January averages of –1°C and 33 cm and August averages of 14°C and 4 cm. Annual snowfall over this same period averaged 643 cm (Oregon Climate Service, 2004).

Eleven glaciers cloak Mount Hood (Fig. 1; Table 1). Late Pleistocene glaciers terminated at approximately 800 m on the West and Middle Forks Hood River (Glisan, Ladd, and Coe), 1200 m on East Fork Hood River (Eliot and Newton Clark), 1050 m on Polallie Creek, 1150 m on White River (White River), 1100 m on Salmon River, and 730 m on Sandy River (Zig Zag, Reid, and Sandy) (William Scott, written communication, 11 August 2004). During the early 1980s, Eliot Glacier (Fig. 1) was the thickest and most voluminous but Newton Clark Glacier covered the greatest area (Driedger and Kennard, 1986) (Table 1). With a total glacier surface area of 13.5 km^2 and a volume of 0.4 km^3, Mount Hood ranked fifth in glacier cover in the Cascade Range (Driedger and Kennard, 1986; Kennard and Driedger, 1987; Carolyn Driedger, written communication, 16 December 2003).

Methods

GLACIER DATA

We assessed historical changes in Mount Hood's glacier termini with repeat ground and aerial photographs, historical written

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TABLE 1

Selected physical characteristics of Mount Hood's glaciers.

Glacier	Type[a]	Aspect[b]	Upper elevation[c] (m)	Lower elevation[d] (m)	Length[e] (m)	Overall slope[f] (%)	Area[g] (km^2)	Maximum thickness[h] (m)	Volume[i] (km^3)	Debris cover[j]
Coe	Cirque	N	3261	1811	3322	43.7	1.25	91	0.0532	High
Eliot	Cirque	NE	3139	1922	3566	34.1	1.68	122	0.0896	High
Ladd	Cirque	NW	2896	2115	1800	43.3	0.90	91	0.0252	Low
Newton Clark	Icefield	SE	3048	2438	1250	48.8	1.99	76	0.0392	Low
White River	Cirque	S	3048	2221	2073	39.9	0.54	46	0.0084	Medium

[a] Data source (this study).
[b] Data source (this study).
[c] Data source (this study with 2000 U.S. Forest Service [USFS] orthophotos).
[d] Data source (this study with 2000 USFS orthophotos).
[e] Data source (this study with 2000 USFS orthophoto).
[f] Data source (this study).
[g] Data source (Driedger and Kennard, 1986).
[h] Data source (Driedger and Kennard, 1986).
[i] Data source (Driedger and Kennard, 1986).
[j] Refers to terminus. Data source (this study with 1995 USFS airphotos).

descriptions, historical field surveys, and global positioning system (GPS) surveys. These data were then compiled in a geographic information system (GIS). Ground photographs taken by Reid at Coe, Eliot, and Newton Clark glaciers in 1901 (photographs on file at the Mazamas office), Langille at White River Glacier in 1902 (Langille et al., 1903), and Richards at Ladd Glacier in 1932 (Richards, 1932) provided benchmarks for each of the five glaciers. Photographs taken from essentially the same photo points in summer 2001 allowed us to visually compare glacier change during the past century.

United States Forest Service (USFS) 1:12,000–1:20,000-scale vertical airphotos from 1946, 1959, 1967, 1972/1973, 1979, 1982, 1989, and 1995, and 1-m-resolution 1994 and 2000 USFS orthophotos were used with select GPS measurements (Coe and Eliot glaciers) to quantify 1946–2001 glacier terminus changes. Airphotos were scanned and georectified to the 1994 digital orthophotos using ERDAS® software. Each terminus was digitized on the georectified airphotos and orthophotos using ArcGIS® software following the Mazamas' criteria for identifying glacier termini—i.e., "the point at which a glacial stream emerges" (Phillips, 1935). Active glacier termini were differentiated from stagnant, debris-covered ice by: (1) an identifiable glacier front; (2) a lobate planimetric form; and (3) a visible connection of the lobate form to a debris-free glacier upslope. Lateral moraine-parallel distances of terminus advance or retreat were subsequently determined using ArcGIS® by plotting the locations of the heads of main outflow streams at successive time periods. We estimate our measurement and mapping error to be approximately 12 m based on the U.S. Geological Survey lowland vertical mapping standard of one-half the contour interval of the map (U.S. Geological Survey, n.d.) and the likelihood that such errors are greater in mountainous areas.

In connecting dating from the post-1946 airphotos, orthophotos, and GPS measurements to the pre-1947 Mazamas surveys, photographs, and historical descriptions, we assumed that the glacier termini shown on the 9 September 1946 vertical airphotos were in essentially the same positions as those measured by the Mazamas in late August and late September 1946. Mazamas survey measurements and estimates (Phillips, 1935, 1938, 1946) were used to back-calculate from 1946 to the 1930s (all glaciers), 1920s (Coe, Eliot, and Ladd), and 1902/1901 (Eliot, Newton Clark, and White River). We estimated the 1901 locations of Coe and Ladd termini based on Reid's descriptions and photograph. Unfortunately, the small scales and large contour intervals of early topographic maps (Langille et al., 1903; U.S. Geological Survey, 1913) precluded their use in this study.

CLIMATE DATA

The climatic foundation for assessing glacier-climate relationships came from the *103-Year High-Resolution Climate Data Set for the Conterminous United States* (see ftp://ftp.ncdc.noaa.gov/pub/data/prism100) gridded, GIS PRISM dataset created by the Oregon Spatial Climate Analysis Service (OSCAS). Four additional years of OSCAS data extended the data set from 1895 to 2001. One 2.5′ latitude × 2.5′ longitude (approximately 4 km × 4 km) data cell centered on Mount Hood's summit was used to represent the climate at each of the five glaciers. Data were divided into a 1 October–30 April accumulation season and 1 May–30 September ablation season following Tangborn (1980) in a water year (WY) format. Five-year running average (RA) temperature and precipitation were calculated for each season to identify trends and to compare with glacier termini variation (Burbank, 1982). Historical climate and glacier change literature was used to assess regional patterns of climate and glacier fluctuations and the causes of the temperature and precipitation patterns.

GLACIER-CLIMATE CORRELATION

A variety of statistical techniques were used to assess the linkage between Mount Hood's glaciers and climate. We used Spearman's rank correlation to identify significant correlations among Mount Hood's cumulative glacier terminus fluctuation records. Spearman's rank correlations, multiple regression, and cross correlation were used to assess the relationship between glacier terminus fluctuations and the five-year RA climate data (i.e., accumulation and ablation season temperature and precipitation). In the glacier-climate analysis, we attempted to correlate the actual (e.g., 1946 and 1959) glacier measurements with climate data averaged over the same period (e.g., 1947–1959). All statistical analyses were accomplished using Quattro® and Statistix® software.

Results

HISTORICAL GLACIER TERMINUS FLUCTUATIONS

The termini of Coe, Eliot, Ladd, Newton Clark, and White River glaciers all receded between 1901 and 2001; however, magnitude, timing, and rate of glacier terminus change varied considerably among these glaciers.

