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Glacier Change on the Three Sisters Volcanoes, Oregon: 1900-2010

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by

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in
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Abstract

A glacier responds to changes in climate by subsequent retreat and advance as a result of changes in snow inputs and outputs. Understanding these changes is important because shrinking glaciers limit and diminish local water resources. They contribute to alpine runoff in the late-summer months by delaying the maximum runoff until late in the melt season. A comprehensive glacier and perennial snowfield inventory has not been completed for the Three Sisters in Central Oregon. Using aerial photography, Digital Elevation Models (DEMs), previous studies, and historical ground based photographs these glacier and perennial snowfields were defined and their surface area change was quantified along with surface area and volume change for the 15 named glaciers for multiple years. The glaciers and perennial snowfields totaled 9.03 ± 1.65 km^2 in 1949 and decreased to 7.1 ± 1.16 km^2 in 2003 giving a total loss of -1.914 ± 0.974 km^2 (-21%). The 15 named glaciers totaled 12.43 ± 0.417 km^2 in ~1900 and decreased to 5.65 ± 0.135 km^2 in 2003 giving a total loss of -6.70 ± 0.439 km^2 (54%) with more loss occurring in the early part of the century. It's estimated that the 15 named glaciers lost roughly 61% of volume from 1900 to 2010. From 1957 to 2010 their surface's dropped in elevation on average by -8.9m, losing an estimated $71.96 \times 10^6 \pm 2.87 \times 10^6$ m^3 (53%) in total volume, seen across accumulation and ablation zones, with more loss happening from 1957 to 1990. There was no relationship found between topography and area. A small correlation was found between slope and increased volume change. Debris cover on glacier surfaces has increased and showed a correlation between decreasing area loss (no correlation with volume changes).

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Last, but certainly not least, I would like to thank my family and friends for your encouragement, questions, and patience over the past few years. You have no idea what it means to me to be able to answer, "it's finished", to the simple question of… "How's the thesis coming?".

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Chapter One – Introduction

Glaciers occur in the alpine regions where the accumulation exceeds ablation. The two main controlling factors are winter snowfall and summer air temperature, which make glaciers good recorders of regional climate changes (Dyurgerov and Meier, 2000; Oerlemans, 2005). A glacier responds to changes in climate by subsequent retreat and advance as a result of changes in the mass inputs and outputs (Hodge, et al., 1998; Hall and Fagre, 2003). Due to the remoteness of alpine regions, they can be good recorders of past climates where few records exist. Since the end of the Little Ice Age (LIA), approximately 150 years ago (Grove, 1988), glaciers have experienced an alternating retreat – advance – retreat cycle with glaciers developing an overall retreat by losing both volume and area (Haeberli, 1995). Shrinking glaciers limit and diminish local water resources. Glaciers are major contributors to alpine runoff in the late-summer months when the need for water is the greatest (Fountain and Tangborn, 1985; Fountain et al., 1997). While glacier shrinkage removes ice from long-term storage and exports it as runoff, supporting drought-affected stream flow, smaller glaciers have reduced capacity to export the water volume needed to maintain flows at historic levels. Increased frequencies of debris flows are associated with retreating glaciers on volcanoes (Pirot, 2010; Legg, 2013). With glacier retreat an increase frequency of debris flows could occur due to glaciers no longer buttressing unconsolidated sediments on lateral moraines (O'Connor et al., 2001). In the Pacific Northwest (PNW) of the United States glaciers have also been losing both area and volume in recent decades (McCabe and Fountain, 1995; McDonald, 1995; Jackson and Fountain, 2007; Marcott et al., 2009; Sitts et al., 2010; Sisson et al., 2011; Dick, 2013; McCabe and Fountain, 2013).

In Oregon, weather patterns are influenced by two primary modes of climatic patterns: the interannual El-Nino Southern Oscillation (ENSO) and the decadal Pacific Decadal Oscillation (PDO) (Mass, 2008). Warm phase ENSO winters have warmer and drier winters and the snowpack thickness is less than average. Cool phase ENSO winters have cooler and wetter winters and snowpack thicknesses are greater than average. PDO warm phase produces cooler sea surface temperatures in the Central North Pacific and warmer temperatures near the coast (Mass, 2008). In a warm PDO phase snowpack thickness in the PNW are below average. The PDO cool phase produces the opposite sea surface temperatures and about average snowpack (Zhang et al., 1997; Chao et al., 2000). Snow water equivalents (the mass of water contained in a snowpack as snow) in the PNW have declined over the past half-century as a result overall increases in air temperature (Mote, 2003; Hamlet et al., 2005; Mote, 2006). An increase in winter temperature causes more precipitation to fall as rain more frequently than snow reducing the winter snow pack thickness resulting in less nourishment to the glacier. The winter snowpack also melts off the glacier sooner allowing for the melt of ice, stored in the glacier to start sooner. This all affects the mass balance of glaciers and has implications on water resources.

Changing glacier area and volume have been examined for many of the Cascade volcanoes and alpine regions of the PNW: Mount Rainier (Driedger and Kennard, 1986; Nylen, 2001, Sisson et al., 2011); Mount Adams (Sitts, et al., 2010); Mount Hood

(Jackson and Fountain, 2007); and the North Cascades (Granshaw and Fountain, 2006; Dick, 2013). Area change can be readily quantified from aerial and ground-based photographs and satellite imagery (Fountain et al., 1997). However, a comprehensive assessment of area change for glacier and perennial snow patch areas has not been completed for the Three Sisters. An assessment of volume change is also a useful metric to link glacier change to climate and to alpine stream flow. Area changes can be noisy indicators due to the dynamics of glacier response to mass input and area-volume relations which are not constant over time (Dyurgerov et al., 2009). Knowledge of volume change over the past century can provide a more accurate assessment of glacier change in response to climate.

Aims and Objectives

Ample data exist for the Three Sisters from which inventories on the changes in glacier area and volume can be created. My thesis provides an extensive examination of the glaciers and snowfields changing area and volume, and how it compares to other regions around the PNW and the world.

This thesis is divided into six chapters. Following the introduction, Chapter Two presents the glacier and perennial snowfield inventories from 1949, 1957, 1990, and 2003, with topographic characteristics for 1957 and 1990. Chapter Three outlines the temporal change for the glacier’s area. Chapter Four presents the temporal volume change and focuses in on Collier Glacier as an ‘index’ glacier. Chapter Five is a presentation of historic and current glacier photographs and an assessment of ‘matching’ photographs, and Chapter Six contains the discussions and conclusions.

Study Area

The Three Sisters Volcanoes, North (3074 m), Middle (3062 m), and South (3157 m) (Figure 1), are stratovolcanoes set within the Cascade Mountain Range that extend from Northern California to Southern British Columbia Canada.

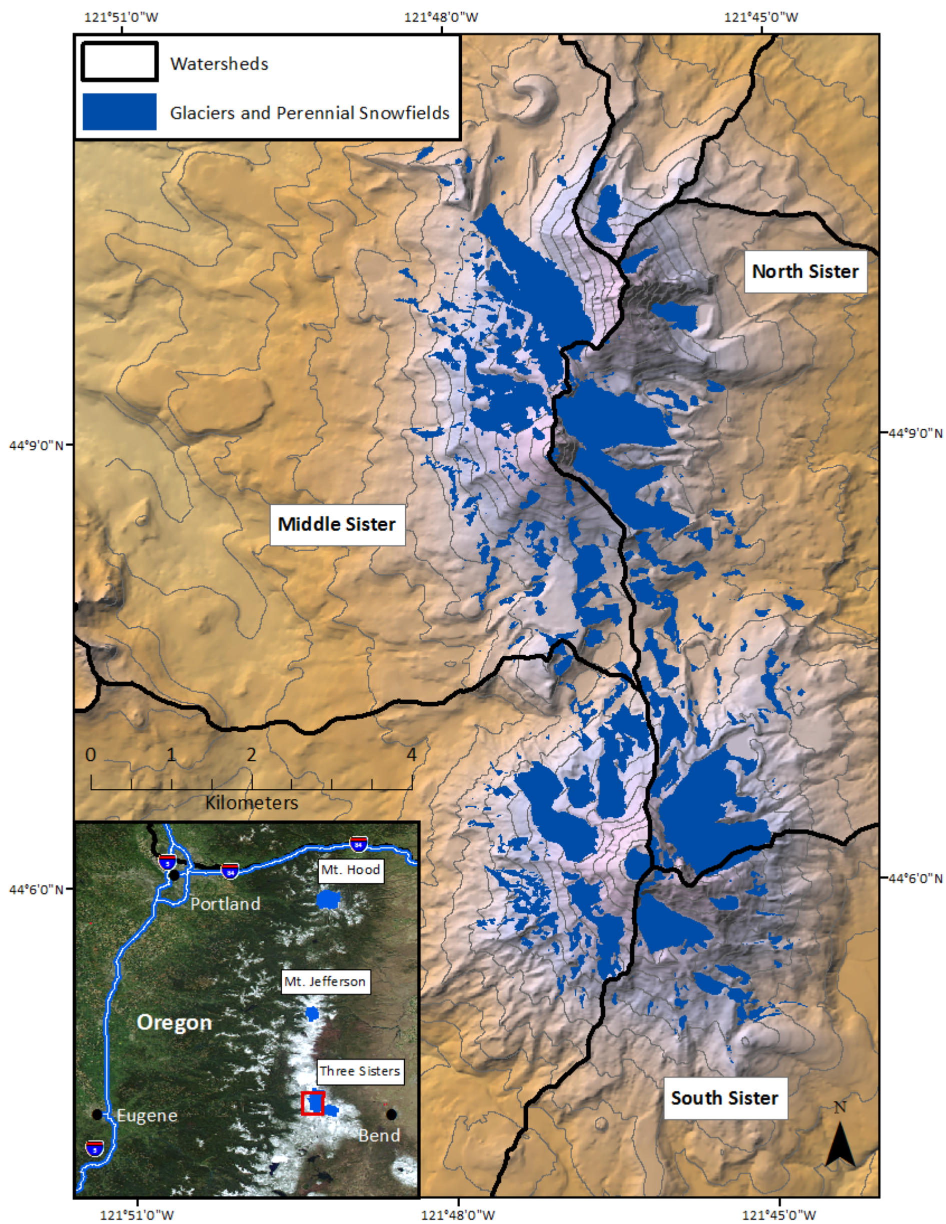


Figure 1. Digital elevation map (USGS, 2010) of the Three Sister Volcanoes, Central Oregon Cascade Range. Displayed are the location of the glaciers and perennial snowfields (in blue) and watershed boundaries (in black). Glacier and perennial snowfields are a combination of surface areas from 1949-2003. Contour interval is 100m. Map is in WGS 84 UTM Zone 10.

They are located in the High Cascades of Central Oregon (44.123 N and 121.777 W), about 40 km west of Bend, Oregon. The volcanoes are within the Three Sisters Wilderness Area in both the Willamette (on the west flanks) and Deschutes (on the east flanks) national forests. A majority of the three edifices rise above treeline which is roughly 2500 m above sea level, with mountain hemlocks and white bark pine dominating the subalpine forests (O'Connor et al., 2001).

The volcanoes are primarily pyroclastic ejecta and lava flows composed of basalt, basaltic andesite, andesite, and dacite erupted during the middle Pleistocene (~720,000 years old) with South Sister having a more recent volcanic history with eruptions occurring from 12,000 to 1,900 years before present (Wozniak, 1982). With exception of the recent volcanism, glacial modifications dominate the landscape (O'Connor et al., 2001). Three sets of moraines have been identified since the last glacial maximum (19-23 ka); oldest moraines >8.1 ka, a second set from 2 to 8 ka, and the third from the LIA (Marcott et al., 2009). They are the result of multiple glaciations during the Holocene with the most recent maximum culminating the LIA sometime between 1850 and 1900 (Sigafoos and Hendricks, 1972; Crandell and Miller, 1974). These non-vegetated unconsolidated moraine deposits of the LIA are dominant features on the volcanoes pointing to the evidence of recent glacial fluctuations (Figure 2).

There are 15 named glaciers on the three volcanoes. Collier, Linn, Thayer, and Villard glaciers are located on North Sister. Diller, Hayden, Irving, and Renfrew glaciers are located on Middle Sister. Carver, Clark, Eugene, Lewis, Lost Creek, Prouty, and Skinner glaciers are located on South Sister.

Oregon’s weather is dominated in summer by a strong East Pacific High pressure system in the Pacific bringing dry stable air into the region (Mass, 2008). This brings sinking air with little cloud formation and almost no precipitation. In winter the East Pacific High weakens to the South, and the Aleutian Low pressure intensifies in the North Pacific bringing storms in off the Pacific moving east towards the Cascades (Mass, 2008).

Figure 2. Photo looking to the south towards Collier Glacier and Middle Sister with the black and white arrows pointing to the moraine crests of the LIA advance. Photo: Justin Ohlschlager September 7, 2011.

The mountains orographically uplift the moist air causing it to condense and precipitate (Ruffner, 1985; Mass, 2008). About 90% of the precipitation falls in the fall, winter and spring months. Annual average precipitation in the region varies from 2500 to 3500 mm falling mainly in the winter months as snow (Taylor, 1993). The glaciers and perennial snowfields on the western flanks of the Three Sisters feed into the McKenzie River which drains into the Willamette River and on the eastern flanks into the Deschutes River.

Previous Studies

Glaciers were first observed on the Three Sisters by J.S. Diller in the summer of 1883 on an expedition to the summits of Mt. Thielsen, Diamond Peak, and the Three Sisters (Russell, 1885). Russell noted that Diller observed a number of considerable glaciers on multiple Cascade peaks that included the Three Sisters. Russell (1905) is the first report on the glaciers and included photographs and observations. He noted their current surface being lower than the adjacent moraine crests (Figure 3). Later Hodge (1925), reported on glacier areas, photography, climbing routes, and a history of the glacier names. Each glacier is described in the report, but there is no mention of how glacier area was estimated.

Figure 3. Photograph of the Diller Glacier (foreground) taken by I.C. Russell August 16, 1903 looking south with the summit of South Sister (background). Photo Source: Jim O'Connor USGS.

Many comprehensive reports and photographs of the Three Sisters glaciers in the early 20th century have been published by the Mazamas, a hiking club in Portland, Oregon (Williams, 1916; Phillips, 1938; Hopson, 1960; Hopson, 1962; Hopson, 1963; Hopson, 1965). Most studies have focused on the Collier Glacier, on the north flank of Middle Sister, with little attention to the changes of the other glaciers (Driedger and Kennard, 1986; McDonald, 1995; O'Connor et al., 2001; Fountain et al., 2007; Beedlow, 2010). A partial inventory of the glaciers was completed using ground-penetrating radar and area-volume estimates (Driedger and Kennard, 1986). Area was derived from the USGS topographic map. Volume was estimated from a few ground penetrating radar points and area-volume scaling. McDonald's (1995) thesis tracked changes in mass of the Collier Glacier as it related to climate. His area changes, estimated from ground-based and aerial photos, were limited to the main trunk. Beedlow (2010) measured the energy balance on Collier Glacier and like McDonald he was only concerned with the main trunk of the glacier. O'Connor et al. (2001) reported on the changes of the 15 named glaciers. The only complete inventory of the glaciers and perennial snowfields was completed by Fountain et al. (2007) summarizing the glacier and perennial snow features found on the 24,000 scale U.S. Geological Survey (USGS) topographic maps, based on photographs taken in 1957. This thesis will be an attempt to complete a full history of the temporal area and volume changes for the glaciers and perennial snowfields since the end of the LIA on the Three Sisters.

For the purposes of this thesis is important to define the terms glacier, perennial snowfield, and seasonal snowfield. A glacier is defined as a perennial snow or ice body that moves (Cuffey and Paterson, 2011). A perennial snowfield is a stagnate body of snow or ice and seasonal snowfields are not persistent between imagery years.

Chapter Two – Glacier Inventory

Introduction

The purpose of this chapter is to compile glacier and perennial snowfield inventories on the Three Sisters Volcanoes and to test whether the glaciers depictions on the USGS 1:24,000 (24K) scale topographic maps accurately reflect glacier boundaries I observe on the same aerial photographs used to create the 24K maps. Glacier and perennial snowfield inventories are necessary to describe their extent and distribution, to assist in providing an estimate of water resources, and offer updated landscape information for recreation and hazard potential. Inventories have been completed elsewhere internationally (Aniya, 1988; Andresassen et al., 2008; DeBeer and Sharp, 2009; Bolch et al., 2010) and in the United States (Nylen, 2001; Granshaw and Fountain, 2006; Basagic and Fountain, 2011; Dick, 2013).

Methods

To investigate the validity of the 24K glacier and perennial snowfield inventory I obtained shapefiles of the outlines from Fountain et al. (2007) and downloaded USGS maps of the region from 1959 and 1988 from the USGS topo viewer website (http://ngmdb.usgs.gov/maps/TopoView). To construct glacier and perennial snowfield inventories for the Three Sisters I used aerial imagery from 1949, 1957, 1990, and satellite imagery from 2003 (Table 1). Single frame vertical aerial imagery (with greater than 50% overlap) taken by the United States Geologic Survey (USGS) in 1949 and 1957 and the United States Department of Agriculture (USDA) in 1990 were orthorectified.

Dr. Jim O'Connor from the Oregon Water Science Center (OWSC) supplied the 1949 and 1990 photographs. The 1957 photographs and 10 m National Elevation Dataset (NED) digital elevation model (DEM) were downloaded from the USGS Earth Explorer and National Map websites, respectively. The NED DEM was produced from the rasterzation of elevation contours from the USGS 24K topographic maps based on the 1957 imagery (USGS, 2010). The 2003 Quickbird satellite imagery was collected and orthorectified by DigitalGlobe Inc. and supplied by Google Earth.

Table 1. Imagery and digital elevation model (DEM) used to compile the glacier inventories and orthorectification process. Data sources and collectors include the United States Geological Survey (USGS) Oregon Water Science Center (OWSC) Portland, OR, the United States Department of Agriculture (USDA), Google Earth, National Aerial Imagery Program (NAIP), Quantum Spatial Inc. (QSI), Portland, OR, and the Oregon Department of Geology and Mineral Industries (DOGAMI). 'I Year' is year imagery was created and 'P Year' is publication or creation year. Vertical aerial data type are single frame.

I Year	P Year	Data Type	Data Collector	Source	Use
1949	2012	Vertical Aerial	USGS	OWSC	Inventory
1957	2012	Vertical Aerial	USGS	www.earthexplorer.usgs.gov	Inventory
1957	2003	10 m NED DEM	USGS	www.nationalmap.gov	Orthorectification
1957	1959	USGS 1:62,000 Map	USGS	ngmdb.usgs.gov/maps	Inventory Validation
1979-82	1988	USGS 1:24,000	USGS	ngmdb.usgs.gov/maps	Inventory Validation
1990	2012	Vertical Aerial	USDA	OWSC	Partial Inventory
1990	2012	10 m DEM	Thesis	Vertical Aerials	Orthorectification
2003	2012	Satellite Imagery	DigitalGlobe	Google Earth Viewer	Inventory
2005	2007	Orthophotos	NAIP	datagateway.nrcs.usda.gov	Orthorectification
2010	2011	Lidar DEM	QSI	DOGAMI	Orthorectification

The 2005 National Aerial Imagery Program (NAIP) orthoimagery were downloaded from the USDA data gateway portal to be used as a guide for orthorectifing single frame aerial imagery. No inventory was generated for this year (2005) because the imagery was taken in July with large amounts of seasonal snow. Finally, I used a light distance and range (lidar) DEM (1 m spatial resolution) produced by Watershed Sciences Inc. (now Quantum Spatial Inc.) in Portland, Oregon for the Oregon Department of Geology and Mineral Industries (DOGAMI). The lidar data were acquired between September 10th and September 12th, 2010, with no accompanying aerial photography, resulting in no data collection for glacial boundaries in 2010.

Orthorectification, Mosaicing, and DEM Creation

The photographs were first georeferenced to rectify surface areas to true plan-view using ERDAS Imagine's Leica Photogrammetry Suite (LPS) (EOS, 2004). The ground coordinate system referenced was the WGS 1984 UTM zone 10N using the 2005 NAIP orthophotographs and the vertical reference was the 1 m resolution lidar DEM. To align the imagery relative to the ground surface, control points were selected in what was assumed to be non-changing features (e.g. bedrock outcrops, large boulders). The imagery in 1949, 1957, and 1990 were stereo images from which a 10 m DEM for each was created using LPS. The stereo images for each year were mosiaced together to a single image file. These DEMs were used to orthorectify the mosaiced aerial imagery.

Digitizing

Vector polygons outlining snow and ice features were digitized at a 1:2000 scale in ArcGIS and Google Earth. This scale is a compromise between efficacy and outline resolution (Sitts et al., 2010). I used, but was not limited to, the 24K scale topographic glacier database as a guide to locate the snow and ice features. I first digitized the 1957 imagery, the same imagery from which the 24K map and outlines were produced. Any feature larger than 0.0001 km^2 (10 m DEM pixel) was digitized. The 1949 and 1990 features on the imagery were then digitized using the 1957 polygons as a guide. The final inventory, 2003, was digitized in Google Earth focusing in on features that were found as perennial in the previous inventories. Polygons were attributed with the identification record number (RECNO) from the 24K inventory, a new identification system specific to this study, and area. A new identification system was necessary because I identified snow patches that were not included in the 24K inventory. Topographic characteristics of elevation, slope, and aspect were calculated for each feature based on the DEMs created.

To determine seasonal versus perennial features, I used rules modified from DeVisser and Fountain (2015).

- Any feature present in the 1949, 1957, 1990, 2003 inventories was considered to be perennial.
- Any feature present in only one inventory was considered to be seasonal and eliminated from the inventory.
- Any feature missing in middle inventories (e.g. found in 1949 missing in 1957 there again in 1990) were considered to be seasonal.
- A feature found in the first two inventories (1949 and 1957) but not in the later ones was considered to be a perennial feature that disappeared.
- Digitized features in 1949 and 1957 were considered seasonal if the following criteria were met; <0.005 km^2 and no landscape modification were visible. Modifications include lateral or terminal moraines and protalus ramparts (Figure 4).

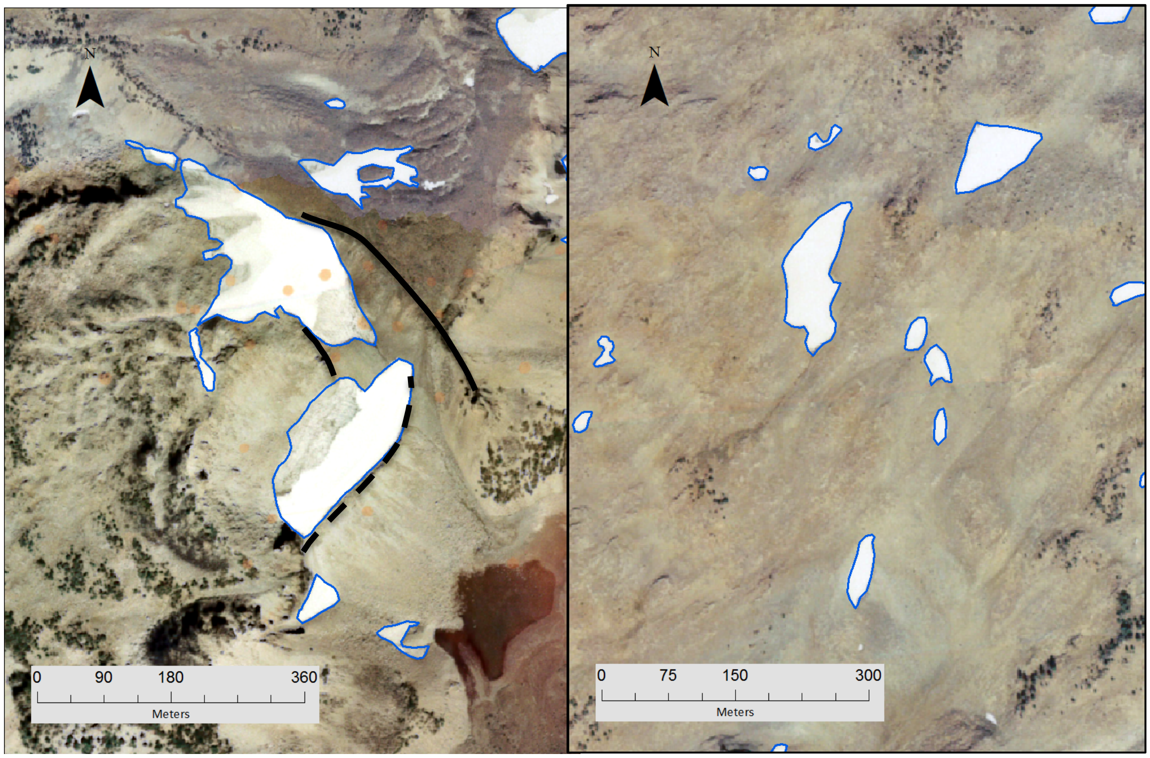


Figure 4. Examples of the presence and lack of landscape modification due to perennial snow or ice. The left image (September 14, 1990) shows perennial features with lateral moraines (solid black lines) and the crest of a protalus rampart (dashed black line) on the southern flank of Middle Sister. The image on the right (September 14, 1990) shows seasonal snow patches on the south west flack of Middle Sister that lack landscape features. Images are in WGS 84 UTM Zone 10.

Uncertainty

The uncertainty of digitizing polygons was calculated using two methods. For the features with clear boundaries, such as the larger glaciers, the uncertainty, U, is the root sum of squares of positional, P; digitizing, D; and interpretation, I, uncertainty (Sitts et al., 2010).

$$U = \sqrt{P^2 + D^2 + I^2} \quad (1)$$

Positional uncertainty is the horizontal error of the image resulting from orthorectification to the surface topography. For this study the positional uncertainty is assumed to be zero because a shift in the horizontal position of a polygon will not affect the surface area for relatively small features. The digitizing uncertainty is the error induced by attempting to digitize the glacier perimeter. The digitizing uncertainty was calculated using Ghilani (2000),

$$D = 1.414\sqrt{A}D_U, \tag{2}$$

where A is the area of the glacier in km^2 and D_U is the linear digitizing uncertainty in km. This approach calculates the uncertainty of a square with an equivalent area to the glacier of interest, regardless of the number of vertices. To determine D_U I evaluated ten outlines, chosen at random, and using the measure tool in ArcGIS I calculated the distance between the digitized outline and the actual edge of the glacier determined at a much higher resolution (1:500).

Interpretation uncertainty is the error caused by shadows, debris-covered ice, and seasonal snow patches that mask the glacier edge. The interpretation uncertainty was estimated by defining the areas (km^2) by drawing polygons in ArcGIS 10.1 on individual features where it could not be determined whether ice was present (Figure 5).

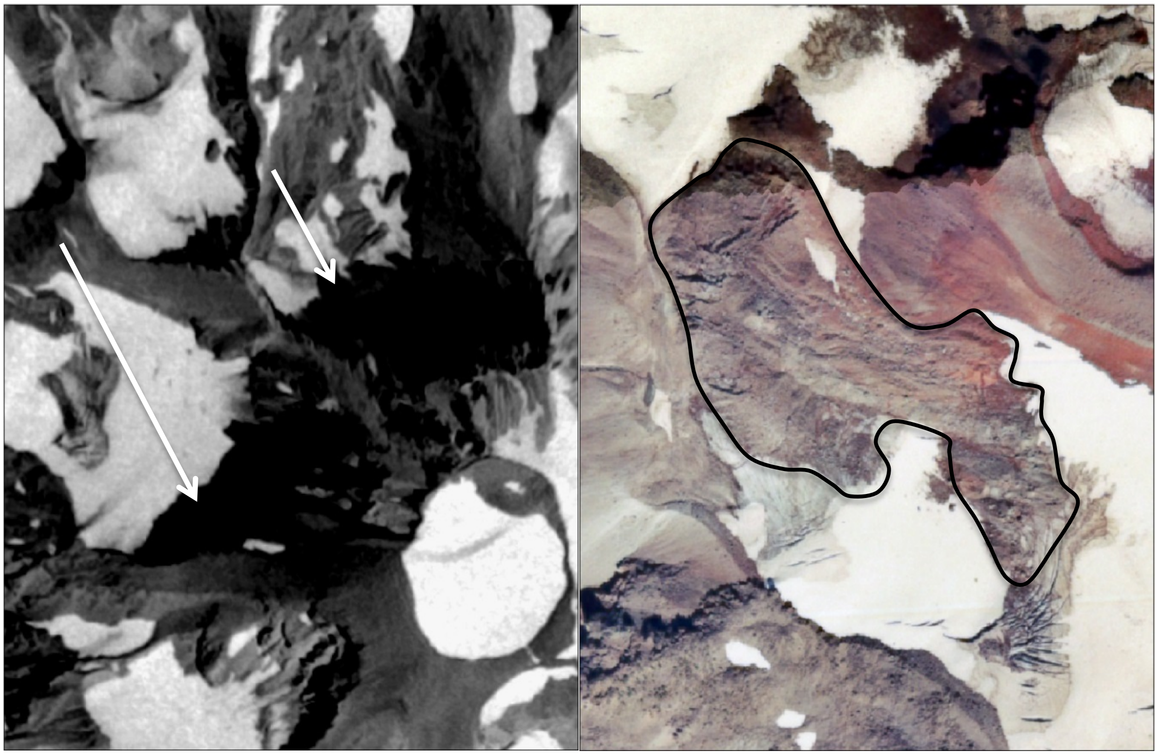


Figure 5. Examples of interpretation uncertainty. Arrows on the left image (September 3, 1957) of the Lost Creek and Skinner glaciers point to glacier zones covered in shadows. The image on the right (September 14, 1990) shows debris covering a glacier (black outline) on the Lost Creek Glacier.

For perennial snow patches a buffer (calculated zone around the defined perennial outline that represents the uncertainty of an outline) was applied to estimate uncertainty (Granshaw and Fountain, 2006). These snow patches can vary in size greatly from year to year making the 'true' edge of the perennial snow unclear. Therefore, a buffer inside of the snow patch provides a more liberal estimate of uncertainty. I applied an inner buffer on the polygons because the true extent of the perennial portion of the snow patch is assumed to be inside of the seasonal snow cover. This reduced the possible size of the features according to the size of buffer applied.

Results

Comparison of the 1959 Three Sister Quadrangle, 1:62,500 map, imagery date 1957, to the 1988 North Sister and South Sister Quadrangles, 1:24,000 maps, imagery dates 1979-1981, showed that the glacier outlines, were updated (Figure 6). Searching the USGS Earth Explorer website for aerial imagery I determined that the glacier outlines on the 1988 map were updated using 1980 aerial imagery. These aerial photos were downloaded and after georeferencing the imagery in ArcGIS the 24K outlines matched nicely with the features in the imagery. These updates to the glacier outlines however were of variable quality. Some snow and ice feature outlines were accurately updated (e.g. now outlining ice in 1988 when missing in 1957), in other instances they were incorrectly updated (e.g. outline were deleted where ice is present) and overall many smaller snowfields present were added to the 1988 map. The aerial photographs of 1980 used in the 1988 maps were taken in July a time of year that much seasonal snow is still present. Consequently, many of the snow/glacial feature's true boundaries on the 1988 maps are masked by seasonal snow. Due to the missing outlines and the snowy nature of the imagery the 24K data were not used as an inventory. The topography for both maps was derived from the 1957 aerial imagery; the 10 m NED DEM of 2003 is based on this imagery. The difference between the two maps was that the glacier outlines had been updated but the topography is the same – another reason to mistrust the 1988 24K maps.

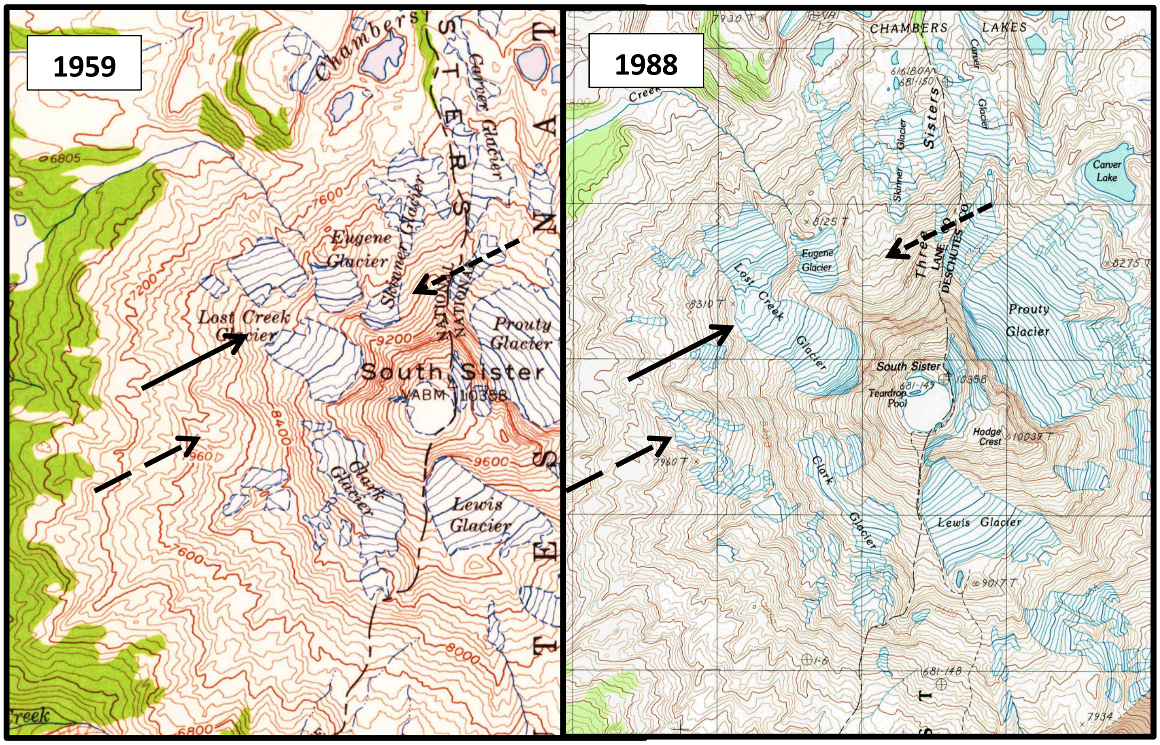


Figure 6. Specific zones on the 1959 1:62,500 scale map, imagery date 1957, (left) and the 1988 1:24,000 scale map imagery date 1957 with limited revision from photos taken in 1979-1982 (lower right) where the glacier outlines have been updated. The solid arrow points to the connection of the Lost Creek Glacier in 1988, the short dashed arrow points to the area on the Skinner Glacier deleted, and the long dashed arrow points to an area where snowfields have been added. Maps are in WGS 84 UTM Zone 10.

The orthorectification and DEM creation for the inventories was completed with quality results for orthorectification and mixed results for DEM creation. The spatial resolution (pixel size) of the orthorectified imagery for 1949 was 2 m, 3 m for 1957, and 1 m for 1990, respectively. Lower resolution of the 1949 and 1957 imagery was a result of poor initial image quality, smaller image scale (higher flight altitude), and black and white rather than color images. The 1990 images lacked complete coverage of the study area. The 1949 and 1957 mosaiced imagery was orthorectified to the 1957 NED DEM due to the poor quality DEMs created for their respective years. The 1949 and 1957 DEMs were found to not represent surfaces accurately due to the same reason for the low resolution of the orthoimagery. Overall, the topography, especially in steeper slopes, was stunted, producing lower than expected elevations. An 8-year difference was determined to be sufficient for orthorectifying the 1949 image to the 1957 NED DEM due to the lack of a quality 1949 DEM. The 1990 mosaiced imagery was orthorectified to the 1990 created DEM.

For larger ice features, of the two sources of uncertainty (digitizing and interpretation) the interpretation typically represented a larger percentage of the total. The digitizing uncertainty was smaller and that was mainly controlled by the area of the feature and the observed Du. A 0.003 km D_U was found for 1949, 1957, and 1990, and 0.001 km for 2003. Even with lower resolution for the 1949 and 1957 orthophotos the same Du was found for all of the imagery orthorectified in this study. This is likely because of the 1:2000 scale at which the snow and ice features were digitized. If the features were digitized at a smaller scale the Du could be different for the different resolution imagery.

For smaller perennial snow patches a buffer uncertainty was calculated. A different sized buffer was applied for the different imagery dependent on the image resolution, date of imagery, and scale of imagery. A 10 m (± 5 m) buffer was used for 1949, 20 m (± 10 m) for 1957, 5 m (± 2.5 m) for 1990, and 5 m (± 2.5 m) for 2003. In general, the uncertainty showed larger ice features having smaller relative uncertainties as compared to smaller features, which had larger relative uncertainties. This result is not surprising because the buffer method yields larger relative uncertainties for the smaller snow features as compared to the root sum of squares method for larger glaciers.

The inventories showed 402 snow and ice features identified in 1949, 402 in 1957, 337 in 1990 (lack of full image coverage), and 122 in 2003. The 1990 inventory was not comprehensive due to incomplete imagery coverage (Figure 7). The 1990 coverage did not include Thayer and Villard glaciers and up to 63 other snow and ice features because according to the rules of perennial versus seasonal snow dates for only 1949 and 1957 do not qualify. The features found in 1949 and 1957 but missing in 1990 due to incomplete coverage were classed as 'no data'. Results showed 122 perennial features present in the 1949, 1957, 1990 (it was assumed that the Thayer and Villard glaciers did not disappear and reform by 2003) inventories, and 121 in 2003 (Table 2). Only one feature disappeared in the 54-year time span from 1949 to 2003. Of the 122 glaciers and perennial snowfields 72 are located on the edifice of North & Middle Sisters with a total of 5.12 ± 1.82 km^2 with an average of 0.073 km^2; South Sister hosts 52 with a total area of 4.76 ± 1.66 km^2, and an average of 0.092 km^2.

As mentioned previously 65 features are not identified in 1990 because of lack of aerial imagery were classified as 'no data' and were not included in any calculations, however some of these features could be perennial. I evaluated these 65 features that were identified in 1949 and 1957 to determine their total area and if they would pass the rules set up for a perennial feature. In 1949 these 65 features totaled 0.41 ± 0.26 km^2 (4.5% of perennial total) and 0.28 ± 0.38 km^2 (2.8%) in 1957. Of the 65 features 30 would have been counted as seasonal because they are smaller than 0.005 km^2 and do not show any signs of landscape modification. It is noted that 35 features could be perennial features that are not included into the total population statistics or analysis. That being said, given the small percentage of area that they represent of the total population their inclusion would not greatly change the population statistics.

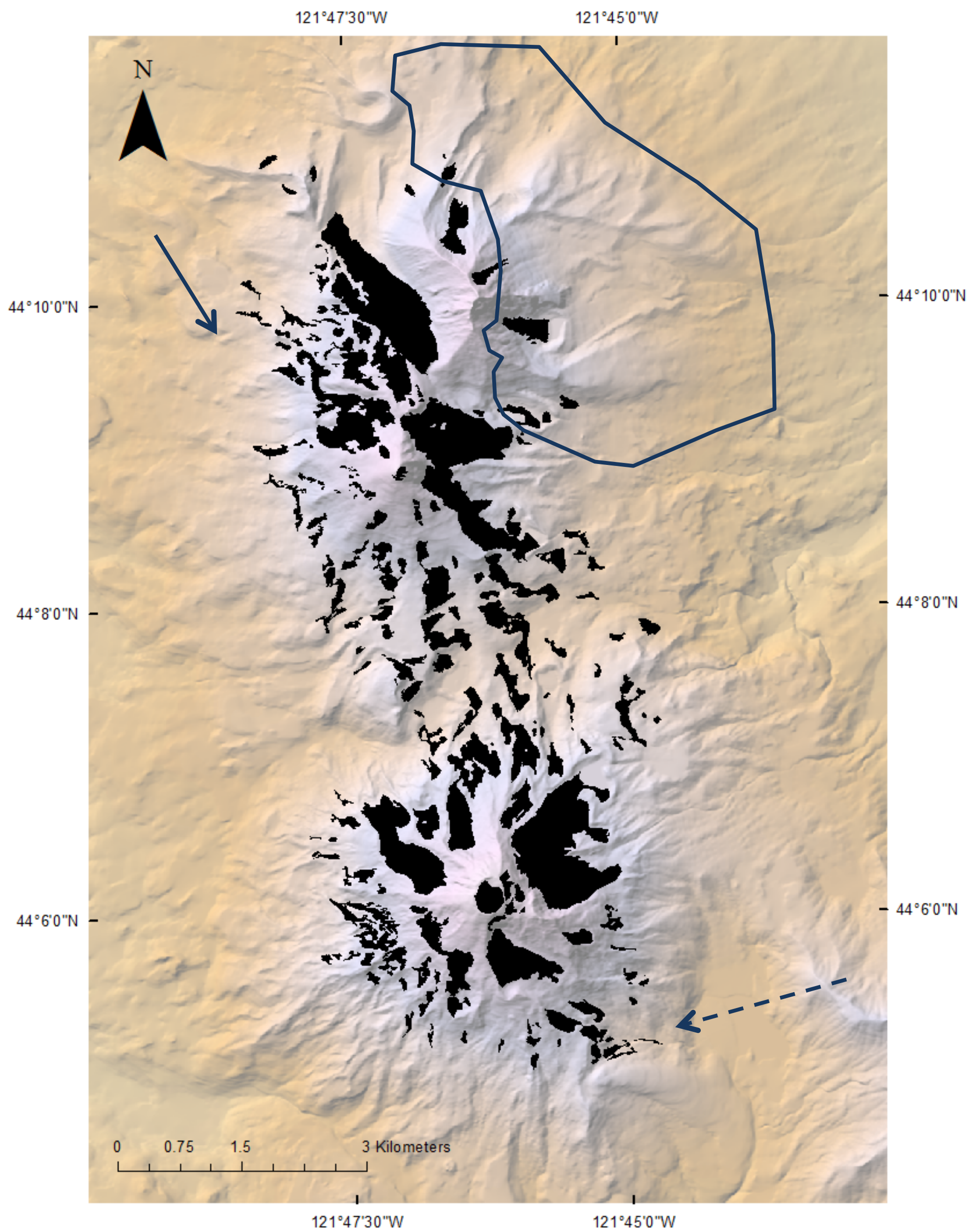


Figure 7. National Elevation Dataset Digital Elevation Model (USGS, 2010) map of the Three Sisters Volcanoes showing the glaciers and perennial snowfields (in black) from the combined outlines from the inventories of 1949, 1957, 1990, and 2003. The blue polygon zone is location of missing aerial photography for 1990. The solid blue arrow points to the perennial snowfield that was lost and the dashed blue arrow points to the largest glacier, Prouty. Map is in WGS 84 UTM Zone 10.

Table 2. The number of total features, seasonal snowfields, glacier and perennial snowfields, and area statistics for each inventory. In 1949 and 1957 a 0.005 km^2 threshold was used as described in the methods.