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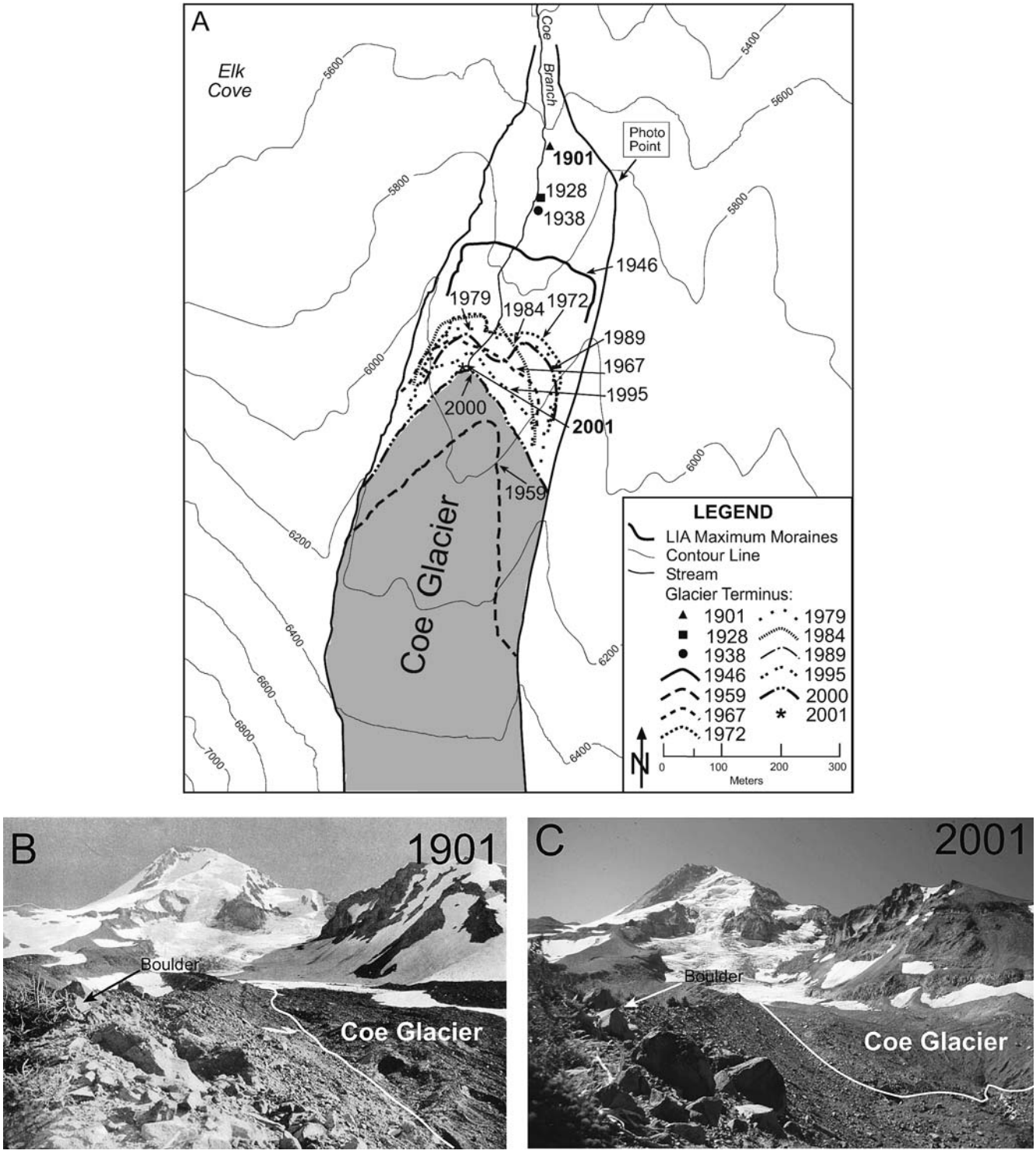


FIGURE 2. Coe Glacier: (A) termini changes, 1901–2001; (B) view upglacier and south along right lateral Little Ice Age moraine, 24 July 1901 (H. F. Reid in Williams, 1912); and (C) same view and photo point on 20 August 2001. See photo point on Figure 2A.

Coe Glacier

Coe Glacier originates in a cirque immediately north of Mount Hood's summit and extends ~3.3 km to the north (Figs. 1 and 2A; Table 1). Reid's photograph from the right lateral moraine (Fig. 2B) shows that the debris-covered terminus extended nearly to the top of the prominent Little Ice Age (LIA) lateral moraines (Lillquist, 1988) and downvalley to a point where the lateral moraine crests dip steeply to the north. Boulders painted near the terminus during the initial MRC survey (Mazamas Research Committee, 1928) are located 82 m upvalley of the 1901 terminus. Mazamas Research Committee measurements reveal 37 m of retreat between 1928 and 1938 (Phillips, 1938) and 58 m of recession between 1938 and 1946 (Phillips, 1946) (Table 2). Advance was noted in only one year, 1935, of the MRC measurements. Coe Glacier rapidly receded 295 m between 1946 and 1959 to its most upvalley position in the past century. A thickening of the upper profile of the glacier (Handewith, 1959) (i.e., kinematic

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TABLE 2

Measured changes in Mount Hood's glacier termini at select intervals over the period 1901–2001.

	1901	1928[a]	1938[b]	1946[c]	1959[d]	1967[e]	1972[f]	1979[g]	1984[h]	1989[i]	1995[j]	2000[k]	2001[l]	Total
Coe	0	−82	−37	−58	−295	104	54	−20	4	−28	−15	−39	4	−408
Eliot	0	−88	−42	−51	−102	20	79	−80	−48	−63	−40	−378	18	−775
Ladd	0	−72	−3	−40		−111	16	−39	−31	−922	84	16		−1102
Newton Clark	0		−150	−111	180	37	−127	154	69	−18	−253	157		−62
White River	0		−561	27	272	−258	22	141	−141	22	−100	−41		−617

[a] Mazamas measurements began on Coe Glacier in 1928, Eliot in 1925, and Ladd in 1927. Neither Newton Clark nor White River glaciers were measured in the 1920s. Data sources for Coe and Ladd (this study) and Eliot (Phillips, 1938).

[b] Mazamas terminus measurements occurred at Coe and Eliot glaciers in 1938, Ladd and White River glaciers in 1936, and Newton Clark Glacier in 1937. Data source (Phillips, 1938).

[c] Data sources for Coe, Eliot, and Ladd (Phillips, 1946; this study with 1946 airphotos), and Newton Clark and White River (this study with 1946 airphotos).

[d] The snow-covered terminus of Ladd Glacier in 1959 prevented measurement from airphotos. Data sources for other glaciers (this study with 1959 airphotos).

[e] Data sources (this study with 1967 airphotos).

[f] Data sources for Coe, Eliot, Newton Clark, and White River glaciers (this study with 1972 airphotos). Data source for Ladd Glacier (this study with 1973 airphotos).

[g] Data sources for all glaciers (this study with 1979 airphotos).

[h] Data sources (this study with 1984 airphotos).

[i] Data sources (this study with 1989 airphotos).

[j] Data sources (this study with 1995 airphotos).

[k] Data sources (this study with 2000 airphotos).

[l] Only the termini of Coe and Eliot were measured in 2001. Data source (this study with GPS data).

wave) resulted in a terminus advance of 104 m by 1967. This advance continued through 1972. Although the terminal position over the past 30 years has oscillated, it showed a net retreat of 94 m. As of summer 2001, Coe Glacier's ice front was still 64 m downvalley of the 1959 terminus. The net 1901–2001 change in the terminus was –408 m, a 12% loss in glacier length, as dramatically illustrated by the 1901 and 2001 photographs (Figs. 2B and 2C).

Eliot Glacier

Eliot Glacier originates in a cirque immediately northeast of Mount Hood's summit and extends about 3.5 km to the northeast (Fig. 1 and 3A; Table 1). In summer 1901, the glacier terminated in the deep canyon of Eliot Branch (Reid, 1905) (Fig. 3B) and extended nearly to the top of the prominent, bounding LIA moraines (Lawrence, 1948; Lundstrom, 1992). The MRC measured 88 m of terminus recession between 1901 and 1925, 42 m of recession between 1925 and 1938, (Phillips, 1938), and 51 m of recession between 1938 and 1946 (Phillips, 1946) (Fig. 3; Table 2). During the 1925–1946 period, advance occurred only in 1932 and 1933 (Phillips, 1938). Significant recession continued through at least 1959 despite a thickening in an upper profile noted by Handewith (1959) and Dodge (1964). The thickening resulted in 79 m of terminus advance between 1967 and 1972. Eliot Glacier retreated 609 m between 1979 and 2000 with 378 m of that retreat occurring between 1995 and 2000 when the lower portion of Eliot Glacier downwasted sufficiently that its terminus was only identifiable as an ice-cored moraine. Eliot Glacier's summer 2000 terminus was at its farthest upvalley position in the past century; however, the summer 2001 terminus had advanced 18 m downvalley. Eliot Glacier had a net 1901–2001 change of –775 m, representing a 22% loss in total length, as illustrated by the recession from the lower trough during the past century (Figs. 3B and 3C).