	1949		1957		1990		2003	
	n	**Area (km^2)**	**n**	**Area (km^2)**	**n**	**Area (km^2)**	**n**	**Area (km^2)**
Total	402	9.85 ± 2.38	402	10.41 ± 4.5	337	7.48 ± 0.74	-	-
Seasonal Total	215	0.41 ± 0.47	215	0.25 ± 0.64	215	0.08 ± 0.08	-	-
No Data	65	0.41 ± 0.26	65	0.28 ± 0.38	-	-	-	-
Perennial Total	122	9.03 ± 1.65	122	9.88 ± 3.38	122	7.40 ± 0.66	121	7.1 ± 1.16
Perennial Mean		0.074		0.081		0.059		0.058
Perennial Median		0.016		0.017		0.006		0.007
Perennial Maximum		1.07		1.23		1.18		1.11
Perennial Minimum		0.005		0.005		0.0002		0.0002

The population distributions of each inventory are highly skewed towards smaller features (Figure 8). Between 1949 and 2003 84-89% of the features were less than 0.1 km^2, in 1949 86%, in 1957 84%, in 1990 88%, and in 2003 87%. Between 1949 and 2003 these small features make up 16-25% of the total ice-covered area, in 1949 2.35 km^2 (25%), in 1957 2.01 km^2 (20%), in 1990 1.23 km^2 (17%), and in 2003 1.11 km^2 (16%). The total area of the perennial features increased from 1949 to 1957 (0.85 ± 3.73 km^2, 9.4%), decreased from 1957 to 1990 (-2.63 ± 3.34 km^2, -26.6%), and did not significantly change from 1990 to 2003 (-0.15 ± 1.32 km^2, -2.1%), with an overall decrease from 1949 to 2003 (-1.93 ± 2.02 km^2, -21.3%). The mean size reflects the same pattern. The Prouty Glacier is the largest glacier, 1.072 ± 0.040 km^2 in 1949 enlarged to 1.115 ± 0.040 km^2 in 2003.

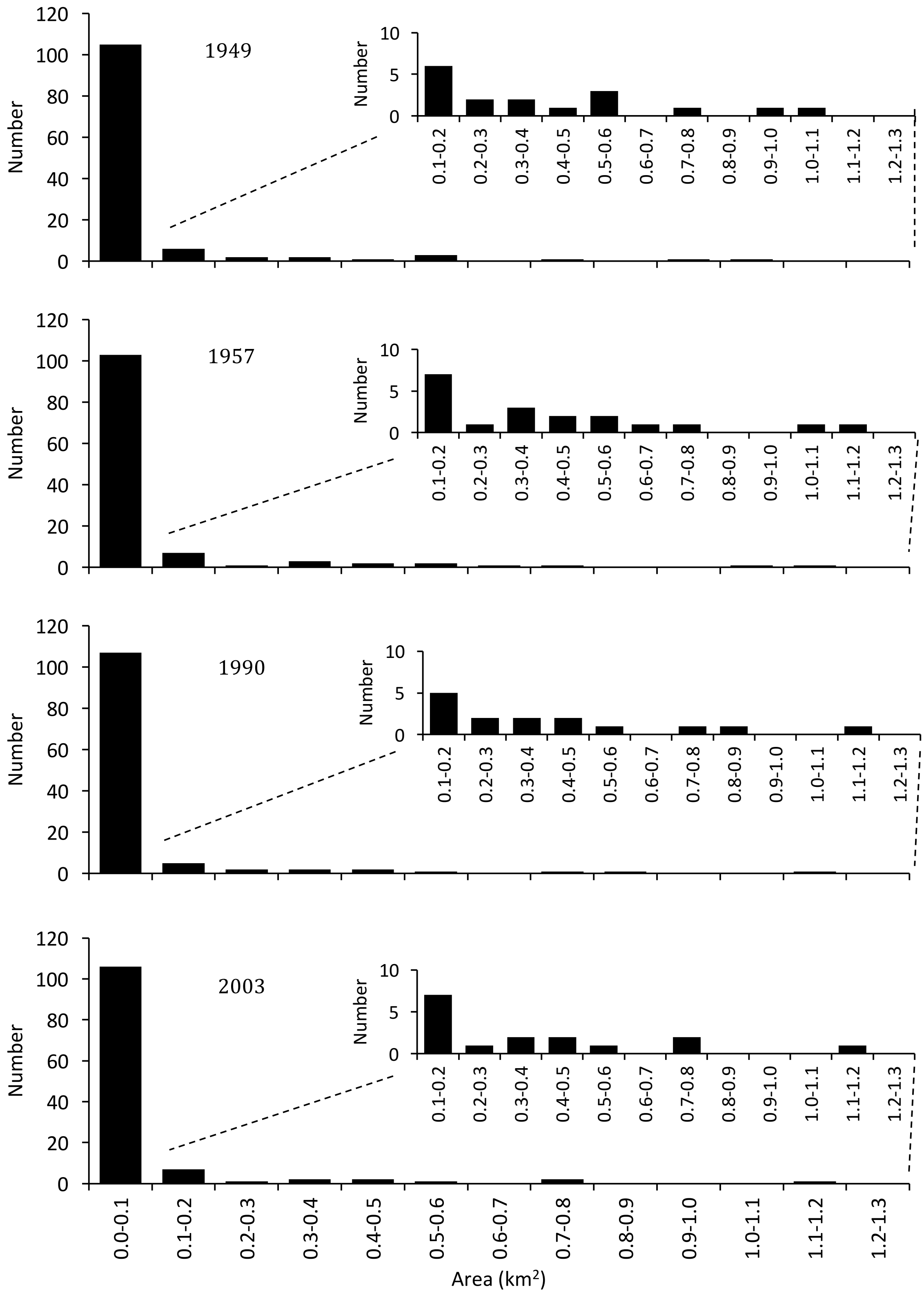


Figure 8. The population distribution of glacier and perennial snowfield area for the inventories. The maximum value for each bin's area range is included in that grouping. Number is number of glaciers and perennial snowfields.

Analysis

To characterize the topography of the glaciers and perennial snowfields the topographic statistics were calculated (Figure 9). Based on the USGS NED 10 m DEM of the 1957 surface and the 1957 outlines, the average elevations of each feature ranged from 2080 m to 3112 m with a mean (median) of 2428 m (2365 m). The average elevation of the spatial distribution of perennial snow and ice is 2518 m. Most of the snow and ice covered area, 9.16 ± 2.82 km^2 (92.7%), was found between 2300 m and 2800 m with the most area (26.2%) occurring between 2400 m and 2500 m. Lowest ice on the mountains was located at 2075 m and the highest ice at 3148 m. Mean slopes ranged from 2.9° to 41.1° with an average of 20.9° (and a median of 20.6°). The glaciers and perennial snowfields faced all directions, most of the area, 7.98 ± 2.74 km^2 (80.7%), faced the NW to E direction.

Based on the created 1990 DEM of the 1990 surface and the 1990 outlines, the average glacier and perennial snowfield elevations ranged from 2069 m to 3123 m with a mean (median) of 2432 m (2373 m). For the total snow and ice covered area average elevation is 2548 m and 6.88 ± 0.57 km^2 (94.8%) was found between the elevations of 2300 m and 2800 m of which 33.7% occurs between 2500 m and 2600 m (Figure 9). The lowest ice was found at 2045 m and the highest at 3150 m. Mean slopes range from 3.8° to 43.4° with an average of 21.4° (20.8°) with 6.99 ± 0.57 km^2 (96.6%) found between 10° and 30°. Again the features faced all directions, most of the area, 6.18 ± 0.44 km^2 (85.4%), falling in the NW to E direction with 5% more ice facing in that direction compared to 1957.

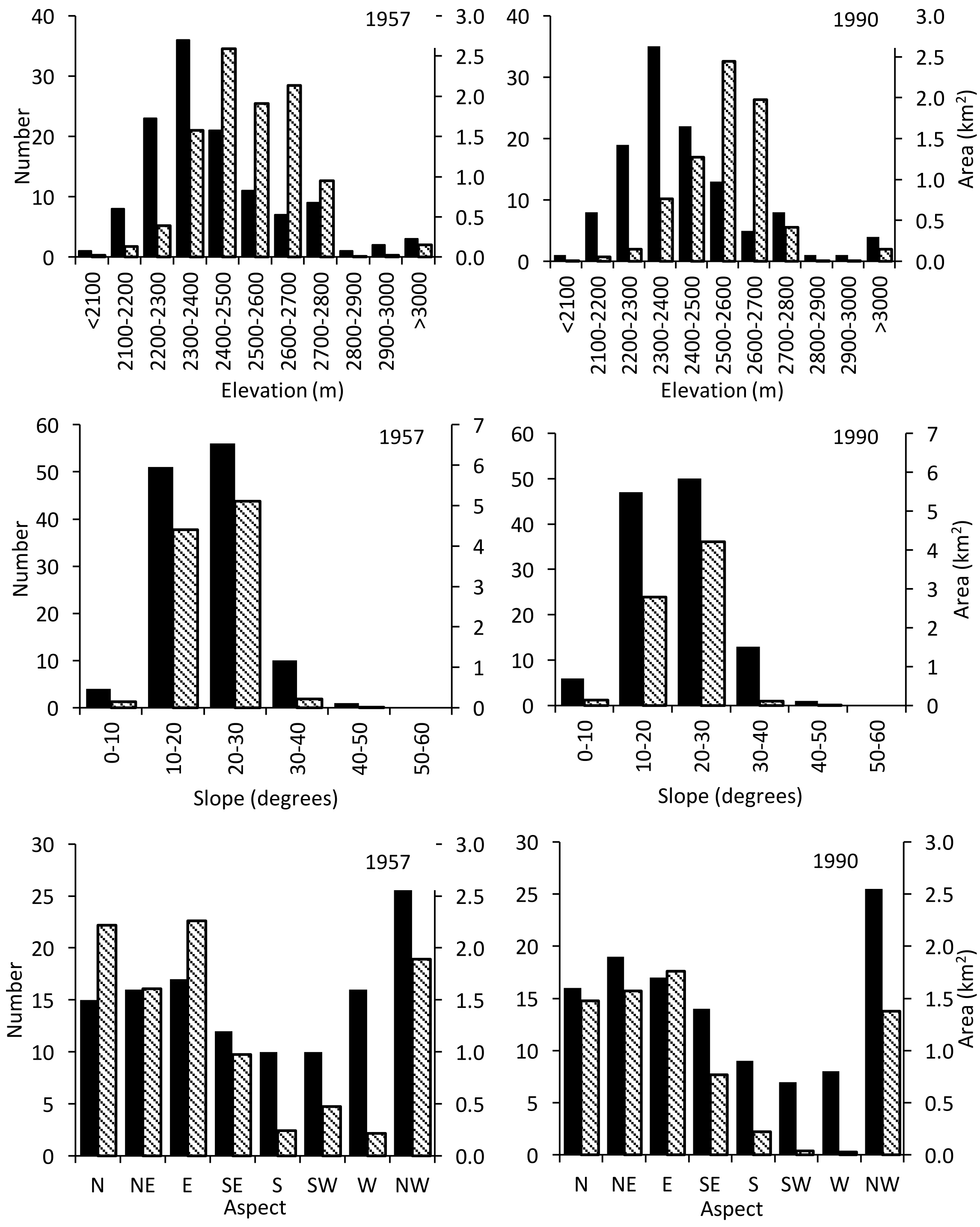


Figure 9. Topographic characteristics of the 1957 (left graphs) and 1990 (right graphs) glacier inventories mean elevation, mean slope, and aspect plotted for number (solid bars) and area (km^2) (hatched bars). Aspect was grouped into 8 directions N=337.5-360 and 0-22.5, NE=22.5-67.5, E=67.5-112.5, SE=112.5-157.5, S=157.5-202.5, SW=202.5-247.5, W=247.5-292.5, NW=292.5-337.5. The maximum value for each bin's area range is included in that grouping.

Glacier and perennial snowfield populations in all inventories were dominated by small features <0.1 km^2, but make up roughly a quarter of the total area with relatively high uncertainties (Figure 10).

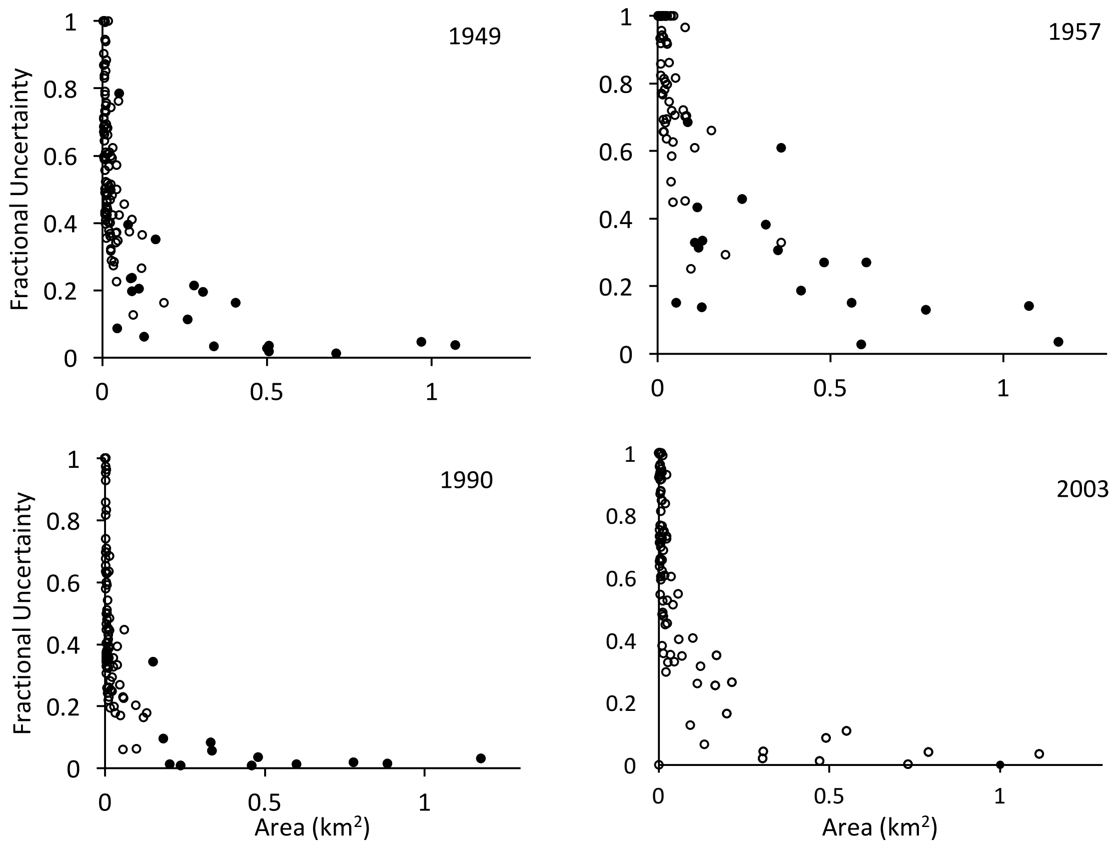


Figure 10. The fractional uncertainty of the glacier and perennial snowfields for the inventories. Open circles are perennial features and solid circles are the 15 named glaciers.

Glaciers versus Perennial Snowfields

To determine whether the inventories of perennial features are glaciers I used two methods: 1) applying an area threshold and 2) estimating movement. Area thresholds are commonly used as criteria for defining the minimum size for glaciers (Spicer, 1986; Raub et al., 2006; DeBeer and Sharp, 2007; Basagic and Fountain, 2011; Dick, 2013). Using a threshold of 0.1 km^2 produces 103 (2.3 ± 2.0 km^2) perennial snowfields and 19 (7.6 ± 1.5 km^2) glaciers in 1957 (Table 3). By this definition, glaciers account for 78% of the perennial ice and snow cover. However, if the small (<0.1 km^2) features were ignored then an important faction of ice cover would be overlooked. Raub et al. (2006) used an area threshold of 0.05 km^2; applying this threshold yields 94 (1.3 ± 1.5 km^2) perennial snowfields and 28 (8.6 ± 3.0 km^2) glaciers. By this definition, the glaciers account for 87% of the total perennial snow and ice cover.

Table 3. Comparison of features that are <0.05 km^2, <0.1 km^2, and >0.1 km^2.

	1949		1957	
	Area	**Count**	**Area**	**Count**
<0.05	1.6 ± 0.83 (18%)	95 (78%)	1.3 ± 1.46 (13%)	94 (77%)
<0.1	2.4 ± 1.09 (27%)	105 (86%)	2.3 ± 1.97 (23%)	103 (84%)
>0.1	6.7 ± 0.56 (73%)	17 (14%)	7.6 ± 1.50 (78%)	19 (16%)

	1990		2003	
	Area	**Count**	**Area**	**Count**
<0.05	0.7 ± 0.30 (9%)	101 (83%)	0.8 ± 0.57 (11%)	102 (84%)
<0.1	1.1 ± 0.36 (15%)	105 (87%)	1.1 ± 0.66 (15%)	106 (87%)
>0.1	6.2 ± 0.27 (85%)	15 (13%)	6.0 ± 0.51 (85%)	16 (13%)

While area thresholds apply an approximate estimate of glaciers versus perennial snow and ice values, the basis is not physical. An alternative approach is to estimate movement – the defining characteristic between glaciers and perennial snow. To determine movement I followed Basagic and Fountain (2011) and estimated whether the critical shear stress exceeds the threshold for movement. If the shear stress at the base of a glacier is greater than 10^5 Pa then the glacier deforms or moves. The shear stress is calculated by,

$$\tau_b = \rho_i g h sin\alpha, \quad (3)$$

where ρ_i is ice density (900 kg m^{-3}), g is gravitational acceleration (9.81 ms^{-2}), h is ice thickness (m), and α is the ice surface slope. I used the maximum slope found in the glacier polygon, providing a conservative estimate (Basagic, 2008; Dick, 2013). The thicknesses were calculated using a scaling relationship for area- volume (Chen and Ohmura, 1990; Bahr et al., 1997) and dividing by the surface area, the thickness was calculated by,

$$h = \alpha A^{\beta - 1}, \quad (4)$$

where α and β are empirical constants and A is the glacier area (km^2). I used the 'Cascade, small glaciers' scaling factors with an α of 21.346 and a β of 1.145 from Chen and Ohmura (1990). Using the 1990 DEM because it was close in time to Driedger and Kennard (1986) the calculated thicknesses matched well with their measured thicknesses (Table 4).

Table 4. The comparison of my estimated average thicknesses in 1990 (shear stress) to the calculated thicknesses by Driedger and Kennard (1986) for the Collier, Prouty, Hayden, and Diller glaciers.

Glacier	Shear Stress Thickness (m)	Driedger and Kennard Thickness (m)
Collier	21	19
Prouty	22	17
Hayden	21	26
Diller	20	20

.

Of the 122 glacier and perennials snowfields in the 1957 inventory 19 (16%) exceeded the critical stress, with a total area of 7.76 ± 1.50 km^2 (79%) and a mean of 0.395 km^2. By 1990 the number of glaciers drops to 9 (7%), with a total of 5.21 ± 0.209 km^2 (79%) and a mean of 0.484 km^2 (Table 5). I applied the 19 glaciers dataset found in 1957 to 1949 and derived the sizes in 1949 and applied 9 glacier dataset from 1990 to 2003. I did not calculate shear stress for 1949 or 2003 because I didn't have DEMs for their years.

Table 5. Comparison of the total glacier and perennial snowfield statistics and glaciers determined by the basal shear stress threshold. Those features determined to be glaciers in 1957 and 1990 were considered to be glaciers in 1949 and 2003 respectively. Max is maximum and min in minimum. Area is km^2.

	1949		1957	
Statistic	**Total**	**>10^5 Pa**	**Total**	**>10^5 Pa**
Number	122	19	122	19
Mean Area	0.072	0.351	0.091	0.408
Median Area	0.021	0.279	0.023	0.347
Max Area	1.07	1.07	1.16	1.16
Min Area	0.005	0.045	0.005	0.05
Total Area	9.03 ± 1.65	6.67 ± 0.56	9.88 ± 3.47	7.76 ± 1.50

	1990		2003	
	Total	**>10^5 Pa**	**Total**	**>10^5 Pa**
Number	122	12	121	12
Mean Area	0.064	0.484	0.060	0.311
Median Area	0.007	0.33	0.008	0.4
Max Area	1.18	1.18	1.11	1.11
Min Area	0.0002	0.15	0.0002	0.16
Total Area	7.40 ± 0.66	5.81 ± 0.21	7.10 ± 1.16	5.51 ± 0.39

The number of glaciers are comparable to the results in 1957 using the area threshold of >0.1 km^2 (Table 6). The difference in area between the glaciers that exceeded the threshold is often less than the uncertainty within each threshold. For the Three Sisters the two methods are roughly equivalent. The area of glaciers estimated by the shear stress is within 25% of the area estimated by the area threshold. Note that the difference increases with time.

Table 6. Comparison of the glacier area thresholds (0.05 and 0.1 km^2) to the shear stress threshold (>10^5 Pa) for a glacier. Those features determined to be glaciers in 1957 and 1990 were considered to be glaciers in 1949 and 2003 respectively. Difference and percentage is for >0.1 km^2 and >10^5. Area is in km^2.

	1949		1957	
	Area	**Count**	**Area**	**Count**
>0.05 km^2	7.43 ± 0.82	27	8.58 ± 2.01	28
>0.1 km^2	6.68 ± 0.63	17	7.61 ± 1.93	19
>10^5 Pa	6.67 ± 0.56	19	7.76 ± 1.50	19
Difference	**0.01**	**2**	**0.15**	**0**
Percent	**0.01%**	**11%**	**2%**	**0%**

	1990		2003	
	Area	**Count**	**Area**	**Count**
>0.05 km^2	6.70 ± 0.36	21	6.30 ± 0.57	19
>0.1 km^2	6.16 ± 0.28	15	5.98 ± 0.51	16
>10^5 Pa	5.21 ± 0.21	9	4.96 ± 0.39	9
Difference	**0.95**	**6**	**1.32**	**7**
Percent	**15%**	**40%**	**22%**	**44%**

In 1957, each method selected 19 glaciers (21 total glaciers), but they were different glaciers and as a result the areas are not identical (Figure 11, Table 7). Using the shear stress all 15 named glaciers exceeded the threshold, using the area threshold all but one named glacier (Villard) were included. Of these five unnamed glaciers that passed the area threshold, three also passed the shear stress threshold. In 1990, only 9 glaciers (9 named) passed the shear stress threshold (they also exceeded the threshold in 1957); the Carver, Clark, Eugene, Irving, Linn, Thayer, and Villard glaciers did not pass. For the area threshold 13 named glaciers passed, Villard and Eugene glaciers did not.

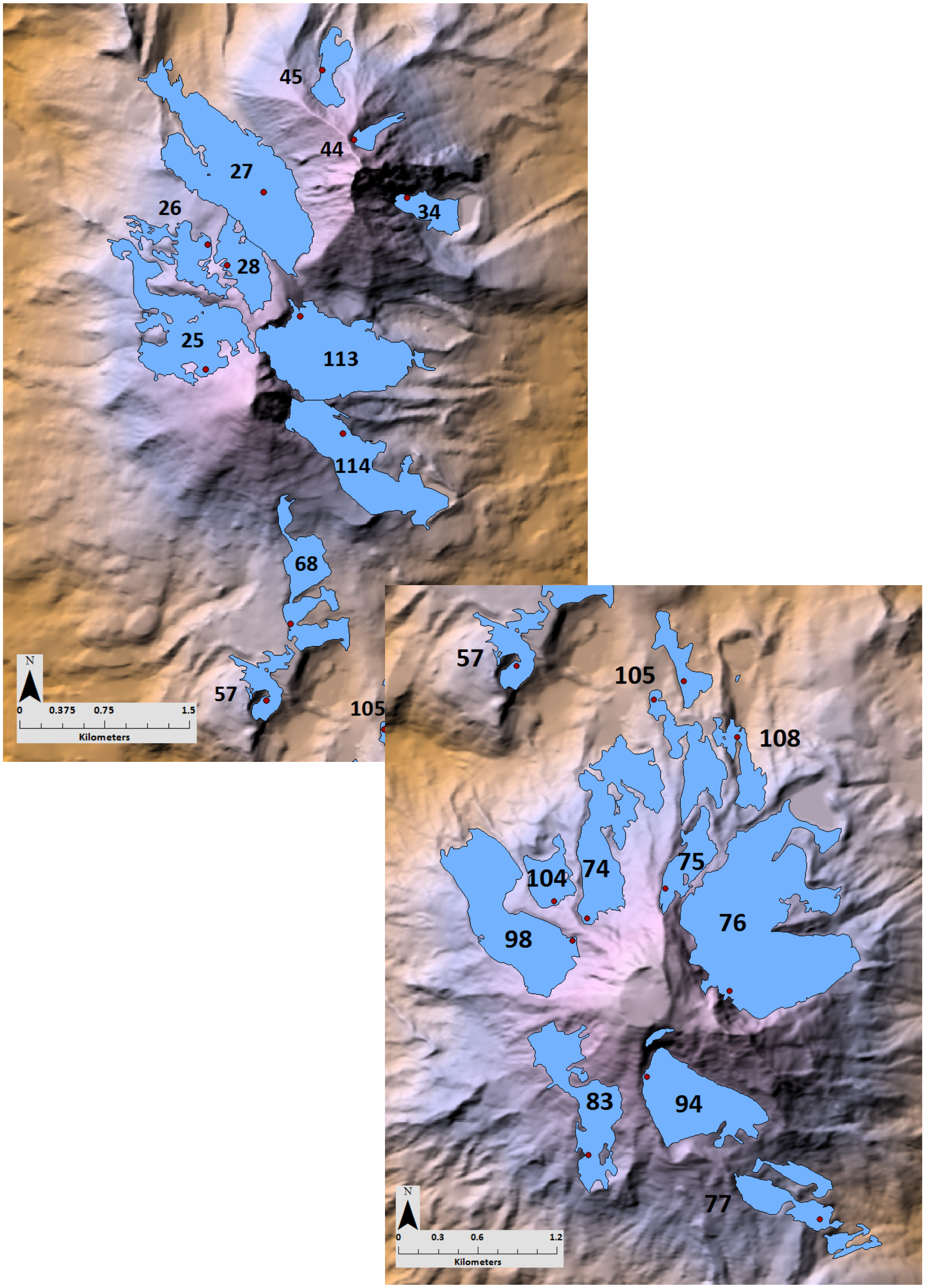


Figure 11. The location of the 21 glaciers identified by either the sheer stress or area threshold with corresponding TS_ID. Red dots are locations of cells with the maximum slope used in basal shear stress calculation. Maps are in WGS 84 UTM Zone 10.

Table 7. Glaciers that passed the area threshold (0.1 km^2) and/or the basal shear stress threshold. RECNO is record number for 24K inventory and TS_ID is identification number from this study.

			1957		1990	
Glacier Name	**RECNO**	**TS_ID**	**Area Threshold**	**>10^5 Pa Threshold**	**Area Threshold**	**>10^5 Pa Threshold**
Collier	4209	27	X	X	X	X
Linn	4228	45	X	X	X	
Thayer	4216	34	X	X	X	
Villard	4227	44		X		
Diller	10525	114	X	X	X	X
Hayden	10518	113	X	X	X	X
Irving	4262	68	X	X	X	
Renfrew	4207	25	X	X	X	X
Carver	4306	105	X	X	X	
Clark	4281	83	X	X	X	
Eugene	4304	104	X	X		
Lewis	4293	94	X	X	X	X
Lost Creek	4297	98	X	X	X	X
Prouty	4272	76	X	X	X	X
Skinner	4270	74	X	X	X	X
Unnamed	4208	26	X		X	
Unnamed	4209	28	X		X	X
Unnamed	4250	57	X	X		
Unnamed	4271	75	X	X		
Unnamed	4273	77	X	X		
Unnamed	4309	108		X		

Discussion and Conclusions

Multiple inventories of the glaciers and perennial snowfields were compiled from orthorectified vertical aerial imagery from 1949, 1957, 1990, and satellite imagery from 2003. Overall, greater uncertainty was found for 1949 and 1957 imagery because of greater seasonal snow cover, lower image resolution, and smaller image scale. Of the two sources of uncertainty for larger glaciers and perennial snowfields (digitizing and interpretation) the interpretation typically represented the larger fraction. The digitizing uncertainty was smaller for larger ice features and that was mainly controlled by the area of the feature and the observed digitizing uncertainty (Du). Smaller perennial snow patches always had higher relative uncertainties using the buffer method compared to larger glaciers using the root sum of squares. These results are consistent with other inventories in North America. Basagic (2008) and Dick (2013) found that uncertainties for small features were larger relative to larger features in their studies of the Sierra Nevada and North Cascades, respectively. DeBeer and Sharp (2007) also found the same result for features in the Canadian Cordillera.

The 24K outlines were based on 1957 imagery used for the 1959 1:62,500 USGS topographic map and updated using 1980 imagery for the 1988 USGS map. However, the 1980 imagery shows large amounts of seasonal snow and as a result, the 24K inventory was not used. This result differed from other regional inventories that found the 24K inventory to be useful (Granshaw and Fountain, 2006; Basagic and Fountain, 2011; Dick, 2013).

The inventories in 1949 and 1957 showed 402 snow and ice features; 1990 showed 337 features. In 1990 65 features were missing due to insignificant coverage in imagery. In 2003 121 features were found as a result of focusing on features that were found as perennial in the previous inventories. The number of perennial features was 122 for 1949 through 1990 and dropped to 121 in 2003. The total area of the glaciers and perennial snowfields shrank from 9.03 ± 165 km^2 to 7.10 ± 1.16 km^2 in 2003. Average feature size shrank from 0.072 km^2 to 0.060 km^2. Of the 65 features that were missing due to insignificant coverage in the 1990 imagery 30 would be considered seasonal snow, and the area total represents a small percentage of the total population area. Comparing the number and area of glaciers and perennial snowfields in 2003

(121, 7.1 ± 1.16 km^2) to previous studies reveals a smaller population and area compared to the Sierra Nevada (1719, 39.15 ± 7.52 km^2) (Basagic and Fountain, 2011) and North Cascades (1935, 236.20 ± 12.60 km^2) (Dick, 2013). This is to be expected because those studies covered a much larger land area. The number and area of glaciers on the Three Sisters (19, 7.76 ± 1.50 in 1957) as compared to other Cascade volcanoes, Mount Hood (12, 7.79 ± 0.33 km^2 in 1946) (Jackson, 2007), Mount Rainier (26, 88.11 ± 0.99 km^2 in 1971) (Nylen, 2001), Mount Adams (12, 21.73 ± 0.99 km^2 in 1969) (Sitts et al., 2010), and Mount Baker (6, 21.52 ± 0.711 km^2 in 1956) (Dick, 2013), is mostly greater in number and smaller in area with a couple of exceptions.

The average elevation (median) of the glacier and perennial snowfield increased from 1957 to 1990, from 2428 m (2365 m) to 2432 m (2373 m) with most ice-covered area being found between 2300 and 2800 m (9.15 km^2 (92.7%) in 1957 and 6.88 km^2 (94.8%) in 1990). The mean feature elevation is lower than those in the Sierra Nevada (3419 m) (Basagic and Fountain, 2011) and higher than those in the North Cascades (1948 m) (Dick, 2013). The elevation band with the greatest ice-covered area also rose from over the same period, from 2400-2500 m (26.2%) in 1957 to 2500-2600 m (33.7%) in 1990. For comparison, in 1957 the elevation band of 2500-2600 m was 19.3% and in 1990 2400-2500 m was 17.5%. Glaciers were found facing all directions in both 1957 and 1990, but a greater percentage was found facing the NW-E directions in 1990 (85.4%) as compared to 1957 (80.7%). This suggests the bulk of glacier cover on the Three Sisters is becoming concentrated higher up as lower elevations snow and ice is being lost more towards the northerly directions. Mean slope of the glaciers showed no significant change 20.9° in 1957 and 21.4° in 1990, with roughly 90% ranging from 10-30°. The average slopes for the glaciers and perennial snowfields are lower than compared to both the Sierra Nevada (28°) and North Cascades (29.7°). All of these results are similar to results found across the American West.

Distinguishing of glaciers from snowfields used a threshold on area (0.1 km^2) and on shear stress. The area threshold of 0.1 km^2 (which was determined to be a better estimate than a threshold of 0.05 km) and shear stress test yielded 19 glaciers in 1957 and yielded the same number of glaciers, with only two differences. In 1990, 15 glaciers were over for the area threshold and the shear stress test yielded 9 glaciers. Based on these results, an area threshold of >0.1 km^2 criteria seems to be a reasonable for determining a glacier on the Three Sisters when topographic information is absent. These results seem in line with other inventories across the American West. Basagic (2008) found that perennial snow and ice features >0.15 km^2 in the Sierra Nevada of Central California all met the glacier definition. Dick (2013) found that an area threshold of 0.1 km^2 in the North Cascades of Northern Washington produced similar results to the glacier definition. She also found that when reducing the shear stress threshold down to 0.925 x 10^5 Pa, it matched well with previous inventories. She concluded that a shear stress threshold was a better estimate of identifying glaciers.

Chapter Three – Temporal Area Change

Introduction

The purpose of this chapter is to examine the temporal change of the glaciers and perennial snowfields on the Three Sisters. In addition to the inventories of chapter 2, I used aerial photography, digital elevations models (DEMs), satellite imagery, oblique ground based photography, and previous studies to reconstruct past changes of individual glacier and perennial snowfields. These data were used to quantify both the magnitude and rate of area change.

Methods

Glacier and perennial snowfield areas were compared between 5 sets of glacier inventories, (1949-1957, 1949-1990, 1957-1990, 1949-2003, and 1990-2003), summarized in chapter 2. I then focus on the 15 named glaciers (the Carver, Clark, Eugene, Lewis, Lost Creek, Prouty, and Skinner glaciers on South Sister and the Collier, Diller, Hayden, Irving, Linn, Renfrew, Thayer, and Villard glaciers on the North and Middle Sisters) to study because they represent most of the ice on the volcanoes, and they have the most extensive historic record (Table 8). The uncertainty for the change in area is estimated from the root sum of squares of the glacier's uncertainties at each time,

$$U_T = \sqrt{(U_1)^2 + (U_2)^2}\ , \qquad (5)$$

where U_1 and U_2 are the uncertainties of the glacier area at inventory time 1 and inventory time 2. The relative uncertainty of the area change is,

$$U_R = \frac{U_T}{A_1}, \quad (6)$$

where A_1 is the area of the initial glacier. If U_R is >1 the area change was not significant.

Table 8. Imagery and previous studies used in this study for examining the 15 named glaciers.

Year	Data Type	Data Collector(s)	Source
~1900	Area	Dr. Jim O'Connor	O'Connor et al., 2001
1925	Area	Dr. Edwin Hodge	Hodge, 1925
1937	Area	Charlie Cannon and Jessica Leonard	Cannon et al., unpublished
1949	Single Frame Vertical Aerial	USGS	USGS – OWSC
1957	Single Frame Vertical Aerial	USGS	www.earthexplorer.usgs.gov
1990	Single Frame Vertical Aerial	USDA	OWSC
2003	Satellite Imagery (QuickBird)	DigitalGlobe	Google Earth
2007	Area	Charlie Cannon and Jessica Leonard	Cannon et al., unpublished

Results and Analysis

Glacier Inventories

To examine change in the glaciers and perennial snowfields I summed the area within four different categories: 1) ≥0.1 km^2, 2) ≤0.1 km^2, 3) significant change (U_R < 1), and 4) insignificant change (Table 9). I used 0.1 km^2 instead of the shear stress threshold because I did not calculate values for 1947 and 2003; the number of glaciers is estimated from the 1957 and 1990 as baselines, respectively. Most glacier and perennial snowfields showed more significant change over longer time periods compared to shorter time periods. Shorter time periods show a greater number of features with insignificant change, 63 (52%) in 1949-1957, 53 (43%) in 1990-2003, and 65 (53%) in 1957-1990, compared to longer time intervals, 11 (9%) in 1949-1990, and 16

(13%) in 1949-2003. Smaller features, <0.1 km^2, make up a larger proportion of the insignificant features. From this point forward I will only discuss glaciers and perennial snowfields that exhibit significant change.

Table 9. Area change based on inventory glaciers on the Three Sisters. 1990 has two glaciers with no data, Thayer and Villard glaciers. Significant change is where U_R <1 and insignificant change are U_R >1.

Temporal Period	Number	Area (km^2)		Area Change (km^2)
1949-2003	**122**	**1949**	**2003**	
Area ≥ 0.1 km^2	17	6.676 ± 0.555	6.017 ± 0.532	-0.659 ± 0.401
Area < 0.1 km^2	105	2.351 ± 1.090	1.070 ± 1.070	-1.281 ± 0.648
Significant Change	106	8.910 ± 1.526	6.995 ± 1.082	-1.914 ± 0.974
Insignificant Change	16			
1949-1957	**122**	**1949**	**1957**	
Area ≥ 0.1 km^2	17	6.676 ± 0.555	7.611 ± 1.505	0.935 ± 0.816
Area < 0.1 km^2	105	2.351 ± 1.090	2.272 ± 1.968	-0.079 ± 1.132
Significant Change	59	8.174 ± 1.067	10.44 ± 2.980	0.832 ± 1.345
Insignificant Change	63			
1949-1990	**122**	**1949**	**1990**	
Area ≥ 0.1 km^2	18	6.565 ± 0.533	6.200 ± 0.284	-0.365 ± 0.332
Area < 0.1 km^2	104	2.306 ± 1.086	1.053 ± 0.343	-1.253 ± 0.579
Significant Change	111	8.789 ± 1.527	7.215 ± 0.600	-1.575 ± 0.853
Insignificant Change	11			
1957-1990	**122**	**1957**	**1990**	
Area ≥ 0.1 km^2	19	7.865 ± 1.597	6.328 ± 0.315	-1.408 ± 0.809
Area < 0.1 km^2	103	2.018 ± 1.876	0.925 ± 0.312	-1.039 ± 0.949
Significant Change	57	9.052 ± 2.457	6.970 ± 0.283	-2.081 ± 1.269
Insignificant Change	65			
1990-2003	**121**	**1990**	**2003**	
Area ≥ 0.1 km^2	16	6.155 ± 0.272	5.979 ± 0.509	-0.290 ± 0.299
Area < 0.1 km^2	105	1.098 ± 0.355	1.107 ± 0.656	-0.012 ± 0.374
Significant Change	67	7.101 ± 0.524	6.717 ± 0.904	-0.384 ± 0.548
Insignificant Change	54			

To examine the effects of time intervals on whether change was significant I grouped the magnitude of change. The distribution clearly shows that over longer time period's area change is skewed towards greater loss and shorter time periods change is smaller (Table 10). For the short time interval of 1949-1957 the bin with the largest number of features (10) gained 10-20% in area, with a total area change of 0.442 ± 0.423 km^2 and an average area change of 0.044 km^2. For the longer timer period of 1957-1990 the bins with the largest number of feature (9) (16%), lost 50-60% and 30-40% with an area change of -0.443 ± 0.243 km^2 and -0.396 ± 0.186 km^2 and an average area of -0.049 km^2 and -0.044 km^2.

Table 10. The distribution of glacier and perennial snowfields with significant area change for the five time periods.

	Bin Count				
Bins	**1949-2003**	**1949-1957**	**1949-1990**	**1957-1990**	**1990-2003**
-100%	1	0	0	0	0
-100%--90%	10	0	19	4	1
-90%--80%	15	0	10	3	0
-80%--70%	12	2	12	1	1
-70%--60%	14	3	7	6	3
-50%--60%	12	3	11	9	2
-50%--40%	6	2	11	7	2
-40%--30%	9	3	8	9	6
-30%--20%	5	8	9	5	8
-20%--10%	6	6	7	5	7
-10%-0%	5	4	7	1	15
0%-10%	8	8	6	5	10
10%-20%	1	10	2	0	4
20%-30%	2	5	0	0	1
30%-40%	0	4	0	0	3
40%-50%	0	0	0	0	2
50%-60%	0	1	0	0	1
60%-70%	0	0	0	0	1
70%-80%	0	0	0	0	0
80%-90%	0	0	0	0	0
90%-100%	0	0	0	0	0
>100%	0	0	0	0	0
Total	**106**	**59**	**109**	**55**	**67**

For 1949-1990 the bin with the largest number of features 19 (17%) lost 90-100% in area with no feature gaining over 20%. The total area change is -0.301 ± 0.105 km^2 with an average area change of -0.016 km^2 (-0.013 km^2). For the longest time period of 1949-2003, the bin with the largest number of features 15 (14%) lost 80-90%

in area with no feature gaining more than 20%. The total area change is -0.169 ± 0.104 km^2 with an average area change of -0.013 km^2. For 1990-2003, the bin with the largest number of features 15 (22%) lost 0-10%. The significant area change is -0.032 ± 0.097 km^2 with an average area change of -0.003 km^2. Since smaller glaciers (< 0.1 km^2), which have more variability, dominate populations it is expected to see insignificant change when examining relatively short time periods.

In the shorter time periods of 1949-1957 and 1990-2003 five and seven glaciers respectively exhibited a significant positive change of greater than 30%. The 5 significant glaciers area represent 3.78% (0.335 km^2) of the total area for 1957 with an average of 0.067 km^2 and the seven glaciers represent 0.6% (0.043 km^2) of the total for 2003 with an average of 0.006 km^2. These features are perennial snow patches; which show greater variability due to seasonal snow cover masking their true perennial boundaries. To assess whether size has an influence on the fractional area change (FAC), change divided by initial area plotted against area was calculated (Figure 12). Overall, smaller glaciers show greater uncertainty and more variability compared to larger glaciers over shorter time periods, less so in longer time periods (Table 11). The largest variability occurred in glacier <0.1 km^2 from 1990-2003 (-100% to 68.3%).

Table 11. The magnitude of variability of significant area change for glaciers and perennial snowfields for the 5 inventory comparisons. Area is in km^2.

	1949-2003		**1949-1957**		**1949-1990**		**1957-1990**		**1990-2003**	
Area	**<0.1**	**≥0.1**	**<0.1**	**≥0.1**	**<0.1**	**≥0.1**	**<0.1**	**≥0.1**	**<0.1**	**≥0.1**
Min	-100 %	-69%	-78%	-29%	-99%	-62%	-99%	-61%	-92%	-16%
Max	25%	9%	35%	51%	13%	18%	-2%	18%	69%	11%

It’s evident that changes in larger glacier and perennial snowfields have smaller relative uncertainties while smaller features show higher relative uncertainties consistent with initial relative uncertainty (Figure 13). Consequently, longer time intervals show more significant change in the small features.