Ladd Glacier

Ladd Glacier originates with Coe Glacier in a cirque northwest of the summit and extends 1.8 km to the northwest (Figs. 1 and 4A; Table 1). Snow cover prevented Reid (1905) from photographing the summer 1901 terminus; however, his description allowed us to estimate that the 1901 glacier terminated ~70 m downvalley of the 1927 snout (Fig. 4A; Table 2). Only 3 m of recession were recorded by MRC surveys between 1927 and 1936 (Phillips, 1938). Mazamas Research Committee measurements show that Ladd Glacier receded 40 m from 1936–1946 (Phillips, 1946). The terminus receded an additional 111 m between 1946 and 1967. Snow cover prevented the identification of the 1959 terminus. However, a 1956 oblique airphoto (Mazamas Research Committee, 1956) revealed little recession between 1946 and 1956, thus it is likely that the majority of the 111 m of recession occurred between 1956 and 1967. A brief, minor advance between 1967 and 1973 preceded the 1973–1989 retreat of 992 m. Unlike the Eliot Glacier's extensive retreat, the majority of this major recession occurred between 1984 and 1989, leaving the former terminus as ice-cored ground and lateral moraine, and the active terminus at the top of an icefall. The 1989 terminus was at its farthest upvalley point of the past century; however, Ladd Glacier advanced 100 m from 1989–2000. Despite the recent advance, the net 1901–2000 change in Ladd Glacier terminus was –1102 m, a 61% loss in length. These values are the highest of any of the five glaciers analyzed (Figs. 4B and 4C).

Newton Clark Glacier

Newton Clark Glacier extends approximately 1.2 km east of Mount Hood's summit (Figs. 1 and 5A; Table 1). It differs from the

TABLE 3

Spearman rank correlations and associated significance (*P*) values of cumulative terminus changes, Mount Hood's glaciers, 1901–2000.

	Coe	Eliot	Ladd	Newton Clark
Eliot	0.8833			
P-value	*0.0029*			
Ladd	0.7833	0.9333		
P-value	*0.0156*	*0.0003*		
Newton Clark	−0.2000	−0.3333	−0.4333	
P-value	*0.6126*	*0.3848*	*0.2489*	
White River	0.2594	0.1590	−0.0753	0.5858
P-value	*0.4927*	*0.6764*	*0.8438*	*0.0958*

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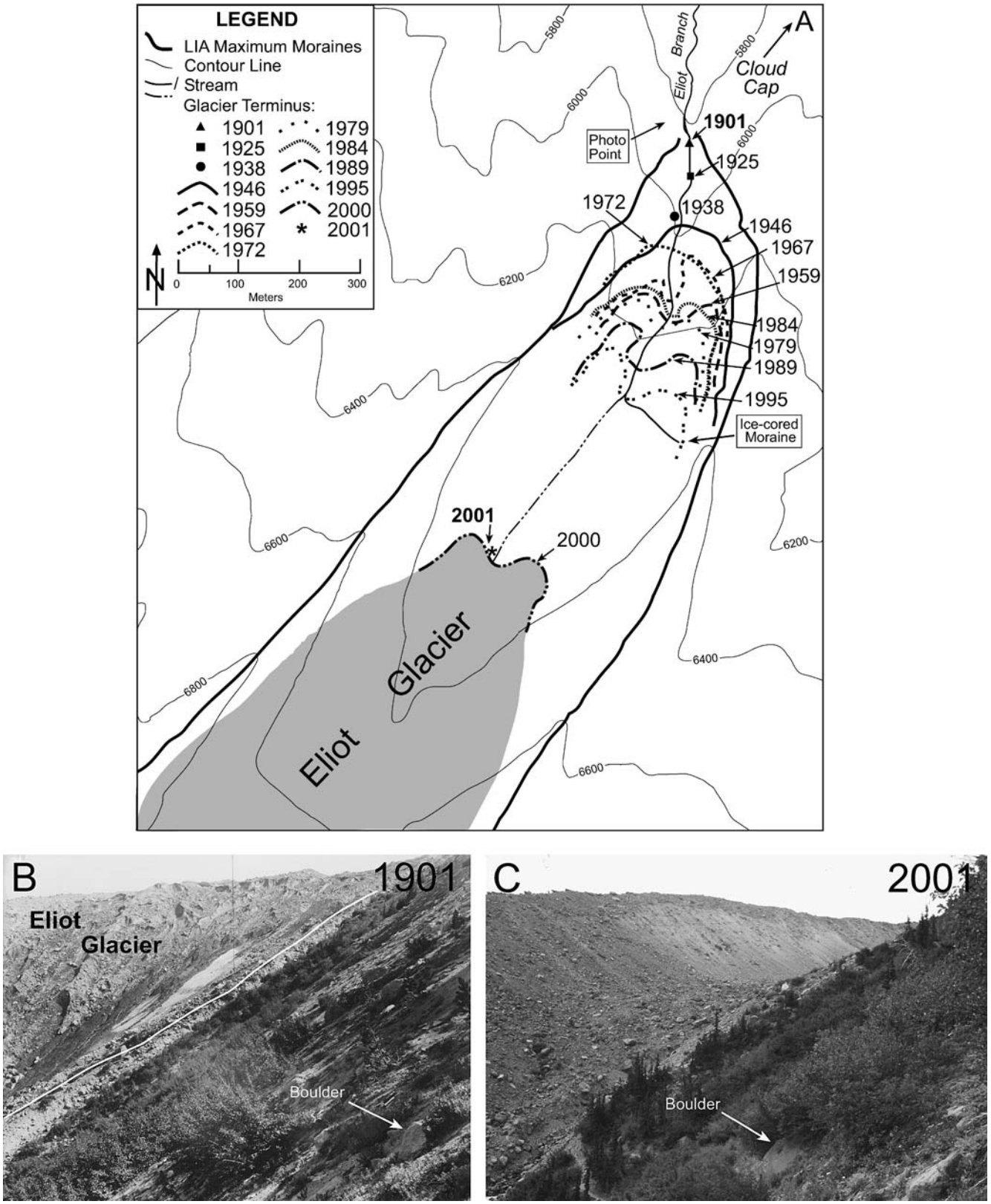


FIGURE 3. Eliot Glacier: (A) termini changes, 1901–2001; (B) view across trough and southeast at right lateral Little Ice Age moraine on 23 July 1901 (H. F. Reid photo in Phillips, 1935); and (C) same view and photo point on 21 August 2001. See photo point on Figure 3A.

other glaciers analyzed in that it comprises a broad icefield constrained by Cooper Spur to the north and Steel Cliff to the west (Fig. 1), and it had termini at the heads of Cold Spring, Newton, and Clark creeks. We measured the Newton Creek terminus because it was the focus of previous glacier observations and measurements. Reid's 1901 photograph (Fig. 5B) (Phillips, 1935) reveals the glacier draped over the edge of a prominent cliff. Mazama Research Committee members, using Gilardi's 1937 photographs (Phillips, 1937), estimated that the

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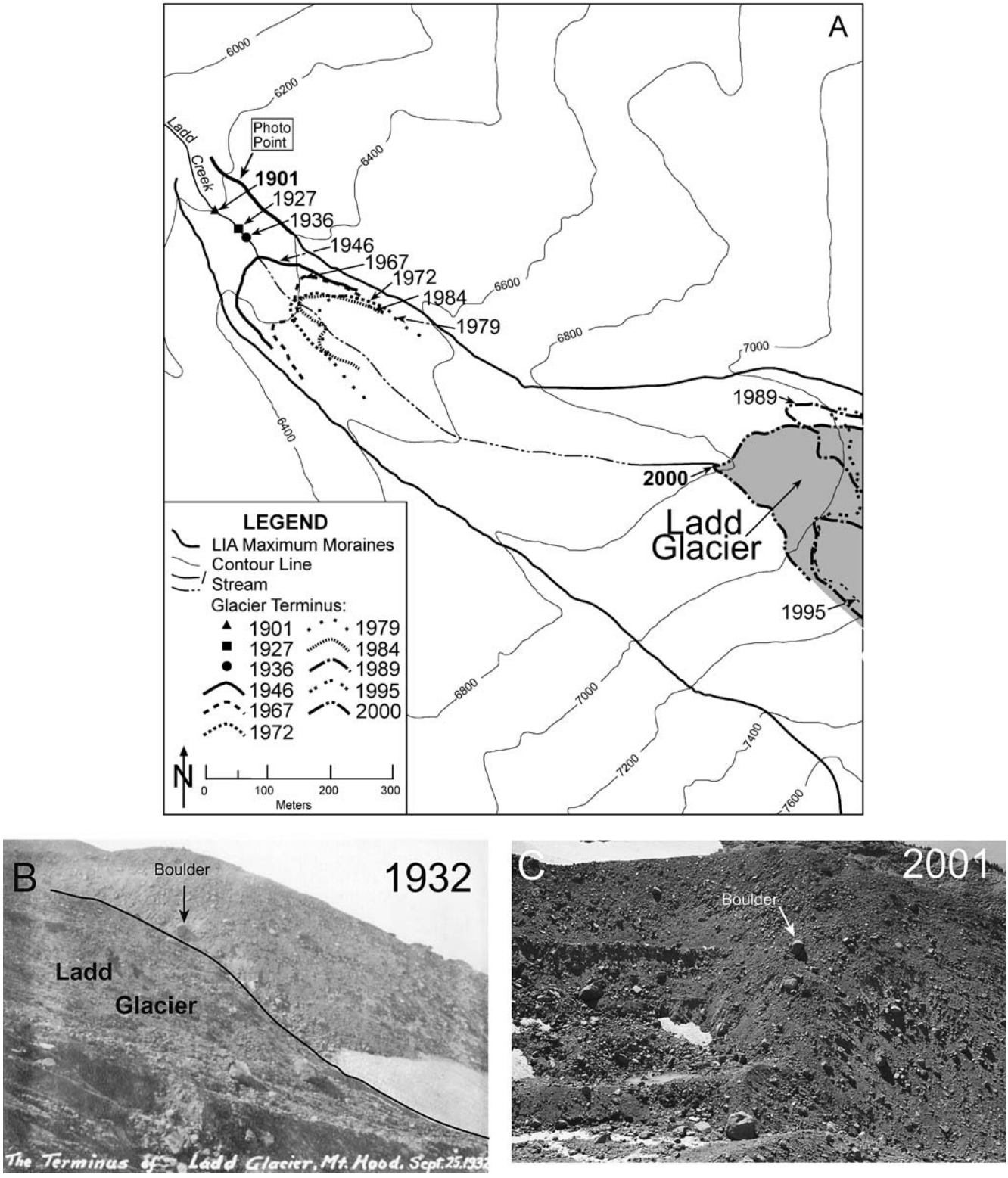