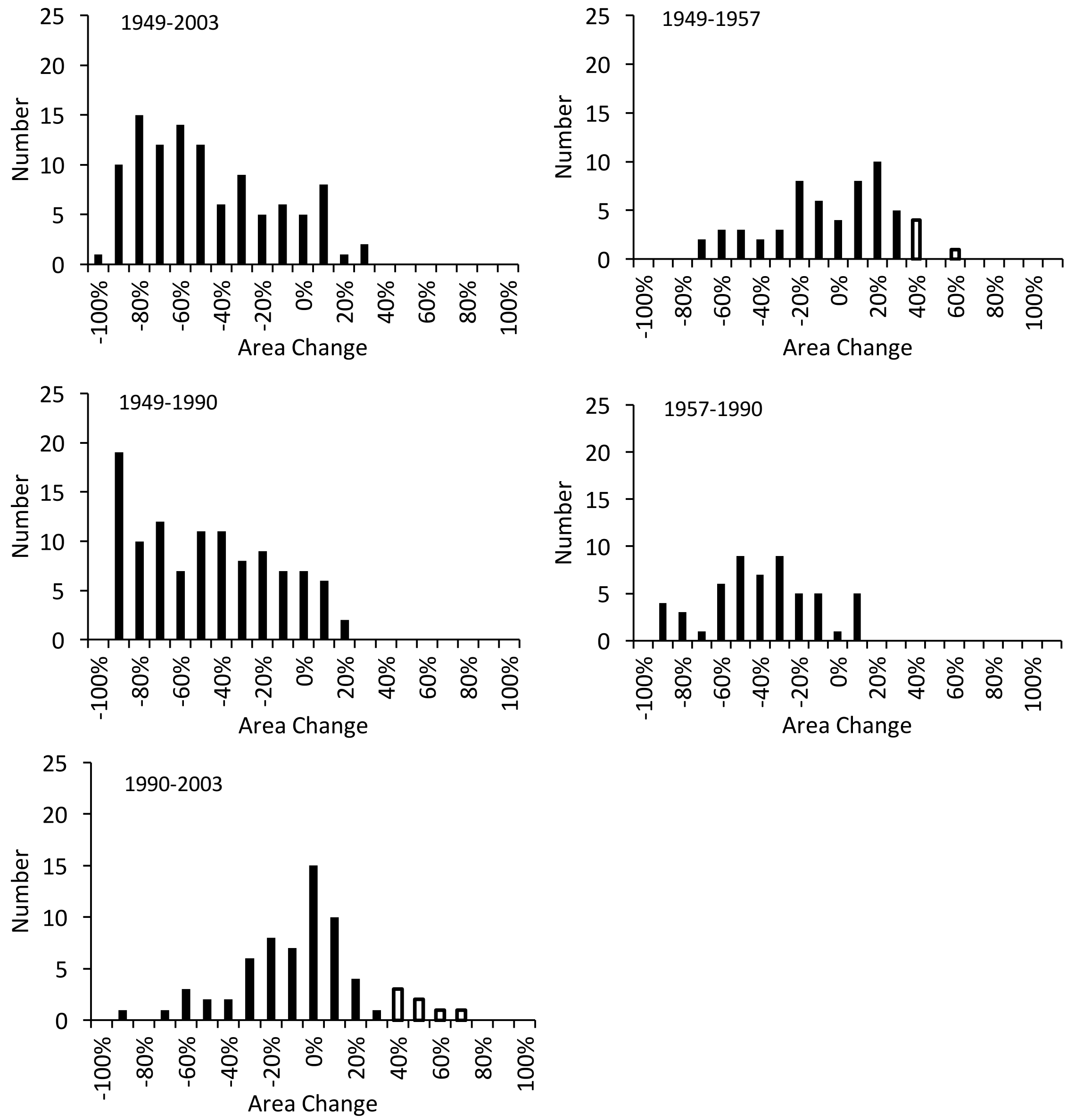


Figure 12. Histograms of the significant area change. Number is number of glaciers. The value of each bin percent range is the maximum of that grouping. Open bars represent perennial snow patches masked by seasonal snow cover resulting in >30% change.

The fractional area plots show that with increasing glacier and perennial snowfield area the uncertainty gets smaller and greater time spans are skewed away from 0%.

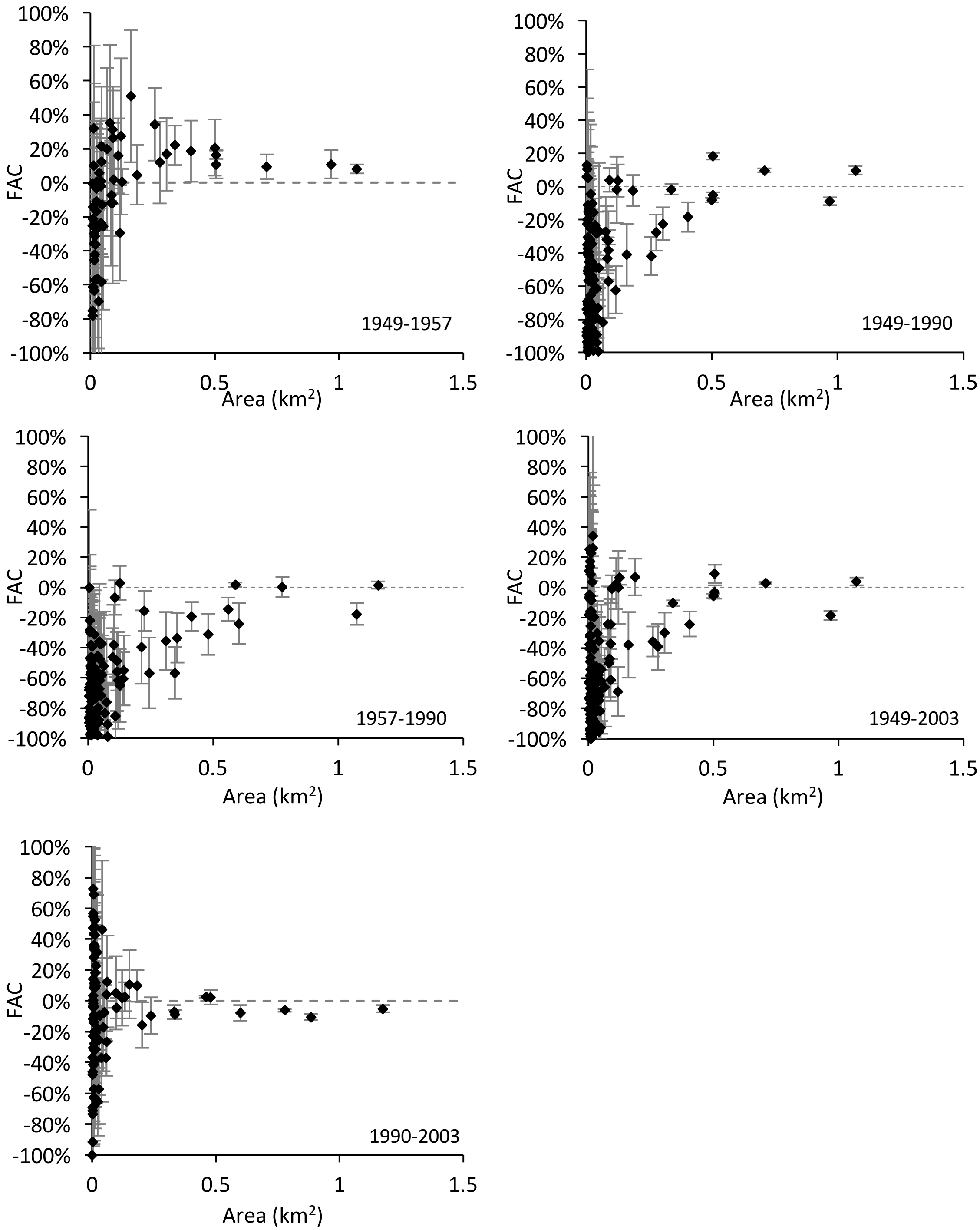


Figure 13. The fractional area plots for significant change glacier and perennial snowfields for 1949-1957, 1957-1990, 1949-1990, 1949-2003, and 1990-2003.

The 15 Named Glaciers

Results

The 15 named glaciers account for 72% (7.16 ± 1.22 km^2) of the total ice-covered area and 15 of the 122 glaciers and perennial snowfields on the Three Sisters in 1957 (Figure 14).

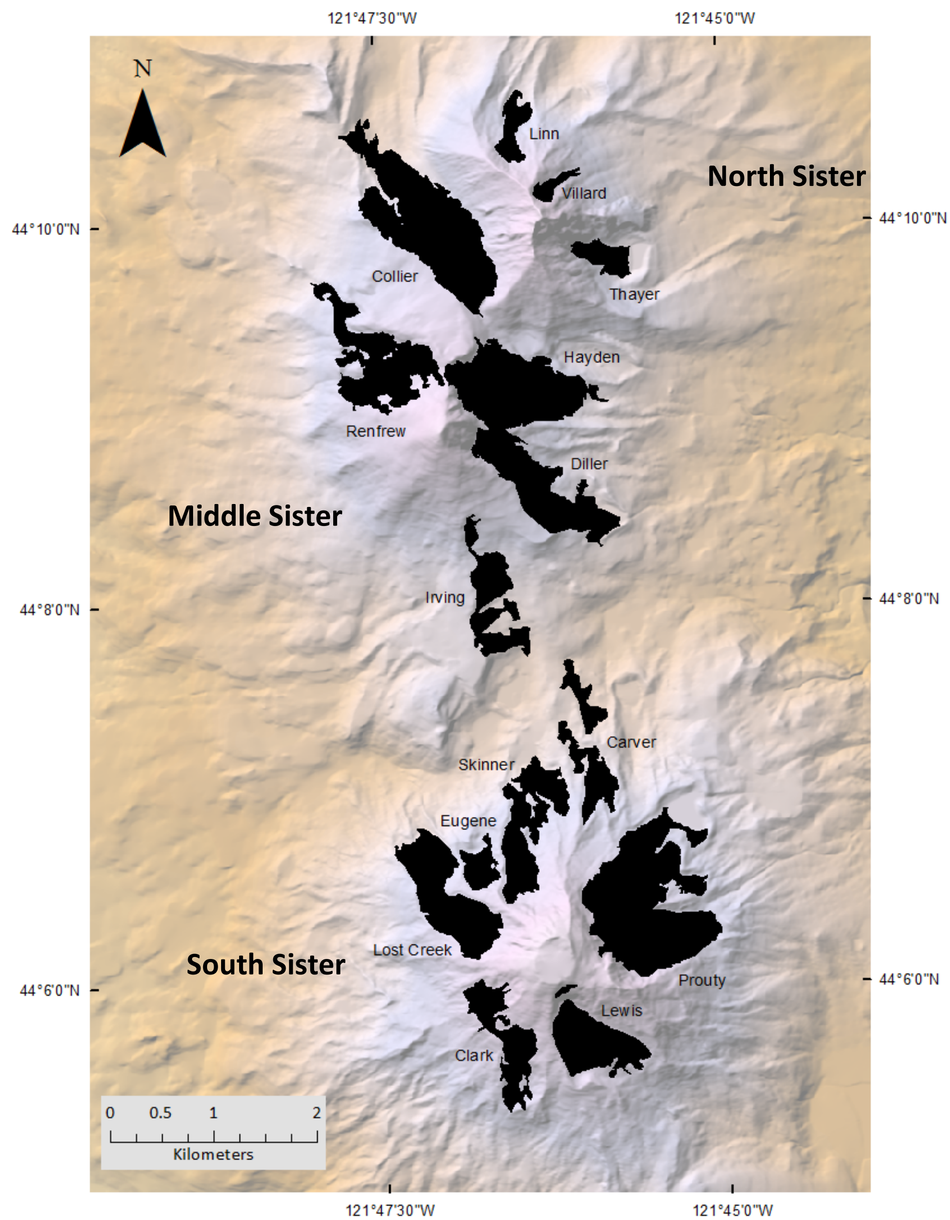


Figure 14. Location of the 15 named glaciers, in black, on the Three Sisters in 1957. The Eugene, Linn, Thayer, and Villard glaciers were identified as non-glaciers in 1990. Map is in WGS 84 UTM Zone 10.

Their average area (0.477 km^2) is much larger than the average glacier and perennial snowfield (0.091 km^2) and their average elevation is 2548 m, which is higher than the glacier population (2428 m). The Villard Glacier is the highest mean elevation 2773 m and Carver Glacier is the lowest (2328 m) in 1957. All 15 glaciers met the critical shear stress threshold to define movement in 1957. Like the total glacier and perennial snowfield population they face all directions. Their range of areas span that of the entire glacier and perennial snowfield population on the mountains with 4 that have areas between 0.05-0.2 km^2, 5 between 0.2-0.5 km^2, 4 between 0.5-0.8 km^2, and 2 larger than 0.8 km^2 (Figure 15; Table 12).

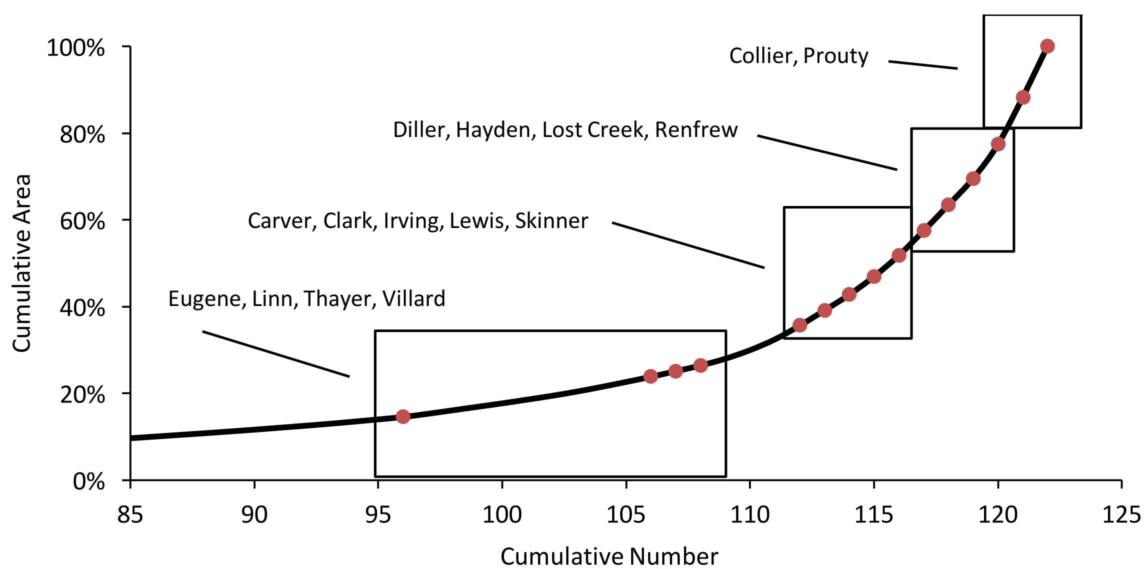


Figure 15. Cumulative area total of the glacier inventory in 1957 with the 15 named glaciers in red.

I used the zonal statistic package in ArcGIS to derive averages, minimums, and maximums for each glacier's elevation, elevation difference (highest elevation subtracted from lowest), slope, and aspect for the 15 named glaciers, using the 1957 10 m NED DEM (Table 12) and compare it to the topographic statistics for other years to observe how they have been changing. Finally, I examine Collier Glacier because it has the most comprehensive data set of all the glaciers.

Table 12. Area, average elevation, elevation difference, average slope, and average aspect of the 15 named glaciers. The characteristics date to 1957 from the USGS 24,000 topographic maps.

Glacier	Volcano	Area (km^2)	Elevation (m)	Elevation Difference (m)	Slope (°)	Aspect (°)
Collier	North	1.074 ± 0.153	2483	545	19	349
Linn	North	0.126 ± 0.008	2507	389	28	7
Thayer	North	0.129 ± 0.043	2434	300	25	94
Villard	North	0.054 ± 0.008	2773	393	39	51
Diller	Middle	0.588 ± 0.017	2496	457	21	82
Hayden	Middle	0.776 ± 0.101	2592	521	20	90
Irving	Middle	0.357 ± 0.117	2347	386	15	127
Renfrew	Middle	0.604 ± 0.164	2623	492	19	297
Carver	South	0.313 ± 0.120	2328	348	16	16
Clark	South	0.347 ± 0.107	2712	360	20	219
Eugene	South	0.117 ± 0.037	2522	190	25	345
Lewis	South	0.414 ± 0.078	2766	457	18	145
Lost Creek	South	0.561 ± 0.085	2545	536	20	324
Prouty	South	1.160 ± 0.042	2617	576	21	42
Skinner	South	0.048 ± 0.130	2469	485	20	350
Mean		0.477	2548		22	
Max.		1.234	2773		39	
Min.		0.054	2328		16	
Total		**7.10 ± 0.369**				

The Little Ice Age (LIA) extents for the 15 named glaciers were derived from LIA moraine locations which record the extent of the glacier at ~1900 when glaciers started to recede. Historic photos from 1903 (Russell, 1905) confirm that glaciers were at or near these neoglacial moraine crests (O’Connor et al., 2001), which is true in other regions around the American West (Basagic and Fountain, 2011; Dick, 2013). O’Connor et al. (2001) mapped the moraines and calculated LIA areas and I remapped the moraine crests from the 1990 aerial orthophotographs, to be sure the mapping was consistent with my methods and to produce digital files of glacier perimeters. The 1990 orthophotographs were used because they are an excellent high quality color image, which enhances contrast.

Hodge (1925) published the earliest account of glacier extent and surface area on the Three Sisters. He included areas of the 15 named glaciers, photos, and a map of the region, however no explanation of methods was given.

Cannon et al. (unpublished) used oblique aerial and ground-based photographs to digitized glacier extents from 1935 to 2007. Their study included surface area and uncertainty calculations for 9 of the 15 glaciers, including: Clark, Collier, Diller, Eugene, Hayden, Lost Creek, Prouty, Renfrew, and Thayer. The surface areas that were used for the temporal study are the outlines from 1935 and 2007.

Areas were defined for the 15 named glaciers for ~1900 (LIA), 1949, 1957, 1990, and 2003 from this thesis and data were collected from other studies for 1925, 1937, and 2007 (Hodge, 1925; Cannon and Leonard, unpublished) (Table 13). Of all the named glaciers, Collier Glacier has one of the most extensive records of the glaciers on the Three Sisters: ~1900, 1925, 1935, 1949, 1957, 1990, 2003, and 2007. Previous studies area estimates for Collier Glacier (McDonald, 1995; Jackson, 2007; Beedlow, 2010) were not used because these studies defined a smaller area of the glacier, as a result, their specific studies were not used. They excluded areas of ice no longer flowing to the main terminus, however, for the purpose of glacial inventories, this area is important to quantify.

Table 13. Named glaciers with the number of extents and the year.

Glacier	Number of Glacier Extents	Years
Carver	6	1900, 1925, 1949, 1957, 1990, 2003
Clark	8	1900, 1925, 1937, 1949, 1957, 1990, 2003, 2007
Collier	10	1900, 1910, 1925, 1931, 1937, 1949, 1957, 1990, 2003, 2007
Diller	8	1900, 1925, 1937, 1949, 1957, 1990, 2003, 2007
Eugene	8	1900, 1925, 1937, 1949, 1957, 1990, 2003, 2007
Hayden	8	1900, 1925, 1937, 1949, 1957, 1990, 2003, 2007
Irving	6	1900, 1925, 1949, 1957, 1990, 2003
Lewis	6	1900, 1925, 1949, 1957, 1990, 2003
Linn	7	1900, 1925, 1949, 1957, 1990, 2003
Lost Creek	8	1900, 1925, 1937, 1949, 1957, 1990, 2003, 2007
Prouty	8	1900, 1925, 1937, 1949, 1957, 1990, 2003, 2007
Renfrew	8	1900, 1925, 1937, 1949, 1957, 1990, 2003, 2007
Skinner	6	1900, 1925, 1949, 1957, 1990, 2003
Thayer	7	1900, 1925, 1937, 1949, 1957, 2003, 2007
Villard	6	1900, 1925, 1949, 1957, 1990, 2003

Area for the LIA of the 15 glaciers calculated by O'Connor et al. (2001) were found to be close to the area's I calculated except for the Lewis and Villard glaciers (Table 14). The LIA extents of these two glaciers were difficult to determine because of the lack of well-defined terminal and lateral moraines. To define an area for each of these glaciers, I averaged the area I estimated with the estimate by O'Connor et al. (2001). The area for the remaining 13 glaciers came from my digitized outlines. The uncertainty for the LIA outlines was estimated by applying a buffer.

Table 14. Comparison of the 15 named glaciers LIA areas from the digitized areas and O'Connor et al. (2001). All areas are in km^2.

Glacier	Digitized Area	O'Connor Area
Carver	1.172 ± 0.164	1.347
Clark	0.448 ± 0.091	0.464
Collier	2.157 ± 0.172	2.236
Diller	1.070 ± 0.117	1.031
Eugene	0.324 ± 0.080	0.210
Hayden	1.054 ± 0.120	1.635
Irving	0.430 ± 0.087	0.388
Lewis	0.558 ± 0.061	1.329
Linn	0.266 ± 0.066	0.280
Lost Creek	0.654 ± 0.105	0.788
Prouty	1.878 ± 0.164	1.905
Renfrew	0.682 ± 0.136	0.664
Skinner	0.721 ± 0.053	0.689
Thayer	0.243 ± 0.045	0.290
Villard	0.055 ± 0.024	0.541
Total	**11.71 ± 0.417**	**13.80**

The area of all 15 glaciers decreased over the past century (Table 15). Total area loss from ~1900 to 2003 is -6.70 ± 0.439 km^2 (-54.2%), ranging from -0.129 ± 0.046 km^2 (-53.1%) at Thayer Glacier to -1.36 ± 0.177 km^2 (-63.1%) at Collier Glacier, with an average area loss of 56%. The area changes exhibited a cycle of rapid retreat, advance/stabilization, and continued slower retreat (Table 16). The largest change occurred from ~1900 to 1949 when glacier area decreased by -6.12 ± 0.440 km^2 (-49.6%). Between 1949 and 1957 glacier area increased by 0.926 ± 0.394 km^2 (15%) as compared to the 1949 area, with the uncertainty being larger than the area change. Between 1957 and 1990 area decreased by -1.33 ± 0.379 km^2 (-19%). From 1990 to 2003 area continued to decrease slightly -0.172 ± 0.162 km^2 (-2.9%).

Table 15. Areas for the 15 named glaciers. Areas italicized and bolded (1990 - Thayer and Villard glaciers) area estimates not direct measurements.

Glacier	LIA ~1900	1925	1937	1949	1957	1990	2003	2007
Carver	1.172 ± 0.164	0.618	-	0.279 ± 0.060	0.313 ± 0.120	0.202 ± 0.002	0.170 ± 0.060	-
Clark	0.448 ± 0.091	0.156	0.127 ± 0.024	0.259 ± 0.030	0.347 ± 0.107	0.150 ± 0.052	0.166 ± 0.042	0.095 ± 0.019
Collier	2.157 ± 0.172	1.789	1.315 ± 0.027	0.969 ± 0.046	1.074 ± 0.153	0.883 ± 0.012	0.790 ± 0.032	0.795 ± 0.042
Diller	1.070 ± 0.117	0.784	0.533 ± 0.003	0.505 ± 0.018	0.588 ± 0.017	0.598 ± 0.007	0.551 ± 0.060	0.428 ± 0.025
Eugene	0.324 ± 0.080	0.401	0.098 ± 0.002	0.089 ± 0.012	0.117 ± 0.037	0.060 ± 0.027	0.068 ± 0.024	0.057 ± 0.003
Hayden	1.054 ± 0.120	0.931	0.740 ± 0.001	0.709 ± 0.001	0.776 ± 0.101	0.778 ± 0.014	0.730 ± 0.002	0.694 ± 0.003
Irving	0.430 ± 0.087	0.249	-	0.305 ± 0.060	0.357 ± 0.117	0.237 ± 0.002	0.214 ± 0.057	-
Lewis	0.943 ± 0.061	0.108	-	0.340 ± 0.011	0.414 ± 0.078	0.334 ± 0.018	0.304 ± 0.007	-
Linn	0.266 ± 0.066	0.160	-	0.126 ± 0.008	0.127 ± 0.017	0.131 ± 0.023	0.134 ± 0.009	0.143 ± 0.009
Lost Creek	0.654 ± 0.105	0.759	0.566 ± 0.014	0.505 ± 0.010	0.561 ± 0.085	0.479 ± 0.016	0.490 ± 0.042	0.506 ± 0.005
Prouty	1.878 ± 0.164	0.666	1.097 ± 0.040	1.072 ± 0.040	1.160 ± 0.042	1.175 ± 0.036	1.115 ± 0.040	0.709 ± 0.022
Renfrew	0.682 ± 0.136	0.748	0.578 ± 0.007	0.500 ± 0.014	0.604 ± 0.164	0.459 ± 0.004	0.472 ± 0.005	0.460 ± 0.041
Skinner	0.721 ± 0.053	0.383	-	0.405 ± 0.066	0.481 ± 0.130	0.331 ± 0.027	0.307 ± 0.013	-
Thayer	0.243 ± 0.045	0.227	0.098 ± 0.014	0.111 ± 0.023	0.129 ± 0.043	***0.105 ± 0.030***	0.114 ± 0.030	0.043 ± 0.011
Villard	0.298 ± 0.024	0.082	-	0.045 ± 0.004	0.054 ± 0.008	***0.044 ± 0.006***	0.021 ± 0.006	-
Total	**12.34 ± 0.417**	**8.061**		**6.22 ± 0.140**	**7.10 ± 0.369**	**5.97 ± 0.089**	**5.65 ± 0.135**	
Δ from 1900				**-6.12 ± 0.440**	**-5.19 ± 0.557**	**-6.52 ± 0.427**	**-6.70 ± 0.439**	
% Change				**-49.6%**	**-42.4%**	**-51.6%**	**-54.2%**	

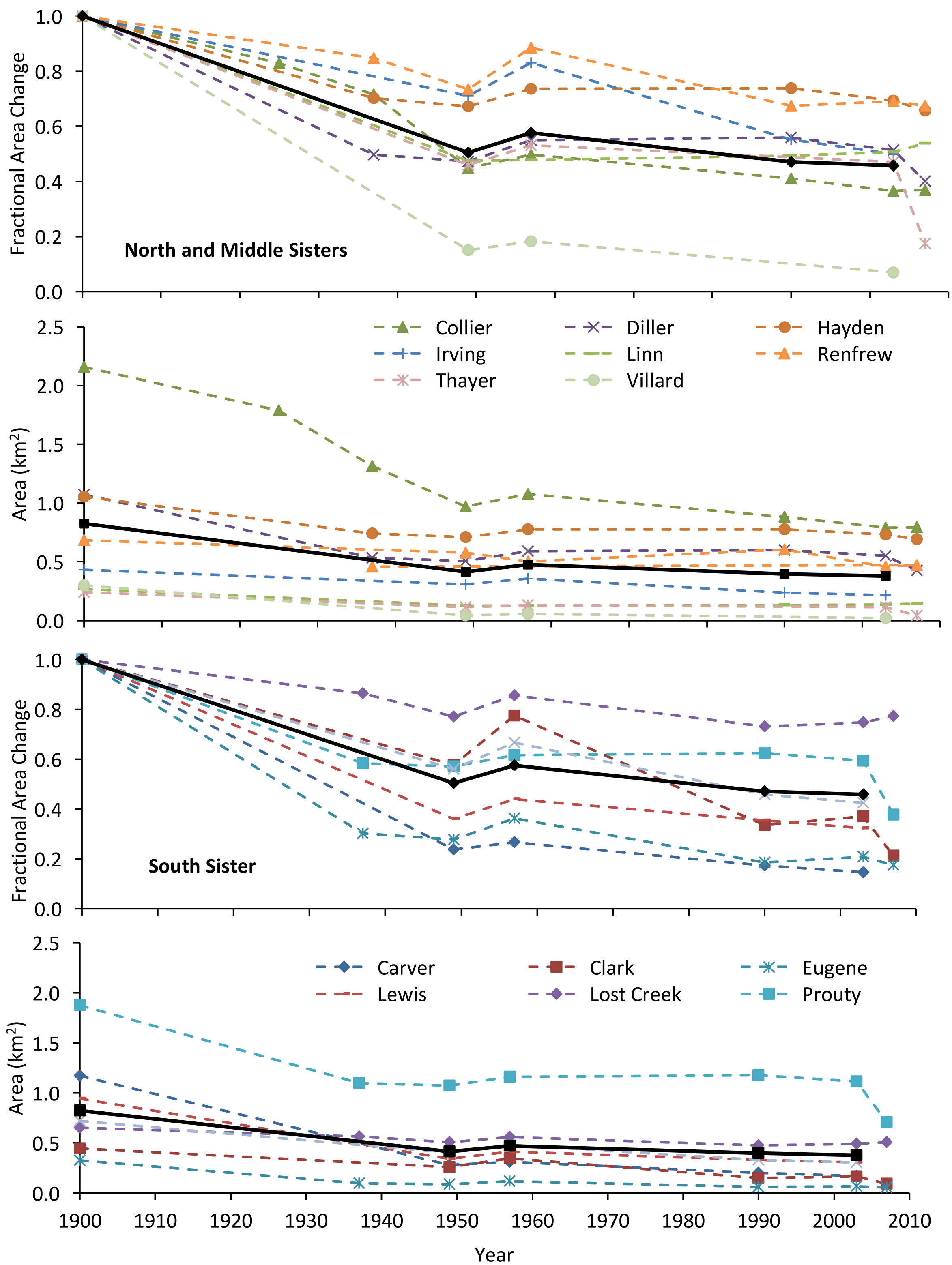


Figure 16. Glacier area change for North & Middle (top two) and South (bottom two) Sisters expressed in area change (km^2) and fractional area change. Solid black line on the graphs is average FAC and area for all the 15 named glaciers. Note that the uncertainty bars are not shown because it is smaller than the symbols.

Four glaciers, the Hayden, Diller, Linn, and Prouty glaciers increased or stayed the same size from 1957-1990 then returned to a decreasing trend from 1990-2003. The four glaciers probably advanced due to debris covered ice. The Villard Glacier lost -2.53 ± 0.024 (-84.9%) from ~1900-1949, which is a larger change compared to the other glaciers. In this case, the LIA area was difficult to determine because of poorly preserved landscape modification. This could be causing the higher rate of loss as compared to the glaciers. Overall, the 15 named glaciers responded synchronously.

To evaluate topographic influence on area change I compared four topographic characteristics, mean elevation, elevation difference, slope, and aspect, from ~1900 to 2003 (Table 12). Average elevation ($r^2 = 0.01$, $p < 0.05$), slope ($r^2 = 0.07$, $p < 0.05$), and aspect ($r^2 = 0.01$, $p < 0.05$) showed poor correlation and statistical insignificance with glacier change from 1900-2003 (Figure 17). The best correlation ($r^2 = 0.22$, $p < 0.05$) was observed with elevation difference, glaciers with larger elevation ranges experienced less glacier loss suggesting higher elevations on larger glaciers are compensating for losses in the lower elevations. The evaluation of the different time period's relationships also showed no strong or consistent correlation between any one topographic characteristic.

It was observed that some glaciers with extensive debris cover on their surfaces showed areas of glacier advance. To investigate a relationship between debris cover and glacier advance/retreat I estimated the fraction of glacier area covered with rock debris and compared it to area change (Figure 18). The area of debris cover was estimated from the aerial and remote imagery. The total area of debris-covered ice increased over the 1949-2003 period. The largest increase was 53% between 1957 and 1990, 0.46 ± 0.006 km^2 in 1957 to 0.97 ± 0.010 km^2 in 1990.

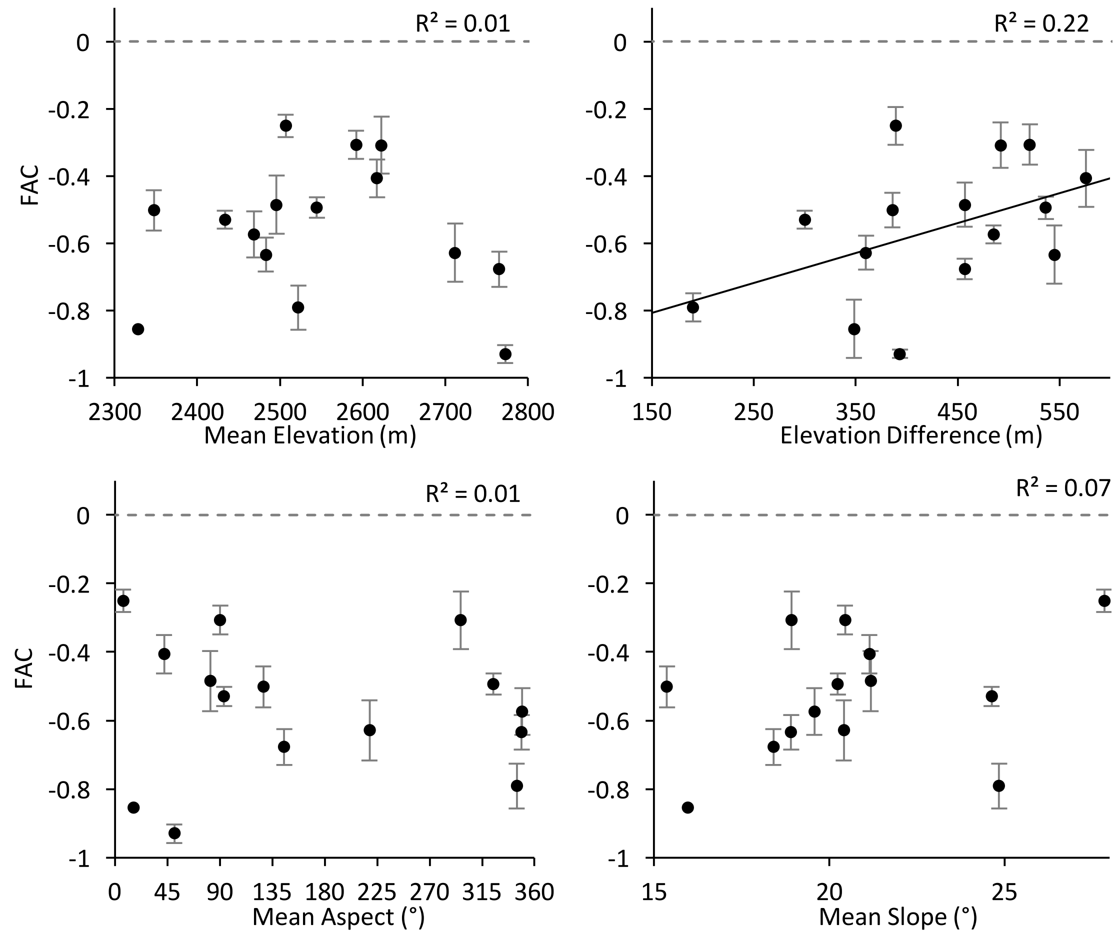


Figure 17. Glacier area change (1900-2003) as a function of average elevation, slope, aspect, and elevation difference. Topographic data from 1957.

A correlation is observed between the area change from 1949-2003 to debris cover for each glacier (r^2=0.19) (Figure 18). It shows that with increasing debris cover the amount of area change decreases. This increase of debris covering ice could account for the glaciers not losing as much area in the latter half of the century as quickly as the first half.

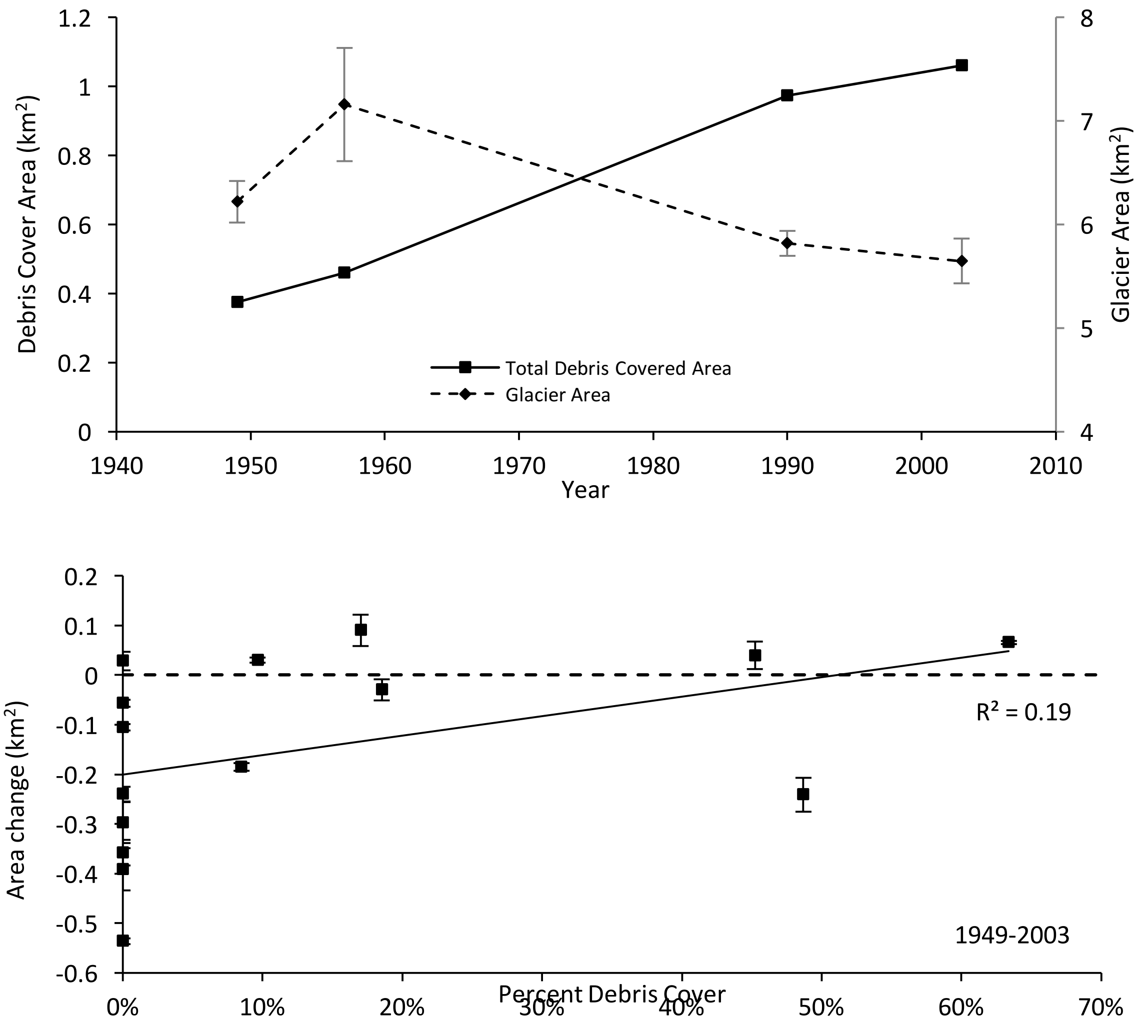


Figure 18. Effect of debris-cover on glacier change. Top – Total area of debris covered ice and total glacier area from 1949 to 2003 of the 15 named glaciers. Bottom - The area change (km^2) and percent debris cover of the 15 named glaciers from 1949-2003. Note that the uncertainty bars for the debris covered area and area change are not shown because it is smaller than the symbols.

Collier Glacier

Collier Glacier has the most extensive record of all the glaciers on the Three Sisters. Generally, Collier followed the same advance/retreat behavior as the other glaciers on the Three Sisters (Figure 19). The magnitude of area changes is roughly similar to the other glaciers in time periods with data. Collier seems to be a reasonable index glacier for the region.

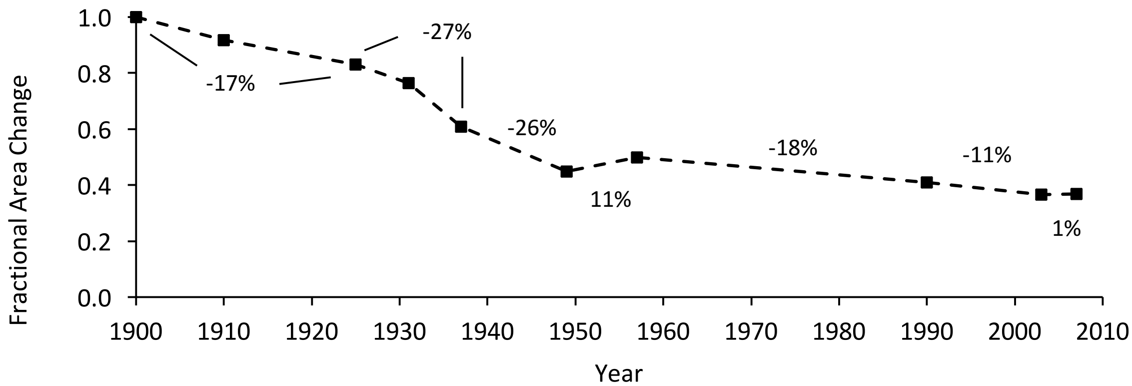


Figure 19. FAC based on ~1900 area and change percentages of Collier Glacier from ~1900 to 2007 showing the calculated changes between years of area data. All area data are included in Table 15 and 16 except for 1910 and 1931 which are 1.98 ± 0.16 km^2 and 1.65 ± 0.14 km^2, respectively. Note: the uncertainty bars are not shown because it is smaller than the symbols.

The areas for 1910, 1.98 ± 0.16 km^2, and 1931, 1.65 ± 0.14 km^2 were estimated from Collier map in O'Connor et al (2001), which was based on ground-based oblique photographs. I used Collier to interpolate the area change from 1925 and 1937 for the glaciers that are missing data (Table 16).

Table 16. Updated areas (km^2) of the 15 named glaciers from estimated (*Italics and bold)* areas for 1925 and 1937 for the using Collier as a reference.

Glacier	LIA ~1900	1925	1937	1949	1957	1990	2003	2007
Carver	1.172 ± 0.164	***0.902 ± 0.470***	***0.555 ± 0.044***	0.279 ± 0.060	0.313 ± 0.120	0.202 ± 0.002	0.170 ± 0.060	-
Clark	0.448 ± 0.091	***0.372 ± 0.194***	0.127 ± 0.024	0.259 ± 0.030	0.347 ± 0.107	0.150 ± 0.052	0.166 ± 0.042	0.095 ± 0.019
Collier	2.157 ± 0.172	***1.789 ± 0.933***	1.315 ± 0.027	0.969 ± 0.046	1.074 ± 0.153	0.883 ± 0.012	0.790 ± 0.032	0.795 ± 0.042
Diller	1.070 ± 0.117	***0.930 ± 0.485***	0.533 ± 0.003	0.505 ± 0.018	0.588 ± 0.017	0.598 ± 0.007	0.551 ± 0.060	0.428 ± 0.025
Eugene	0.324 ± 0.080	***0.255 ± 0.133***	0.098 ± 0.002	0.089 ± 0.012	0.117 ± 0.037	0.060 ± 0.027	0.068 ± 0.024	0.057 ± 0.003
Hayden	1.054 ± 0.120	***0.967 ± 0.504***	0.740 ± 0.001	0.709 ± 0.001	0.776 ± 0.101	0.778 ± 0.014	0.730 ± 0.002	0.694 ± 0.003
Irving	0.430 ± 0.087	***0.372 ± 0.194***	***0.297 ± 0.061***	0.305 ± 0.060	0.357 ± 0.117	0.237 ± 0.002	0.214 ± 0.057	-
Lewis	0.943 ± 0.061	***0.771 ± 0.402***	***0.549 ± 0.081***	0.340 ± 0.011	0.414 ± 0.078	0.334 ± 0.018	0.304 ± 0.007	-
Linn	0.266 ± 0.066	***0.230 ± 0.120***	***0.185 ± 0.033***	0.126 ± 0.008	0.127 ± 0.017	0.131 ± 0.023	0.134 ± 0.009	0.143 ± 0.009
Lost Creek	0.654 ± 0.105	***0.610 ± 0.318***	0.566 ± 0.014	0.505 ± 0.010	0.561 ± 0.085	0.479 ± 0.016	0.490 ± 0.042	0.506 ± 0.005
Prouty	1.878 ± 0.164	***1.673 ± 0.873***	1.097 ± 0.040	1.072 ± 0.040	1.160 ± 0.042	1.175 ± 0.036	1.115 ± 0.040	0.709 ± 0.022
Renfrew	0.682 ± 0.136	***0.625 ± 0.326***	0.578 ± 0.007	0.500 ± 0.014	0.604 ± 0.164	0.459 ± 0.004	0.472 ± 0.005	0.460 ± 0.041
Skinner	0.721 ± 0.053	***0.610 ± 0.318***	***0.466 ± 0.051***	0.405 ± 0.066	0.481 ± 0.130	0.331 ± 0.027	0.307 ± 0.013	-
Thayer	0.243 ± 0.045	***0.208 ± 0.108***	0.098 ± 0.014	0.111 ± 0.023	0.129 ± 0.043	***0.105 ± 0.030***	0.114 ± 0.030	0.043 ± 0.011
Villard	0.298 ± 0.024	***0.223 ± 0.116***	***0.127 ± 0.036***	0.045 ± 0.004	0.054 ± 0.008	***0.044 ± 0.006***	0.021 ± 0.006	-
Total	**12.34 ± 0.417**	***10.54 ± 0.385***	**7.331 ± 0.143**	**6.22 ± 0.140**	**7.10 ± 0.369**	**5.97 ± 0.089**	**5.65 ± 0.135**	
Δ from 1900		**-1.80 ± 0.568**	**-5.01 ± 0.441**	**-6.12 ± 0.440**	**-5.19 ± 0.557**	**-6.52 ± 0.427**	**-6.70 ± 0.439**	
% Change		**-14.6**	**-40.6**	**-49.6**	**-42.4**	**-51.6**	**-54.2**	

I used a ratio of the area change for Collier and set is equal to the same ratio for other 14 glaciers and solved for the unknown area,

$$\frac{A_{C-1900}-A_{C-1925}}{A_{C-1900}-A_{C-2003}}=\frac{A_{x-1900}-A_{x-1925}}{A_{x-1900}-A_{x-2003}}, \tag{7}$$

were A_c is the area of Collier (km^2) and A_x is the area of the glacier that is being solved for A_{x-1925} is the unknown. This was calculated using 1925 and 1937 data from Collier Glacier. The uncertainty was calculated by using the same method to estimate area for 1949, with the difference between that estimate and the measured 1949 area as the uncertainty.The estimates for 1925 were compared those areas to the results of Hodge (1925). His areas were treated suspect because his report lacked data collection information. I assumed that the Collier Glacier's area estimate to be the most accurate due to the lack of debris cover on the glacier surface clearly showing the glaciers boundary. I estimated the total area for 1925 to be 10.54 ± 0.385 km^2 this is larger than the Hodge (1925) estimate of 8.06 km^2 (Table **17**). The Diller, Eugene, Hayden, Irving, Linn, Lost Creek, Renfrew, Thayer and Villard glaciers estimates were each within roughly 0.15 km^2 of Hodges calculation. Ten glaciers that I estimated for 1925, have larger areas than there calculated by Hodge's areas, with Prouty Glacier have the largest difference, 1.01 km^2.

Table 17. Areas and difference (km^2) of the 15 major glaciers from Hodge (1925) and calculated areas for 1925 using Collier as a reference.

Glacier	1925 Hodge Area	1925 Calculated Area	Difference
Carver	0.618	0.902 ± 0.071	0.284
Clark	0.156	0.372 ± 0.081	0.216
Collier	1.789	1.789 ± 0.064	0.000
Diller	0.784	0.930 ± 0.209	0.146
Eugene	0.401	0.255 ± 0.035	-0.146
Hayden	0.931	0.967 ± 0.086	0.036
Irving	0.249	0.372 ± 0.077	0.123
Lewis	0.108	0.771 ± 0.114	0.663
Linn	0.160	0.230 ± 0.041	0.07
Lost Creek	0.759	0.610 ± 0.007	-0.149
Prouty	0.666	1.673 ± 0.223	1.007
Renfrew	0.748	0.625 ± 0.001	-0.123
Skinner	0.383	0.610 ± 0.067	0.227
Thayer	0.227	0.208 ± 0.036	-0.019
Villard	0.082	0.223 ± 0.063	0.141
Total	**8.06**	**10.5 ± 0.385**	**2.48**

Without direct measurements from aerial photographs, large differences for a few glaciers, and lack of information on Hodge's collection methods, I trust my estimations more.

Discussion and Conclusions

The glaciers and perennial snowfields on the Three Sisters have lost area over the period of ~1900-2003. Decadal changes were synchronous, with rapid retreat, advance/stabilization, and continued slower retreat. The greatest area loss occurred between LIA (~1900) to 1949 (8.00 ± 2.33 km^2). Glaciers and perennial snowfields generally advanced in the period 1949-1990. For the period 1949-2003 the glaciers and perennial snowfields that changed significantly (relative uncertainty <1) lost area -1.914 ± 0.097 km^2 (21%). Longer time periods exhibited more significant changes than shorter time periods. In general, smaller glaciers lost larger fractions of their area and showed more variability. Overall, time periods showed statistically significant change over the study period. The variability in the smaller glaciers with larger uncertainty masked the change that is taking place.

The 15 named glaciers lost 6.693 ± 0.439 km^2 (54%) of their area from ~1900-2003, with an average loss for named glaciers of 0.404 km^2, which is similar to area changes across the PNW. Thayer Glacier changed the least, -0.129 ± 0.046 km^2 (-53.1%), and the largest change was at Collier, -1.36 ± 0.177 km^2 (-63.1%). The area change for the named glaciers was always significant even with glaciers with smaller areas. Smaller glaciers are still observed with significant change as compared to the smaller features of perennial snow.

The change of the 15 named glaciers is consistent with other studies in the American West and Western Canada. Glaciers in the Sierra Nevada have shown a 55% decrease in area between 1903 and 2004 (Basagic and Fountain, 2011), and glaciers in Rocky Mountain National Park have declined by 40% from 1909-2004 (Hoffman et al., 2007). To the north, glaciers in the North Cascades including Mt. Baker have decreased by 56% from ~1900-2009 (Dick, 2013), glaciers on Rainier have declined by 22% from 1913-1994 (Nylen, 2001), glaciers on Adams have declined by 49% from 1904-2006 (Sitts el al., 2010) and on Hood glaciers have declined by 40% from 1909-2004 (Jackson and Fountain, 2007).

Topography has no demonstrated effect on the magnitude of glacier change. Perhaps a combination of variables has major effects on area change, as shown by Basagic and Fountain (2011) and Dick (2013). However, glaciers with greater elevation difference showed less area change. This suggests that there is some relationship between glaciers with higher elevation ranges (which is related to maximum elevations) and less area change.

Rock debris cover on glacier surfaces increased by 0.681 ± 0.006 km^2 (64%) from 1949 to 2003 with the greatest increase occurring between 1957 and 1990, 0.46 ± 0.012 km^2. This corresponds with a positive but not significant correlation between the rate of area change and debris cover. Debris cover could be insulating the glaciers enough to slow down melting rates. This may contribute to observed area changes over the last century. Prior to 1957 glaciers deceased rapidly and had little to no rock debris cover and since then, as rock debris cover has increased, their rate of change has decreased.

Collier Glacier is a relatively good index glacier for the Three Sisters because the magnitude of area changes is roughly similar to the other glaciers in time periods with data. Its area change was used to interpolate area changes for the other 14 named glaciers for 1925 and 1937. This estimated total area for 1925 (10.54 ± 0.385 km^2) is larger than then the total area calculated by Hodge (1925) (8.06 km^2) (Table 17). Without direct measurements from aerial photographs, large differences for a few glaciers, and lack of information on Hodge's collection methods, I trust my estimations more.

When examining how glaciers have been changing over time, area change is one characteristic to investigate. In the next chapter I will be exploring how the volume of 15 named glaciers has been changing in order to get a better idea of how and what factors have been affect the glaciers on the Three Sisters.

Chapter Four – Volume Change

Introduction

The purpose of this chapter is to examine the volume change of the 15 named glaciers, presented in Chapter 3. I chose these glaciers because they have the most extensive record and well defined boundaries of all the glacier and perennial snowfields on the Three Sisters. I used aerial photography, digital elevations models (DEMs), and lidar data to reconstruct the surface topography from which glacier volume change is estimated.

Methods

Volume change was estimated for three time periods, 1957-1990, 1990-2010, and 1957-2010 because the DEMs were of good quality. The DEMs created from the 1949 and 1957 aerial photographs were of poor quality due to low image resolution, image distortion, and low textural resolution as previously explained. A comparison of my DEM from 1957 and the NED DEM created from the same imagery revealed that 1957 NED was of better quality as explained in Chapter 2. Elevation of each cell in one DEM was subtracted from the same cell location in the next DEM, and the cells were summed for volume change. The 1957 and 1990 DEMs had the same cell size of 10 m whereas the 2010 lidar-derived DEM had a cell size of 1 m. The 2010 lidar DEM was coarsened to 10 meters using a bilinear resampling in ArcGIS 10.1. To insure that each raster cell exactly overlaid the same cell in another DEM, each DEM was 'snapped' to the 1957 DEM. Because the glacier area changes over time, to derive the volume change, the largest possible glacier boundary was defined by the intersection of the 3 glacier extents 1957, 1990, and 2003. To assess uncertainty the region was divided into control zones and glacier areas (Figure 20 and Figure 21).

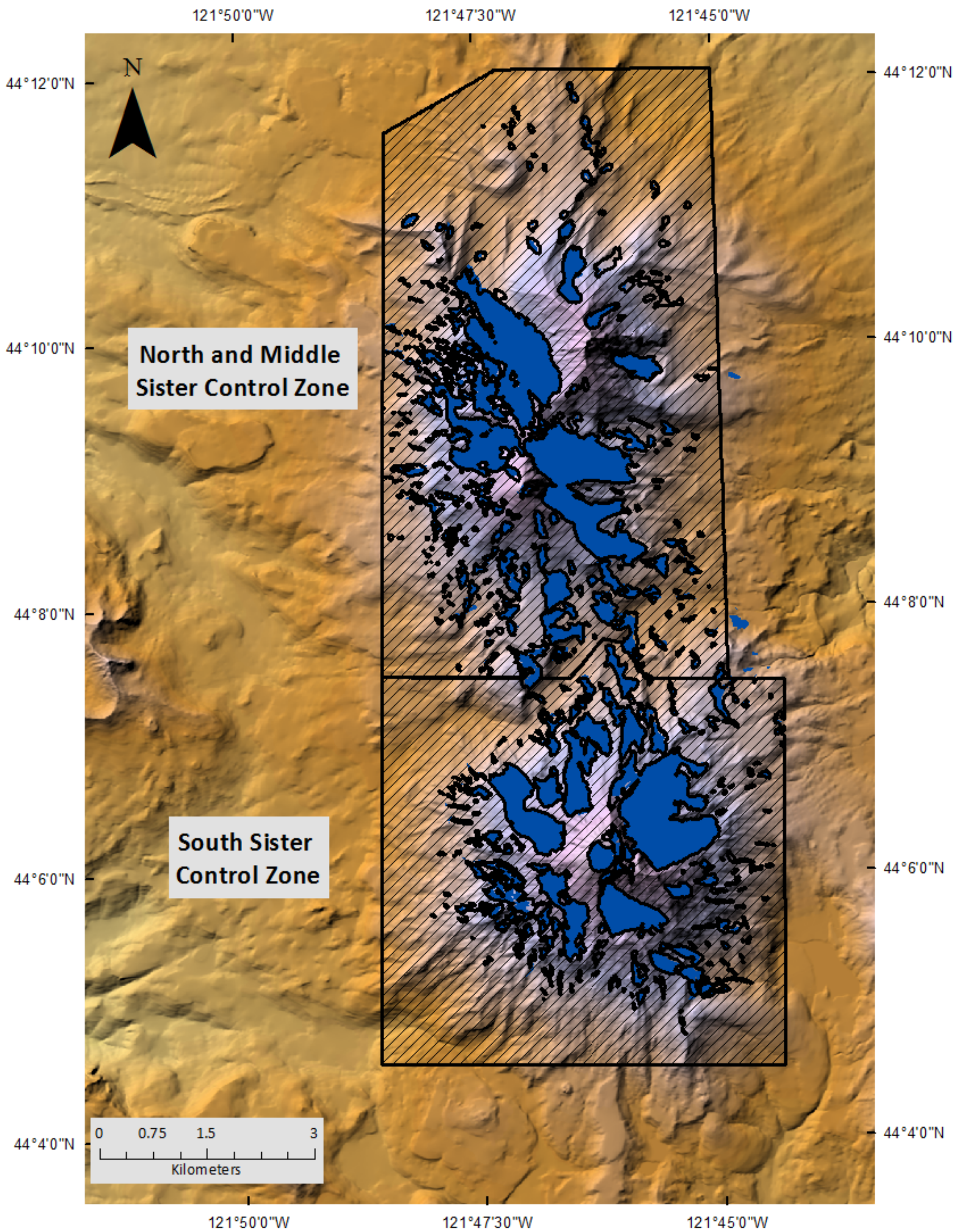


Figure 20. Locations of the control zones (hatched marked zones) for the volume change analysis used for 1957-2010. The blue regions are the glacier and perennial snowfield extents in 1957. Map is in WGS 84 UTM Zone 10.

The control zones are regions free of snow and ice and the surface elevation is presumed constant over time. Different control zones for 1957-2010 (used for 1957-2010) and 1990-2010 (used for 1957-1990 and 1990-2010) were needed because the spatial extent of DEM in 1990 was smaller than those in 1957 and 2010 resulting in smaller control areas.

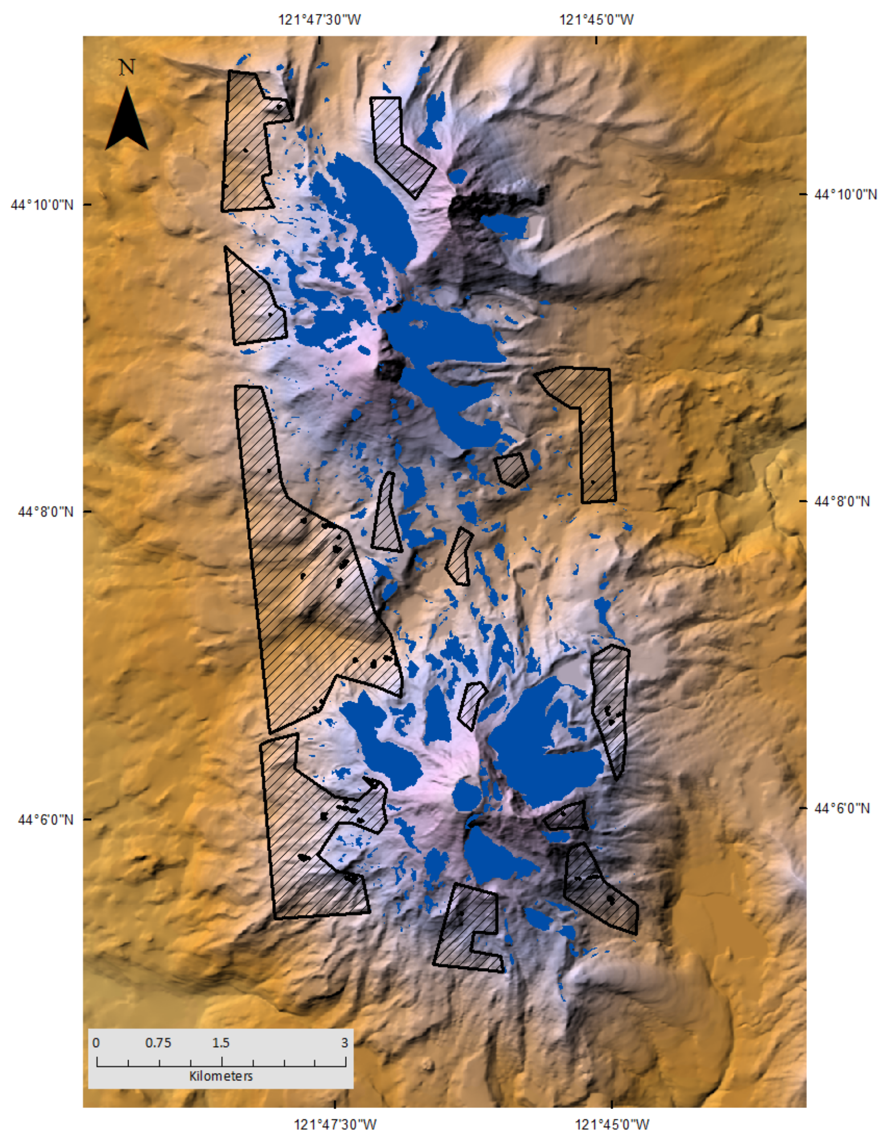


Figure 21. Locations of the control zones (hatched) for the volume change for 1957-1990 and 1990-2010. These control zones are free of snow and ice. The blue regions are the glacier and perennial snowfield extents in 1990. Map is in WGS 84 UTM Zone 10.

Differences in the elevation of the control zones between DEMs were used as the uncertainty for the glacier elevation change. Following Zhang et al. (2005), the root mean square error (RMSE) of apparent elevation change in the control zones is calculated and divided by the RMSE of the glacier surface change yielding a fraction of change that is uncertain.

Because of the steep slopes encountered in glacial terrain I binned the control zones and ice-covered areas according to ten degrees slope bins. I assumed that horizontal surfaces will have a smaller uncertainty than steeply sloping surfaces. This rests on the notion that small shifts in the horizontal georeferencing of the DEMs produce larger vertical differences on steeper slopes.

The younger DEM was subtracted from the older DEM (i.e. 2010 subtracted from 1957) producing a raster of differenced elevations (ArcGIS 10.1), where negative values represent elevation loss and positive values represent elevation gain. The differenced elevations were categorized according to slope data and binned in 10° increments for both the control and ice-covered areas. The total volume change within each slope bin for either the ice-covered area or control zone is,

$$\Delta V_j = A \sum_{i=1}^{n} \Delta Z_{ij}, \quad (8)$$

where n is the number of cells within a slope bin j within the glacier perimeter, A is the area of a cell, and ΔZ_i is the difference in elevation for each cell with in bin j. These volume change values were summed across all, m, bins to estimate the total volume change for a glacier,

$$\Delta V = \sum_{j=1}^{m} \Delta V_j. \quad (9)$$

To calculate uncertainty of the volume change the root mean square error was calculated for each glacier slope bin in the control zone,

$$R_j = \sqrt{\frac{\sum_{i=1}^{n} (\Delta Z_{ij})^2}{n}}, \quad (10)$$

R_j is also calculated for the change in elevation of the glacier surface. The uncertainty of the volume change for each slope bin is a fractional uncertainty of the RMSE for the control zones (R_c) and glacier area (R_g) derived from (10) which is F,

$$F = \frac{R_c}{R_g}. \quad (11)$$

The uncertainty, U, of the volume change within each slope bin is,

$$U = \pm \frac{|\Delta V| * F}{2}. \quad (12)$$

The total volume uncertainty across a glacier area is the root sum of squares across all slope bins.

Results

Three of the original five DEMs were deemed to be of ample quality to use for the volume change calculations; 1957 NED, 1990, and 2010. Visual inspection of the differenced 1957 and 2010 DEMs showed differences in the control zones around South Sister were greater than on North & Middle Sisters. As a result, the control zones on South Sister were applied to only to South Sister named glaciers and the control zones for North & Middle Sisters. No similar pattern was observed for 1957-1990 and 1990-2010 differenced DEMs. Uncertainties ranged from 4-6 m, in 10° slope bins, to 21-28m m in 80° slope bins, as expected (Figure 22; Table 18).

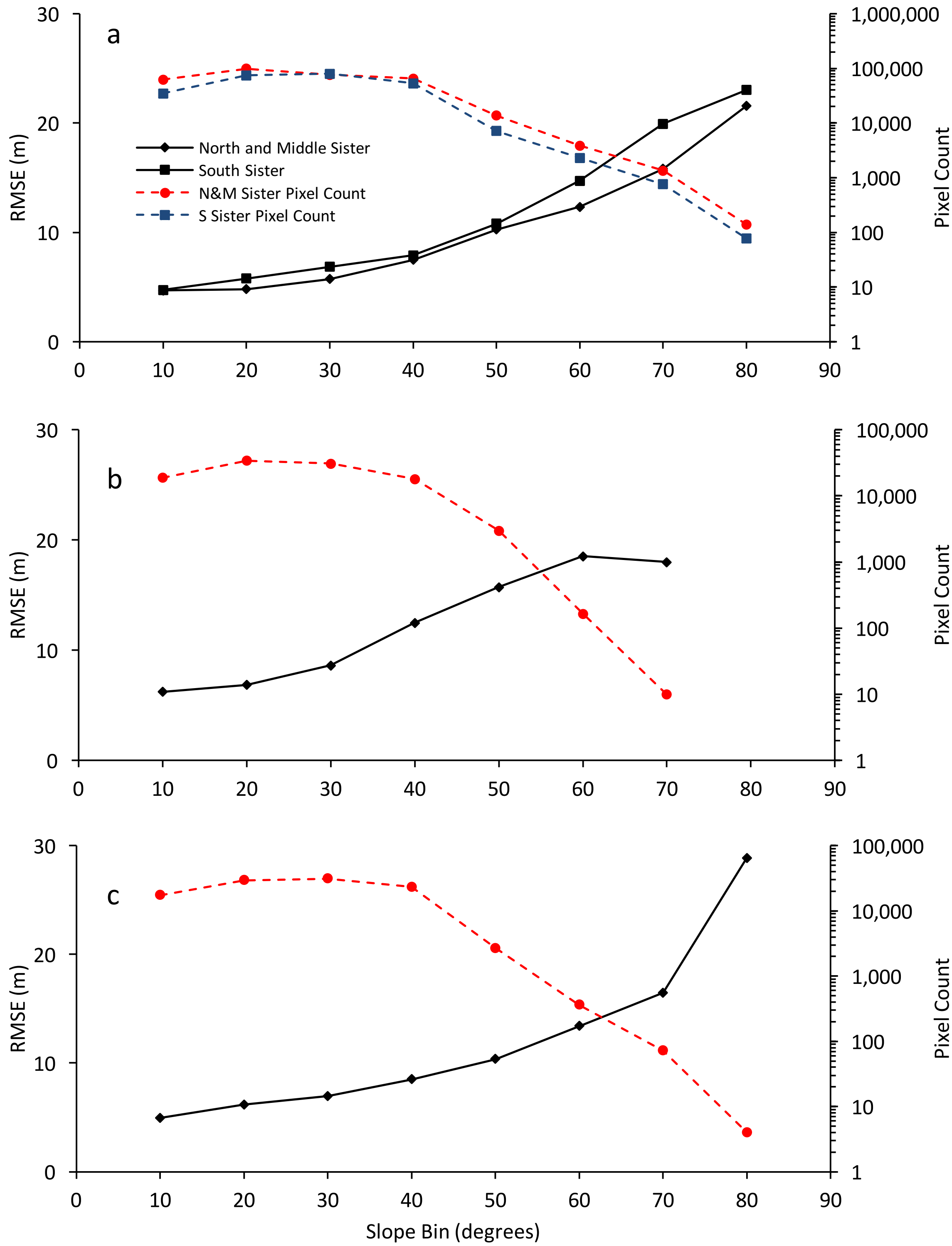


Figure 22. Root mean square error (RMSE) uncertainty (black) and pixel count (blue and red) for a) 1957-2010 North & Middle and South Sisters, b) 1957-1990, c) 1990-2010 binned by slope shows a nonlinear increase of uncertainty as the slope increases. The value of each bin percent range is the maximum of that grouping.

Table 18. Root mean square error (RMSE) and pixel count per slope bin from the uncertainty estimates for the surface change from 1957-2010, 1957-1990, and 1990-2010.

	1957-2010				1957-1990		1990-2010	
	North & Middle Sisters		South Sister					
Slope	RMSE	Pixel Count	RMSE	Pixel Count	RMSE	Pixel Count	RMSE	Pixel Count
10	4.7	62,400	4.7	34,692	6.2	18,760	4.9	17,432
20	4.8	98,753	5.8	74,092	6.9	33,966	6.2	29,613
30	5.7	76,383	6.8	79,830	8.6	30,817	6.9	31,217
40	7.5	65,299	7.9	53,129	12.5	17,950	8.5	23,245
50	10.3	13,637	10.8	7,166	15.7	2,988	10.3	2,674
60	12.3	3,843	14.7	2,304	18.5	165	13.4	363
70	15.8	1,337	19.9	759	18.0	10	16.5	72
80	21.6	139	23.0	78			28.8	4

Uncertainty increased nonlinearly with slope. The 80 degree slope bin showed an anomalous spike in 1990-2010 and the 70 degree slope bin showed an anomalous drop in 1957-1990 both of which may be due to small sample sizes.

All glaciers on the Three Sisters lost volume from 1957 to 2010 (Table 19, Figure 23) with a total loss of 72.0 x 10^6 ± 2.87 x 10^6 m^3, averaging -8.9 m of surface lowering over all of the glaciers. The volume lost ranged from -0.688 x 10^6 ± 0.136 x 10^6 m^3 at Villard Glacier to -15.7 x 10^6 ± 1.38 x10^6 m^3 at Collier Glacier. Specific volume change (total volume change divided by surface area) ranged from -2.4 ± 0.4 m at Irving Glacier to -15.5 ± 1.2 m at Diller Glacier.

Table 19. Volume change estimates from 1957-2010 with specific volume change and percent uncertainty of volume change for the glaciers on the Three Sisters Volcanoes. South Sister glaciers names are italicized.

Glacier	Volume Change ($m^3 \times 10^6$)	% Uncertainty of Volume Change	Specific Volume Change (m)
Collier	-15.68 ± 1.380	9%	-14.3 ± 1.3
Diller	-10.62 ± 0.800	8%	-15.5 ± 1.2
Hayden	-12.93 ± 1.078	8%	-15.2 ± 1.3
Irving	-0.86 ± 0.151	17%	-2.4 ± 0.4
Linn	-1.61 ± 0.242	15%	-9.5 ± 1.4
Renfrew	-3.89 ± 0.679	17%	-6.3 ± 1.1
Thayer	-2.08 ± 0.236	11%	-13.5 ± 1.5
Villard	-0.69 ± 0.136	20%	-11.9 ± 2.3
Carver	-1.48 ± 0.384	26%	-4.7 ± 1.2
Clark	-1.42 ± 0.396	28%	-4.1 ± 1.1
Eugene	-1.15 ± 0.219	19%	-9.4 ± 1.8
Lewis	-2.79 ± 0.654	23%	-6.5 ± 1.5
Lost Creek	-4.28 ± 0.594	14%	-7.4 ± 1.0
Prouty	-9.44 ± 1.582	17%	-7.3 ± 1.2
Skinner	-3.03 ± 0.510	17%	-6.1 ± 1.0
Total	**-71.96 ± 2.867**		

Parts of the Hayden, Diller, Lost Creek, Prouty, and Skinner glaciers showed thickening and advance of ice in their ablation zones (lower portion of the glacier) over this time period (1957-2010). These zones thickened between 20-40 m and are covered in rock debris. Debris covering the surface of the glaciers has increased from 1949-2003 as described in Chapter 3. Even with zones of thickening these glaciers still exhibited net volume loss. Overall, glaciers on South Sister lost less volume compared to North & Middle Sister glaciers, $-23.6 \times 10^6 \pm 2.08 \times 10^6$ m^3 and $-48.4 \times 10^6 \pm 1.97 \times 10^6$ m^3.

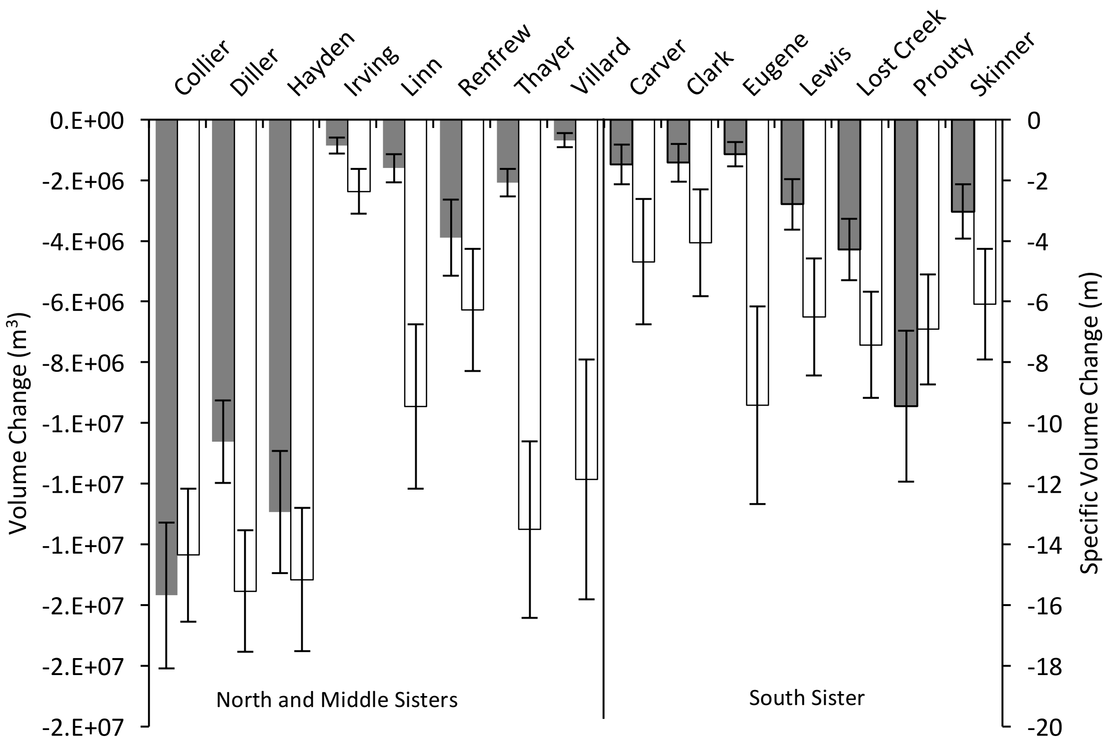


Figure 23. Total volume (filled bars) and specific volume change (open bars) from 1957-2010 shows the average thickness change average across the glaciers North & Middle Sisters and South Sister glaciers.

From 1957 to 1990 all glaciers lost volume (Table 20, Figure 24) with a total loss of $-43.11 \times 10^6 \pm 3.50 \times 10^6$ m^3 (-5.7 ± 2.5 m), ranging from $-0.455 \times 10^6 \pm 0.262 \times 10^6$ m^3 (-0.8 ± 0.5 m) at Clark Glacier to $-9.77 \times 10^6 \pm 1.98 \times 10^6$ m^3 (-9.0 ± 2.8 m) at Collier Glacier, with an average loss of 13.32×10^6 m^3. This is an underestimate because the Thayer, Villard glaciers and ~12% of the Hayden Glacier had no data available for 1990.

Table 20. Volume change estimates from 1957-1990 with specific volume change and percent uncertainty of volume change for the glaciers on the Three Sisters Volcanoes. The Thayer and Villard glaciers and roughly 12% of the Hayden* have no data for 1990. South Sister glaciers names are italicized.

Glacier	Volume Change ($m^3 \times 10^6$)	% Uncertainty of Volume Change	Specific Volume Change (m)
Collier	-9.765 ± 1.980	20%	-9.0 ± 1.8
Diller	-3.590 ± 0.723	20%	-5.4 ± 1.1
Hayden*	-6.509 ± 1.266	19%	-7.8 ± 1.5
Irving	-0.450 ± 0.253	56%	-1.3 ± 0.7
Linn	-0.661 ± 0.290	44%	-4.7 ± 2.1
Renfrew	-0.455 ± 0.157	35%	-0.8 ± 0.3
Thayer Villard	No Data	No Data	No Data
Carver	-0.584 ± 0.262	45%	-1.9 ± 0.9
Clark	-3.128 ± 0.694	22%	-9.2 ± 2.0
Eugene	-1.201 ± 0.302	25%	-10.3 ± 2.6
Lewis	-1.465 ± 0.648	44%	-3.5 ± 1.5
Lost Creek	-3.122 ± 0.701	22%	-5.6 ± 1.3
Prouty	-8.609 ± 1.997	23%	-6.7 ± 1.5
Skinner	-3.574 ± 0.677	19%	-7.6 ± 2.8
Total	**-43.11 ± 3.495**		

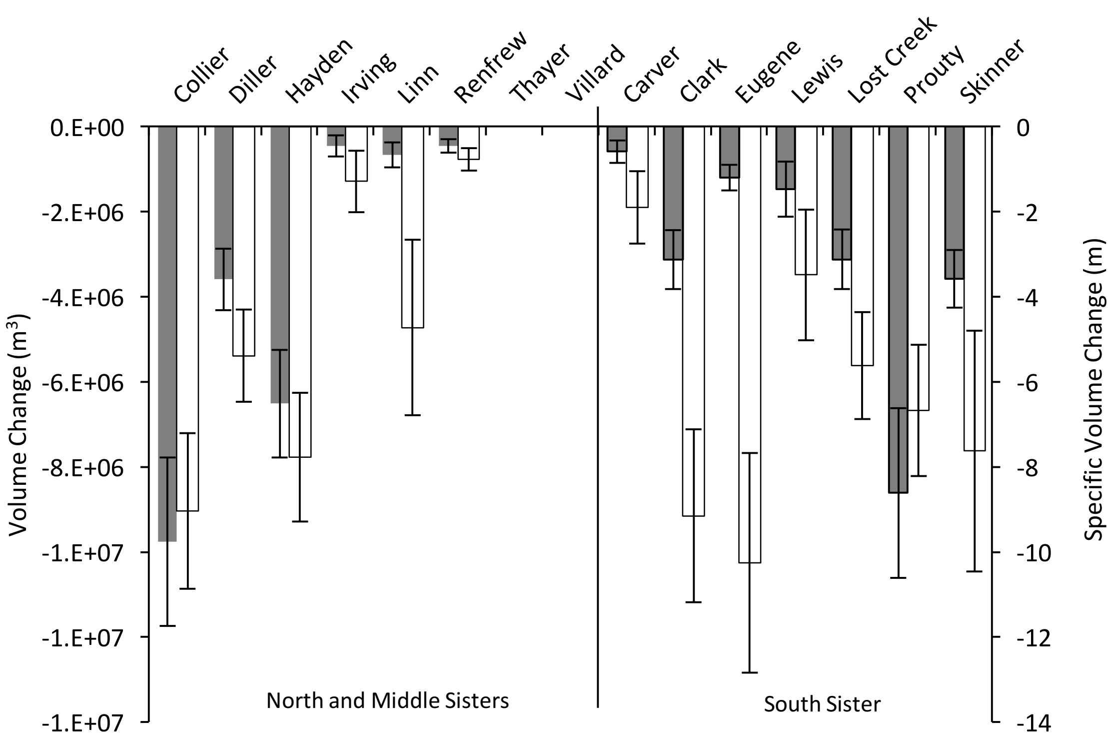


Figure 24. Total volume (filled bars) and specific volume change (open bars) from 1957-1990. In general the North & Middle Sister glaciers show higher volume loss than South Sister glaciers.

From 1990 to 2010 all the glaciers, except Clark and Skinner, lost volume (Table 21, Figure 25) with a total loss of 25.19 x 10^6 ± 2.30 x10^6 m^3 (-3.4 ± 1.8 m), ranging from a gain of 0.851 x 10^6 ± 0.280 x 10^6 m^3 (4.7 ± 1.6 m) at Clark Glacier to a loss of -6.77 x 10^6 ± 1.00 x10^6 m^3 (-11.0 ± 1.6 m) at Diller Glacier, with an average loss of 1.94 x 10^6 m^3. Again, these totaled values are an underestimate because the Thayer, Villard glaciers and ~12% of the Hayden Glacier had no data available for 1990.

Table 21. Volume change estimates from 1990-2010 with specific volume change and percent uncertainty of volume change for the glaciers on the Three Sisters Volcanoes. The Thayer and Villard glaciers and roughly 12% of the Hayden* have no data for 1990. South Sister glaciers names are italicized.

Glacier	Volume Change (m^3 x 10^6)	% Uncertainty of Volume Change	Specific Volume Change (m)
Collier	-5.792 ± 1.341	23%	-6.6 ± 1.5
Diller	-6.770 ± 1.002	15%	-11.0 ± 1.6
Hayden*	-6.054 ± 1.034	17%	-7.7 ± 1.3
Irving	-0.397 ± 0.136	34%	-1.6 ± 1.0
Linn	-1.037 ± 0.240	23%	-6.7 ± 1.6
Renfrew	-2.792 ± 0.694	25%	-5.6 ± 1.4
Thayer Villard	No Data	No Data	No Data
Carver	-0.755 ± 0.278	37%	-3.7 ± 1.3
Clark	0.851 ± 0.280	33%	4.7 ± 1.6
Eugene	-0.070 ± 0.049	70%	-1.0 ± 0.7
Lewis	-1.421 ± 0.426	30%	-4.1 ± 1.2
Lost Creek	-0.670 ± 0.183	27%	-1.3 ± 0.4
Prouty	-0.881 ± 0.624	71%	-0.7 ± 0.5
Skinner	0.587 ± 0.273	47%	1.5 ± 0.7
Total	**-25.19 ± 2.295**		

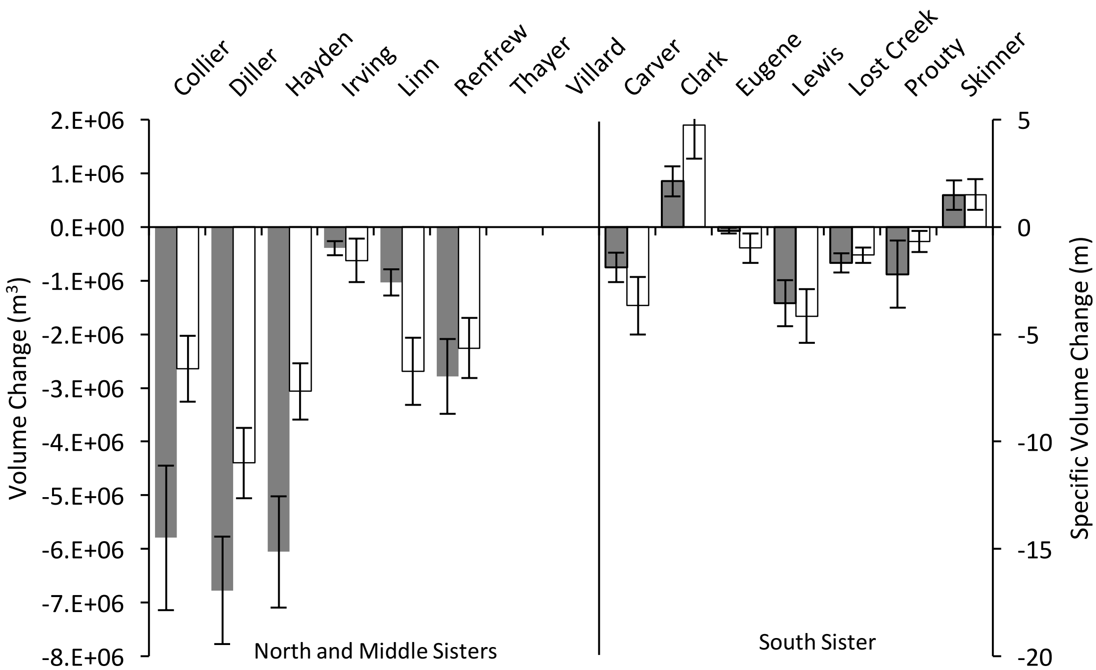


Figure 25. Total volume change and specific volume change from 1990-2010. In general the North & Middle Sister glaciers (filled bars and hatched) show higher volume loss than South Sister glaciers (open bars and dots), which showed some total volume gain.

Pronounced thinning, typically 10 to 15 m across the glaciers and in some places >40 m, was observed on North & Middle Sisters. The glaciers specific volume change for North & Middle glaciers averaged -11.3 m as compared to South Sister glaciers, averaging -6.5 m. Even with parts of some glaciers thickening from 1990 to 2010, all of the 15 named glaciers lost elevation during the 1957-2010 period.

Volume loss was observed in both the ablation and accumulation zones on all glaciers (Figure 26 and Figure **27**). On the North & Middle Sisters, volume loss was observed in the accumulation zones of Collier, Diller, and Hayden glaciers. On the South Sister glaciers, significant lost was also observed in the accumulation zones of the glaciers; however it is not as pronounced.

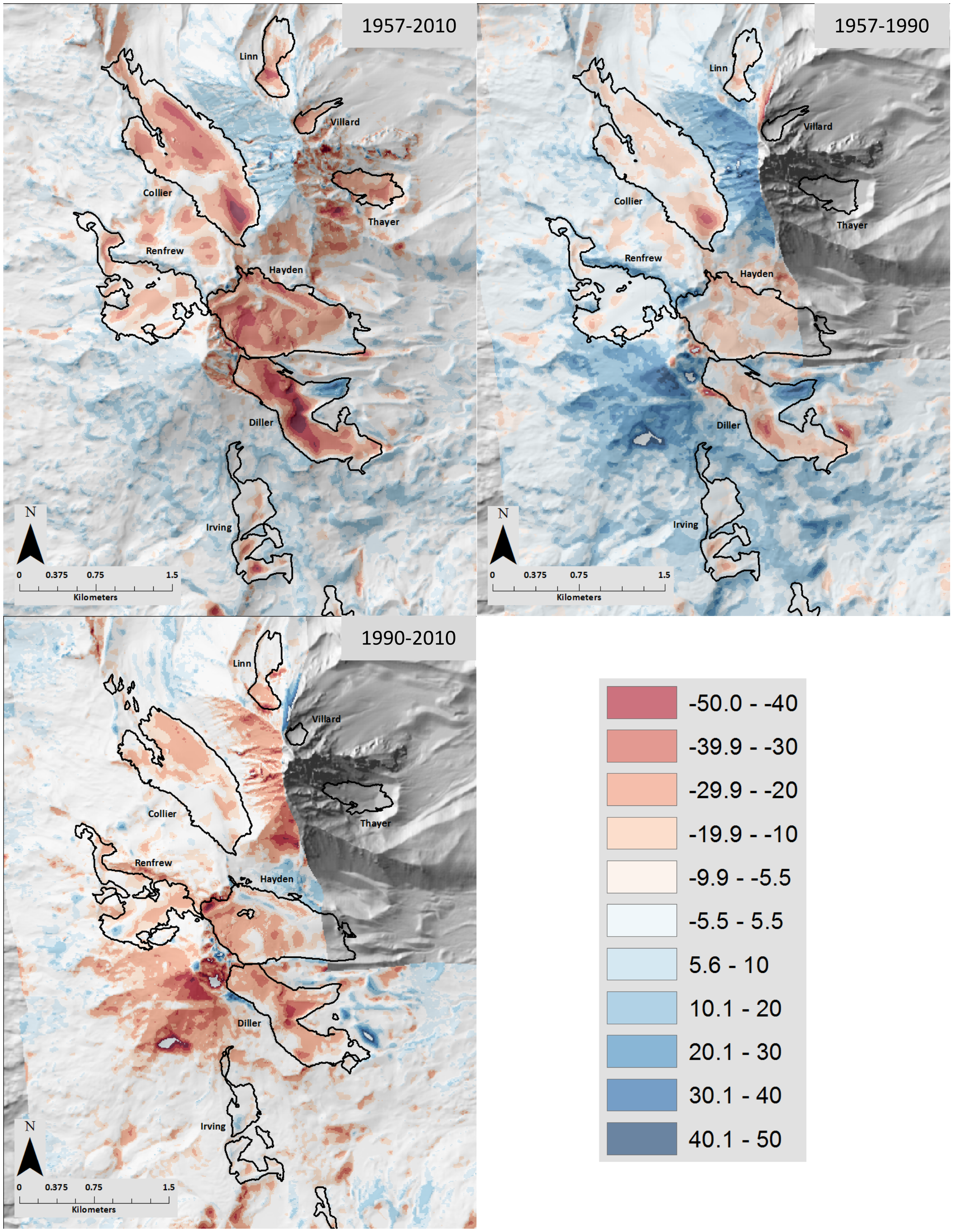


Figure 26. Difference maps showing the spatial distribution of elevation change (m) from 1957-2010, 1957-1990, and 1990-2010 of the 15 named glaciers on North & Middle Sister. Areas in red are volume loss and blue are volume gain. Glacier outlines, in black, are a combination of the outlines to encompass maximum possible area of the glacier. Grey shaded area is no data. Maps are in WGS 84 UTM Zone 10.