FIGURE 4. Ladd Glacier: (A) termini changes, 1932–2001; (B) view across trough and southwest at left lateral Little Ice Age moraine on 25 September 1932 (Richards, 1932); and (C) same view and photo point on 19 August 2001. See photo point on Figure 4A.

glacier receded about 150 m and thinned by about 30 m between 1901 and 1937 (Phillips, 1938) (Table 2). We measured 111 m of retreat from the estimated 1937 terminus to the 1946 ice front shown on the vertical airphoto. The 1946 terminus was at its most upvalley point of the past century. Post-1946 termini were characterized by alternating advances and retreats (+217 m between 1946 and 1967, –127 m between 1967 and 1972, +223 m between 1972 and 1984, and –271 m between 1984 and 1995). The 2000 position of the Newton Clark Glacier terminus extended 157 m downvalley of the 1995 position. Ground photographs from 2001 reveal a dramatically thinner ice front than that of 1901 (Figs. 5B and 5C). Despite the differences seen in the ground photos, the net 1901–2000 change in the Newton Clark terminus was only –62 m, a 5% decline in length. This represents the least terminus retreat of any of the glaciers analyzed.

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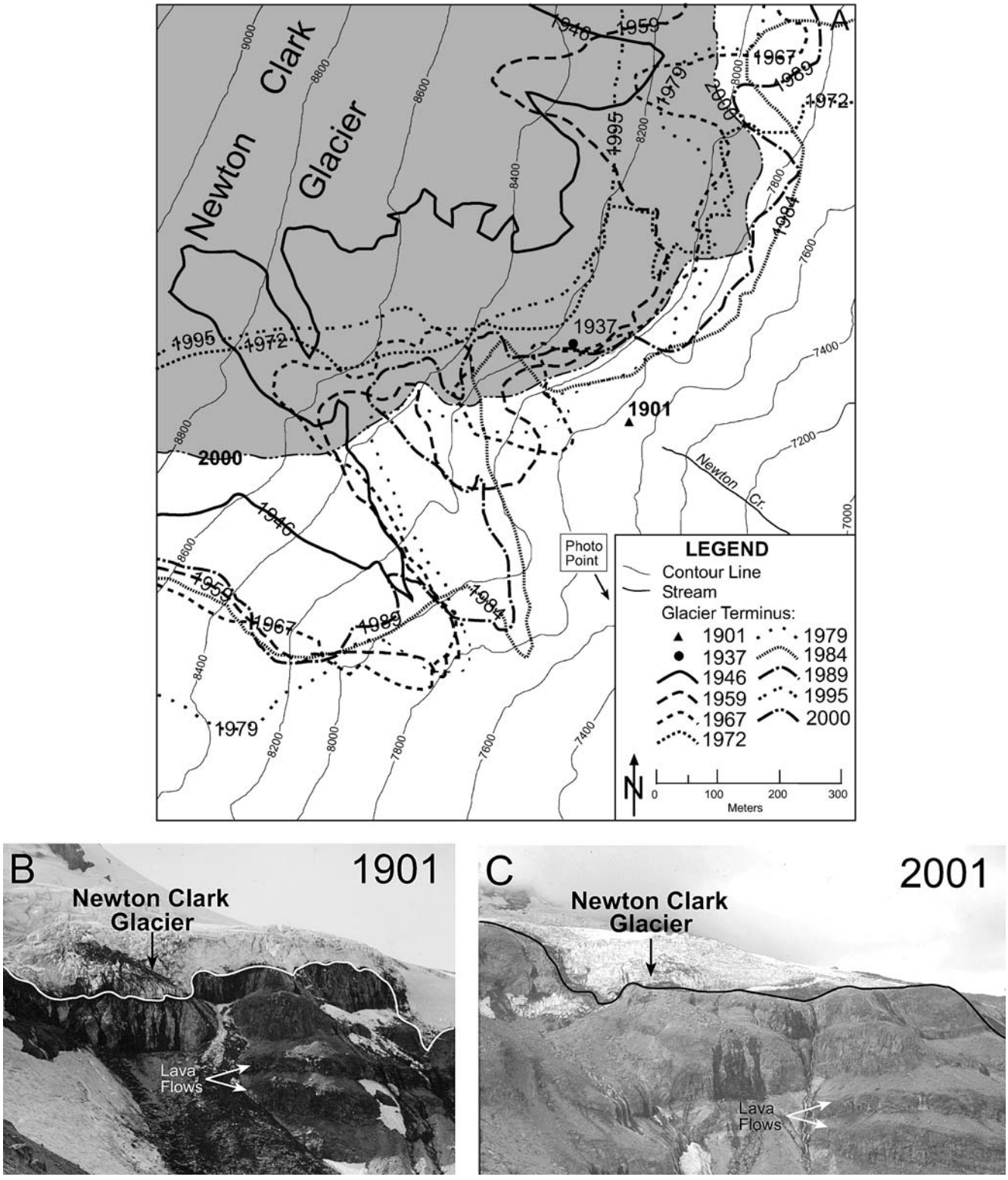


FIGURE 5. Newton Clark Glacier: (A) terminus changes, 1937–2001; (B) view upglacier and north at Newton Creek terminus from late Pleistocene eruptive deposits (Scott et al., 1997) on 25 July 1901; and (C) same view and photo point on 15 September 2001. See photo point on Figure 5A.