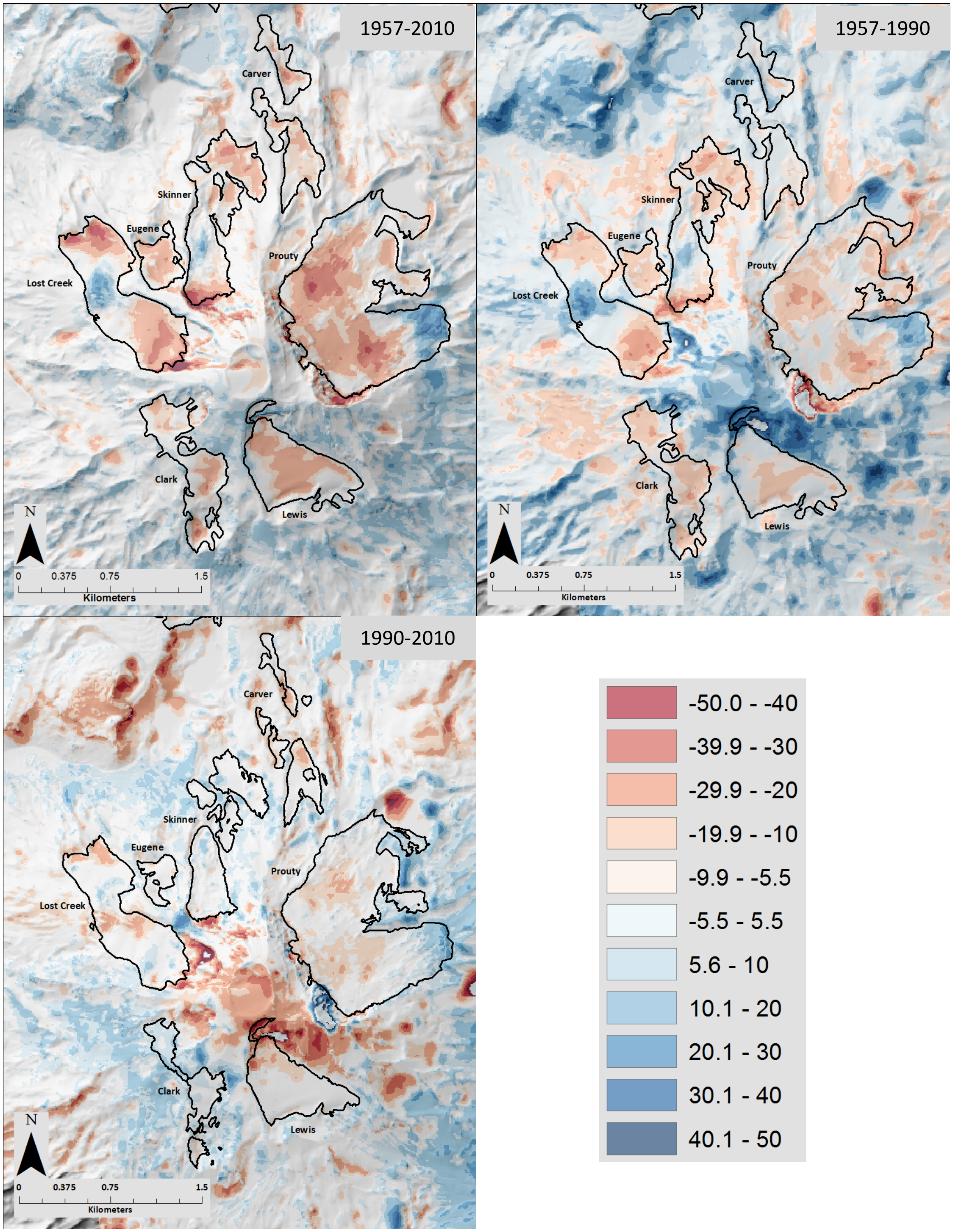


Figure 27. Maps showing the spatial distribution of elevation change (m) of the 15 named glaciers on South Sister. Areas in red represent volume loss and colors in blue represent volume gain from 1957-2010, 1957-1990, and 1990-2010. Glacier outlines, in black, are a combination of the outlines to encompass maximum possible area of the glacier. Maps are in WGS 84 UTM Zone 10.

Masking out zones of statistically insignificant surface change from 1957 to 2012 shows that the spatial distribution of surface change that is not significant zones are mostly limited to the glacier boundaries and where we expect the equilibrium line (Figure 28). Overall, significant volume loss can be seen spatially across entire glaciers.

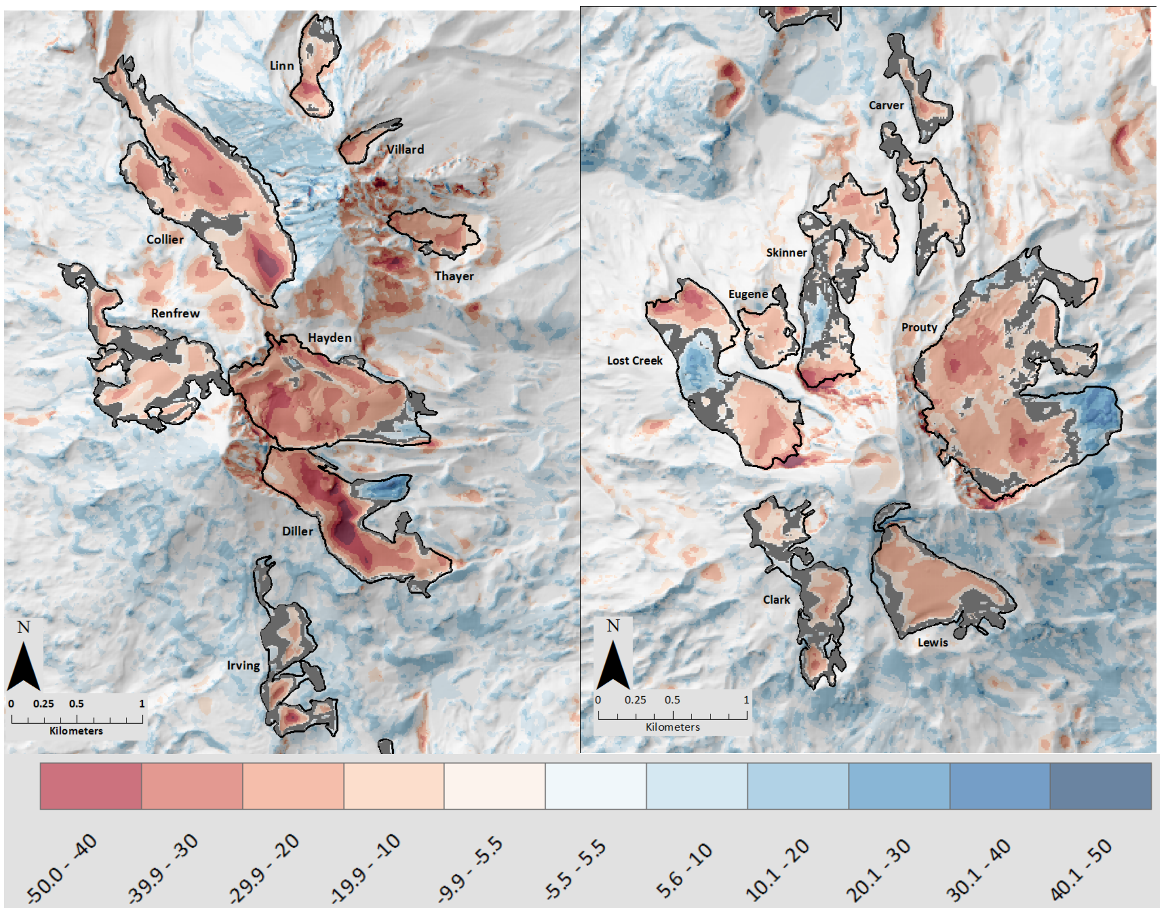


Figure 28. The spatial distribution of elevation change of the 15 named glaciers on the Three Sisters with statistically insignificant volume change zones in gray. Areas in red represent volume loss and colors in blue represent volume gain from 1957-2010. Glacier outlines, in black, are the largest of the outlines within those respective temporal ranges. Maps are in WGS 84 UTM Zone 10.

Finally, I examined the elevation change of unnamed perennial snowfield in the crater of South Sister. This perennial snowfield from 1957-2010 lost a total volume of $-0.537 \times 10^6 \pm 0.164 \times 10^6$ m^3 and dropped in surface elevation by -4.82 ± 2.59 m.

Analysis

To estimate the fraction of total ice volume lost on the Three Sisters since 1900 and 1957 I calculated the volume of the 15 named glaciers using a area volume scaling relationship (Chen and Ohmura, 1990; Bahr et al., 1997). The estimated total volume in 1900 is 255.0 x 10^6 ± 6.77 x 10^6 m^3 and in 1957 is 141.3 x 10^6 ± 13.2 x 10^6 m^3. The uncertainty was the difference between the calculated estimate using the two methods. As a result, the 15 named glaciers lost a total volume of ~47 % from 1900-1957 (relative to 1990) and ~53% from 1957-2010 (relative to 1957), ~31% from 1957-1990, and ~18% from 1990-2010 (relative to 1957). More loss occurred during 1957-1990 compared to 1990-2010, with a few exceptions, most notably, Diller Glacier. From 1957-1990 the Diller Glacier lost an average of -5.4 m and from 1990-2010 it lost and -11.0 m.

Substantial local thinning was observed on both Collier and Diller glaciers. The Collier Glacier thinned by as much as 45-50 m from 1957-2010 in the accumulation zone above 2600 m. The Diller Glacier lost up to 45-50 m of elevation near the middle of the glacier between 2400-2600 m (Figure 29). As a qualitative check on these thinning estimates I compared aerial and groundbased oblique photographs to determine if these changes could be observed. Photos showed outcrops were exposed more and visible thinning

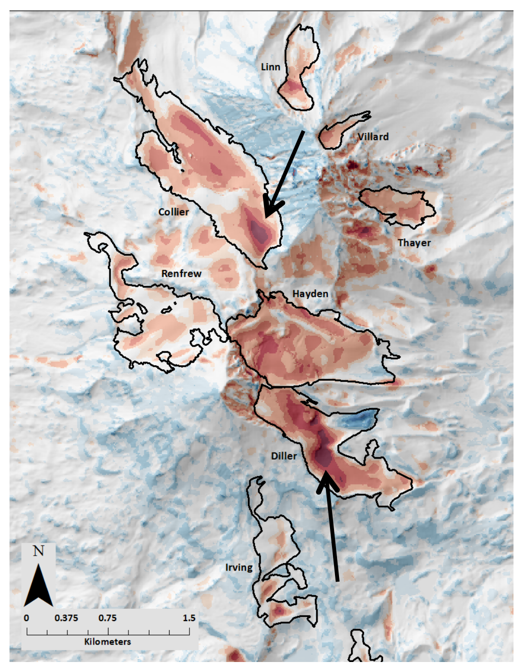


Figure 29. Map showing location of substantial thinning on the Collier and Diller glaciers from 1957-2010. Map is in WGS 84 UTM Zone 10.

along glacier boundaries can be seen with observed loss in the ablation zone (Figure 30).

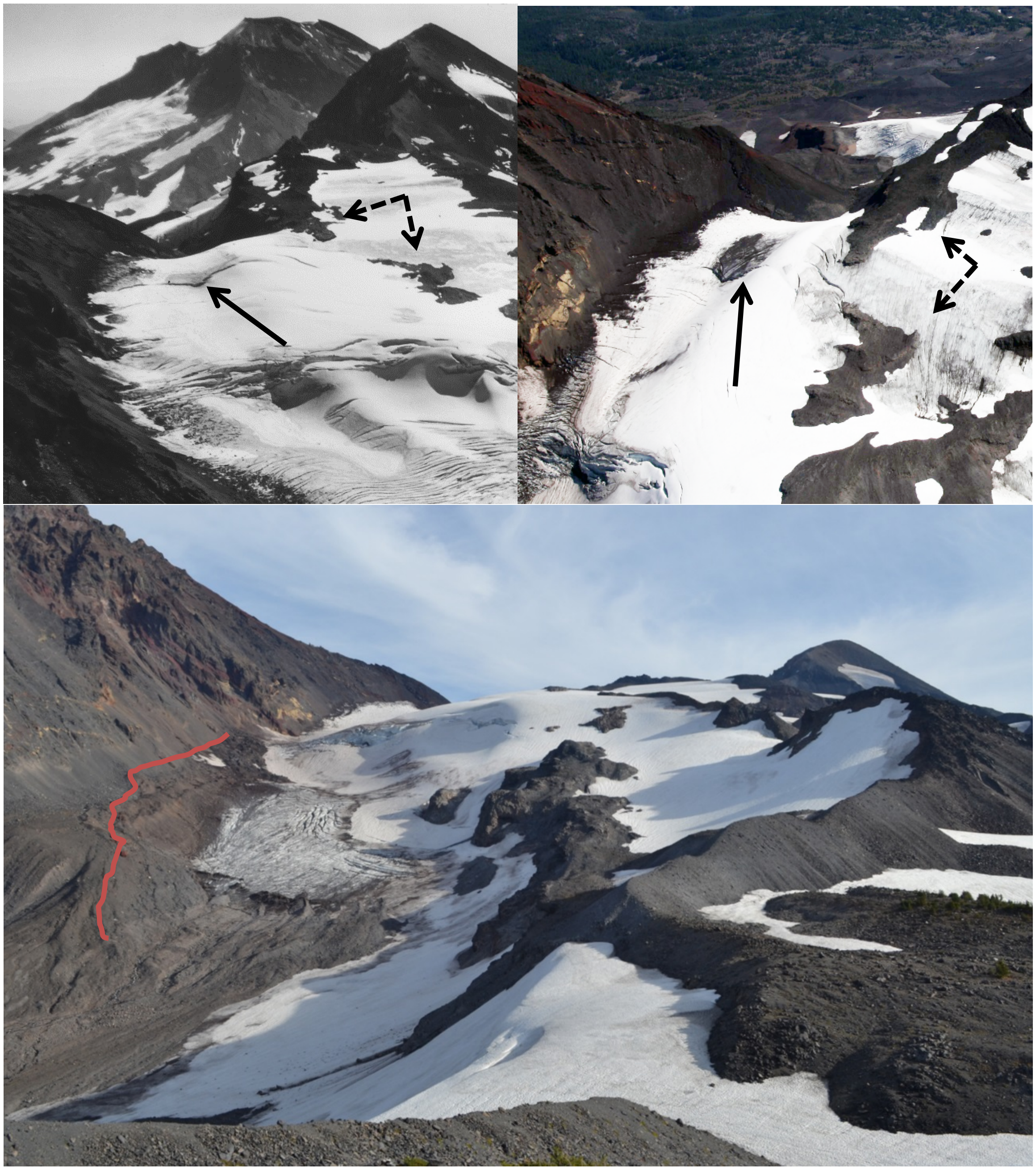


Figure 30. Comparison of the Collier Glacier from September 21, 1960 (Top left, photo taken by Austin Post) and August 24, 2007 (Top right, photo taken by John Scurlock). Based on the volume change calculation the glacier has lost up 45 m of surface elevation in the accumulation zone where the solid black arrows are pointing. Notice the exposure of bedrock within the glacier as the surface elevation has been dropped (dashed arrows). Bottom photo of the Collier Glacier showing the approximate location of the glacier boundary based on oblique aerial photos from around 1960 on a photo taken in September 28, 2012 (Justin Ohlschlager). Photo Sources: 1960 - University of Washington; 2007 - Portland State University and Mazamas.

To examine whether topography has an influence I compared the variation of glacier loss (1957-2010) to the 1957 mean elevation, elevation difference, slope, and aspect. The results showed poor correlation and statistical insignificance with the exception to slope on South Sisters glaciers (Figure 31 and Figure **32**).

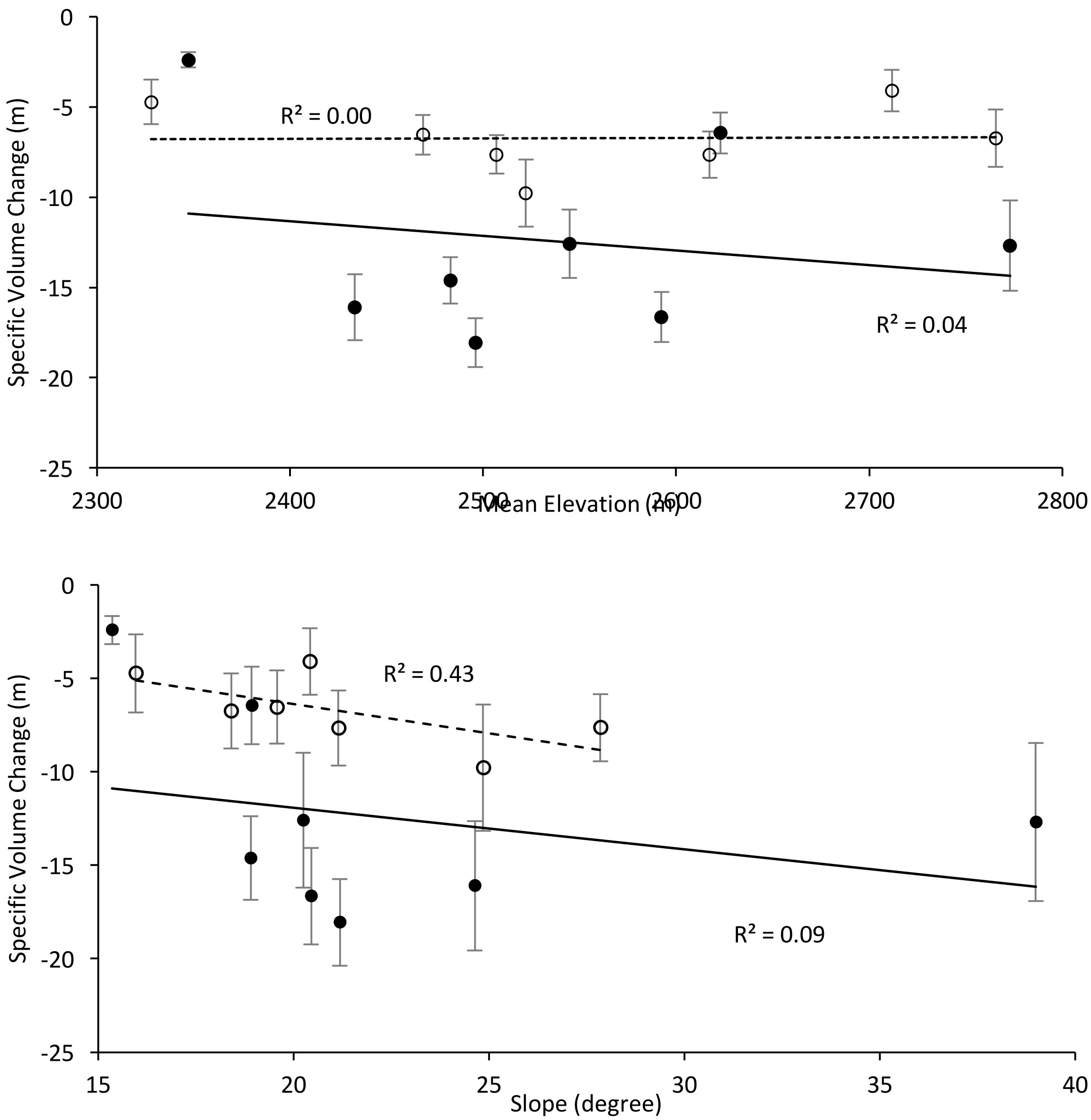
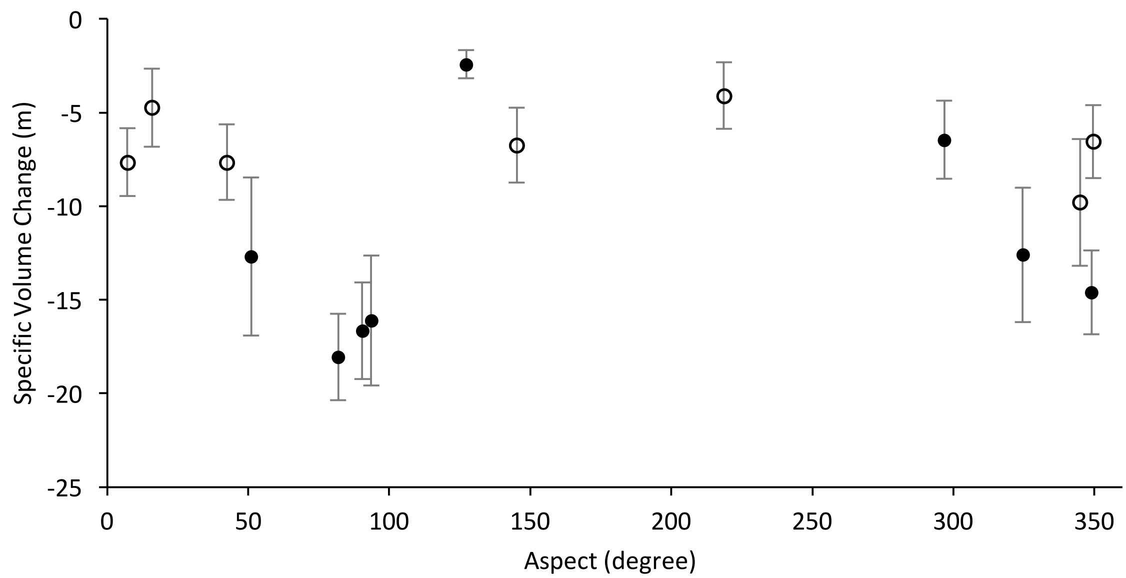


Figure 31. Specific volume change (1957-2010) as a function of average elevation and slope. The open circles and dash line are South Sister glaciers and the filled circles and solid line are North & Middle Sisters glaciers.

The best correlation was between the slope and volume change for the South Sister glaciers, increased slope – greater loss ($r^2 = 0.43$) but was not significant ($p < 0.05$).



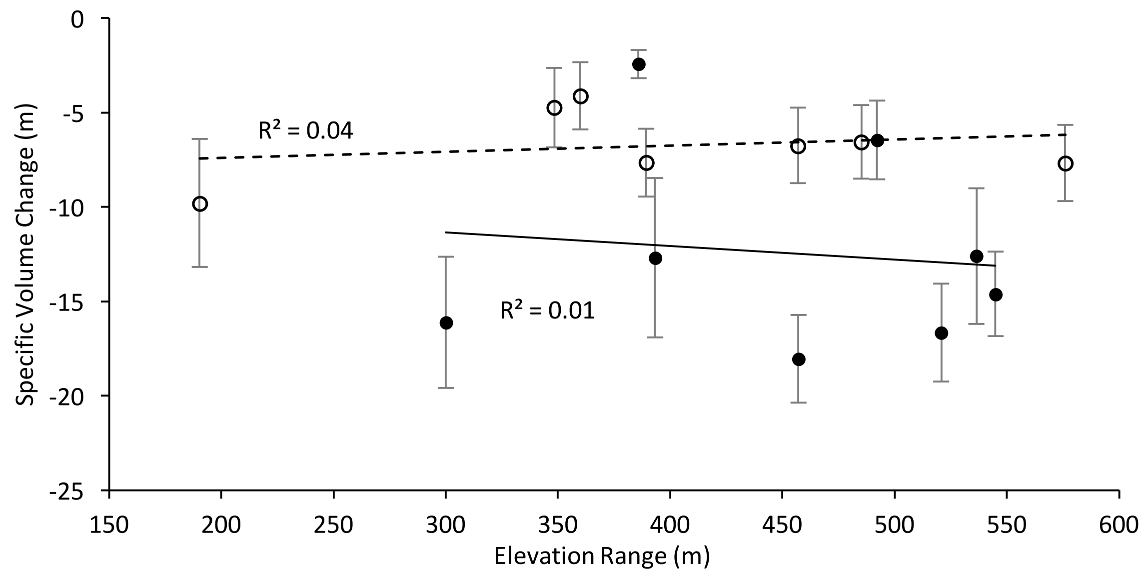


Figure 32. Specific volume change (1957-2010) as a function of average aspect and elevation difference. The open circles and dashed line are South Sister glaciers and the filled circles and solid line are North & Middle Sisters glaciers.

When examining the plots for 1957-1990 and 1990-2010, no topographic variable showed correlation to volume change. Glaciers with a southerly aspect showed lower specific volume change as compared to other glaciers. This might be due to the fact that there is more ice in the northerly aspect, thus more ice to lose. Perhaps a combination of variables have a greater correlation on glacier volume change then just one variable alone.

To examine if the debris cover affects the volume change I plotted the specific volume change versus the debris cover percentage and with aspect (Figure 33). The specific volume change was not significantly correlated with debris cover, which differs from the correlation seen between the area change and debris cover.

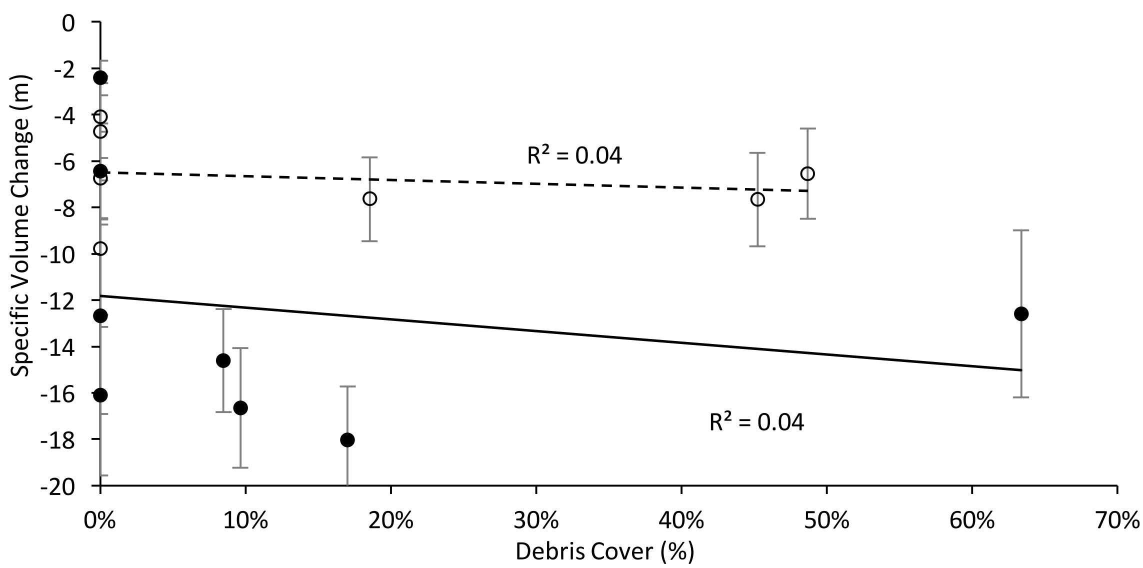


Figure 33. Specific volume change (1957-2010) as a function of debris cover. The open circles and dashed line are South Sister glaciers and the closed circles and solid line are North & Middle Sisters glaciers.

Thickening zones on the Diller, Hayden, Lost Creek, Prouty, and Skinner glaciers are covered by rock debris which could be thick enough to insulate the ice, reducing ice melting, and promoting advance. However, not all debris-covered regions showed signs of thickening. Glaciers with debris cover faced between the NW to E directions with no debris on glaciers facing SE to W (via the south). This might be due to that larger glaciers (Collier, Diller, Hayden, Prouty) facing in these directions and eroding the mountains creating steep headwalls, and this eroded debris is being collected on their surfaces because of larger surface areas and lower slopes. The glaciers with debris cover on their surfaces are below these steep eroded headwalls with surfaces > 40°. The erosion of these headwalls contributed debris to the glaciers (Figure 34).

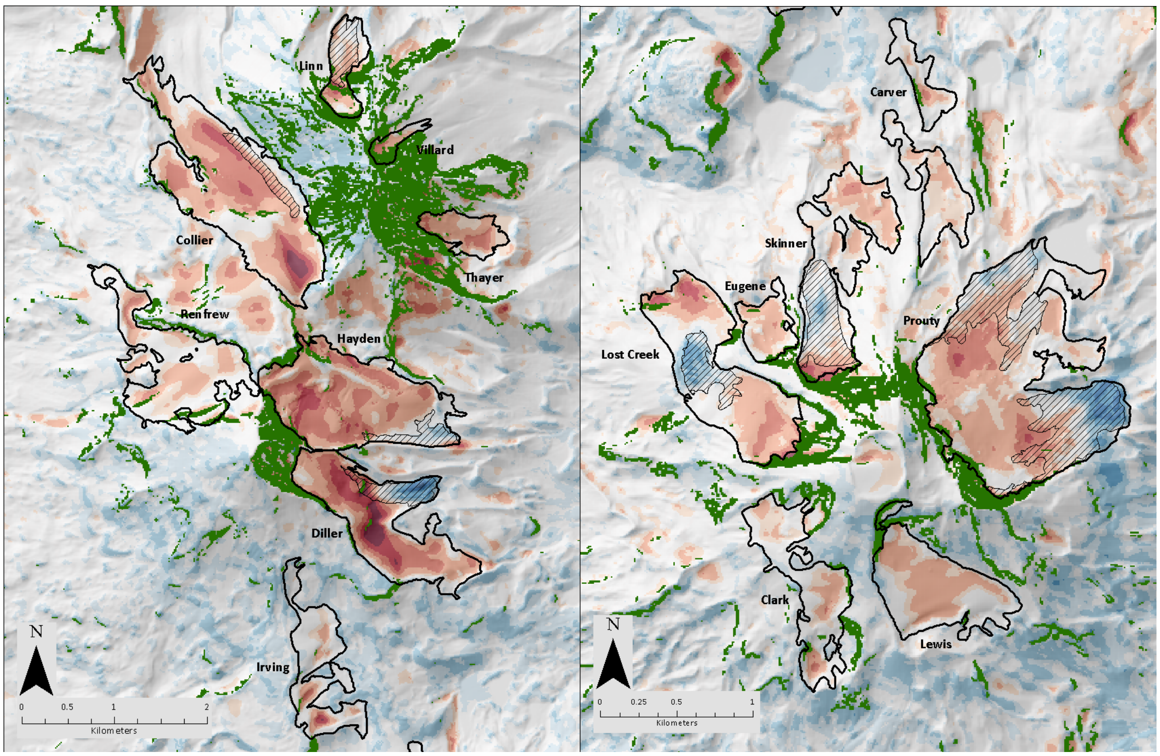


Figure 34. Maps showing the spatial distribution of elevation change of the 15 named glaciers on the Three Sisters with Slopes above 40° green. Glacier outlines, in black and debris covered ice zones are the hatched marked areas. Map is in WGS 84 UTM Zone 10.

To examine if there is a relationship between volume change and area change I plotted the volume change versus the area change, from 1957-2010 (area change is from 1957-2003) (Figure 35). There was no observed relationship between the area change and volume change on South Sister. However, the glaciers on the North &

Middle Sisters revealed a slight correlation (r^2 = 0.24) - it shows that with increasing area change the volume loss increased.

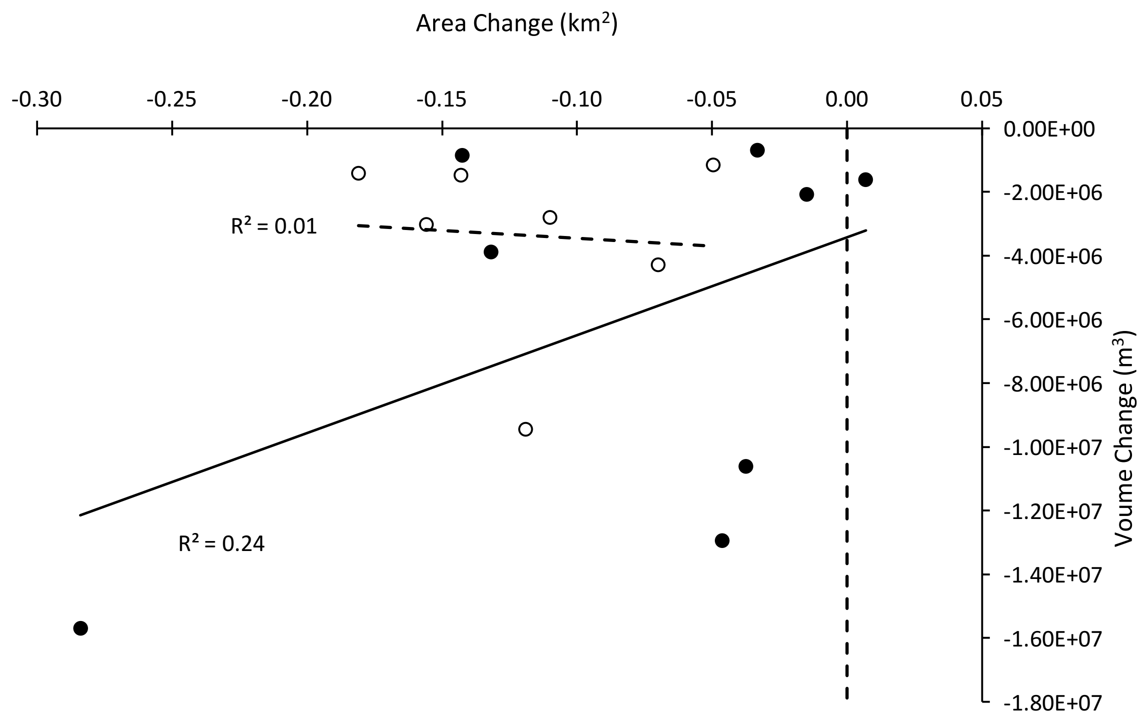


Figure 35. Volume change (1957-2010) as a function of area change. The open circles and dashed line are South Sister glaciers and the closed circles and solid line are North & Middle Sisters glaciers.

To examine the variation of glacier volume loss or gain with elevation, the specific volume change is averaged across 100 m elevation bands and plotted against elevation (Figure 36). The North & Middle Sisters glaciers on the Three Sisters have lost significant volume across their entire elevations. The elevations with the greatest volume change occurred in the 2400-2700 m range, and commonly peaking at 2500 and 2700m. The South Sister's glaciers exhibit volume loss – less volume loss to volume gain – more volume loss pattern as they move higher in elevation. This pattern is observed across the accumulation and ablation zones. The elevations with the greatest volume change occurred in two zones 2300-2400 m and 2700-2900 m ranges. The elevation band with the greatest fraction of volume loss was the 2700 m and 2800 m band. Most glaciers, across all of the Three Sisters, show increased volume loss around 2500 m and 2700 m. The elevation band with the greatest fraction of volume loss was the 2600 m and 2700 m band, which had 31% of the total volume loss across all glaciers.

The four largest glaciers (Collier, Hayden, Diller, and Prouty) all have lost significant volume in their midsections or higher in elevation. This is likely due to the fact that these glaciers have an already thin terminus due to significant lost since the LIA and as a result there is more ice to be lost in their mid-sections.

Several glaciers exhibited areas that thickened during the 1957-2010 period. The Diller, Hayden and Prouty had terminus thickening and advance along with the Lost Creek, and Skinner glaciers having had mid-sections that thickened. This thickening was only observed in the elevation plots for glaciers on the South Sisters (Lost Creek, Prouty, and Skinner). This thickening occurred between 2500 m and 2600 m and, as stated previously was observed with debris covered ice.

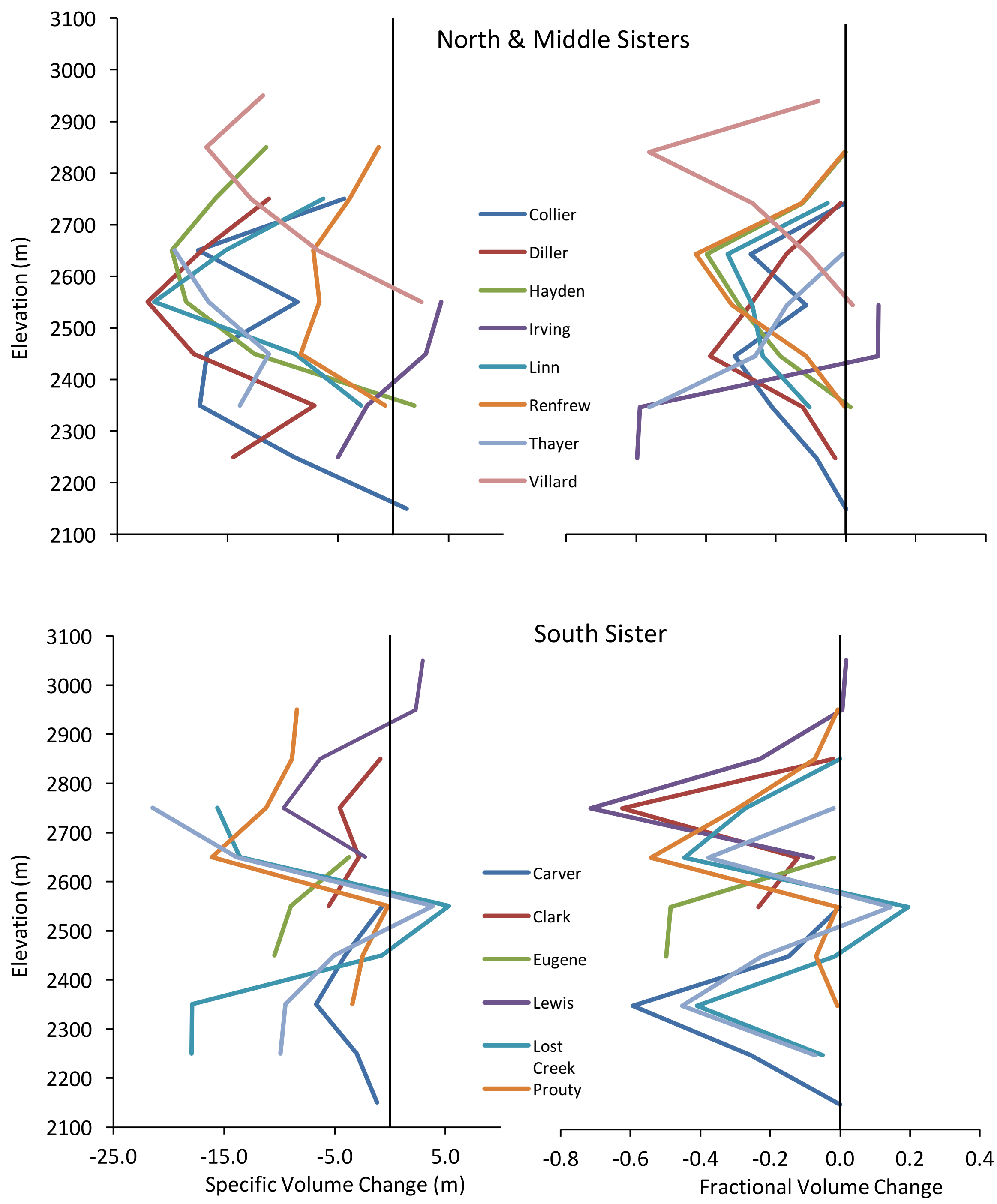


Figure 36. Specific volume change (left) and fractional volume change (Right) from 1957-2010 as a function of elevation for the North & Middle Sister glaciers (Top) and South Sister glaciers (bottom). Data is plotted at 100 m intervals centered on mid-interval.

Discussion and Conclusions

The volume change of the 15 named glaciers showed all glaciers losing mass from 1900 to 2010. It's estimated that the volume lost a total of ~61% from 1900 to 2010. Overall, glaciers lost 71.98 x 10^6 ± 2.87 x 10^6 m^3 from 1957-2010. Most glaciers lost more volume from 1957-1990 then from 1990-2010 as expected from the area change, with a few exceptions, most notable Diller Glacier. These results are comparable to the volume change study that was completed by Sisson et al. (2010) for Mount Rainier. He found that the glacier and perennial snowfields had an average specific volume change of -7.06 m which is slightly less than the average of -8.9 m on the Three Sisters. Over the 37/38 (1970-2007/2008) year period the glaciers on Mount Rainier lost ~14% of ice and perennial snow volume, while on the Three Sisters glaciers lost ~53% of volume over a 53 year time period. Despite a 15 year difference in estimating volume, it is likely that the glaciers on the Three Sisters have lost a greater percentage of their ice than on Mount Rainier. The volume change decreases also compare to the overall volume decrease that has been observed in the alpine regions around the globe (Bauder et al., 2007; DeBeer and Sharp, 2007; Lambrecht and Kuhn, 2007). Bauder et al. (2007) found that selected glaciers in the Swiss Alp's lost a total volume 8.7 km^3 from 1920-2007. DeBeer and Sharp (2007) found that the glaciers in the Southern Canadian Cordillera lost a volume of 13 ± 3 km^3 from 1951/52-2001. Lambrecht and Kuhn (2007) found that glaciers in the Austrian Alp's lost a total volume about 5 km^3 from 1969-1998.

The uncertainty of volume change was binned by slope and, as expected, there were lower uncertainties in lower slopes. Each bin's uncertainty was applied to each cell depending on the slope of that cell, which resulted in a better understanding of uncertainty for the volume differencing.

The analysis of topographic controls on the volume change of the 15 named glaciers showed no significant correlations. The best outcomes were volume change relationship to mean elevation on North & Middle Sister glaciers and volume change to slope for South Sister glaciers, with the other variables (aspect and elevation difference) showing no significance or correlation. Sisson et al. (2011) also found that there was a poor correlation with ice volume losses and aspect. Possibly a combination of variables have a major effect on volume change rather than specific variables. North & Middle Sister glaciers with greater mean elevation showed less area change and South Sister glaciers with steeper slopes show greater volume loss.

Overall, The North & Middle Sisters glaciers on the Three Sisters have lost significant volume across their entire elevations, and the South Sisters glaciers exhibit a more volume loss – less volume loss to volume gain – more volume loss pattern as they move higher in elevation. This observation is different than what was observed on Mount Rainier. The glaciers there exhibited a more traditional pattern of more loss in the ablation zone and thickening in the accumulation zone. The elevations with the greatest volume change occurred in the 2400-2700 m range, and commonly peaking at 2500 and 2700m. The elevation band with the greatest fraction of volume loss was the 2600 m and 2700 m band, which had 31% of the total volume loss across all glaciers.

Several glaciers exhibited areas that thickened from 1957 through 2010. The

Diller, Hayden, Lost Creek, Prouty, and Skinner glaciers all had sections or termini that thickened. This thickening occurred between 2450 m and 2600 m and was observed in areas that are debris-covered. Several glaciers (Prouty, Lost Creek, and Irving) show thickening around 2600 m. It is likely that with an already thinned terminus zones, there is more glacier ice to be lost is the midsections. I suspect that debris cover was ample enough to insulate the ice. Glaciers with debris cover on their surface faced between the NW to E directions compared to glaciers with no debris on them mainly facing SE to W. This might be due to larger glaciers (Collier, Diller, Hayden, and Prouty) in these directions, erosion of the mountains. This eroded debris is being collected on the larger surface areas and lower slopes below steep headwalls with surface slopes > 40°. The erosion of these headwalls is most likely contributing debris to the glaciers because all of these areas are located below these steep eroding headwalls.

The relationship of volume change and debris cover was not as clear as its relationship to area change. One notable observation was that even with zones of thickening on some glaciers all of the glaciers lost volume. This was also observed on Mount Rainier (Sisson et al., 2011). The Emmons and Winthrop glaciers both had terminal thickening and advanced but still overall lost volume over the study period. In all cases these zones are debris covered. Like on both volcanoes, glaciers have seemed to follow overall decreases in volume with local zones and terminal advances that correspond to debris covered ice.

In conclusion, glacier volumes lost ~53% from 1957-2010 with higher rates of loss from 1957-1990 compared to 1990-2010, with a few exceptions, and two glaciers gained volume from 1990-2010. Zones of some glaciers with debris covered ice thickened over the study periods. No correlation was observed between single topographic variables. These results are comparable to changes observed on Mount Rainier (Sisson et al., 2011) and other alpine regions around the globe (Bauder et al., 2007; DeBeer and Sharp, 2007; Lambrecht and Kuhn, 2007).

Chapter Five – Historic Photos

Introduction

The purpose of this chapter is to compile and examine the historic photographic record of the glaciers on the Three Sisters and report on the efforts to 'match' a number of the photos in order to continue the qualitative documentation of the glaciers.

Historic Photos

The historic photograph record of the glaciers on the Three Sisters is extensive (Table 22). As mentioned in previous chapters J.S. Diller first observed glaciers on the Three Sisters in the summer of 1883 on an expedition to the summits of Mt. Thielsen, Diamond Peak, and the Three Sisters (Russell, 1885). Russell noted that Diller observed a number of considerable glaciers on multiple Cascade peaks that included the Three Sisters.

Table 22. Photo list of the glaciers on the Three Sisters presented in this chapter.

Glacier(s)	Volcano	Date	Photographer	Source/Publication
Collier	North	August 1910	Clarence Winter	Jim O'Connor, USGS
Collier	North	July 14, 1914	EF Martin	Jim O'Connor, USGS
Collier	North	September 8, 1920	FW Cleator	Jim O'Connor, USGS
Collier	North	September 28, 1938	Ruth Hopson Keen	Jim O'Connor, USGS
Collier	North	August 11, 1944	Ruth Hopson Keen	Jim O'Connor, USGS
Collier	North	September 23, 1951	Ruth Hopson Keen	Jim O'Connor, USGS
Collier	North	August 14, 1973	Ruth Hopson Keen	Jim O'Connor, USGS
Diller	Middle	August 16, 1903	IC Russell	Russell, 1905
Diller	Middle	September 24, 1937	AJ Gilardi	The Mazamas
Diller-Hayden	Middle	September 24, 1937	AJ Gilardi	The Mazamas
Diller-Hayden-Irving	Middle	August 14, 1910	Ira Williams	Jim O'Connor, USGS
Hayden	Middle	August 16, 1903	IC Russell	Russell, 1905
Hayden	Middle	August 16, 1903	IC Russell	Russell, 1905
Carver-Eugene-Irving-Lost Creek-Prouty-Skinner	South	August 12, 1910	Clarence Winter	The Mazamas

The first scientific report of the glaciers came from I.C. Russell (1905), he included his photographs of the glaciers and of areas he observed the shrinking glaciers. He observed that the current glacier surfaces were lower than the adjacent moraine crest (Figure 37.)

Figure 37. Clockwise from top, photo taken August 16, 1903 looking southeast towards Diller Glacier (foreground and Broken Top (background). Photo taken August 16, 1903 looking west towards Hayden Glacier (right) and Middle Sister (Background). Photo taken August 16, 1903 looking east towards Hayden Glacier. All photos taken by I.C. Russell and sourced by Dr. Jim O'Connor, USGS.

The next report on the glaciers, as noted in previous chapters, came from Edwin Hodges (1925), *Mount Multnomah: Ancient Ancestor of the Three Sisters.* In this report he reported on the geology and glaciers of the Three Sisters and his hypothesis that the volcanoes were all once part of one larger volcano he called Mount Multnomah. This hypothesis was later debunked, however in the report he noted the current glacier sizes and had a few photographs of the glaciers. These photographs mainly consisted of up-close photos of ice with no sense of reference or photos of the mountains from a far distance.

Along with the early reports and photographs many other photographs of the Three Sisters glaciers have been published by the Mazamas, an alpine hiking club in Portland, Oregon (Williams, 1916; Phillips, 1938; Hopson, 1960; Hopson, 1965). The Mazamas have both lead alpine hikes where ground based oblique photographs have been taken in the region of the Three Sisters and funded aerial photo surveys to document glaciers across the Pacific Northwest (Research Committee of the Mazamas, 1938) (Figure 38).

Figure 38. Aerial photographs (Photograph taken by A.J. Gilardi) of the Diller (left) and Hayden (right) glaciers taken September 24, 1937 funded by the Research Committee of the Mazamas (sourced by the Mazamas).

The Mazamas recognized that the glaciers in the Pacific Northwest had been retreating (Williams, 1916; Phillips, 1938) and in response they have funded research investigating the changing the alpine zones. Along with these efforts many other photographs have been taken across the Three Sisters in the early part of the 20th century (Figure 39).

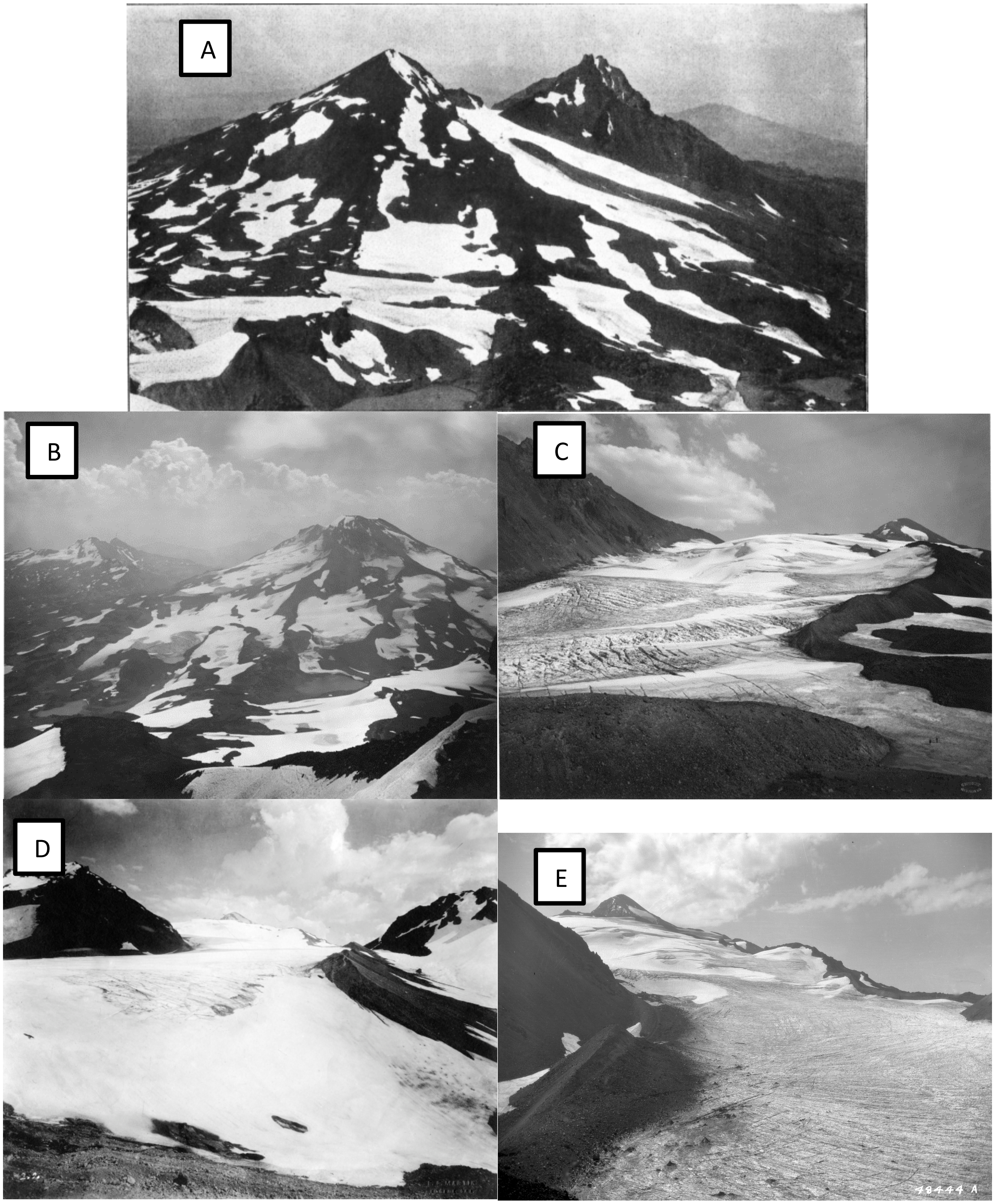


Figure 39. Historic photos of the Three Sisters and its glaciers. **A)** Photo taken August 14, 1910 from the south summit of South Sister looking north by Ira Williams. Photo source: Jim O'Connor, USGS. **B)** Photo taken August 12, 1910 from the summit of Middle Sister looking south towards South Sister and Broken Top by Clarence Winter. Photo source: Jim O'Connor, USGS courtesy of the Mazamas. **C)** Photo taken August 1910 from the south face of Little Brother by Clarence Winter. Photo source: Jim O'Connor, USGS. **D)** Photo taken July 14, 1914 from the Collier Cone looking south towards Middle Sister by E.F. Martin, USGS. Photo source: Jim O'Connor, USGS. **E)** Photo taken September 8, 1920 from Collier Cone looking south towards Middle Sister by Fred W. Cleator, USFS. Photo source: Jim O'Connor, USGS.

Matching

Photographs taken with the intent of 'matching' are taken in order to document the glacier change in a qualitative sense. In the Three Sister region matching was started in the late 1930's by Dr. Ruth Hopson Keen. From 1934 to 1973 Dr. Keen took 19 matching photos of the Collier Glacier taken from Collier Cone looking south (Figure 40). Her reports published in the Mazamas Annuals (Hopson, 1960; Hopson, 1961; Hopson, 1962; Hopson, 1965) detail her observations on the changing glacier and alpine zones. Her photographs have offered an amazing window into how dramatically Collier glacier has been receding up valley from is terminus at Collier Cone in the early part of the century.

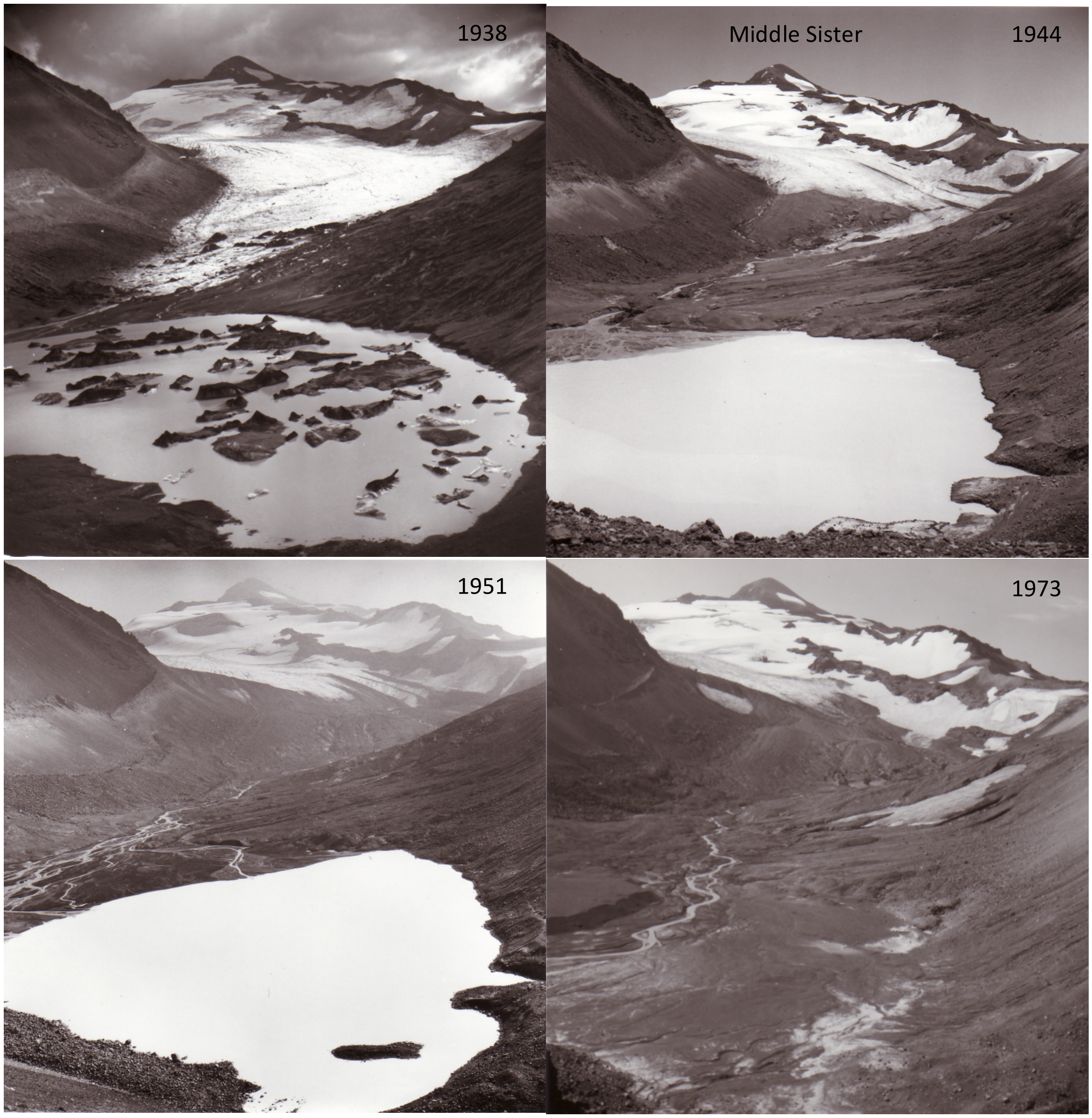


Figure 40. Ruth Hopson Keen photos of Collier Glacier taken from Collier Cone looking South towards Middle Sister. **1938)** Taken September 28, 1938. **1944)** Taken August 11, 1944. **1951)** Taken September 23, 1951. **1973)** Taken August 14, 1973. All Photos were published by the Mazamas hiking club and were sourced by Dr. Jim O'Connor at the USGS.

Photo matching was continued in the 1990's by USGS scientists Dave Wieprecht, Jasper Hardison, and Jim O'Connor. They have matched many historic photographs in the region in order to continue the documentation of the shrinking glaciers (O'Connor, 2013) (Figure 41).

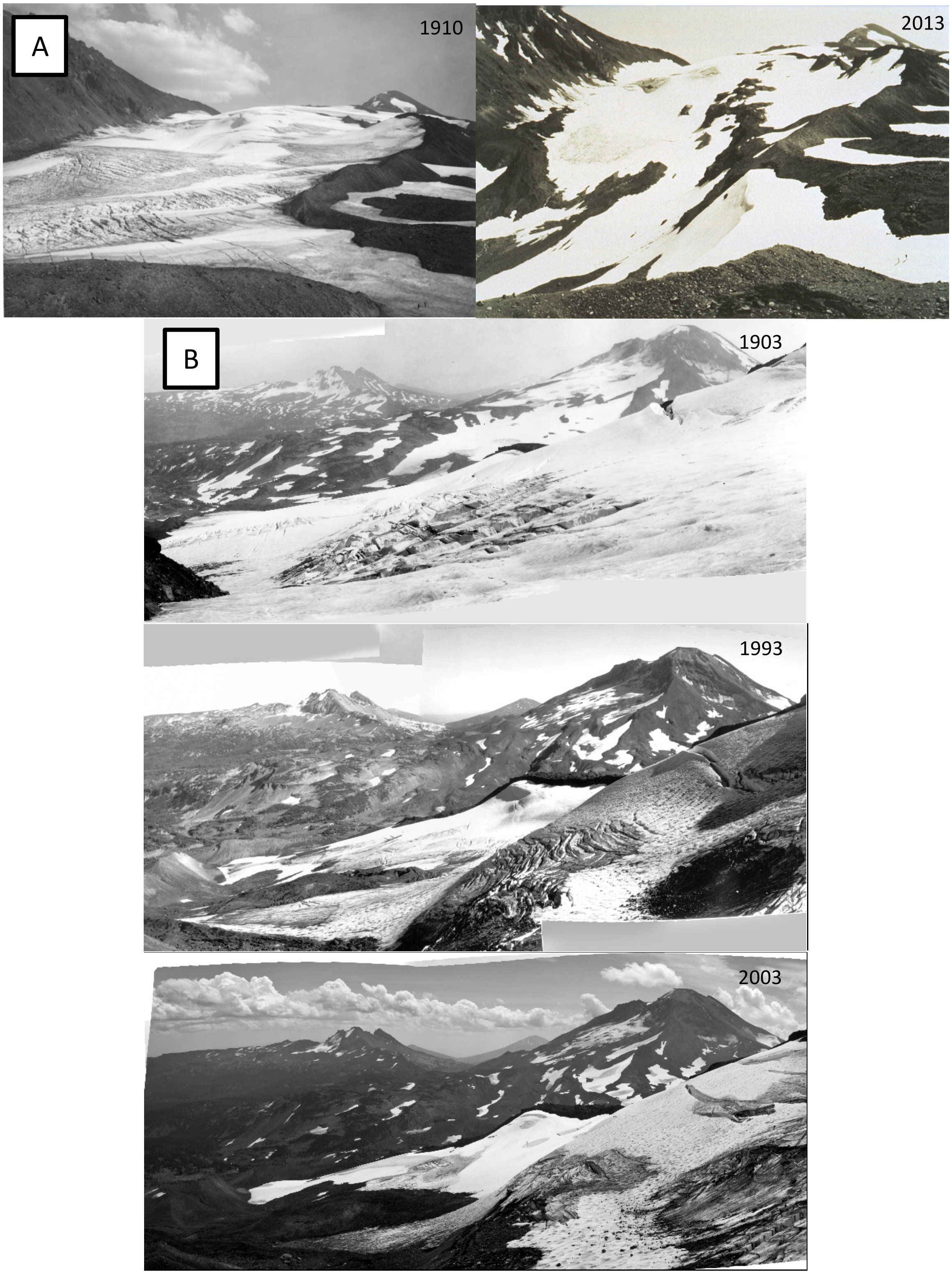


Figure 41. A) Photo of Collier Glacier Taken by Clarence Winters, August 1910, matched by Dave Wieprecht from Little Brother looking South towards Middle Sister. **B)** Photo taken by IC Russell August 16, 1903 with photo matches by David Weiprecht on August 16, 2003 and Jim O'Connor on August 17' 2013. All Photos were sourced by Dr. Jim O'Connor at the USGS.

In the summer of 2012 I matched three historic photos to continue the tradition and documentation (Figure 42).

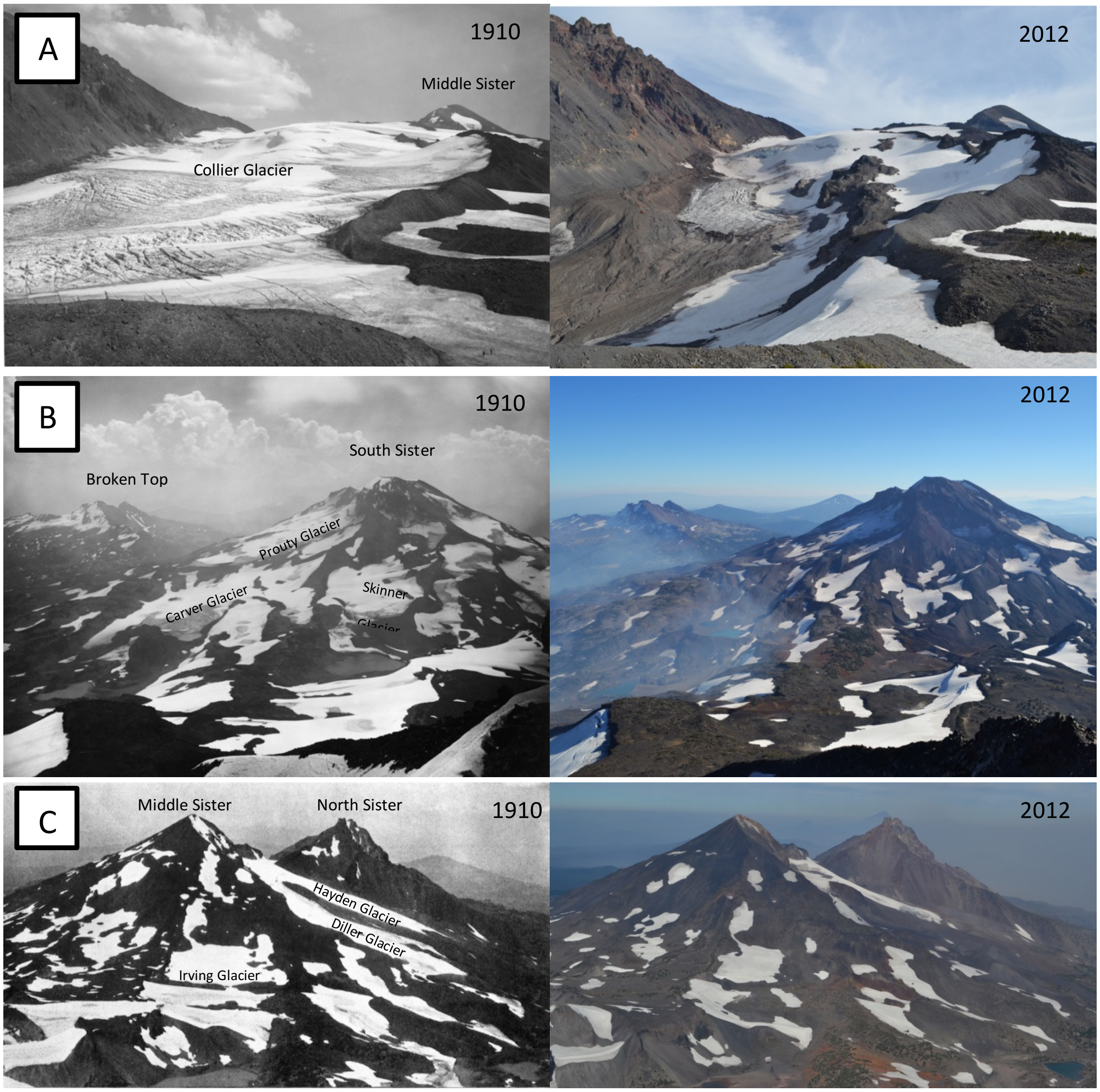


Figure 42. Photo matches of historic photos taken of the Three Sisters and its glaciers. **A)** 1910 photo taken August 1910 from the south face of Little Brother by Clarence Winter. Photo source: Jim O'Connor, USGS. 2012 photo from roughly same location on September 28, 2012 by Justin Ohlschlager. **B)** 1910 photo taken August 12, 1910 from the Summit of Middle Sister looking South towards South Sister and Broken Top by Clarence Winter. Photo source: Jim O'Connor, USGS. 2012 photo from roughly same location on October 7, 2012 by Justin Ohlschlager (notice smoke from the Pole Creek Fire). **C)** 1910 photo taken August 14, 1910 from the Summit of South Sister looking north towards Middle and North Sisters by Ira Williams. Photo source: Jim O'Connor, USGS. 2012 photo from roughly same location on September 27, 2012 by Justin Ohlschlager.

Three photos were matched, the 1910 Clarence Winter photo of Collier glacier, the 1910 Clarence Winter photo of glacier on the North face of South Sister taken from the summit of Middle Sister, and the 1910 Ira Williams photo of the glaciers on the south and east faces of Middle Sister taken from the summit of South Sister.

Discussion

Historic photographs of the Three Sisters glacier offer insight as to how the glaciers have been changing qualitatively over time. They offer an opportunity to fully understand how the glaciers have been changing sometimes when no other data is present.

J.S. Diller first observed glaciers on the Three Sisters in the summer of 1883 with the first scientific publication that reported and documented the glaciers coming from I.C. Russell (1905). In his report he noted, described, and took many photos the glaciers in the region. He noticed their current surface being lower than the adjacent moraine crests. The next major report on the glaciers was from Edwin Hodges (1925). In the report he noted the current glacier sizes and had a few photographs of the glaciers. Many photographs of the Three Sisters glaciers have been published by the Mazamas taken on alpine hikes and aerial photo surveys to record the glaciers across the Pacific Northwest. They recognized that the glaciers in the Pacific Northwest had been retreating from year to year.

Photographs for 'matching' purposes were started in the late 1930's by Dr. Ruth Hopson Keen. From 1934 to 1973 Dr. Keen took 19 matching photos and her reports published in the Mazamas annuals detail her observations on the changing glacier and alpine zones.   Photo matching was continued in the 1990's by USGS scientists Dave Wieprecht, Jasper Hardison, and Jim O'Connor. They have matched many historic photographs in the region in order to continue the documentation of the shrinking glaciers.

Continued photographic documentation of the glaciers on the Three Sisters is useful for both quantitative and qualitative purposes. They offer a low cost and effective way to record glacier extents and with the advancement of ground based photogrammetric software these photographs could offer even more insight into their dynamic change.

Chapter Six – Discussion and Conclusions

Multiple inventories of the glaciers and perennial snowfields were compiled from orthorectified vertical aerial imagery from 1949, 1957, 1990, and satellite imagery from 2003. The inventories in 1949 and 1957 showed 402 snow and ice features; 1990 showed 337 features. In 1990 65 features were missing due to insignificant coverage in imagery. In 2003 121 features were found as a result of focusing on features that were found as perennial in the previous inventories. The number of perennial features was 122 for 1949 through 1990 and dropped to 121 in 2003. The total area of the glaciers and perennial snowfields shrank from 9.03 ± 1.65 km^2 in 1949 to 7.10 ± 1.16 km^2 in 2003. Comparing the number and area of glaciers and perennial snowfields in 2003 (121, 7.1 ± 1.16 km^2) to previous studies reveals a smaller population and area compared to the Sierra Nevada (1719, 39.15 ± 7.52 km^2) (Basagic and Fountain, 2011) and North Cascades (1935, 236.20 ± 12.60 km^2) (Dick, 2013). This is to be expected because those studies covered a much larger land area. The number and area of glaciers on the Three Sisters (19, 7.76 ± 1.50 in 1957) as compared to other Cascade volcanoes, Mount Hood (12, 7.79 ± 0.33 km^2 in 1946) (Jackson, 2007), Mount Rainier (26, 88.11 ± 0.99 km^2 in 1971) (Nylen, 2001), Mount Adams (12, 21.73 ± 0.99 km^2 in 1969) (Sitts et al., 2010), and Mount Baker (6, 21.52 ± 0.711 km^2 in 1956) (Dick, 2013), is mostly greater in number and smaller in area with a couple of exceptions.

It was found that the 24K glacier and perennial snowfield inventory did not represent the outlines of 1957, but had been updated using 1980 imagery that shows large amounts of seasonal snow and as a result, the 24K inventory was not used. This result differed from other regional inventories that found the 24K inventory to be useful (Granshaw and Fountain, 2006; Basagic and Fountain, 2011; Dick, 2013).

The average elevation (median) of the glacier and perennial snowfield increased from 1957 to 1990, from 2428 m (2365 m) to 2432 m (2373 m) with most ice-covered area being found between 2300 and 2800 m. The mean feature elevation is lower than those in the Sierra Nevada (3419 m) (Basagic and Fountain, 2011) and higher than those in the North Cascades (1948 m) (Dick, 2013). The elevation band with the greatest ice-covered area also rose from over the same period, from 2400-2500 m (26.2%) in 1957 to 2500-2600 m (33.7%) in 1990. Glaciers were found facing all directions in both 1957 and 1990, but a greater percentage was found facing the NW-E directions in 1990 (85.4%) as compared to 1957 (80.7%). This suggests the bulk of glacier cover on the volcanoes is becoming concentrated higher up as lower elevation snow and ice is being lost more towards the northerly directions. Mean slope of the glaciers showed no significant change 20.9° in 1957 and 21.4° in 1990, with roughly 90% ranging from 10-30°. The average slopes for the glaciers and perennial snowfields are lower than compared to both the Sierra Nevada (28°) and North Cascades (29.7°). All of these results are similar to results found across the American West.

Distinguishing of glaciers from snowfields used a threshold on area (0.1 km^2) and on shear stress. The area threshold of 0.1 km^2 (which was determined to be a better estimate than a threshold of 0.05 km^2) and shear stress test yielded 19 glaciers in 1957 with the same number of glaciers, with only two differences. In 1990, 15 glaciers were over for the area threshold and the shear stress test yielded only 9 glaciers. Based on these results, an area threshold of >0.1 km^2 criteria seems to be a reasonable for determining a glacier on the Three Sisters when topographic information is absent. These results seem in line with other inventories across the American West. Basagic (2008) found that perennial snow and ice features >0.15 km^2 in the Sierra Nevada of Central California all met the glacier definition. Dick (2013) found that an area threshold of 0.1 km^2 in the North Cascades of Northern Washington produced similar results to the glacier definition. She also found that when reducing the shear stress threshold down to 0.925 x 10^5 Pa it matched well with previous inventories. She concluded that a shear stress threshold was a better estimate of identifying glaciers.

The glaciers and perennial snowfields on the Three Sisters have lost area over the period of ~1900-2003. Decadal changes were synchronous, with rapid retreat, advance/stabilization, and continued slower retreat. Glaciers and perennial snowfields generally advanced in the period 1949-1990. For the period 1949-2003 the glaciers and perennial snowfields that changed significantly (relative uncertainty <1) lost area -1.914 ± 0.097 km^2 (21%). Longer time periods exhibited more significant changes than shorter time periods. In general, smaller glaciers lost larger fractions of their area and showed more variability. Overall, time periods showed statistically significant change over the study period. The variability in the smaller glaciers with larger uncertainty masked the change that is taking place.

The 15 named glaciers lost 54% of their area from ~1900-2003, with an average loss for named glaciers of 0.404 km^2, which is similar to area changes across the PNW. Thayer Glacier changed the least (-53.1%) and the largest change was at Collier (-63.1%).

The area change for the named glaciers was always significant even with glaciers with smaller areas. Smaller glaciers are still observed with significant change as compared to the smaller features of perennial snow.

The change of the 15 named glaciers is consistent with other studies in the American West and Western Canada. Glaciers in the Sierra Nevada have shown a 55% decrease in area between 1903 and 2004 (Basagic and Fountain, 2011) and glaciers in Rocky Mountain National Park have declined by 40% from 1909-2004 (Hoffman et al., 2007). To the North, glaciers in the North Cascades including Mt. Baker have decreased by 56% from ~1900-2009 (Dick, 2013), glaciers on Rainier have declined by 22% from 1913-1994 (Nylen, 2001), glaciers on Adams have declined by 49% from 1904-2006 (Sitts el al., 2010) and on Hood glaciers have declined by 40% from 1909-2004 (Jackson and Fountain, 2007).

Topography has no demonstrated effect on the magnitude of glacier change. Perhaps a combination of variables has major effects on area change, as shown by Basagic and Fountain (2011) and Dick (2013). However, glaciers with greater elevation difference showed less area change. This suggests that there is some relationship between glaciers with higher elevation ranges (which is related to maximum elevations) and less area change.

Rock debris cover on glacier surfaces increased by 64% from 1949 to 2003 with the greatest increase occurring between 1957 and 1990. This corresponds with a positive but not significant correlation between the rate of area change and debris cover. Debris cover could be insulating the glaciers enough to slow down melting rates.

This may contribute to observed area changes over the last century. Prior to 1957 glaciers deceased rapidly and had little to no rock debris cover and since then, as rock debris cover has increased, their rate of change has decreased.

Collier Glacier is a relatively good index glacier for the Three Sisters because the magnitude of area changes is roughly similar to the other glaciers in time periods with data.

The volume change of the 15 named glaciers showed all glaciers losing mass from 1900 to 2010. It's estimated that the volume lost a total of ~61% from 1900 to 2010. Overall, glaciers lost $71.98 \times 10^6 \pm 2.87 \times 10^6$ m^3 from 1957-2010. Most glaciers lost more volume from 1957-1990 than from 1990-2010 as expected from the area change, with a few exceptions. These results are comparable to the volume change study that was completed by Sisson et al. (2010) for Mount Rainier. Over the 37/38 (1970-2007/2008) year period the glaciers on Mount Rainier lost ~14% of ice and perennial snow volume, while on the Three Sisters glaciers lost ~53% of volume over a 53 time period. Despite a 15 year difference in estimating volume, it is likely that the glaciers on the Three Sisters have lost a greater percentage of their ice then on Mount Rainier. The volume change decreases also compare to the overall volume decrease that has been observed in the alpine regions around the globe (Bauder et al., 2007; DeBeer and Sharp, 2007; Lambrecht and Kuhn, 2007). Bauder et al. (2007) found that selected glaciers in the Swiss Alp's lost a total volume 8.7 km^3 from 1920-2007. DeBeer and Sharp (2007) found that the glaciers in the Southern Canadian Cordillera lost a volume of 13 ± 3 km^3 from 1951/52-2001. Lambrecht and Kuhn (2007) found that glaciers in the Austrian Alp's lost a total volume about 5 km^3 from 1969-1998.

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The North & Middle Sisters glaciers on the Three Sisters have lost significant volume across their entire elevations, and the South Sister's glaciers exhibit a more volume loss – less volume loss to volume gain – more volume loss pattern as they move higher in elevation. This observation is different than what was observed on Mount Rainier. The glaciers there exhibited a more traditional pattern of more loss in the ablation zone and thickening in the accumulation zone.

Several glaciers exhibited areas that thickened from 1957 through 2010. The Diller, Hayden, Lost Creek, Prouty, and Skinner glaciers all had sections or termini that thickened. This thickening occurred between 2450 m and 2600 m and was observed in areas that are debris covered. Several glaciers (Prouty, Lost Creek, and Irving) show thickening around 2600 m. It is likely that with an already thinned terminus zones, there is more glacier ice to be lost is the midsections. I suspect that debris cover was ample enough to insulate the ice. Glaciers with debris cover on its surface faced between the NW to E directions with no debris on glaciers facing SE to W. This might be due to larger glaciers (Collier, Diller, Hayden, and Prouty) in these directions, erosion of the mountains. This eroded debris is being collected on the larger surface areas and lower slopes below steep headwalls with surface slopes > 40°. The erosion of these headwalls is most likely contributing debris to the glaciers because all of these areas are located below these steep eroding headwalls.

The relationship of volume change and debris cover was not as clear as its relationship to area change. One notable observation was that even with zones of thickening on some glaciers all of the glaciers lost volume. This was also observed on Mount Rainier (Sisson et al., 2011). The Emmons and Winthrop glaciers both had terminal thickening and advanced but still overall lost volume over the study period. In all cases these zones are debris covered. Like on both volcanoes, glaciers have seemed to follow overall decreases in volume with local zones and terminal advances that correspond to debris covered ice.

Historic photographs of the Three Sisters glacier offer insight as to how the glaciers have been changing qualitatively over time. They offer an opportunity to fully understand how the glaciers have been changing sometimes when no other data is present. Continued photographic documentation of the glaciers on the Three Sisters is important for quantitative and qualitative purposes. They offer a low cost and effective way to record glacier extents and with the advancement of ground based photogrammetric software these photographs could offer even more insight into their dynamic change.

Future Work

There is more work to be done in the investigation of the glaciers on the Three Sisters. The first step would be the search for more aerial photography in the area in order to fine tune the area change trends throughout the last century. Next, would be to get quality data in order to pin down the current extent of the glaciers in 2015.

Another step would be to continue the volume change calculations with the soon to be released lidar dataset collected for DOGAMI in September 2014. In addition to this, developing quality DEMs from historical aerial photographs would be critical for understanding how the volume has been change in more detail.

An analysis of the area and volume change compared to the climatic changes in the region is needed. Glaciers respond to these changes and understanding their relationship could offer better insight into how the glaciers have been changing as well as how they will change in the future.

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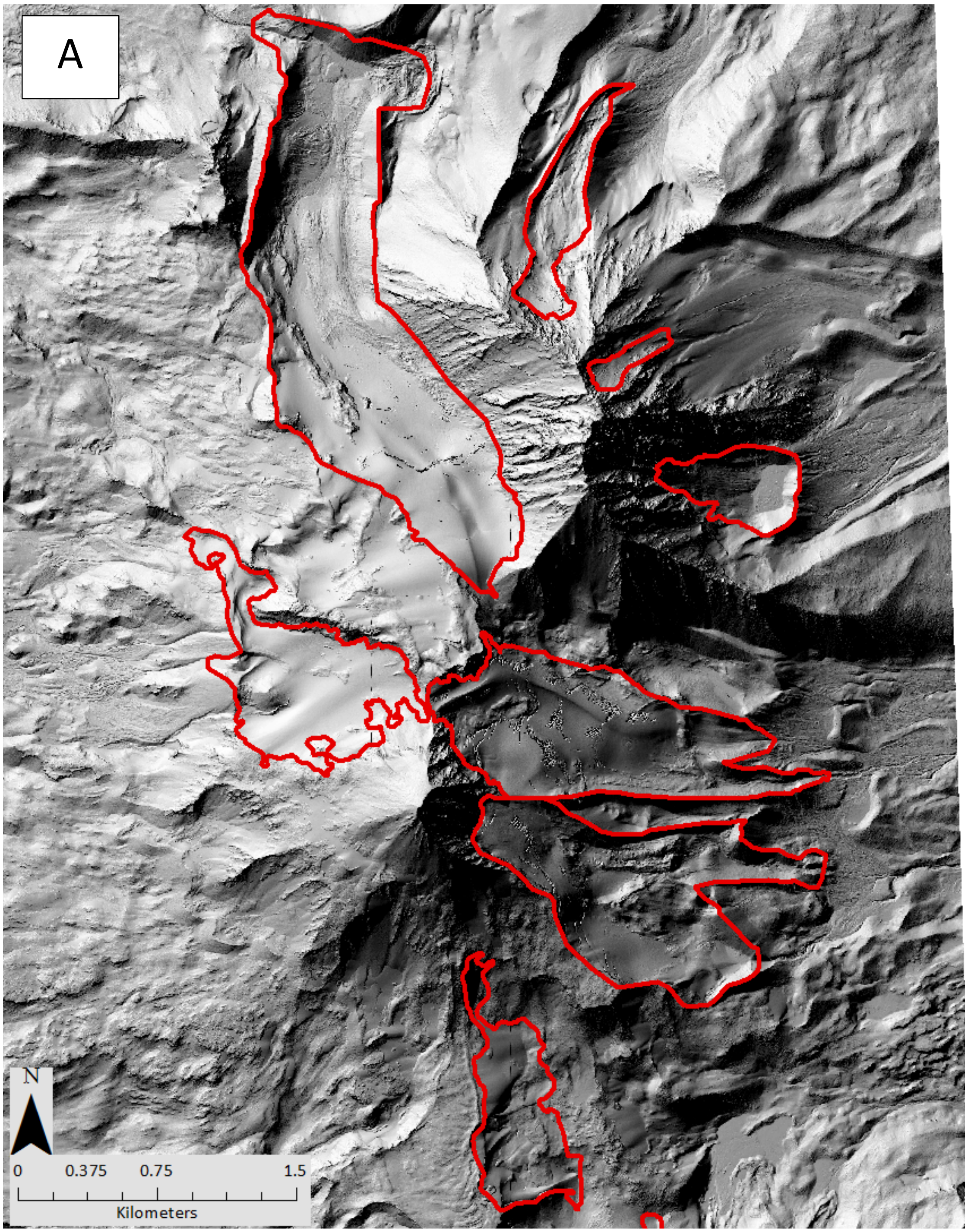
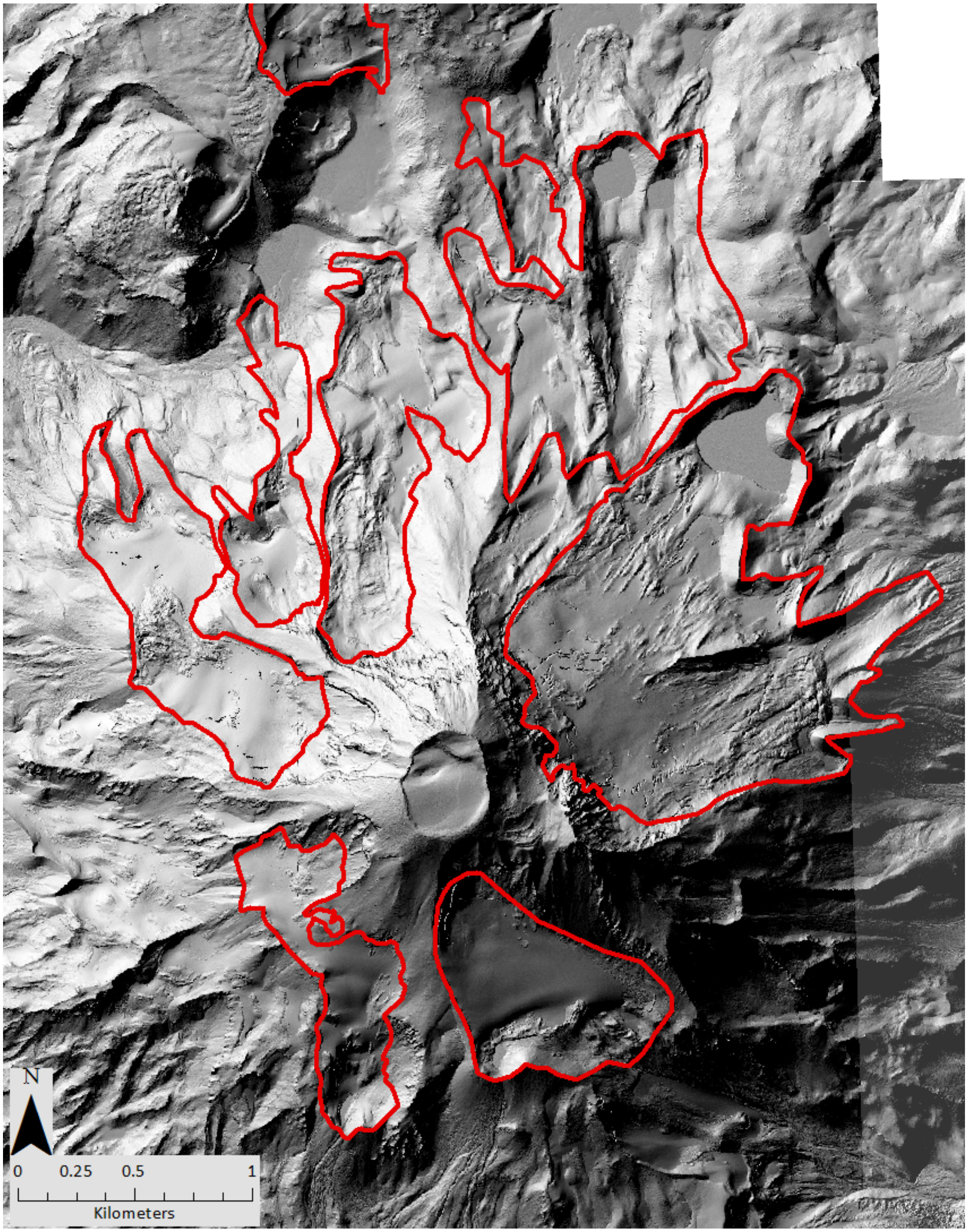
Appendix A – LIA Glacier Outline Inventories Maps

The outlines of the 15 named glaciers (in red) for the LIA identified by a combination of aped moraines from O'Connor et al. (2001), 1990 aerial imagery, and the 2010 lidar dataset. Maps are in WGS 84 UTM Zone 10. A) North & Middle Sisters and B) South Sisters.