White River Glacier

White River Glacier originates south of Mount Hood's summit in a cirque bounded by Steel Cliff, Crater Rock, and an unnamed ridge to the west (Figs. 1 and 6A). It extends approximately 2.1 km south to a point well above timberline (Table 1). In summer 1870, White River Glacier was significantly longer, extending approximately 150 m below timberline (Hague, 1871). Reid (1905, p. 196) described the 1901 White River Glacier terminus as 2100 m elevation "at the head of a very deep canyon". Langille's (1903) photograph (Fig. 6B) reveals that White River Glacier may have been connected with Coalman

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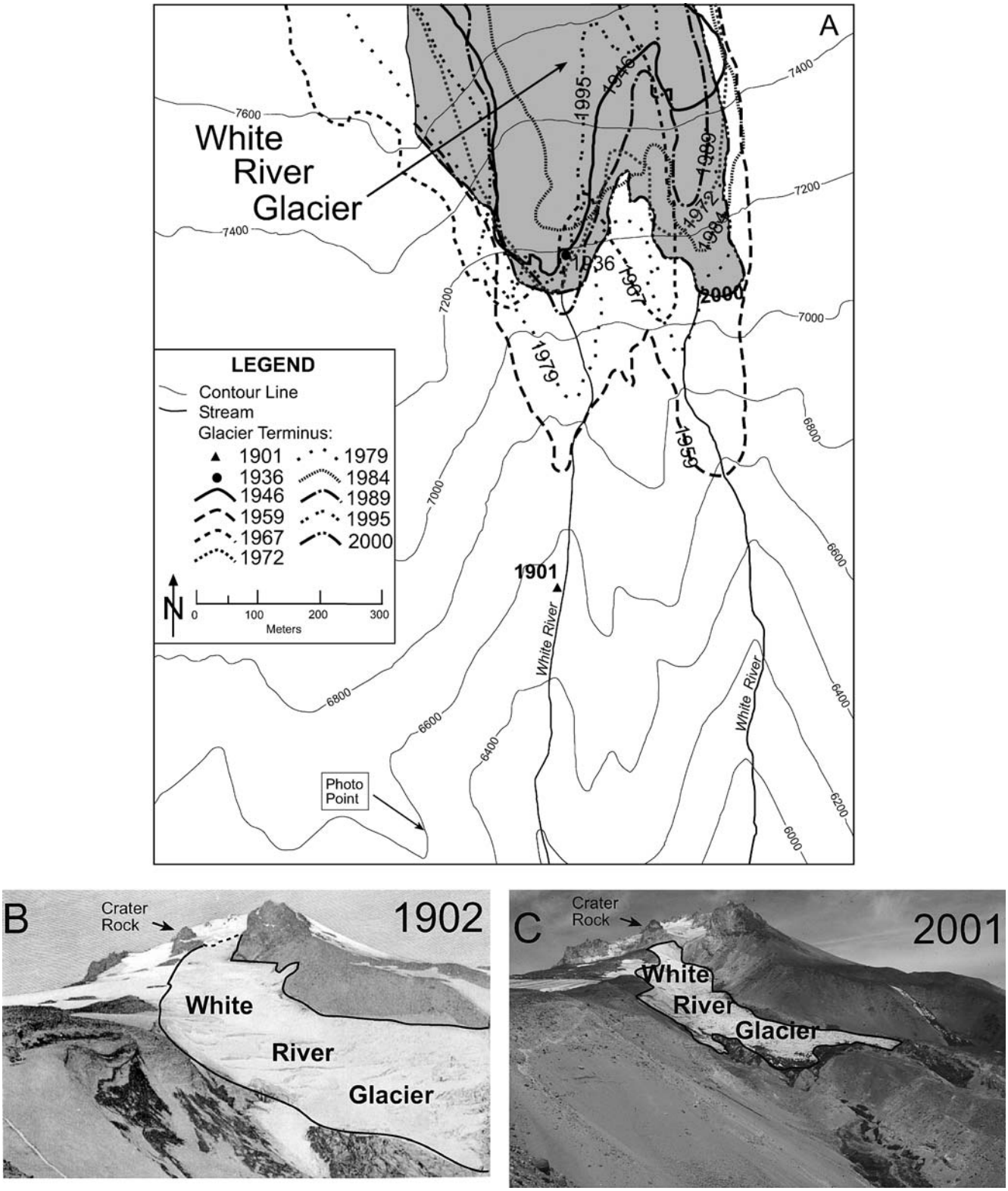


FIGURE 6. White River Glacier: (A) terminus changes, 1901–2001; (B) view of terminus from late Pleistocene and Holocene eruptive deposits in 1902 (Langille, 1903); and (C) same view and photo point on 14 September 2001. See photo point on Figure 6A. The dashed line at the top of the White River Glacier in 1902 indicates that the White River may have separated from the Coalman Glacier.

Glacier above Crater Rock. However, J. N. LeConte's photograph in Williams (1912) shows that White River Glacier was separated from Coalman Glacier. A Mazamas survey in 1936, coupled with Reid's estimate of his photopoint being "500 yards downvalley of the terminus" indicates that White River Glacier retreated 561 m between 1901 and 1936 (Phillips, 1938) (Table 2). Since 1936, White River Glacier has experienced alternating periods of advance and retreat—i.e., +299 m between 1936 and 1959, −258 m between 1959 and 1967, +163 m between 1967 and 1979, −141 m between 1979 and 1984, +22 m from 1984 to 1989, and −141 m from 1989 to 2000. Thickening of the upper glacier noted in 1958 and 1959 by Handewith (1959) likely impacted the terminus advance between 1967–1972. Despite

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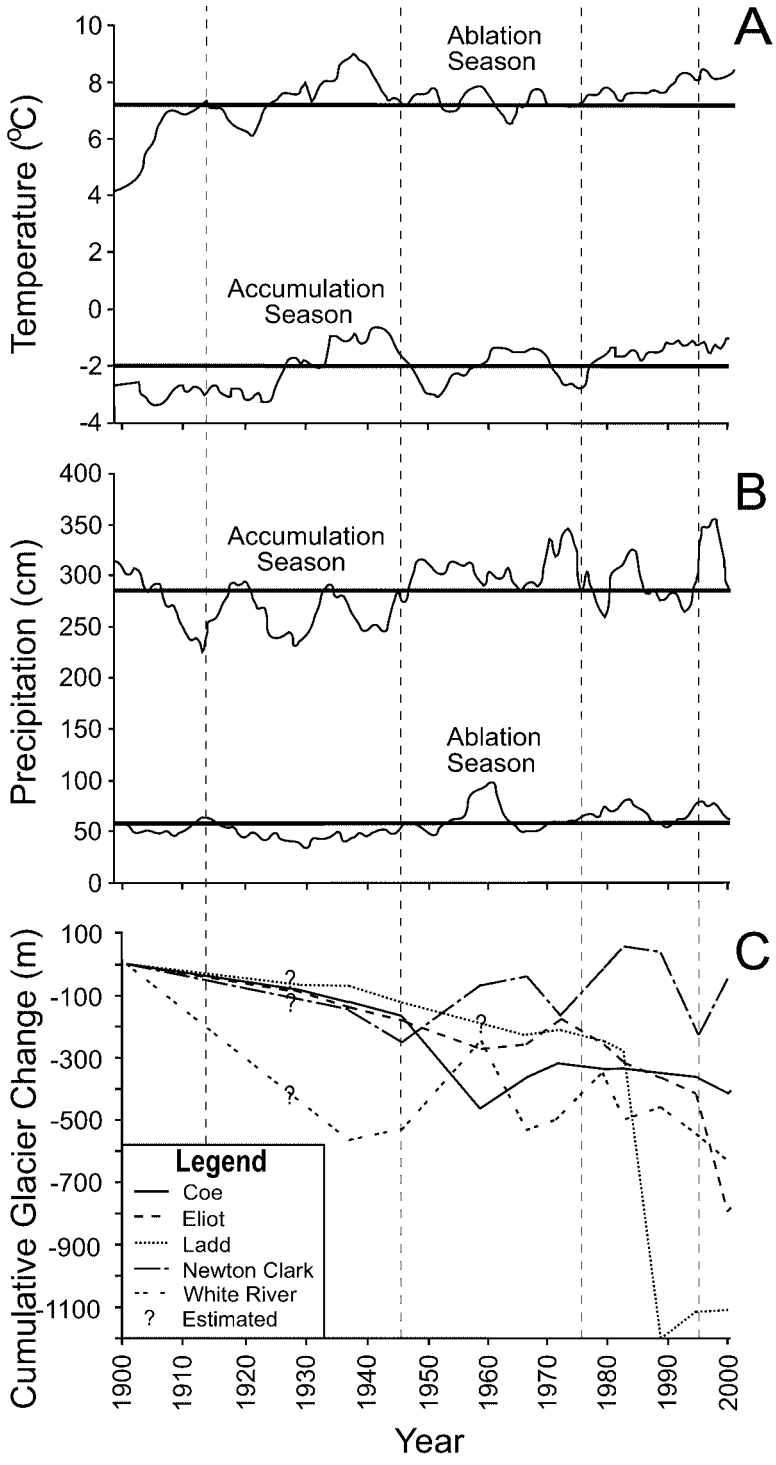


FIGURE 7. Climate and glacier terminus fluctuations, 1896–2001. (A) Five-year running average (RA) (thin lines) and 1896–2001 average (thick lines) ablation and accumulation season temperatures. (B) Five-year RA (thin lines) and 1896–2001 average (thick lines) ablation and accumulation season precipitation. (C) Cumulative glacier terminus fluctuations. See text for data sources.

the alternating nature of advances and retreats over at least the past 60 years, the net 1901–2000 change in White River Glacier terminus was –617 m, a 30% decline in length (Figs. 6B and 6C).