N
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0.25
0.5
1
Kilometers

Appendix B – Glacier Inventories Features

Each feature from the inventories is listed below with the following attributes, Glacier Name, TS_ID is the unique identifier, RECNO are the values from the original 24K dataset (Fountain et al., 2007), Perennial – determined as a perennial glacier or snowfield, S - is the mean slope (°), Z - is the mean elevation (m), D - is the mean aspect (°). The topographic statistics were calculated for 1957 and 1990.

1949

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	1		X	0.00533	0.00358	-	-	-	-	-
	2			0.00236	0.00204	-	-	-	-	-
	3			0.00245	0.00219	-	-	-	-	-
	4		X	0.01470	0.00710	-	-	-	-	-
	5		X	0.02635	0.01313	-	-	-	-	-
	6		X	0.03289	0.00899	-	-	-	-	-
	7		X	0.00508	0.00362	-	-	-	-	-
	8		X	0.05083	0.02157	-	-	-	-	-
	9		X	0.00781	0.00461	-	-	-	-	-
	10		X	0.01671	0.00866	-	-	-	-	-
	11		X	0.00691	0.00459	-	-	-	-	-
	12		X	0.00983	0.00515	-	-	-	-	-
	13			0.00780	0.00485	-	-	-	-	-
	14			0.00112	0.00194	-	-	-	-	-
	15			0.01385	0.01377	-	-	-	-	-
	16			0.00131	0.00149	-	-	-	-	-
	17	4194	X	0.01230	0.00839	-	-	-	-	-
	18	4196	X	0.01755	0.02006	-	-	-	-	-
	19	4198	X	0.02522	0.00817	-	-	-	-	-
	20	4201	X	0.01455	0.00881	-	-	-	-	-
	21	4202	X	0.00995	0.00395	-	-	-	-	-
	22	4204		0.00250	0.00362	-	-	-	-	-
	23	4205	X	0.01940	0.01104	-	-	-	-	-
	24	4206	X	0.03270	0.01386	-	-	-	-	-
Renfrew	25	4207	X	0.50036	0.01371	-	-	-	-	-
	26	4208	X	0.12180	0.04435	-	-	-	-	-
Collier	27	4209	X	0.96858	0.04592	-	-	-	-	-
	28	4209	X	0.18674	0.03038	-	-	-	-	-
	29	4210	X	0.03581	0.01018	-	-	-	-	-
	30	4211	X	0.04381	0.01634	-	-	-	-	-
	31	4212	X	0.00978	0.00399	-	-	-	-	-
	32	4213		0.00078	0.00333	-	-	-	-	-
	33	4214	X	0.02007	0.00760	-	-	-	-	-
Thayer	34	4216	X	0.11144	0.02273	-	-	-	-	-
	35	4217		0.00569	0.00395	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	36	4219	X	0.00560	0.00387	-	-	-	-	-
	37	4220	X	0.00870	0.00760	-	-	-	-	-
	38	4221	X	0.01103	0.00807	-	-	-	-	-
	39	4222	X	0.00916	0.00913	-	-	-	-	-
	40	4223	X	0.00706	0.00416	-	-	-	-	-
	41	4224	X	0.00686	0.00733	-	-	-	-	-
	42	4225	X	0.00933	0.00405	-	-	-	-	-
	43	4226	X	0.02243	0.01368	-	-	-	-	-
Villard	44	4227	X	0.04464	0.00389	-	-	-	-	-
Linn	45	4228	X	0.12622	0.00775	-	-	-	-	-
	46	4229		0.03517	0.01665	-	-	-	-	-
	47	4233	X	0.00845	0.00424	-	-	-	-	-
	48	4234	X	0.02520	0.00802	-	-	-	-	-
	49	4237		0.04503	0.01053	-	-	-	-	-
	50	4242		0.00357	0.00274	-	-	-	-	-
	51	4243		0.04017	0.01804	-	-	-	-	-
	52	4244	X	0.04220	0.01444	-	-	-	-	-
	53	4245		0.00441	0.00372	-	-	-	-	-
	54	4246		0.01283	0.00477	-	-	-	-	-
	55	4247		0.00771	0.00570	-	-	-	-	-
	56	4248		0.02148	0.00981	-	-	-	-	-
	57	4250	X	0.07856	0.03108	-	-	-	-	-
	59	4252	X	0.04103	0.01521	-	-	-	-	-
	60	4254	X	0.01799	0.00724	-	-	-	-	-
	61	4255	X	0.04327	0.02476	-	-	-	-	-
	62	4256	X	0.00763	0.00559	-	-	-	-	-
	63	4257	X	0.01416	0.00600	-	-	-	-	-
	64	4258	X	0.02315	0.00838	-	-	-	-	-
	66	4260	X	0.08983	0.03685	-	-	-	-	-
Irving	68	4262	X	0.30547	0.05949	-	-	-	-	-
	69	4263	X	0.00885	0.00377	-	-	-	-	-
	70	4264	X	0.08524	0.02003	-	-	-	-	-
	71	4265	X	0.11904	0.03156	-	-	-	-	-
	72	4266	X	0.04648	0.01614	-	-	-	-	-
	73	4268		0.02364	0.00744	-	-	-	-	-
Skinner	74	4270	X	0.40526	0.06607	-	-	-	-	-
	75	4271	X	0.09015	0.02147	-	-	-	-	-
Prouty	76	4272	X	1.07183	0.03928	-	-	-	-	-
	77	4273	X	0.16180	0.05699	-	-	-	-	-
	78	4274	X	0.02582	0.01546	-	-	-	-	-
	80	4277	X	0.01113	0.00834	-	-	-	-	-
	81	4278		0.01691	0.01271	-	-	-	-	-
	82	4280	X	0.01713	0.00838	-	-	-	-	-
Clark	83	4281	X	0.25864	0.02931	-	-	-	-	-
	84	4282		0.00220	0.00272	-	-	-	-	-
	85	4283	X	0.01605	0.01095	-	-	-	-	-
	86	4284	X	0.01675	0.00735	-	-	-	-	-
	87	4286	X	0.02926	0.01736	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	88	4287	X	0.04970	0.03793	-	-	-	-	-
	89	4288	X	0.06621	0.03024	-	-	-	-	-
	90	4289	X	0.01033	0.00632	-	-	-	-	-
	91	4290	X	0.04272	0.02133	-	-	-	-	-
	92	4291	X	0.02593	0.01335	-	-	-	-	-
	93	4292	X	0.00686	0.00576	-	-	-	-	-
Lewis	94	4293	X	0.33958	0.01118	-	-	-	-	-
	95	4294	X	0.02980	0.01438	-	-	-	-	-
	96	4295	X	0.09414	0.01199	-	-	-	-	-
	97	4296	X	0.02447	0.00979	-	-	-	-	-
Lost Creek	98	4297	X	0.50533	0.00924	-	-	-	-	-
	99	4298	X	0.04309	0.00977	-	-	-	-	-
	100	4299	X	0.00495	0.00656	-	-	-	-	-
	101	4300	X	0.01176	0.00891	-	-	-	-	-
	102	4301	X	0.02355	0.01106	-	-	-	-	-
	103	4302	X	0.02332	0.00860	-	-	-	-	-
Eugene	104	4304	X	0.08944	0.01769	-	-	-	-	-
Carver	105	4306	X	0.27911	0.06000	-	-	-	-	-
	106	4307	X	0.03190	0.01992	-	-	-	-	-
	107	4308	X	0.01955	0.00996	-	-	-	-	-
	108	4309	X	0.05121	0.04024	-	-	-	-	-
	109	4310	X	0.08319	0.03115	-	-	-	-	-
	110	4311	X	0.00918	0.00451	-	-	-	-	-
	111	4329		0.00569	0.00434	-	-	-	-	-
	112	4348	X	0.01618	0.01070	-	-	-	-	-
Hayden	113	10518	X	0.70938	0.00945	-	-	-	-	-
Diller	114	10525	X	0.50542	0.01789	-	-	-	-	-
	115			0.00196	0.00269	-	-	-	-	-
	116			0.00195	0.00188	-	-	-	-	-
	117			0.00223	0.00307	-	-	-	-	-
	118			0.00219	0.00192	-	-	-	-	-
	119			0.00076	0.00122	-	-	-	-	-
	120		X	0.01525	0.00713	-	-	-	-	-
	121		X	0.02630	0.01954	-	-	-	-	-
	122		X	0.00884	0.00994	-	-	-	-	-
	123		X	0.00776	0.00461	-	-	-	-	-
	124		X	0.01279	0.00574	-	-	-	-	-
	125		X	0.01207	0.00429	-	-	-	-	-
	126		X	0.01363	0.00629	-	-	-	-	-
	127		X	0.00658	0.00453	-	-	-	-	-
	128			0.00249	0.00225	-	-	-	-	-
	129			0.00196	0.00180	-	-	-	-	-
	130		X	0.00959	0.00901	-	-	-	-	-
	131			0.00602	0.00555	-	-	-	-	-
	132			0.00546	0.00356	-	-	-	-	-
	133			0.00230	0.00227	-	-	-	-	-
	134			0.00336	0.00429	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	135			0.00148	0.00188	-	-	-	-	-
	136		X	0.01195	0.00512	-	-	-	-	-
	137		X	0.00603	0.00417	-	-	-	-	-
	138			0.00283	0.00307	-	-	-	-	-
	139		X	0.00739	0.00747	-	-	-	-	-
	140			0.00438	0.00372	-	-	-	-	-
	141		X	0.01439	0.00644	-	-	-	-	-
	142			0.00448	0.00341	-	-	-	-	-
	143			0.00914	0.00669	-	-	-	-	-
	144			0.00311	0.00258	-	-	-	-	-
	145			0.00634	0.00478	-	-	-	-	-
	146		X	0.02714	0.00783	-	-	-	-	-
	147			0.00487	0.00286	-	-	-	-	-
	148			0.00364	0.00257	-	-	-	-	-
	149			0.02344	0.01188	-	-	-	-	-
	150		X	0.00751	0.00710	-	-	-	-	-
	151			0.00679	0.00386	-	-	-	-	-
	152			0.01144	0.00625	-	-	-	-	-
	153			0.00211	0.00195	-	-	-	-	-
	154			0.00100	0.00264	-	-	-	-	-
	155			0.00248	0.00307	-	-	-	-	-
	156			0.00211	0.00302	-	-	-	-	-
	157			0.00037	0.00092	-	-	-	-	-
	158			0.00027	0.00109	-	-	-	-	-
	159			0.00013	0.00052	-	-	-	-	-
	160			0.00075	0.00146	-	-	-	-	-
	161			0.00004	0.00031	-	-	-	-	-
	162			0.00137	0.00272	-	-	-	-	-
	163			0.00155	0.00245	-	-	-	-	-
	164			0.00051	0.00194	-	-	-	-	-
	165			0.00194	0.00250	-	-	-	-	-
	166			0.00039	0.00092	-	-	-	-	-
	167		X	0.01307	0.01157	-	-	-	-	-
	168		X	0.00937	0.00734	-	-	-	-	-
	169			0.00396	0.00418	-	-	-	-	-
	170			0.00396	0.00378	-	-	-	-	-
	171			0.00050	0.00086	-	-	-	-	-
	172			0.00774	0.00534	-	-	-	-	-
	173			0.00316	0.00280	-	-	-	-	-
	174			0.00108	0.00224	-	-	-	-	-
	175			0.00418	0.00562	-	-	-	-	-
	176			0.00196	0.00233	-	-	-	-	-
	177			0.00008	0.00052	-	-	-	-	-
	178			0.00239	0.00305	-	-	-	-	-
	179			0.00039	0.00117	-	-	-	-	-
	180			0.00265	0.00310	-	-	-	-	-
	181			0.00147	0.00256	-	-	-	-	-
	182			0.00048	0.00109	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	183			0.00161	0.00361	-	-	-	-	-
	184			0.00161	0.00182	-	-	-	-	-
	185		X	0.00547	0.00494	-	-	-	-	-
	186			0.00228	0.00320	-	-	-	-	-
	187			0.00081	0.00231	-	-	-	-	-
	188			0.00162	0.00254	-	-	-	-	-
	189			0.00014	0.00059	-	-	-	-	-
	190			0.00127	0.00161	-	-	-	-	-
	191			0.00014	0.00047	-	-	-	-	-
	192			0.00264	0.00339	-	-	-	-	-
	193			0.00002	0.00024	-	-	-	-	-
	194		X	0.00723	0.00965	-	-	-	-	-
	195			0.00056	0.00090	-	-	-	-	-
	196			0.00099	0.00146	-	-	-	-	-
	197		X	0.01211	0.00841	-	-	-	-	-
	198			0.00151	0.00210	-	-	-	-	-
	199			0.00599	0.00373	-	-	-	-	-
	200			0.00092	0.00162	-	-	-	-	-
	201			0.00442	0.00552	-	-	-	-	-
	202			0.00066	0.00127	-	-	-	-	-
	203			0.00115	0.00208	-	-	-	-	-
	204			0.00259	0.00248	-	-	-	-	-
	205			0.00026	0.00072	-	-	-	-	-
	206			0.00892	0.00782	-	-	-	-	-
	207			0.00460	0.00581	-	-	-	-	-
	208			0.00525	0.00427	-	-	-	-	-
	209			0.00240	0.00267	-	-	-	-	-
	210			0.00162	0.00319	-	-	-	-	-
	211			0.00333	0.00477	-	-	-	-	-
	212			0.00536	0.00579	-	-	-	-	-
	213		X	0.00405	0.00551	-	-	-	-	-
	214			0.00057	0.00094	-	-	-	-	-
	215			0.00149	0.00197	-	-	-	-	-
	216			0.00296	0.00494	-	-	-	-	-
	217			0.00104	0.00143	-	-	-	-	-
	218			0.00140	0.00205	-	-	-	-	-
	219			0.00124	0.00140	-	-	-	-	-
	220			0.00038	0.00107	-	-	-	-	-
	221			0.00188	0.00306	-	-	-	-	-
	222			0.00037	0.00136	-	-	-	-	-
	223			0.00444	0.00487	-	-	-	-	-
	224			0.00316	0.00319	-	-	-	-	-
	225			0.00608	0.00710	-	-	-	-	-
	226			0.00081	0.00129	-	-	-	-	-
	227		X	0.01033	0.00880	-	-	-	-	-
	228			0.00021	0.00057	-	-	-	-	-
	229			0.00447	0.00600	-	-	-	-	-
	230			0.00472	0.00681	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	231			0.00507	0.00563	-	-	-	-	-
	232			0.00108	0.00145	-	-	-	-	-
	233			0.00072	0.00138	-	-	-	-	-
	234			0.00033	0.00114	-	-	-	-	-
	235			0.00021	0.00071	-	-	-	-	-
	236			0.00003	0.00043	-	-	-	-	-
	237			0.00059	0.00101	-	-	-	-	-
	238			0.00024	0.00093	-	-	-	-	-
	239			0.00205	0.00226	-	-	-	-	-
	240			0.00007	0.00033	-	-	-	-	-
	241			0.00264	0.00599	-	-	-	-	-
	242			0.00029	0.00136	-	-	-	-	-
	243			0.00088	0.00155	-	-	-	-	-
	244			0.00064	0.00102	-	-	-	-	-
	245			0.00008	0.00038	-	-	-	-	-
	246			0.00028	0.00079	-	-	-	-	-
	247		X	0.00471	0.00281	-	-	-	-	-
	248			0.00026	0.00075	-	-	-	-	-
	249			0.00068	0.00173	-	-	-	-	-
	250			0.00028	0.00095	-	-	-	-	-
	251			0.00154	0.00279	-	-	-	-	-
	252			0.00078	0.00115	-	-	-	-	-
	253			0.00256	0.00233	-	-	-	-	-
	254			0.00039	0.00082	-	-	-	-	-
	255			0.00001	0.00020	-	-	-	-	-
	256			0.00034	0.00092	-	-	-	-	-
	257			0.00132	0.00246	-	-	-	-	-
	258			0.00151	0.00170	-	-	-	-	-
	259			0.00248	0.00270	-	-	-	-	-
	260			0.00009	0.00058	-	-	-	-	-
	261			0.00049	0.00151	-	-	-	-	-
	262			0.00050	0.00116	-	-	-	-	-
	263			0.00034	0.00104	-	-	-	-	-
	264			0.00112	0.00132	-	-	-	-	-
	265			0.00224	0.00234	-	-	-	-	-
	266			0.00356	0.00505	-	-	-	-	-
	267			0.00066	0.00120	-	-	-	-	-
	268			0.01329	0.00877	-	-	-	-	-
	269				0.00000	-	-	-	-	-
	270			0.00026	0.00072	-	-	-	-	-
	271			0.00090	0.00134	-	-	-	-	-
	272				0.00000	-	-	-	-	-
	273			0.00158	0.00164	-	-	-	-	-
	274			0.00010	0.00050	-	-	-	-	-
	275			0.00132	0.00274	-	-	-	-	-
	276			0.00233	0.00234	-	-	-	-	-
	277			0.00138	0.00286	-	-	-	-	-
	278			0.00051	0.00139	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	279			0.00087	0.00157	-	-	-	-	-
	280			0.00017	0.00087	-	-	-	-	-
	281			0.00032	0.00118	-	-	-	-	-
	282			0.00001	0.00018	-	-	-	-	-
	283			0.00075	0.00108	-	-	-	-	-
	284			0.00090	0.00123	-	-	-	-	-
	285			0.01881	0.01163	-	-	-	-	-
	286			0.00250	0.00323	-	-	-	-	-
	287			0.00626	0.00356	-	-	-	-	-
	288			0.00091	0.00158	-	-	-	-	-
	289			0.00012	0.00047	-	-	-	-	-
	290			0.00177	0.00286	-	-	-	-	-
	291			0.00797	0.00983	-	-	-	-	-
	292			0.00106	0.00124	-	-	-	-	-
	293			0.00079	0.00120	-	-	-	-	-
	294			0.00177	0.00218	-	-	-	-	-
	295			0.00077	0.00160	-	-	-	-	-
	296			0.00331	0.00239	-	-	-	-	-
	297			0.00396	0.00351	-	-	-	-	-
	298			0.00056	0.00114	-	-	-	-	-
	299			0.00171	0.00238	-	-	-	-	-
	300			0.00126	0.00223	-	-	-	-	-
	301			0.00842	0.00485	-	-	-	-	-
	302			0.00159	0.00306	-	-	-	-	-
	303			0.00449	0.00290	-	-	-	-	-
	304			0.00013	0.00049	-	-	-	-	-
	305			0.00006	0.00033	-	-	-	-	-
	306		X	0.00383	0.00263	-	-	-	-	-
	307			0.00029	0.00079	-	-	-	-	-
	308		X	0.00467	0.00494	-	-	-	-	-
	309			0.00128	0.00254	-	-	-	-	-
	310			0.00347	0.00226	-	-	-	-	-
	311			0.00109	0.00197	-	-	-	-	-
	312			0.00018	0.00058	-	-	-	-	-
	313			0.00357	0.00312	-	-	-	-	-
	314			0.00175	0.00187	-	-	-	-	-
	315			0.00693	0.00597	-	-	-	-	-
	316			0.00095	0.00134	-	-	-	-	-
	317			0.00074	0.00199	-	-	-	-	-
	318			0.00219	0.00224	-	-	-	-	-
	319			0.00064	0.00111	-	-	-	-	-
	320			0.00099	0.00243	-	-	-	-	-
	321			0.00480	0.00280	-	-	-	-	-
	322			0.00745	0.00334	-	-	-	-	-
	323			0.00057	0.00108	-	-	-	-	-
	324			0.00474	0.00333	-	-	-	-	-
	325			0.00458	0.00267	-	-	-	-	-
	326			0.00363	0.00378	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	327			0.00361	0.00293	-	-	-	-	-
	328			0.00292	0.00239	-	-	-	-	-
	329			0.00211	0.00287	-	-	-	-	-
	330			0.00098	0.00148	-	-	-	-	-
	331			0.00134	0.00166	-	-	-	-	-
	332			0.00341	0.00227	-	-	-	-	-
	333			0.00702	0.00334	-	-	-	-	-
	334			0.00364	0.00238	-	-	-	-	-
	335			0.00681	0.00381	-	-	-	-	-
	336			0.00139	0.00185	-	-	-	-	-
	337			0.00020	0.00062	-	-	-	-	-
	338			0.01115	0.00520	-	-	-	-	-
	339		X	0.00372	0.00264	-	-	-	-	-
	340		X	0.00897	0.00500	-	-	-	-	-
	341		X	0.00713	0.00460	-	-	-	-	-
	342			0.00110	0.00169	-	-	-	-	-
	343			0.00126	0.00205	-	-	-	-	-
	344			0.00070	0.00126	-	-	-	-	-
	345			0.00219	0.00361	-	-	-	-	-
	346			0.00104	0.00158	-	-	-	-	-
	347			0.00248	0.00318	-	-	-	-	-
	348			0.00096	0.00121	-	-	-	-	-
	349			0.00093	0.00150	-	-	-	-	-
	350			0.00068	0.00204	-	-	-	-	-
	351			0.00086	0.00189	-	-	-	-	-
	352		X	0.00818	0.00601	-	-	-	-	-
	353			0.00308	0.00241	-	-	-	-	-
	354			0.00095	0.00137	-	-	-	-	-
	355			0.00106	0.00153	-	-	-	-	-
	356			0.00182	0.00233	-	-	-	-	-
	357			0.00094	0.00151	-	-	-	-	-
	358		X	0.00923	0.00730	-	-	-	-	-
	359			0.00134	0.00163	-	-	-	-	-
	360		X	0.00377	0.00327	-	-	-	-	-
	361		X	0.00648	0.00539	-	-	-	-	-
	362			0.00488	0.00515	-	-	-	-	-
	363			0.00234	0.00239	-	-	-	-	-
	364			0.00132	0.00142	-	-	-	-	-
	365			0.00106	0.00247	-	-	-	-	-
	366			0.00672	0.00381	-	-	-	-	-
	367			0.00100	0.00150	-	-	-	-	-
	368			0.00094	0.00135	-	-	-	-	-
	369			0.00061	0.00118	-	-	-	-	-
	370			0.00340	0.00275	-	-	-	-	-
	371			0.00059	0.00091	-	-	-	-	-
	372				0.00029	-	-	-	-	-
	373			0.00004	0.00044	-	-	-	-	-
	374			0.00001	0.00027	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	375			0.00020	0.00063	-	-	-	-	-
	376			0.00221	0.00305	-	-	-	-	-
	377			0.00063	0.00143	-	-	-	-	-
	378			0.00058	0.00110	-	-	-	-	-
	379			0.00463	0.00432	-	-	-	-	-
	380			0.00454	0.00355	-	-	-	-	-
	381			0.00019	0.00060	-	-	-	-	-
	382			0.00001	0.00027	-	-	-	-	-
	383		X	0.00305	0.00394	-	-	-	-	-
	384			0.00226	0.00257	-	-	-	-	-
	385			0.00221	0.00251	-	-	-	-	-
	386			0.00001	0.00022	-	-	-	-	-
	387			0.00660	0.00465	-	-	-	-	-
	388			0.00020	0.00081	-	-	-	-	-
	389			0.00206	0.00255	-	-	-	-	-
	390			0.00000	0.00046	-	-	-	-	-
	391			0.00175	0.00182	-	-	-	-	-
	392			0.00022	0.00068	-	-	-	-	-
	393			0.00021	0.00088	-	-	-	-	-
	394			0.00010	0.00039	-	-	-	-	-
	395			0.00020	0.00059	-	-	-	-	-
	396			0.00144	0.00154	-	-	-	-	-
	397			0.00042	0.00122	-	-	-	-	-
	398			0.00004	0.00036	-	-	-	-	-
	399			0.00057	0.00103	-	-	-	-	-
	400			0.00161	0.00261	-	-	-	-	-
	401			0.00045	0.00089	-	-	-	-	-
ND	402					-	-	-	-	-
	403			0.00059	0.00108	-	-	-	-	-
	404			0.00059	0.00129	-	-	-	-	-
	405			0.00053	0.00097	-	-	-	-	-
	406			0.00010	0.00040	-	-	-	-	-

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Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	1		X	0.00634	0.00779	29.7	2416	2393	2447	191.3
	2			0.00327	0.00606	20.2	2333	2317	2348	160.6
	3			0.00496	0.00607	33.9	2747	2727	2772	206.8
	4		X	0.00803	0.01133	29.3	2366	2344	2408	184.2
	5		X	0.02702	0.02478	37.1	2270	2194	2353	313.3
	6		X	0.00999	0.01820	53.8	2234	2202	2307	116.0
	7		X	0.00385	0.00600	27.2	2361	2342	2381	315.6
	8		X	0.03789	0.04485	30.1	2261	2211	2309	7.5
	9		X	0.00940	0.01168	35.8	2382	2341	2421	354.8
	10		X	0.00715	0.01325	28.9	2157	2132	2185	14.2

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	11		X	0.00734	0.01062	23.8	2256	2227	2281	358.4
	12		X	0.00383	0.00604	32.7	2168	2155	2188	2.3
	13			0.00251	0.00489	45.4	2102	2075	2138	51.4
	14			0.00087	0.00298	48.6	2200	2184	2214	82.2
	15			0.02361	0.03200	23.4	2272	2216	2350	64.1
	16			0.00250	0.00466	28.9	2796	2776	2813	260.7
	17	4194	X	0.00839	0.01231	49.4	2968	2862	3036	110.1
	18	4196	X	0.03733	0.06170	34.1	2744	2621	2868	249.2
	19	4198	X	0.02253	0.01816	49.6	2668	2561	2754	174.5
	20	4201	X	0.02594	0.01802	45.1	2728	2624	2859	155.7
	21	4202	X	0.00857	0.00707	37.8	2713	2676	2750	131.8
	22	4204		0.00053	0.00396	36.2	2376	2352	2405	93.3
	23	4205	X	0.01297	0.01894	36.4	2163	2132	2195	46.1
	24	4206	X	0.02813	0.02984	39.9	2394	2319	2466	317.6
Renfrew	25	4207	X	0.60392	0.16394	48.5	2623	2334	2827	296.8
	26	4208	X	0.15522	0.10271	38.1	2561	2365	2737	316.9
Collier	27	4209	X	1.07415	0.15311	44.7	2483	2177	2722	349.0
	28	4209	X	0.19550	0.05730	36.8	2700	2598	2800	331.6
	29	4210	X	0.03796	0.01936	25.7	2563	2518	2584	266.6
	30	4211	X	0.04930	0.03486	37.6	2341	2309	2415	65.6
	31	4212	X	0.00769	0.00718	29.3	2298	2290	2309	110.8
	32	4213		0.00125	0.00808	29.5	2371	2336	2402	131.6
	33	4214	X	0.01278	0.01206	36.6	2275	2207	2344	130.4
Thayer	34	4216	X	0.12909	0.04330	53.9	2434	2340	2640	93.6
	35	4217		0.00145	0.00397	23.7	2149	2136	2160	108.4
	36	4219	X	0.00554	0.00791	31.5	2338	2316	2368	39.3
	37	4220	X	0.00895	0.01518	26.6	2318	2300	2341	311.5
	38	4221	X	0.01214	0.01598	31.0	2353	2310	2397	299.4
	39	4222	X	0.01282	0.02088	28.1	2470	2432	2516	279.4
	40	4223	X	0.00582	0.00749	21.9	2403	2382	2427	272.9
	41	4224	X	0.00526	0.01303	22.5	2434	2373	2487	286.8
	42	4225	X	0.00965	0.00887	30.4	2481	2457	2509	286.5
	43	4226	X	0.02012	0.02512	29.0	2311	2232	2393	308.3
Villard	44	4227	X	0.05423	0.00819	52.8	2773	2542	2935	51.0
Linn	45	4228	X	0.12710	0.01742	50.4	2507	2338	2727	7.1
	46	4229		0.03301	0.03488	36.5	2350	2256	2466	68.4
	47	4233	X	0.01777	0.01170	38.1	2340	2271	2422	336.3
	48	4234	X	0.02534	0.01615	41.0	2356	2301	2426	72.2
	49	4237		0.04287	0.02515	43.1	2354	2273	2507	21.2
	50	4242		0.00250	0.00432	29.7	2186	2182	2195	81.2
	51	4243		0.02776	0.02811	43.9	2144	2094	2196	58.9
	52	4244	X	0.03228	0.02412	30.8	2224	2187	2287	105.4
	53	4245		0.00965	0.00760	18.4	2236	2219	2253	358.8
	54	4246		0.00627	0.00724	32.7	2140	2107	2182	33.4
	55	4247		0.00540	0.00918	52.0	2071	2047	2122	357.3
	56	4248		0.00936	0.01168	25.3	2111	2092	2127	58.1
	57	4250	X	0.10638	0.06494	45.6	2345	2282	2408	78.8
	59	4252	X	0.04021	0.02896	31.3	2161	2131	2210	45.8

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	60	4254	X	0.01043	0.01049	22.0	2319	2290	2339	172.3
	61	4255	X	0.01812	0.02781	32.6	2264	2221	2311	133.3
	62	4256	X	0.00739	0.01046	33.4	2460	2427	2499	183.0
	63	4257	X	0.00997	0.00955	9.8	2340	2337	2341	180.0
	64	4258	X	0.02243	0.01532	39.9	2300	2276	2330	319.4
	66	4260	X	0.07921	0.07649	35.7	2402	2307	2496	179.6
Irving	68	4262	X	0.35687	0.11733	43.9	2347	2205	2591	127.3
	69	4263	X	0.00881	0.00757	23.4	2359	2345	2373	155.8
	70	4264	X	0.07909	0.03585	27.9	2265	2207	2312	103.4
	71	4265	X	0.08399	0.05923	41.1	2272	2126	2438	115.4
	72	4266	X	0.04055	0.02377	32.1	2159	2120	2232	70.5
	73	4268		0.01875	0.01233		2135	2093	2175	43.4
Skinner	74	4270	X	0.48067	0.12981	48.7	2469	2266	2751	349.6
	75	4271	X	0.11408	0.04956	56.1	2614	2487	2884	29.1
Prouty	76	4272	X	1.16001	0.04195	68.2	2617	2386	2962	42.4
	77	4273	X	0.24446	0.11220	45.8	2393	2187	2618	88.0
	78	4274	X	0.04360	0.02731	43.3	2551	2475	2663	85.8
	80	4277	X	0.01691	0.01588	32.4	2258	2207	2324	335.3
	81	4278								
	82	4280	X	0.01237	0.01546	39.8	2507	2439	2577	213.2
Clark	83	4281	X	0.34747	0.10671	42.1	2712	2519	2879	218.6
	84	4282		0.00535	0.00939	44.5	2567	2523	2601	155.3
	85	4283	X	0.02435	0.02974	42.5	2535	2467	2643	155.6
	86	4284	X	0.01151	0.00888	40.6	2369	2334	2412	100.2
	87	4286	X	0.01270	0.01630	41.3	2346	2308	2400	1.4
	88	4287	X	0.04570	0.05536	47.7	2454	2319	2568	285.0
	89	4288	X	0.07936	0.05585	37.0	2469	2368	2564	312.4
	90	4289	X	0.00698	0.01171	29.1	2437	2425	2462	227.3
	91	4290	X	0.05241	0.04282	39.0	2546	2472	2698	234.6
	92	4291	X	0.02480	0.02816	40.0	2606	2545	2706	227.5
	93	4292	X	0.01077	0.01240	34.0	2635	2585	2666	237.8
Lewis	94	4293	X	0.41448	0.07740	50.6	2766	2605	3062	145.3
	95	4294	X	0.02377	0.03411	43.7	3027	2944	3095	94.7
	96	4295	X	0.09595	0.02413	31.3	3112	3097	3131	164.4
	97	4296	X	0.03263	0.02814	51.8	3085	3001	3148	60.3
Lost Creek	98	4297	X	0.56058	0.08497	56.3	2545	2274	2811	324.6
	99	4298	X	0.04356	0.01952	46.0	2744	2670	2864	100.6
	100	4299	X	0.00428	0.01187	48.1	2462	2360	2535	58.2
	101	4300	X	0.00369	0.00995	26.3	2285	2250	2315	306.9
	102	4301	X	0.01965	0.02021	42.8	2329	2242	2398	313.8
	103	4302	X	0.01751	0.01426	42.1	2415	2356	2465	300.6
Eugene	104	4304	X	0.11740	0.03701	48.2	2522	2436	2626	344.8
Carver	105	4306	X	0.31267	0.11985	37.4	2328	2199	2547	15.9
	106	4307	X	0.02376	0.03231	37.2	2246	2196	2302	333.0
	107	4308	X	0.02673	0.02130	39.8	2356	2282	2425	334.4
	108	4309	X	0.08680	0.05953	53.0	2344	2199	2451	27.3
	109	4310	X	0.07328	0.05290	29.5	2301	2230	2354	68.9

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	110	4311	X	0.00685	0.00719	24.5	2443	2427	2459	114.7
	111	4329		0.00289	0.00711	30.5	2268	2247	2285	30.2
	112	4348	X	0.02561	0.02365	40.7	2347	2272	2415	69.6
Hayden	113	10518	X	0.77649	0.10085	61.1	2592	2314	2835	90.4
Diller	114	10525	X	0.58848	0.01689	53.3	2496	2291	2748	81.9
	115			0.00087	0.00230	17.2	2293	2287	2300	179.8
	116			0.00021	0.00151	22.3	2278	2270	2284	148.5
	117			0.00001	0.00149	9.4	2263	2259	2266	230.2
	118			0.00015	0.00100	6.1	2258	2256	2259	190.6
	119			0.00029	0.00029	7.8	2254	2254	2254	176.0
	120		X	0.00556	0.01312	29.7	2386	2360	2441	241.4
	121		X	0.02121	0.03054	28.5	2361	2310	2420	257.4
	122		X	0.01080	0.02125	35.8	2479	2403	2580	265.4
	123		X	0.00193	0.00605	26.8	2308	2293	2325	252.0
	124		X	0.01688	0.01110	40.7	2128	2100	2187	354.7
	125		X	0.01703	0.01179	52.2	2926	2830	3000	322.5
	126		X	0.01502	0.01152	38.8	2485	2453	2517	307.7
	127		X	0.00660	0.00811	39.3	2470	2450	2502	242.8
	128			0.00121	0.00501	30.8	2434	2419	2446	240.4
	129			0.00166	0.00341	33.7	2544	2523	2558	170.4
	130		X	0.00925	0.01304	43.8	2323	2296	2371	324.5
	131			0.00270	0.01173	33.9	2418	2391	2444	294.8
	132			0.00132	0.00506	41.8	2407	2372	2451	182.6
	133			0.00071	0.00298	31.1	2364	2355	2378	227.9
	134			0.00152	0.00578	37.0	2448	2404	2494	190.4
	135			0.00074	0.00279	24.5	2446	2430	2462	200.5
	136		X	0.01080	0.01176	37.1	2733	2659	2793	276.8
	137		X	0.00387	0.00670	35.5	2523	2496	2552	280.7
	138			0.00077	0.00365	24.2	2457	2444	2475	293.8
	139		X	0.00167	0.00854	38.9	2346	2317	2384	310.6
	140			0.00102	0.00358	34.1	2300	2280	2319	309.1
	141		X	0.00925	0.01100	27.1	2107	2093	2128	61.7
	142			0.00306	0.00585	21.2	2166	2147	2191	84.1
	143			0.00199	0.00660	17.7	2091	2080	2108	72.5
	144			0.00098	0.00267	24.1	2107	2097	2120	14.4
	145			0.00115	0.00416	27.0	2110	2097	2126	32.2
	146		X	0.01978	0.01549	16.7	2080	2075	2085	42.6
	147			0.00061	0.00233	15.2	2116	2109	2123	73.7
	148			0.00164	0.00376	32.5	2145	2132	2159	91.2
	149			0.01767	0.02088	39.0	2211	2165	2259	65.9
	150		X	0.00680	0.01065	22.0	2360	2348	2373	57.9
	151			0.00477	0.00681	25.9	2231	2217	2261	56.4
	152									
	153			0.00083	0.00235	18.4	2280	2276	2286	263.9
	154			0.00079	0.00357	26.1	2292	2266	2314	308.3
	155			0.00114	0.00411	21.5	2267	2250	2289	295.0
	156			0.00067	0.00448	22.4	2328	2293	2364	276.9
	157			0.00080	0.00080	23.3	2259	2251	2267	268.7

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	158			0.00041	0.00041	21.8	2397	2395	2399	258.4
	159			0.00045	0.00045	16.7	2399	2397	2403	290.2
	160			0.00003	0.00132	19.2	2375	2366	2385	280.3
	161			0.00023	0.00023	19.8	2359	2359	2359	272.7
	162			0.00139	0.00501	26.7	2340	2314	2372	289.1
	163			0.00087	0.00087	24.3	2213	2201	2218	285.8
	164			0.00020	0.00288	26.7	2234	2206	2271	313.9
	165			0.00009	0.00174	29.0	2185	2179	2198	326.1
	166			0.00024	0.00024	6.5	2172	2172	2173	326.0
	167		X	0.00312	0.00949	35.9	2224	2160	2286	330.8
	168		X	0.00242	0.00623	25.6	2148	2132	2160	10.5
	169			0.00088	0.00460	33.6	2157	2136	2191	323.7
	170			0.00001	0.00189	24.9	2181	2158	2201	284.5
	171			0.00007	0.00083	18.9	2298	2295	2302	341.1
	172			0.00370	0.00807	37.6	2333	2305	2355	10.0
	173			0.00083	0.00326	24.8	2226	2203	2242	286.0
	174			0.00009	0.00214	32.4	2217	2191	2238	296.1
	175			0.00119	0.00119	30.8	2183	2135	2219	313.0
	176			0.00126	0.00126	21.9	2249	2243	2255	325.5
	177			0.00030	0.00030	22.6	2279	2278	2281	250.7
	178			0.00003	0.00225	27.4	2240	2228	2258	263.1
	179			0.00004	0.00136	24.1	2196	2184	2207	253.9
	180			0.00036	0.00275	22.8	2179	2163	2197	297.3
	181			0.00011	0.00166	25.4	2260	2242	2276	280.8
	182			0.00000	0.00050	15.4	2172	2170	2174	308.1
	183			0.00041	0.00450	30.4	2272	2235	2320	261.2
	184			0.00470	0.01092	34.4	2439	2375	2503	281.5
	185		X	0.00139	0.00611	39.1	2471	2405	2565	289.4
	186			0.00100	0.00100	17.6	2213	2206	2219	318.6
	187			0.00080	0.00080	20.3	2183	2172	2192	255.6
	188			0.00006	0.00135	23.9	2210	2199	2230	264.0
	189			0.00000	0.00068	17.5	2211	2206	2215	269.1
	190			0.00060	0.00207	22.8	2204	2197	2213	284.0
	191			0.00002	0.00061	33.1	2244	2239	2250	291.2
	192			0.00071	0.00363	27.0	2304	2281	2328	271.6
	193			0.00000	0.00045	24.0	2314	2310	2318	285.5
	194		X	0.00475	0.01435	26.7	2292	2259	2331	277.8
	195			0.00012	0.00091	17.8	2256	2251	2260	267.9
	196			0.00039	0.00198	21.3	2377	2369	2384	213.5
	197		X	0.00329	0.01156	25.4	2365	2344	2396	241.9
	198			0.00008	0.00088	19.6	2281	2277	2284	262.7
	199			0.00000	0.00085	12.3	2296	2293	2299	232.2
	200			0.00001	0.00069	10.0	2277	2275	2279	282.5
	201			0.00006	0.00137	8.9	2285	2280	2290	270.8
	202			0.00008	0.00090	14.9	2312	2308	2314	302.9
	203			0.00014	0.00150	13.1	2321	2316	2325	207.6
	204			0.00009	0.00206	24.3	2285	2280	2295	202.9
	205			0.00005	0.00104	11.1	2225	2223	2227	222.4

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	206			0.00119	0.00319	18.7	2200	2191	2205	342.4
	207			0.00291	0.00860	41.8	2254	2192	2317	326.1
	208			0.00112	0.00417	35.7	2232	2193	2251	332.3
	209			0.00001	0.00150	30.8	2196	2183	2213	332.7
	210			0.00010	0.00265	25.2	2220	2197	2244	309.5
	211			0.00060	0.00355	32.2	2206	2185	2235	326.4
	212			0.00031	0.00342	30.4	2221	2171	2254	328.0
	213		X	0.00122	0.00702	28.9	2283	2225	2325	311.0
	214			0.00012	0.00101	25.6	2342	2336	2350	299.3
	215			0.00050	0.00244	25.3	2345	2334	2361	290.7
	216			0.00024	0.00249	26.8	2214	2199	2247	332.7
	217			0.00038	0.00187	25.7	2265	2254	2273	339.8
	218			0.00029	0.00214	30.7	2249	2240	2267	310.8
	219			0.00038	0.00155	32.4	2252	2242	2268	315.2
	220			0.00115	0.00115	33.9	2226	2212	2244	298.3
	221			0.00160	0.00499	31.7	2347	2325	2363	308.5
	222			0.00041	0.00041	22.3	2303	2300	2306	271.0
	223			0.00095	0.00420	31.0	2285	2276	2293	302.5
	224			0.00168	0.00513	30.1	2364	2354	2376	208.5
	225			0.00003	0.00433	32.2	2390	2363	2426	250.1
	226			0.00137	0.00358	18.5	2564	2557	2572	206.1
	227		X	0.00119	0.00627	29.3	2386	2350	2418	184.0
	228			0.00016	0.00095	32.2	2448	2441	2454	201.8
	229			0.00108	0.00801	29.1	2369	2334	2409	218.9
	230			0.00220	0.00817	28.7	2370	2320	2417	164.2
	231			0.00017	0.00224	23.2	2304	2287	2318	126.8
	232			0.00016	0.00111	15.5	2348	2344	2352	133.8
	233			0.00013	0.00125	19.8	2361	2356	2365	153.5
	234			0.00062	0.00273	30.2	2448	2435	2469	201.9
	235			0.00009	0.00107	29.0	2427	2415	2438	213.0
	236			0.00000	0.00110	37.5	2436	2425	2444	225.6
	237			0.00032	0.00169	18.1	2449	2441	2457	177.0
	238			0.00412	0.00857	41.4	2660	2629	2694	177.4
	239			0.00309	0.00897	26.4	2436	2409	2467	138.1
	240			0.00033	0.00187	25.3	2473	2459	2486	153.0
	241			0.00131	0.00842	32.1	2148	2120	2182	71.1
	242			0.00027	0.00295	18.9	2172	2158	2188	161.9
	243			0.00055	0.00224	25.8	2245	2234	2256	93.0
	244			0.00072	0.00346	30.7	2210	2189	2232	139.4
	245			0.00055	0.00055	30.2	2206	2200	2212	121.4
	246			0.00003	0.00109	27.9	2234	2223	2243	118.8
	247		X	0.00310	0.00483	40.1	2301	2284	2326	154.7
	248			0.00035	0.00171	26.7	2338	2327	2348	154.4
	249			0.00046	0.00271	34.9	2386	2361	2413	165.8
	250			0.00081	0.00352	35.6	2483	2462	2502	37.7
	251			0.00175	0.00574	30.5	2433	2415	2458	39.5
	252			0.00099	0.00246	23.5	2258	2252	2267	53.7
	253			0.00085	0.00318	36.9	2222	2205	2242	85.6