HISTORICAL CLIMATE PATTERNS

Five-year RA temperatures increased during the 1896–2001 WY period—~1.5°C in the accumulation season and ~4°C in the ablation season (Fig. 7A). Accumulation and ablation season temperatures were at their lowest levels in ~1900, 0.7°C and 3.1°C, respectively, cooler than the 1896–2001 averages. By 1940, temperatures had climbed to reach their highest levels of the century—i.e., five-year RA accumulation season temperatures were approximately 1.4°C higher and ablation season temperatures were 1.5°C higher than the 1896–2001 averages. Temperatures began to decline soon after 1940 and generally continued to drop until ~1975. Five-year RA accumulation season temperatures fell 0.6°C, and five-year RA ablation season temperatures dropped 0.1°C below the 1896–2001 averages during this second coldest period of the past century. Since ~1975, five-year RA accumulation and ablation season temperatures have generally risen 1.0°C and 1.2°C, respectively, above the 1896–2001 averages. The second warmest five year period during the past century occurred from 1996–2000.

Overall, five-year RA accumulation and ablation season precipitation increased during the 1896–2001 WY period (Fig. 7B).

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Within this pattern, precipitation generally declined between 1896–1948 and increased from 1948–present. Five-year RA accumulation season precipitation has been above the 1896–2001 mean by as much as 70 cm (+20%) during seven different periods. Conversely, five-year RA accumulation season precipitation has been below the long-term mean six times by as much as 105 cm (–37%). The wettest five-year RA accumulation seasons occurred in 1995–1999 when each averaged 336 cm of precipitation. The driest five-year RA accumulation seasons occurred in 1927–1931 with an average of 238 cm.

GLACIERS AND CLIMATE

The pronounced period of retreat displayed by all of Mount Hood's glaciers from 1901 through the mid-1930s, and all but White River Glacier through 1946 (Fig. 7C), coincided with generally rising temperatures (especially following 1924) and falling precipitation (1925–1930 and 1938–1944). Falling temperatures and rising precipitation beginning in the early 1940s appears to have initiated advances in all glaciers; however, the timing of these advances varied. Newton Clark and White River glaciers were advancing by 1959, Coe and Eliot by 1967, and Ladd by 1973. Retreat was the overall trend of glaciers from the mid-1970s to the mid-1990s, corresponding with generally rising temperatures since the mid-1970s and periods of declining precipitation in 1975–1980 and 1986–1993. Increasing precipitation appears to have dampened the impacts of rising temperatures on glacier termini, especially during the past decade, when the Coe, Eliot, Ladd, and Newton Clark glaciers each advanced.

Spearman rank correlation analysis of cumulative glacier terminus fluctuation data reveals that Mount Hood's northern glaciers fluctuated similarly over the past century (Table 3). Coe, Eliot, and Ladd glacier terminus fluctuations were strongly correlated, while Newton Clark and White River were not ($p < 0.05$). These results suggest that the Coe, Eliot, and Ladd glacier terminus fluctuations responded to common factors or forcing mechanisms. Unfortunately, none of the statistical tests showed significant, strong to moderate correlations among glacier terminus fluctuations and the various climate variables. Thus, statistical analysis did little to support the qualitative observations of glacier-climate relations mentioned above.

Discussion

GLACIER-CLIMATE LINKAGES

Each of Mount Hood's glaciers retreated overall during 1901–2001. Statistical analysis shows that Coe, Eliot, and Ladd glaciers displayed generally synchronous patterns of advance and retreat within this overall period of retreat. The similar pattern of Mount Hood's northern glacier terminus fluctuations, combined with qualitative analysis of glacier terminus fluctuation and climate data, suggests that temperature and precipitation played a significant role in Mount Hood's glacier terminus fluctuations during the past century.

Supporting evidence for glacier-climate linkages comes from other mountainous areas around the PNW. The general patterns of glacier terminus change seen at Mount Hood—i.e., retreat from 1901 through the mid-1940s, advance from the mid-1940s through the mid-1970s, and retreat from the mid-1970s through the mid-1990s—have been observed in Washington's North Cascades (Hubley, 1956; Harper, 1993; Pelto and Reidel, 2001), South Cascades (Heliker et al., 1983; Driedger, 1993), and Olympics (Spicer, 1989), and in Oregon's Central Cascades (Hopson, 1960; O'Connor et al., 2001). The historical glacier terminus fluctuations may have been set in motion by rising, mid- to late 19th century temperatures that caused significant ablation, making glaciers more susceptible to 20th century climate changes (Burbank, 1982). The general correspondence of glacier terminus fluctuations across ~6° latitude in mountainous terrain suggests that regional scale, interannual- to interdecadal-scale weather and climate events helped shape Mount Hood's glacier fluctuations over the past century.

PNW weather and climate changes are forced by atmosphere and ocean interactions. One such coupled atmosphere-ocean circulation forcing mechanism, the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; JISAO/SMA Climate Impacts Group, 1999), affects glacier climate on decadal and interdecadal scales throughout the PNW (e.g., McCabe and Fountain, 1995; Bitz and Battisti, 1999; Kovanen, 2003). The PDO (Mantua et al., 1997) is characterized by 20- to 30-year-long phases (JISAO/SMA Climate Impacts Group, 1999) in the north Pacific Ocean. Warm phase October–March air temperatures are higher and precipitation is lower than normal, with below-normal PNW spring snowpack (Mantua, 2002). Cool phases have the opposite characteristics. Mantua et al (1997) and Mantua (2002) identified four PDO phases during the past century—cool from 1890 to 1924, warm from 1925 to 1946, cool from 1947 to 1976, and warm from 1977 to the mid-1990s. These phases correspond well with Mount Hood's historical temperature and precipitation patterns, and glacier terminus fluctuations (Fig. 7), as they do elsewhere in the PNW (Kovanen, 2003).

OTHER FACTORS AFFECTING GLACIER TERMINUS FLUCTUATIONS

Much circumstantial evidence supports the linkage between Mount Hood's glaciers and ocean-atmosphere forced climate changes; however, the lack of strong, statistically significant correlations between glaciers and climate variables indicate that these glaciers were not well synchronized with climate changes. Variations in the terminus responses of Mount Hood's glaciers over time further support this point—i.e., Coe, Eliot, and Ladd glacier termini fluctuated very differently than did the termini of Newton Clark and White River glaciers. Further, even the termini of the Coe, Eliot, and Ladd glaciers occupied their most upvalley points at different times during the past century. Such differences in overall glacier response and response time may occur because of a myriad of local factors (Nesje and Dahl, 2000; Pelto and Hedlund, 2001; Klok and Oerlemans, 2004).

Some of the differences between the terminus fluctuations of Mount Hood's glaciers may be attributed to the physical characteristics of each of the glaciers (Table 1). The three corresponding glaciers are similar in type, aspect, elevation of source area, and thickness. However, the relatively small size of these glaciers may reduce their climate sensitivity (Klok and Oerlemans, 2004). Further, the climate sensitivity of the Newton Clark Glacier may also be hampered by its wide terminus (Klok and Oerlemans, 2004).

Given Mount Hood's setting, it is also likely that volcanic and geothermal activity, subglacial topography, and debris cover have also played an important local role in Mount Hood's historical glacier termini fluctuations. Heat associated with volcanic and geothermal activity can accelerate melting of glacial ice, firn, and snowpack, thus decreasing glacier mass balance and ultimately reducing glacier length. Conversely, such activity may enhance basal melting and basal sliding, thus causing glacier advance (Frank and Krimmel, 1978; Zimbelman et al., 2000; Sturm et al., 1991). A series of minor eruptions, including glowing lava at Crater Rock (Fig. 1), occurred between 1853 and 1869 (Harris, 1988), and in 1907 (Sylvester, 1908a, 1908b). Fumaroles and warm ground near Crater Rock produced caves beneath snowfields (Phillips and Collins, 1935) and bisected White River Glacier (Sylvester, 1908a, 1908b; Cameron 1988), thus reducing the accumulation area feeding the terminus. Separation of White River Glacier from its upper accumulation zone (now the Coalman Glacier) occurred between 1894 (see M. W. Gorman's photograph in Russell, 1904, plate 12) and 1912 (see J. N. LeConte's photograph in Williams,

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1912, p. 75). Minor eruption and geothermal effects likely enhanced a climatically reduced glacial mass, thus collectively resulting in rapid recession and associated thinning of White River Glacier between 1901 and the mid-1930s. Volcanic and geothermal activity does not appear to have changed since 1907.

Subglacial topography may have influenced the sensitivity of Mount Hood's glacier terminus fluctuations to climate change. Icefalls form as glacial ice passes over abrupt, convex-upward topography. Tensile stresses at icefalls (Benn and Evans, 1998) thin glaciers, thus reducing the amount of ice reaching the terminus and ultimately affecting glacier front positions (Venteris et al., 1997). Newton Clark Glacier terminates atop an escarpment beyond which it has not extended since before 1901. Post-LIA warming, combined with icefall-induced thinning of the downwasted glacial ice, likely severed the upper glacier and its accumulation zone from a lower portion of the glacier, ultimately resulting in recession to the top of the escarpment. Similarly, the terminus of the Ladd Glacier thinned and receded 922 m between 1984 and 1989 to the top of a bedrock escarpment that once underlaid a prominent icefall. Since 1989, the portion of the glacier below the icefall has become an ice-cored ground moraine complete with thermokarst terrain. The tensile stresses imposed on glaciers at icefalls, combined with the generally thin nature of Mount Hood's glaciers—i.e., all were less than ~120 m thick in the mid-1980s (Driedger and Kennard, 1986)—will likely keep the Newton Clark and Ladd glaciers from advancing beyond the escarpments unless very positive mass balance conditions again develop.

Differences in superglacial debris cover may have affected the climate sensitivity of Mount Hood's glaciers. Debris cover decreases glacier ablation rates (e.g., Ogilvie, 1904; Sharp, 1949; Nakawo and Young, 1982; Kirkbride and Warren, 1999; Nakawo et al., 1999), thus reducing glacier sensitivity to mass balance changes (Benn and Evans, 1998). Twentieth century warming has amplified mountain mass wasting processes, thus adding debris to alpine glacier surfaces (Diolaiuti et al., 2003). Coe, Eliot, and Ladd glacier termini have been debris covered since before late ablation season airphotos were taken in September, 1935. Lundstrom (1992) determined that 60% of Eliot Glacier's ablation area was covered with >1 cm of debris which has decreased thermal conduction and ultimately ablation rates. Further, increased debris cover downglacier resulted in a net ablation decrease thus a less negative net mass balance. Despite the extensive debris cover, Eliot Glacier experienced significant terminus retreat (this study) and thinning (Lundstrom, 1993) in recent years. Extensive ablation zone debris cover has also likely reduced ablation rates on Coe and Ladd glaciers rendering them less sensitive to changing temperatures during the past century.

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References Cited

Benn, D. I., and Evans, D. J. A., 1998: *Glaciers and Glaciation.* London: Arnold, 734 pp.

Bitz, C. M., and Battisti, O. S., 1999: Interannual to decadal variability in climate and the mass balance in Washington, western Canada and Alaska. *Journal of Climate,* 12: 3181–3199.

Burbank, D. W., 1982: Correlations of climate, mass balances, and glacial fluctuations at Mount Rainier, Washington, U.S.A. since 1850. *Arctic and Alpine Research,* 14: 137–148.

Cameron, K. A., 1988: Fumarole fields and thermal features at Mount Hood, Oregon. *Northwest Science,* 62: 82.

Cameron, K. A., and Pringle, P., 1986: Post-glacial lahars of the Sandy River Basin, Mount Hood, Oregon. *Northwest Science,* 60: 225–237.

Cameron, K. A., and Pringle, P., 1987: A detailed chronology of the most recent major eruptive period at Mount Hood, Oregon. *Geological Society of America Bulletin,* 99: 845–851.

Crandell, D. R., 1980: *Recent Eruptive History of Mount Hood, Oregon, and Potential Hazards From Future Eruptions.* U.S. Geological Survey Bulletin 1492.

Diolaiuti, G., D'Agata, C., and Smiraglia, C., 2003: Belvedere Glacier, Monte Rosa, Italian Alps: Tongue thickness and volume variations in the second half of the 20th century. *Arctic, Antarctic, and Alpine Research,* 35: 255–263.

Dodge, N. A., 1964: Recent measurements on the Eliot Glacier. *Mazama,* 46: 47–49.

Dodge, N. A., 1971: The Eliot Glacier: New methods and some interpretations. *Mazama,* 53: 25–29.

Dodge, N. A., 1987: Eliot Glacier: Net mass balance. *Mazama,* 69: 52–55.

Driedger, C. L., 1993: *Glaciers on Mount Rainier*: Water Fact Sheet. U.S. Geological Survey Open-File Report 92-474.

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

Frank, D. G., and Krimmel, R. M., 1978: Volcanic effects on snow and ice on Mount Baker, Washington. *In* Geological Survey Research 1978. U.S. Geological Survey Professional Paper 1100:213.

Gannett, H., 1903: Introduction. *In* Langille, H. D., Plummer, F. G., Dodwell, A., Rixon, T. F., and Leiberg, J. B., *Forest Conditions in the Cascade Range Forest Preserve Oregon.* U.S. Geological Survey Professional Paper 9: 15–26.

Hague, A., 1871: Mount Hood. *In* King, C. (ed.), On the discovery of actual glaciers on the mountains of the Pacific Slope. *American Journal of Science* (3rd Series), 1: 165–167.

Handewith, H., 1959: Recent glacier variations on Mt. Hood. *Mazama,* 41: 23–27.

Harper, J. T., 1993: Glacier terminus fluctuations on Mount Baker, Washington, U.S.A., 1940–1990, and climatic variations. *Arctic and Alpine Research,* 25: 332–340.

Harris, S. L., 1988: Fire mountains of the West: The Cascade and Mono Lake volcanoes. Missoula: Mountain Press, 379 pp.

Heliker, C. C., Johnson, A., and Hodge, S. M., 1983: *The Nisqually Glacier, Mount Rainier, Washington, 1857–1979: A summary of the long-term observations and a comprehensive bibliography.* U.S. Geological Survey Open-File Report 83-541.

Hopson, R. E., 1960: Collier Glacier—a photographic record. *Mazama,* 42: 15–26.

Hubley, R. C., 1956: Glaciers of the Washington Cascade and Olympic Mountains; their present activity and its relation to local climatic trends. *Journal of Glaciology,* 2: 669–674.

JISAO/SMA Climate Impacts Group, 1999: *Impacts of climate variability and change in the Pacific Northwest.* Seattle: self published, 109 pp.

Johannesson, T., 1989: A simple method for determining the response time of glaciers. *In* Oerlemans, J. (ed.), *Glacier Fluctuations and Climatic Change.* Boston: Kluwer Academic Publishers, 343–352.

Kennard, P. M., and Driedger, C. L., 1987: Estimated ice volumes on Cascade Volcanoes: Mount Baker, Glacier Peak, and Mount Adams