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	254			0.00001	0.00052	28.7	2267	2263	2271	55.7
	255			0.00033	0.00033	22.3	2263	2260	2267	73.7
	256			0.00041	0.00041	21.7	2256	2255	2259	82.6
	257			0.00021	0.00211	35.0	2309	2284	2344	90.0
	258			0.00082	0.00263	34.1	2174	2161	2191	67.0
	259			0.00230	0.00501	35.1	2481	2448	2514	110.3
	260			0.00075	0.00075	32.8	2422	2414	2432	142.1
	261			0.00003	0.00194	25.0	2327	2309	2345	57.6
	262			0.00053	0.00222	35.9	2409	2397	2420	46.6
	263			0.00043	0.00232	26.0	2373	2360	2388	38.4
	264			0.00052	0.00181	20.1	2352	2344	2361	41.5
	265			0.00074	0.00287	30.3	2354	2342	2367	78.1
	266			0.00240	0.00784	38.6	2282	2258	2309	21.5
	267			0.00010	0.00118	34.5	2450	2438	2465	87.8
	268			0.00771	0.01467	38.2	2344	2261	2412	69.4
	269			0.02479	0.00000					
	270			0.00008	0.00170	32.3	2671	2654	2689	42.4
	271			0.00023	0.00153	21.6	2758	2753	2765	34.8
	272			0.00184	0.00000					
	273			0.00106	0.00274	28.7	2214	2201	2228	46.8
	274			0.00049	0.00049	35.6	2187	2182	2194	82.7
	275			0.00044	0.00362	34.2	2243	2216	2270	49.8
	276			0.00308	0.00541	23.4	2293	2278	2305	104.8
	277			0.00060	0.00381	25.9	2278	2262	2297	92.3
	278			0.00025	0.00187	17.2	2244	2239	2254	67.0
	279			0.00010	0.00149	25.0	2272	2264	2281	101.1
	280			0.00082	0.00343	30.1	2359	2336	2379	74.4
	281			0.00132	0.00509	24.3	2363	2351	2378	56.6
	282			0.00007	0.00088	23.9	2421	2415	2428	65.0
	283			0.00063	0.00192	24.2	2229	2223	2236	112.3
	284			0.00044	0.00165	9.9	2230	2229	2231	92.7
	285			0.00487	0.01127	30.0	2188	2154	2218	36.1
	286			0.00013	0.00288		2131	2108	2147	18.8
	287			0.00170	0.00578		2167	2146	2188	43.8
	288			0.00024	0.00168	17.3	2229	2224	2235	330.3
	289			0.00052	0.00052	9.7	2130	2130	2132	84.9
	290			0.00022	0.00143	25.9	2089	2079	2098	353.6
	291			0.00013	0.00211	33.5	2036	2031	2045	33.2
	292			0.00019	0.00113	5.9	2115	2113	2116	97.7
	293			0.00004	0.00068	13.3	2077	2074	2079	28.9
	294			0.00063	0.00062	15.2	2068	2064	2072	44.8
	295			0.00028	0.00028	10.4	2094	2093	2095	139.0
	296			0.00077	0.00302	30.2	2115	2106	2129	3.6
	297			0.00091	0.00323	25.8	2281	2272	2291	73.1
	298			0.00027	0.00157	28.9	2254	2245	2266	100.8
	299			0.00193	0.00481	36.4	2259	2242	2283	35.9
	300			0.00094	0.00094	28.3	2286	2276	2299	129.0
	301			0.00183	0.00458	32.1	2252	2229	2274	116.4

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	302			0.00028	0.00346	18.2	2162	2142	2183	107.6
	303			0.00616	0.00771	57.8	2438	2406	2473	118.8
	304			0.00037	0.00170	16.9	2803	2798	2805	11.0
	305			0.00001	0.00071	19.1	2816	2812	2821	307.1
	306		X	0.00362	0.00560	23.1	2816	2798	2827	340.1
	307			0.00022	0.00140	48.7	2787	2762	2814	115.7
	308		X	0.00664	0.01051	44.4	2780	2758	2816	54.3
	309			0.01524	0.01626	47.6	2539	2520	2572	130.8
	310			0.00516	0.00880	34.6	2791	2760	2816	161.2
	311			0.00522	0.00711	39.2	2813	2760	2869	180.6
	312			0.00018	0.00123	36.9	2737	2730	2746	52.7
	313			0.00008	0.00083	36.7	2113	2109	2121	86.5
	314			0.00036	0.00036	33.3	2092	2091	2093	30.0
	315			0.00178	0.00502	27.3	2180	2160	2195	26.2
	316			0.00493	0.00751	41.7	2243	2226	2265	3.2
	317			0.00023	0.00248	5.5	2187	2180	2194	13.1
	318			0.00194	0.00419	29.6	2573	2530	2614	57.8
	319			0.00067	0.00197	32.2	2251	2249	2253	141.6
	320			0.00077	0.00360	35.3	2290	2270	2307	73.0
	321			0.00494	0.00623	28.1	2290	2264	2320	43.1
	322			0.00491	0.00719	26.1	2234	2211	2278	66.5
	323			0.00019	0.00115	34.1	2148	2138	2159	38.5
	324			0.00194	0.00377		2037	2020	2057	20.4
	325			0.00222	0.00372		2131	2122	2147	65.1
	326			0.00071	0.00294		2202	2185	2223	58.0
	327			0.00145	0.00410	48.8	2267	2246	2292	111.3
	328			0.00184	0.00364	41.9	2227	2204	2245	121.0
	329			0.00581	0.00708	27.4	2241	2225	2266	319.9
	330			0.00384	0.00506	24.3	2316	2310	2332	330.4
	331			0.00087	0.00283	2.2	2181	2180	2181	47.6
	332			0.00075	0.00221	19.0	2171	2169	2175	27.2
	333			0.00229	0.00393	31.2	2169	2152	2185	10.2
	334			0.00276	0.00446	23.3	2159	2159	2162	310.5
	335			0.00270	0.00723	23.7	2117	2101	2138	359.3
	336			0.00001	0.00048	24.2	2063	2061	2066	336.2
	337			0.00032	0.00152	33.9	2121	2117	2126	347.8
	338			0.00103	0.00466	24.9	2088	2071	2103	355.9
	339		X	0.00326	0.00548	38.5	2269	2252	2292	8.5
	340		X	0.00197	0.00532	52.5	2236	2204	2285	29.6
	341		X	0.00393	0.00677	32.6	2228	2203	2260	287.6
	342			0.00328	0.00661	8.5	2290	2287	2292	9.9
	343			0.00194	0.00518	20.9	2259	2242	2275	302.5
	344			0.00047	0.00199	7.8	2307	2305	2309	302.7
	345			0.00033	0.00349	17.8	2230	2208	2250	306.8
	346			0.00002	0.00107	18.0	2168	2165	2172	301.0
	347			0.00075	0.00463	20.3	2412	2394	2437	279.7
	348			0.00029	0.00146	27.1	2544	2537	2551	243.2
	349			0.00003	0.00111	23.9	2364	2356	2372	227.3

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	350			0.00363	0.00832	36.0	2813	2787	2831	192.2
	351			0.00227	0.00516	26.1	2434	2423	2449	257.3
	352		X	0.00169	0.00599	20.6	2356	2339	2372	205.2
	353			0.00136	0.00348	22.9	2330	2320	2341	195.6
	354			0.00090	0.00231	13.3	2334	2332	2338	199.2
	355			0.00030	0.00193	29.5	2298	2284	2311	204.1
	356			0.00011	0.00100	12.7	2263	2259	2266	191.4
	357			0.00038	0.00167	20.7	2289	2285	2295	248.3
	358		X	0.00273	0.00906	37.6	2246	2228	2283	312.4
	359			0.00263	0.00432	11.5	2323	2320	2326	243.2
	360		X	0.00334	0.00478	22.7	2283	2278	2287	187.3
	361		X	0.00215	0.00620	29.8	2248	2241	2259	281.1
	362			0.00112	0.00399	27.8	2276	2273	2282	289.3
	363			0.00031	0.00281	21.2	2242	2241	2244	339.3
	364			0.00004	0.00131	18.2	2227	2220	2232	303.0
	365			0.00136	0.00320	29.2	2189	2180	2202	300.9
	366			0.00966	0.00872	30.3	2282	2244	2318	321.9
	367			0.00018	0.00198	22.3	2190	2178	2202	300.9
	368			0.00080	0.00233	14.4	2129	2125	2134	356.2
	369			0.00028	0.00140	18.1	2275	2269	2278	308.2
	370			0.00005	0.00102	30.8	2239	2227	2248	338.6
	371			0.00085	0.00241	27.5	2602	2592	2614	174.2
	372			0.00098	0.00232	34.4	2544	2527	2559	239.8
	373			0.00158	0.00505	24.7	2330	2314	2353	46.7
	374			0.00336	0.00752	41.6	2620	2588	2670	118.2
	375			0.00001	0.00117	28.8	2343	2339	2347	316.8
	376			0.00020	0.00219	27.4	2121	2109	2137	311.2
	377			0.00034	0.00178	14.1	2308	2303	2314	209.1
	378			0.00154	0.00413	32.0	2254	2224	2277	350.6
	379			0.00021	0.00241	28.1	2182	2166	2196	357.5
	380				0.00000					
	381			0.00096	0.00234	33.1	2256	2242	2273	323.4
	382			0.00012	0.00136	30.5	2254	2240	2270	309.9
	383		X	0.00385	0.00667	36.1	2205	2194	2219	58.5
	384			0.00149	0.00361	27.1	2193	2190	2206	293.0
	385			0.00101	0.00323	52.0	2250	2232	2289	98.3
	386			0.00298	0.00516	38.7	2297	2272	2324	358.3
	387			0.00097	0.00376	26.1	2174	2158	2182	348.3
	388			0.00079	0.00079	15.5	2128	2124	2132	83.2
	389			0.00039	0.00170	38.0	2062	2049	2077	16.2
	390			0.00070	0.00070	36.5	2503	2493	2515	95.8
	391			0.00031	0.00156	21.1	2201	2199	2204	128.8
	392			0.00048	0.00048	9.0	2122	2121	2123	19.5
	393			0.00026	0.00190	10.7	2276	2274	2279	97.3
	394			0.00030	0.00157	9.6	2249	2247	2251	207.2
	395			0.00007	0.00157	21.2	2269	2265	2273	212.4
	396			0.00051	0.00179	24.7	2337	2328	2347	149.5
	397			0.00007	0.00124	9.9	2131	2128	2132	70.4

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	398			0.00012	0.00096	22.5	2149	2146	2153	354.8
	399			0.00001	0.00083	37.8	2195	2191	2202	132.6
	400			0.00212	0.00505	38.1	2419	2403	2438	5.7
	401			0.00044	0.00166	19.8	2399	2396	2401	204.2
	402			0.00831	0.00830	19.1	2151	2143	2164	340.9
	403			0.00077	0.00277	18.2	2583	2574	2593	265.5
	404			0.00075	0.00251	22.1	2600	2592	2609	290.2
	405			0.00074	0.00219	34.8	2627	2613	2639	306.9
	406			0.00001	0.00051	27.8	2631	2628	2635	292.3

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Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	1		X	0.0042637	0.00153	18.8	2416	2393	2447	191.3
	2			0.0015591	0.00086	-	-	-	-	-
	3			0.0025493	0.00111	-	-	-	-	-
	4		X	0.0038495	0.00132	13.5	2333	2317	2348	160.6
	5		X	0.0068561	0.00278	18.1	2747	2727	2772	206.8
	6		X	0.0090641	0.00376	20.0	2366	2344	2408	184.2
	7		X	0.0033007	0.00119	24.3	2270	2194	2353	313.3
	8		X	0.0259226	0.00922	24.9	2234	2202	2307	116.0
	9		X	0.008226	0.00296	19.1	2361	2342	2381	315.6
	10		X	0.0036989	0.00222	8.7	2261	2211	2309	7.5
	11		X	0.0041175	0.00206	22.0	2382	2341	2421	354.8
	12		X	0.0047956	0.00159	18.5	2157	2132	2185	14.2
	13			-	-	-	-	-	-	-
	14			-	-	-	-	-	-	-
	15			-	-	-	-	-	-	-
	16			0.0014402	0.00087	-	-	-	-	-
	17	4194	X	0.0012339	0.00106	15.1	2256	2227	2281	358.4
	18	4196	X	0.0131051	0.00896	22.1	2168	2155	2188	2.3
	19	4198	X	0.0116068	0.00266	29.6	2102	2075	2138	51.4
	20	4201	X	0.0112884	0.00400	35.4	2200	2184	2214	82.2
	21	4202	X	0.0058816	0.00152	15.3	2272	2216	2350	64.1
	22	4204		0.0017227	0.00130	-	-	-	-	-
	23	4205	X	0.0016005	0.00119	25.1	2796	2776	2813	260.7
	24	4206	X	0.0123325	0.00485	41.1	2968	2862	3036	110.1
Renfrew	25	4207	X	0.45918	0.00386	23.3	2744	2621	2868	249.2
	26	4208	X	0.119574	0.01962	36.5	2668	2561	2754	174.5
Collier	27	4209	X	0.88349	0.01212	31.0	2728	2624	2859	155.7
	28	4209	X	0.182037	0.01732	27.0	2713	2676	2750	131.8
	29	4210	X	0.0275112	0.00544	24.4	2376	2352	2405	93.3
	30	4211	X	0.009151	0.00393	21.0	2163	2132	2195	46.1
	31	4212	X	0.0004117	0.00058	20.8	2394	2319	2466	317.6

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	32	4213		-	-	-	-	-	-	-
	33	4214	X	0.0045474	0.00149	18.9	2623	2334	2827	296.8
Thayer	34	4216	X	0.1050	0.03000	20.3	2561	2365	2737	316.9
	35	4217		0.0002583	0.00045	-	-	-	-	-
	36	4219	X	0.0043342	0.00175	18.9	2483	2177	2722	349.0
	37	4220	X	0.0052948	0.00313	14.9	2700	2598	2800	331.6
	38	4221	X	0.0091976	0.00414	11.5	2563	2518	2584	266.6
	39	4222	X	0.0077539	0.00421	18.0	2341	2309	2415	65.6
	40	4223	X	0.0034818	0.00162	11.6	2298	2290	2309	110.8
	41	4224	X	0.0043139	0.00306	14.5	2371	2336	2402	131.6
	42	4225	X	0.0044381	0.00199	26.8	2275	2207	2344	130.4
	43	4226	X	0.0041677	0.00347	24.6	2434	2340	2640	93.6
Villard	44	4227	X	0.044	0.00600	16.0	2149	2136	2160	108.4
Linn	45	4228	X	0.13083	0.02313	20.2	2338	2316	2368	39.3
	46	4229		-	-	-	-	-	-	-
	47	4233	X	0.0058663	0.00213	10.5	2318	2300	2341	311.5
	48	4234	X	0.0105577	0.00341	18.2	2353	2310	2397	299.4
	49	4237		-	-	-	-	-	-	-
	50	4242		-	-	-	-	-	-	-
	51	4243		-	-	-	-	-	-	-
	52	4244	X	0.0162399	0.00315	17.3	2470	2432	2516	279.4
	53	4245		-	-	-	-	-	-	-
	54	4246		-	-	-	-	-	-	-
	55	4247		-	-	-	-	-	-	-
	56	4248		-	-	-	-	-	-	-
	57	4250	X	0.0570461	0.01290	17.2	2403	2382	2427	272.9
	59	4252	X	0.0211188	0.00525	18.1	2434	2373	2487	286.8
	60	4254	X	0.0062305	0.00207	18.1	2481	2457	2509	286.5
	61	4255	X	0.0026877	0.00262	18.9	2311	2232	2393	308.3
	62	4256	X	0.0022154	0.00181	39.0	2773	2542	2935	51.0
	63	4257	X	0.0043194	0.00148	27.9	2507	2338	2727	7.1
	64	4258	X	0.0115557	0.00302	19.3	2350	2256	2466	68.4
	66	4260	X	0.0386139	0.01516	30.6	2340	2271	2422	336.3
Irving	68	4262	X	0.23707	0.00207	26.6	2356	2301	2426	72.2
	69	4263	X	0.0071188	0.00172	26.4	2354	2273	2507	21.2
	70	4264	X	0.0484291	0.00824	13.9	2186	2182	2195	81.2
	71	4265	X	0.0448504	0.01208	25.5	2144	2094	2196	58.9
	72	4266	X	0.0125101	0.00492	15.2	2224	2187	2287	105.4
	73	4268		-	-	-	-	-	-	-
Skinner	74	4270	X	0.33117	0.02709	12.6	2236	2219	2253	358.8
	75	4271	X	0.05552	0.00332	24.5	2140	2107	2182	33.4
Prouty	76	4272	X	1.17513	0.03630	20.6	2071	2047	2122	357.3
	77	4273	X	0.0954627	0.01939	17.7	2111	2092	2127	58.1
	78	4274	X	0.0037592	0.00262	16.8	2345	2282	2408	78.8
	80	4277	X	0.0064555	0.00310	16.0	2161	2131	2210	45.8
	81	4278		0.0033548	0.00303	-	-	-	-	-
	82	4280	X	0.0052158	0.00328	12.9	2319	2290	2339	172.3
Clark	83	4281	X	0.15034	0.05173	16.4	2264	2221	2311	133.3

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	84	4282		0.0000684	0.00022	-	-	-	-	-
	85	4283	X	0.0109124	0.00422	23.5	2460	2427	2499	183.0
	86	4284	X	0.0074576	0.00244	2.9	2340	2337	2341	180.0
	87	4286	X	0.0003564	0.00055	19.8	2300	2276	2330	319.4
	88	4287	X	0.000439	0.00075	14.4	2402	2307	2496	179.6
	89	4288	X	0.0120305	0.00764	15.4	2347	2205	2591	127.3
	90	4289	X	0.0001661	0.00048	13.5	2359	2345	2373	155.8
	91	4290	X	0.0046596	0.00449	15.0	2265	2207	2312	103.4
	92	4291	X	0.0141079	0.00628	18.0	2272	2126	2438	115.4
	93	4292	X	0.0060951	0.00245	19.1	2159	2120	2232	70.5
Lewis	94	4293	X	0.33407	0.01847	0.0	2135	2093	2175	43.4
	95	4294	X	0.0251631	0.00821	19.6	2469	2266	2751	349.6
	96	4295	X	0.0979368	0.00613	24.9	2614	2487	2884	29.1
	97	4296	X	0.0219892	0.00646	21.1	2617	2386	2962	42.4
Lost Creek	98	4297	X	0.47872	0.01627	24.6	2393	2187	2618	88.0
	99	4298	X	0.0309241	0.00553	32.0	2551	2475	2663	85.8
	100	4299	X	0.0008929	0.00085	16.8	2258	2207	2324	335.3
	101	4300	X	0.0011713	0.00082	-	-	-	-	-
	102	4301	X	0.0066213	0.00332	24.3	2507	2439	2577	213.2
	103	4302	X	0.0152771	0.00429	20.4	2712	2519	2879	218.6
Eugene	104	4304	X	0.06017	0.02691	31.9	2567	2523	2601	155.3
Carver	105	4306	X	0.20175	0.00228	21.4	2535	2467	2643	155.6
	106	4307	X	0.0138842	0.00671	30.3	2369	2334	2412	100.2
	107	4308	X	0.0187037	0.00470	23.3	2346	2308	2400	1.4
	108	4309	X	0.037429	0.01249	22.5	2454	2319	2568	285.0
	109	4310	X	0.0565664	0.01297	22.1	2469	2368	2564	312.4
	110	4311	X	0.0039669	0.00149	11.3	2437	2425	2462	227.3
	111	4329		0.0003261	0.00053	-	-	-	-	-
	112	4348	X	0.0003584	0.00070	17.8	2546	2472	2698	234.6
Hayden	113	10518	X	0.77787	0.01439	21.2	2606	2545	2706	227.5
Diller	114	10525	X	0.59824	0.00747	22.6	2635	2585	2666	237.8
	115			0.0001885	0.00041	-	-	-	-	-
	116			0.0001554	0.00026	-	-	-	-	-
	117			-	-	-	-	-	-	-
	118			-	-	-	-	-	-	-
	119			-	-	-	-	-	-	-
	120		X	0.0014562	0.00188	18.4	2766	2605	3062	145.3
	121		X	0.002456	0.00289	22.9	3027	2944	3095	94.7
	122		X	0.0007804	0.00114	5.7	3112	3097	3131	164.4
	123		X	0.0009651	0.00133	33.9	3085	3001	3148	60.3
	124		X	0.0069993	0.00256	20.2	2545	2274	2811	324.6
	125		X	0.0103916	0.00227	27.4	2744	2670	2864	100.6
	126		X	0.0024749	0.00167	33.2	2462	2360	2535	58.2
	127		X	0.0005913	0.00094	16.2	2285	2250	2315	306.9
	128			0.0001849	0.00033	-	-	-	-	-
	129			0.0012627	0.00069	-	-	-	-	-
	130		X	0.0003001	0.00035	24.6	2329	2242	2398	313.8

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	131			0.0002026	0.00029	-	-	-	-	-
	132			0.0000475	0.00019	-	-	-	-	-
	133			0.0007418	0.00082	-	-	-	-	-
	134			0.0003281	0.00064	-	-	-	-	-
	135			0.0002461	0.00034	-	-	-	-	-
	136		X	0.0057219	0.00218	27.0	2415	2356	2465	300.6
	137		X	0.000392	0.00048	24.8	2522	2436	2626	344.8
	138			-	-	-	-	-	-	-
	139		X	0.0005208	0.00064	16.0	2328	2199	2547	15.9
	140			0.0007245	0.00067	-	-	-	-	-
	141		X	0.0010633	0.00099	21.5	2246	2196	2302	333.0
	142			0.0011232	0.00100	-	-	-	-	-
	143			0.002128	0.00168	-	-	-	-	-
	144			0.0000725	0.00019	-	-	-	-	-
	145			0.0010336	0.00126	-	-	-	-	-
	146		X	0.0064823	0.00222	24.3	2356	2282	2425	334.4
	147			-	-	-	-	-	-	-
	148			0.0014012	0.00078	-	-	-	-	-
	149			-	-	-	-	-	-	-
	150		X	0.0044427	0.00279	23.1	2344	2199	2451	27.3
	151			-	-	-	-	-	-	-
	152			0.0033791	0.00235	-	-	-	-	-
	153			0.0001226	0.00048	-	-	-	-	-
	154			0.0007863	0.00071	-	-	-	-	-
	155			0.0012504	0.00113	-	-	-	-	-
	156			0.0005859	0.00088	-	-	-	-	-
	157			0.0000299	0.00013	-	-	-	-	-
	158			0.0000157	0.00008	-	-	-	-	-
	159			-	-	-	-	-	-	-
	160			0.0000592	0.00019	-	-	-	-	-
	161			0.00005	0.00005	-	-	-	-	-
	162			0.0003542	0.00051	-	-	-	-	-
	163			-	-	-	-	-	-	-
	164			-	-	-	-	-	-	-
	165			-	-	-	-	-	-	-
	166			-	-	-	-	-	-	-
	167		X	0.0015564	0.00206	19.0	2301	2230	2354	68.9
	168		X	0.0000313	0.00017	18.0	2443	2427	2459	114.7
	169			-	-	-	-	-	-	-
	170			0.0000569	0.00016	-	-	-	-	-
	171			0.0000486	0.00015	-	-	-	-	-
	172			0.0009369	0.00113	-	-	-	-	-
	173			0.0002999	0.00045	-	-	-	-	-
	174			-	-	-	-	-	-	-
	175			-	-	-	-	-	-	-
	176			-	-	-	-	-	-	-
	177			-	-	-	-	-	-	-
	178			0.000029	0.00013	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	179			-	-	-	-	-	-	-
	180			-	-	-	-	-	-	-
	181			-	-	-	-	-	-	-
	182			-	-	-	-	-	-	-
	183			-	-	-	-	-	-	-
	184			0.0012082	0.00140	-	-	-	-	-
	185		X	0.0007906	0.00079	25.0	2268	2247	2285	30.2
	186			-	-	-	-	-	-	-
	187			-	-	-	-	-	-	-
	188			-	-	-	-	-	-	-
	189			-	-	-	-	-	-	-
	190			-	-	-	-	-	-	-
	191			-	-	-	-	-	-	-
	192			-	-	-	-	-	-	-
	193			-	-	-	-	-	-	-
	194		X	0.0000795	0.00031	27.1	2347	2272	2415	69.6
	195			-	-	-	-	-	-	-
	196			0.0000015	0.00004	-	-	-	-	-
	197		X	0.0009772	0.00133	20.4	2592	2314	2835	90.4
	198			-	-	-	-	-	-	-
	199			-	-	-	-	-	-	-
	200			-	-	-	-	-	-	-
	201			-	-	-	-	-	-	-
	202			-	-	-	-	-	-	-
	203			-	-	-	-	-	-	-
	204			0.0000681	0.00017	-	-	-	-	-
	205			-	-	-	-	-	-	-
	206			-	-	-	-	-	-	-
	207			0.0003633	0.00064	-	-	-	-	-
	208			0.0002068	0.00030	-	-	-	-	-
	209			-	-	-	-	-	-	-
	210			-	-	-	-	-	-	-
	211			-	-	-	-	-	-	-
	212			0.0000822	0.00022	-	-	-	-	-
	213		X	0.0005061	0.00070	21.2	2496	2291	2748	81.9
	214			-	-	-	-	-	-	-
	215			0.0005876	0.00064	-	-	-	-	-
	216			-	-	-	-	-	-	-
	217			-	-	-	-	-	-	-
	218			-	-	-	-	-	-	-
	219			-	-	-	-	-	-	-
	220			-	-	-	-	-	-	-
	221			-	-	-	-	-	-	-
	222			-	-	-	-	-	-	-
	223			0.0001036	0.00020	-	-	-	-	-
	224			0.0000073	0.00007	-	-	-	-	-
	225			-	-	-	-	-	-	-
	226			0.0002579	0.00039	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	227		X	0.0004835	0.00066	14.2	2293	2287	2300	179.8
	228			-	-	-	-	-	-	-
	229			0.000176	0.00033	-	-	-	-	-
	230			-	-	-	-	-	-	-
	231			-	-	-	-	-	-	-
	232			-	-	-	-	-	-	-
	233			-	-	-	-	-	-	-
	234			-	-	-	-	-	-	-
	235			-	-	-	-	-	-	-
	236			0.0000036	0.00013	-	-	-	-	-
	237			-	-	-	-	-	-	-
	238			-	-	-	-	-	-	-
	239			0.000036	0.00019	-	-	-	-	-
	240			-	-	-	-	-	-	-
	241			0.000206	0.00040	-	-	-	-	-
	242			-	-	-	-	-	-	-
	243			-	-	-	-	-	-	-
	244			-	-	-	-	-	-	-
	245			-	-	-	-	-	-	-
	246			-	-	-	-	-	-	-
	247		X	0.0014563	0.00092	15.4	2278	2270	2284	148.5
	248			-	-	-	-	-	-	-
	249			-	-	-	-	-	-	-
	250			0.0001348	0.00030	-	-	-	-	-
	251			0.000921	0.00109	-	-	-	-	-
	252			0.0001148	0.00029	-	-	-	-	-
	253			-	-	-	-	-	-	-
	254			-	-	-	-	-	-	-
	255			-	-	-	-	-	-	-
	256			-	-	-	-	-	-	-
	257			-	-	-	-	-	-	-
	258			-	-	-	-	-	-	-
	259			-	-	-	-	-	-	-
	260			-	-	-	-	-	-	-
	261			-	-	-	-	-	-	-
	262			0.0000105	0.00008	-	-	-	-	-
	263			0.0000152	0.00011	-	-	-	-	-
	264			-	-	-	-	-	-	-
	265			-	-	-	-	-	-	-
	266			-	-	-	-	-	-	-
	267			-	-	-	-	-	-	-
	268			-	-	-	-	-	-	-
	269			-	-	-	-	-	-	-
	270			-	-	-	-	-	-	-
	271			0.0003508	0.00038	-	-	-	-	-
	272			-	-	-	-	-	-	-
	273			-	-	-	-	-	-	-
	274			-	-	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	275			-	-	-	-	-	-	-
	276			-	-	-	-	-	-	-
	277			-	-	-	-	-	-	-
	278			-	-	-	-	-	-	-
	279			-	-	-	-	-	-	-
	280			0.0010758	0.00119	-	-	-	-	-
	281			0.0008394	0.00099	-	-	-	-	-
	282			0.0000305	0.00015	-	-	-	-	-
	283			-	-	-	-	-	-	-
	284			-	-	-	-	-	-	-
	285			-	-	-	-	-	-	-
	286			-	-	-	-	-	-	-
	287			-	-	-	-	-	-	-
	288			0.0003746	0.00042	-	-	-	-	-
	289			0.0000053	0.00006	-	-	-	-	-
	290			0.0002154	0.00048	-	-	-	-	-
	291			0.0003297	0.00068	-	-	-	-	-
	292			-	-	-	-	-	-	-
	293			-	-	-	-	-	-	-
	294			-	-	-	-	-	-	-
	295			0.0000596	0.00016	-	-	-	-	-
	296			0.0002039	0.00028	-	-	-	-	-
	297			0.0006885	0.00096	-	-	-	-	-
	298			0.0001103	0.00025	-	-	-	-	-
	299			-	-	-	-	-	-	-
	300			-	-	-	-	-	-	-
	301			0.00127	0.00080	-	-	-	-	-
	302			-	-	-	-	-	-	-
	303			0.0017234	0.00086	-	-	-	-	-
	304			0.0003968	0.00041	-	-	-	-	-
	305			-	-	-	-	-	-	-
	306		X	0.0043297	0.00159	5.4	2263	2259	2266	230.2
	307			0.0007478	0.00073	-	-	-	-	-
	308		X	0.0051575	0.00264	5.1	2258	2256	2259	190.6
	309			0.0031901	0.00279	-	-	-	-	-
	310			0.0023136	0.00089	-	-	-	-	-
	311			0.000208	0.00053	-	-	-	-	-
	312			0.0001314	0.00025	-	-	-	-	-
	313			-	-	-	-	-	-	-
	314			-	-	-	-	-	-	-
	315			-	-	-	-	-	-	-
	316			-	-	-	-	-	-	-
	317			-	-	-	-	-	-	-
	318			-	-	-	-	-	-	-
	319			-	-	-	-	-	-	-
	320			-	-	-	-	-	-	-
	321			-	-	-	-	-	-	-
	322			-	-	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	323			-	-	-	-	-	-	-
	324			-	-	-	-	-	-	-
	325			-	-	-	-	-	-	-
	326			-	-	-	-	-	-	-
	327			-	-	-	-	-	-	-
	328			-	-	-	-	-	-	-
	329			0.0022609	0.00171	-	-	-	-	-
	330			0.002118	0.00113	-	-	-	-	-
	331			-	-	-	-	-	-	-
	332			-	-	-	-	-	-	-
	333			-	-	-	-	-	-	-
	334			-	-	-	-	-	-	-
	335			-	-	-	-	-	-	-
	336			-	-	-	-	-	-	-
	337			-	-	-	-	-	-	-
	338			-	-	-	-	-	-	-
	339		X	0.0039442	0.00121	7.6	2254	2254	2254	176.0
	340		X	0.0045588	0.00160	14.3	2386	2360	2441	241.4
	341		X	0.0021023	0.00137	16.5	2361	2310	2420	257.4
	342			0.0009977	0.00073	-	-	-	-	-
	343			0.0008759	0.00057	-	-	-	-	-
	344			0.0008648	0.00074	-	-	-	-	-
	345			0.000039	0.00014	-	-	-	-	-
	346			-	-	-	-	-	-	-
	347			0.0000798	0.00023	-	-	-	-	-
	348			0.0000469	0.00016	-	-	-	-	-
	349			-	-	-	-	-	-	-
	350			0.0017152	0.00154	-	-	-	-	-
	351			0.0000407	0.00013	-	-	-	-	-
	352		X	0.0002546	0.00059	27.2	2479	2403	2580	265.4
	353			0.0004369	0.00048	-	-	-	-	-
	354			-	-	-	-	-	-	-
	355			0.0000814	0.00029	-	-	-	-	-
	356			-	-	-	-	-	-	-
	357			0.000019	0.00011	-	-	-	-	-
	358		X	0.0008022	0.00129	15.4	2308	2293	2325	252.0
	359			0.0000951	0.00022	-	-	-	-	-
	360		X	0.0003774	0.00073	23.9	2128	2100	2187	354.7
	361		X	0.0015546	0.00090	29.8	2926	2830	3000	322.5
	362			0.0012789	0.00113	-	-	-	-	-
	363			-	-	-	-	-	-	-
	364			-	-	-	-	-	-	-
	365			-	-	-	-	-	-	-
	366			-	-	-	-	-	-	-
	367			-	-	-	-	-	-	-
	368			0.001193	0.00073	-	-	-	-	-
	369			0.0007215	0.00053	-	-	-	-	-
	370			0.0013183	0.00093	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	371			0.0011116	0.00066	-	-	-	-	-
	372			0.0000597	0.00016	-	-	-	-	-
	373			0.0002653	0.00070	-	-	-	-	-
	374			0.0007443	0.00131	-	-	-	-	-
	375			0.0003471	0.00037	-	-	-	-	-
	376			0.0001141	0.00030	-	-	-	-	-
	377			0.0001524	0.00025	-	-	-	-	-
	378			0.002242	0.00117	-	-	-	-	-
	379			0.0005371	0.00049	-	-	-	-	-
	380			0.0011228	0.00096	-	-	-	-	-
	381			0.0003744	0.00037	-	-	-	-	-
	382			0.0001306	0.00030	-	-	-	-	-
	383		X	0.0007991	0.00096	25.4	2485	2453	2517	307.7
	384			0.0004852	0.00081	-	-	-	-	-
	385			0.0013552	0.00082	-	-	-	-	-
	386			0.0005452	0.00074	-	-	-	-	-
	387			0.0006705	0.00058	-	-	-	-	-
	388			0.0000441	0.00014	-	-	-	-	-
	389			0.0001368	0.00023	-	-	-	-	-
	390			0.000155	0.00029	-	-	-	-	-
	391			-	-	-	-	-	-	-
	392			-	-	-	-	-	-	-
	393			0.0001052	0.00000	-	-	-	-	-
	394			-	-	-	-	-	-	-
	395			-	-	-	-	-	-	-
	396			-	-	-	-	-	-	-
	397			0.0000531	0.00027	-	-	-	-	-
	398			0.0000925	0.00019	-	-	-	-	-
	399			-	-	-	-	-	-	-
	400			-	-	-	-	-	-	-
	401			0.0014912	0.00093	-	-	-	-	-
	402			0.0016251	0.00105	-	-	-	-	-
	403			0.000693	0.00060	-	-	-	-	-
	404			0.0005469	0.00065	-	-	-	-	-
	405			0.0004472	0.00043	-	-	-	-	-
	406			0.000016	0.00009	-	-	-	-	-

2003

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	1		X	0.00669	0.00403	-	-	-	-	-
	4		X	0.00340	0.00256	-	-	-	-	-
	5		X	0.00934	0.00613	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	6		X	0.00656	0.00575	-	-	-	-	-
	7		X	0.00317	0.00226	-	-	-	-	-
	8		X	0.01935	0.01620	-	-	-	-	-
	9		X	0.00657	0.00459	-	-	-	-	-
	10		X	0.00371	0.00397	-	-	-	-	-
	11		X	0.00638	0.00455	-	-	-	-	-
	12		X	0.00415	0.00303	-	-	-	-	-
	17	4194	X	0.00078	0.00128	-	-	-	-	-
	18	4196	X	0.02358	0.02194	-	-	-	-	-
	19	4198	X	0.00428	0.00371	-	-	-	-	-
	20	4201	X	0.01222	0.00599	-	-	-	-	-
	21	4202	X	0.00534	0.00292	-	-	-	-	-
	23	4205	X	0.00046	0.00092	-	-	-	-	-
	24	4206	X	0.01380	0.00949	-	-	-	-	-
Renfrew	25	4207	X	0.47160	0.00532	-	-	-	-	-
	26	4208	X	0.12180	0.03855	-	-	-	-	-
Collier	27	4209	X	0.78968	0.03180	-	-	-	-	-
	28	4209	X	0.19970	0.03294	-	-	-	-	-
	29	4210	X	0.02496	0.01132	-	-	-	-	-
	30	4211	X	0.01351	0.01008	-	-	-	-	-
	31	4212	X	0.00133	0.00174	-	-	-	-	-
	33	4214	X	0.00315	0.00206	-	-	-	-	-
Thayer	34	4216	X	0.11418	0.02988	-	-	-	-	-
	36	4219	X	0.00334	0.00320	-	-	-	-	-
	37	4220	X	0.00707	0.00622	-	-	-	-	-
	38	4221	X	0.01011	0.00775	-	-	-	-	-
	39	4222	X	0.00863	0.00791	-	-	-	-	-
	40	4223	X	0.00359	0.00338	-	-	-	-	-
	41	4224	X	0.00470	0.00571	-	-	-	-	-
	42	4225	X	0.00428	0.00392	-	-	-	-	-
	43	4226	X	0.00445	0.00531	-	-	-	-	-
Villard	44	4227	X	0.02088	0.00623	-	-	-	-	-
Lynn	45	4228	X	0.13433	0.00875	-	-	-	-	-
	47	4233	X	0.00992	0.00479	-	-	-	-	-
	48	4234	X	0.00642	0.00522	-	-	-	-	-
	52	4244	X	0.01212	0.00636	-	-	-	-	-
	57	4250	X	0.05945	0.02389	-	-	-	-	-
	59	4252	X	0.01736	0.01055	-	-	-	-	-
	60	4254	X	0.00233	0.00283	-	-	-	-	-
	61	4255	X	0.00201	0.00332	-	-	-	-	-
	62	4256	X	0.00320	0.00298	-	-	-	-	-
	63	4257	X	0.00637	0.00416	-	-	-	-	-
	64	4258	X	0.01367	0.00650	-	-	-	-	-
	66	4260	X	0.05654	0.03095	-	-	-	-	-
Irving	68	4262	X	0.21420	0.05653	-	-	-	-	-
	69	4263	X	0.00962	0.00368	-	-	-	-	-
	70	4264	X	0.04490	0.01488	-	-	-	-	-
	71	4265	X	0.03716	0.02240	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	72	4266	X	0.00854	0.00725	-	-	-	-	-
Skinner	74	4270	X	0.30733	0.01323	-	-	-	-	-
	75	4271	X	0.03487	0.01234	-	-	-	-	-
Prouty	76	4272	X	1.11460	0.03902	-	-	-	-	-
	77	4273	X	0.10039	0.04084	-	-	-	-	-
	78	4274	X	0.01027	0.00964	-	-	-	-	-
	80	4277	X	0.00700	0.00733	-	-	-	-	-
	82	4280	X	0.00306	0.00429	-	-	-	-	-
Clark	83	4281	X	0.16636	0.04235	-	-	-	-	-
	85	4283	X	0.01663	0.01006	-	-	-	-	-
	86	4284	X	0.00717	0.00473	-	-	-	-	-
	87	4286	X	0.00161	0.00148	-	-	-	-	-
	88	4287	X	0.00356	0.00479	-	-	-	-	-
	89	4288	X	0.02259	0.01655	-	-	-	-	-
	90	4289	X	0.00271	0.00332	-	-	-	-	-
	91	4290	X	0.01071	0.00909	-	-	-	-	-
	92	4291	X	0.01122	0.01113	-	-	-	-	-
	93	4292	X	0.00783	0.00565	-	-	-	-	-
Lewis	94	4293	X	0.30421	0.00651	-	-	-	-	-
	95	4294	X	0.01076	0.00783	-	-	-	-	-
	96	4295	X	0.09330	0.01190	-	-	-	-	-
	97	4296	X	0.00760	0.00722	-	-	-	-	-
Lost Creek	98	4297	X	0.49016	0.04186	-	-	-	-	-
	99	4298	X	0.02791	0.00916	-	-	-	-	-
	100	4299	X	0.00182	0.00281	-	-	-	-	-
	101	4300	X	0.00163	0.00183	-	-	-	-	-
	102	4301	X	0.00949	0.00590	-	-	-	-	-
	103	4302	X	0.01878	0.00845	-	-	-	-	-
Eugene	104	4304	X	0.06766	0.02366	-	-	-	-	-
Carver	105	4306	X	0.16976	0.05968	-	-	-	-	-
	106	4307	X	0.01521	0.01141	-	-	-	-	-
	107	4308	X	0.02461	0.01300	-	-	-	-	-
	108	4309	X	0.02356	0.01709	-	-	-	-	-
	109	4310	X	0.04160	0.02132	-	-	-	-	-
	110	4311	X	0.00685	0.00407	-	-	-	-	-
	112	4348	X	0.00393	0.00409	-	-	-	-	-
Hayden	113	10518	X	0.73048	0.00176	-	-	-	-	-
Diller	114	10525	X	0.55070	0.06031	-	-	-	-	-
	120		X	0.00194	0.00303	-	-	-	-	-
	121		X	0.00300	0.00407	-	-	-	-	-
	122		X	0.00206	0.00309	-	-	-	-	-
	123		X	0.00050	0.00083	-	-	-	-	-
	124		X	0.00476	0.00366	-	-	-	-	-
	125		X	0.01482	0.00530	-	-	-	-	-
	126		X	0.00338	0.00359	-	-	-	-	-
	127		X	0.00133	0.00210	-	-	-	-	-
	130		X	0.00242	0.00262	-	-	-	-	-

Glacier Name	TS_ID	RECNO	Perennial	Area (km^2)	Uncertainty (km^2)	S	Z	Zmin	Zmax	D
	136		X	0.00740	0.00871	-	-	-	-	-
	137		X	0.00224	0.00275	-	-	-	-	-
	139		X	0.00039	0.00075	-	-	-	-	-
	141		X	0.00009	0.00023	-	-	-	-	-
	146		X	0.00278	0.00204	-	-	-	-	-
	150		X	0.00507	0.00489	-	-	-	-	-
	167		X	0.00177	0.00294	-	-	-	-	-
	168		X	0.00000		-	-	-	-	-
	185		X	0.00207	0.00228	-	-	-	-	-
	194		X	0.00080	0.00131	-	-	-	-	-
	197		X	0.00030	0.00051	-	-	-	-	-
	213		X	0.00108	0.00158	-	-	-	-	-
	227		X	0.00013	0.00039	-	-	-	-	-
	247		X	0.00178	0.00187	-	-	-	-	-
	306		X	0.00426	0.00281	-	-	-	-	-
	308		X	0.00444	0.00414	-	-	-	-	-
	339		X	0.00305	0.00194	-	-	-	-	-
	340		X	0.00267	0.00292	-	-	-	-	-
	341		X	0.00113	0.00150	-	-	-	-	-
	352		X	0.00025	0.00065	-	-	-	-	-
	358		X	0.00237	0.00284	-	-	-	-	-
	360		X	0.00073	0.00142	-	-	-	-	-
	361		X	0.00217	0.00208	-	-	-	-	-
	383		X	0.00284	0.00283	-	-	-	-	-