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in Washington, and Mount Jefferson in Oregon. *EOS, Transactions of the American Geophysical Union,* 68(16): 308.
Kirkbride, M. P., and Warren, C. R., 1999: Tasman Glacier, New Zealand: 20th century thinning and predicted calving retreat. *Global and Planetary Change,* 22: 11–28.
Klok, E. J., and Oerlemans, J., 2004: Climate reconstructions derived from global glacier length records. *Arctic, Antarctic, and Alpine Research,* 36: 575–583.
Kovanen, D. J., 2003: Decadal variability in climate and glacier fluctuations on Mt Baker, Washington, USA. *Geografiska Annaler,* 85A: 43–55.
Langille, H. D., Plummer, F. G., Dodwell, A., Rixon, T. F., and Leiberg, J. B., 1903: *Forest Conditions in the Cascade Range Forest Preserve, Oregon.* U.S. Geological Survey Professional Paper 9.
Lawrence, D. B., 1948: Mt. Hood's latest eruption and glacier advances. *Mazama,* 30: 22–29.
Lillquist, K. D., 1988: Holocene fluctuations of the Coe Glacier, Mount Hood, Oregon. M.Sc. thesis. Geography Department, Portland State University, 128 pp.
Lundstrom, S. C., 1992: The budget and effect of superglacial debris on Eliot Glacier, Mount Hood, Oregon. Ph.D. dissertation. University of Colorado, 183 pp.
Lundstrom, S. C. 1993: Photogrammetric analysis of 1984–89 surface altitude change of the partially debris-covered Eliot Glacier, Mount Hood, Oregon, U.S.A. *Annals of Glaciology,* 17: 167–170.
Mantua, N. 2002: The Pacific Decadal Oscillation. *In* McCracken, M. C., and Perry, J. S. (eds.), *The Encyclopedia of Global Environmental Change, Vol. 1, The Earth System: Physical and Chemical Dimension of Global Environmental Change.* Chichester: John Wiley, 592–594.
Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C., 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society,* 78: 1069–1079.
Mason, R. S., 1954: Recent survey of Coe and Eliot Glaciers. *Mazama,* 36: 37–39.
Mason, R. S., 1955: Eliot and Coe Glaciers still shrinking. *Mazama,* 37: 39.
Mason, R. S., 1957: Research committee report. *Mazama,* 39: 39.
Mazamas Research Committee, 1925: First Annual Report of the Research Committee. *Mazama,* 7: 67–72.
Mazamas Research Committee, 1927: Third Annual Report of Research Committee. *Mazama,* 9: 92–93.
Mazamas Research Committee, 1928: Report of the Research Committee. *Mazama,* 10: 101–108.
Mazamas Research Committee, 1935: Glaciers of Mount Hood, Oregon, 1935. Unpublished report on file at Mazamas office, Portland, Oregon.
Mazamas Research Committee, 1938: An aerial photographic survey of the glaciers of Mt. Hood, Mt. Jefferson and The Three Sisters, Oregon. Unpublished report on file at Mazamas office, Portland, Oregon.
Mazamas Research Committee, 1946: Aerial photographic survey of the glaciers in the Oregon Cascades on Mount Hood, Mount Jefferson, The Three Sisters, Broken Top and Bachelor Butte Extinct Glacier. Unpublished report on file at Mazamas office, Portland, Oregon.
Mazamas Research Committee, 1956: An aerial photographic survey of the glaciers of Mt. Hood, Mt. Jefferson and the Three Sisters of Oregon. Unpublished report on file at Mazamas office, Portland, Oregon.
McCabe, G. J., and Fountain, A. G., 1995: Relations between atmospheric circulation and mass balance of South Cascade Glacier, Washington, U.S.A. *Arctic and Alpine Research,* 27: 226–233.
Menzies, J., 2002: Glaciers and Ice Sheets. *In* Menzies, J. (ed.), *Modern and Past Glacial Environments.* Oxford: Butterworth Heinemann, 53–78.
Miller, A. J., Chai, F., Chiba, S., Moisan, J. R., and Neilson, D. J., 2004: Decadal-scale climate and ecosystem interactions in the north Pacific Ocean. *Journal of Oceanography,* 60: 163–188.
Nakawo, M., and Young, G. J., 1982: Estimate of glacier ablation under a debris layer from surface temperature and meteorological variables. *Journal of Glaciology,* 28: 29–34.
Nakawo, M., Yabuki, H., and Sakai, A., 1999: Characteristics of Khumbu Glacier, Nepal Himalaya: recent change in the debris-covered area. *Annals of Glaciology,* 28: 118–122.
Nesje, A., and Dahl, S. O., 2000: *Glaciers and Environmental Change.* London: Arnold, 203 pp.
O'Connor, J. E., Hardison, J. H., III, and Costa, J. E., 2001: *Debris Flows from Failures of Neoglacial-Age Moraine Dams in the Three Sisters and Mount Jefferson Wilderness Areas, Oregon.* U.S. Geological Professional Paper 1606.
Ogilvie, I. H., 1904: The effect of superglacial debris on the advance and retreat of some Canadian glaciers. *Journal of Geology,* 12: 722–743.
Oregon Climate Service, 2004: Monthly means and extremes: Government Camp, OR. http://www.ocs.orst.edu. Accessed 15 June 2004.
Pelto, M. S., and Hedlund, C., 2001. Terminus behavior and response time of North Cascade glaciers, Washington, U.S.A. *Journal of Glaciology,* 47: 497–506.
Pelto, M. S., and Reidel, J., 2001: Spatial and temporal variations in annual balance of North Cascade glaciers, Washington 1984–2000. *Hydrological Processes,* 15: 3461–3472.
Phillips, K. N., 1935: Recent changes in Hood's glaciers. *Mazama,* 17: 45–50.
Phillips, K. N., 1937: Glaciers of Mount Hood, Oregon, 1935–36. Unpublished report by the Mazamas Research Committee to the Committee on Glaciers, American Geophysical Union. On file at Mazamas office, Portland, Oregon.
Phillips, K. N., 1938: Our vanishing glaciers: Observations by the Mazama Research Committee on glaciers of the Cascade Range, in Oregon. *Mazama,* 20: 24–41.
Phillips, K. N., 1946: Research report for 1946. *Mazama,* 27: 53–55.
Phillips, K. N., and Collins, J. R., 1935: Fumaroles on Mount Hood. *Mazama,* 17: 19–21.
Reid, H. F., 1905: The glaciers of Mt. Hood and Mt. Adams. *Mazama,* 2: 194–200.
Reid, H. F., 1906: Studies of the glaciers of Mount Hood and Mount Adams. Sonder-Abdruck aus Zeitschrift für Gletcher kunde I. Band: 113–132.
Richards, C. P., 1932: Unpublished report to F. E. Matthes. On file at Mazamas office, Portland, Oregon.
Russell, I. C., 1904: *Volcanoes of North America.* New York: Macmillan, 346 pp.
Scott, W. E., Gardner, C. A., Sherrod, D. R., Tilling, R. I., Lanphere, M. A., and Conrey, R. M., 1997: *Geologic History of Mount Hood Volcano, Oregon—A Field-Trip Guidebook.* U.S. Geological Survey Open-File Report 97-263.
Sharp, R. P., 1949: Studies of superglacial debris on valley glaciers. *American Journal of Science,* 247: 289–315.
Spicer, R. C., 1989: Recent variations of Blue Glacier, Olympic Mountains, Washington, U.S.A. *Arctic and Alpine Research,* 21: 1–21.
Sturm, M., Hall, D. K., Benson, C. S., and Field, W. O., 1991: Non-climatic control of glacier-terminus fluctuations in the Wrangell and Chugach Mountains, Alaska, U.S.A. *Journal of Glaciology,* 37: 348–356.
Sylvester, A. H., 1908a: Evidences of recent volcanic activity and the glaciers of Mt. Hood, Oregon. *Science,* 27: 585.
Sylvester, A. H., 1908b: Is our noblest volcano awakening to new life: A description of the glaciers and evidences of volcanic activity of Mount Hood. *National Geographic,* 19: 515–525.
Tangborn, W. V., 1980: Two models for estimating climate-glacier relationships in the North Cascades, Washington, U.S.A. *Journal of Glaciology,* 25: 3–21.
Thompson, D. W. J., and Wallace, J. M., 1998: The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters,* 25: 1297–1300.
U.S. Geological Survey, 1913: Mount Hood. 1:125,000-scale topographic map.

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U.S. Geological Survey, n.d.: National Mapping Program Standards. http://geography.usgs.gov/standards. Accessed 15 December 2004.

Venteris, E. R., Whillans, I. M., and van der Veen, C. J., 1997: Effect of extension rate on terminus position, Columbia Glacier, Alaska, U.S.A. *Annals of Glaciology,* 24: 49–53.

Wallace, J. M., and Gutzler, D. S., 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review,* 109: 784–812.

Walters, R. A., and Meier, M. F., 1989: Variability of glacier mass balances in western North America. *In* Peterson, D. H. (ed.) *Aspects of Climate Variability in the Pacific and the Western Americas.* Washington: American Geophysical Union, 365–374.

White, C., 1980: *Geology and Geochemistry of Mt. Hood Volcano.* Oregon Department of Geology and Mineral Industries Special Paper 8:26 pp.

Williams, J. H., 1912: *The Guardians of the Columbia.* Tacoma: John H. Williams, 142 pp.

Wise, W. S., 1969: Geology and petrology of the Mt. Hood Area: A study of High Cascade volcanism. *Geological Society of America Bulletin,* 80: 969–1006.

Zimbelman, D. R., Rye, R. O., and Landis, G. P., 2000: Fumaroles in ice caves on the summit of Mount Rainier: Preliminary stable isotope, gas and geochemical studies. *Journal of Volcanology and Geothermal Research,* 97: 457–473.

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