HISTORIC GLACIER AND CLIMATE FLUCTUATIONS AT MOUNT ADAMS, WA AND EFFECTS ON REGIONAL WATER SUPPLY

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by

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ABSTRACT

HISTORIC GLACIER AND CLIMATE FLUCTUATIONS AT MOUNT ADAMS, WA AND EFFECTS ON REGIONAL WATER SUPPLY

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Terminus fluctuations of 10 glaciers at Mount Adams, Washington, were assessed for the time period 1901-2006. Correlations were made with temperature and precipitation patterns for each glacier, along with runoff contributions to the Klickitat River. Historic air photos, maps, glacier descriptions, and climate records used in conjunction with GIS analysis show a period of retreat for all glaciers through 1949. Since 1949, however, a diverse set of fluctuations were revealed, ranging from a 147 m retreat on the Gotchen Glacier to a 605 m advance of the Rusk Glacier. Terminus fluctuations of six glaciers showed correlations with temperature, whereas precipitation only correlated with three. Examination of streamflow contributions to the Klickitat River showed no significant change in total annual flow; however, minor shifts were seen in seasonal flow percentages. Local characteristics of each glacier influenced both the degree of fluctuation and resulting streamflow contribution.

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CHAPTER I

INTRODUCTION

Research Problem

Glaciers grow and shrink in response to changes in temperature and snowfall. The specific response of a glacier to a change in climate is determined by its mass balance, the difference between the amount of accumulation and ablation of snow and ice. If the difference between gains and losses is positive, the glacier has a positive mass balance, while those glaciers losing mass have a negative mass balance. Over time, these mass balance shifts are transferred through the glacier, resulting in similar shifts to areal extents and terminus positions (Benn & Evans, 1998). Because small alpine glaciers are highly responsive to changes in temperature and precipitation, they become critical indicators of climate change through their shifting mass balance and terminus positions. Since direct measurements of mass balance are not only time consuming but economically unfeasible over large areas, glacier termini and areal measurements have been used as tools for determining past climate change (Fountain, Krimmel, & Trabant, 1997).

Warming since the end of the Little Ice Age (LIA) has resulted in countless environmental changes on a global scale and caused terminus retreat in many of the world's glaciers (Haeberli, Zemp, Frauenfelder, Hoelzle, & Kaab, 2005). This widespread loss of glacial mass and termini retreat is particularly evident in the Pacific Northwest. Observations of Washington State's North Cascade Range glaciers show an average retreat of 550 m (1,804 ft) for a total of approximately 30% of volume lost since the end of the LIA (Pelto, 1993). A study of Mount Rainier's glaciers in Washington State shows an overall loss in area by 21.6% between 1913 and 1994 (Nylen, 2004). Additionally, each of the five glaciers studied on Oregon's Mount Hood experienced overall retreat since 1901 (Jackson, 2007; Lillquist & Walker, 2006). While the response of an individual glacier is affected largely by changes in climate, specific geographic characteristics may influence how much snow and ice will accumulate and melt on any specific glacier. Such factors may include snowline, latitude, altitude, slope, orientation, radiational shading, continentality, debris cover, and geothermal activity (Pelto, 1993). To improve our understanding of these many complex glacier interactions in the Pacific Northwest, several monitoring programs have been established to measure mass balance, areal coverage, and terminus behavior of the glaciers in the North Cascades (Pelto, 1993), on Mount Rainier (Fountain et al., 1997), the Blue Glacier in the Olympic Mountains (University of Washington, 2005), and on Oregon's Mount Hood (Jackson, 2006).

In addition to knowledge gained by these direct glacial measurements, research conducted by these programs have contributed much to our understanding of glacial hydrology and the impacts on runoff, water resources, and hydrologic hazards. These studies have become the topic of greater interest by many researchers as glacier-derived runoff is utilized for local water supplies, irrigation, power generation, and influences habitat management (Mayo, 1984). With a general trend of worldwide glacier retreat, concern arises over the effects on glacier-derived streamflow. If the loss of glacier mass continues, summer discharge will be gradually reduced, resulting in summer water shortages (Braun, Weber, & Schulz, 2000). Other effects have been found in areas with glacial streamflow in the Pacific Northwest as a result of climate changes. Streamflow from these glacierized regions has shown decreases in magnitude with shifts toward earlier peaks in spring runoff (Regonda, Rajagopalan, Clark, & Pitlick, 2005). With glacier retreat becoming a common theme worldwide, researchers have been attempting to develop models to predict streamflow from glacierized regions. While our total knowledge of glacier runoff is improving, it is still small in relation to the significance of the resource, the hazards involved, and the current extent of glaciers (Mayo, 1984; Pelto, 1993).

Research Objectives

The purpose of this research is to explore historic glacier fluctuations, their causes, and associated river discharge at Mount Adams, Washington (Figure 1). Specifically, three questions will be addressed: 1) how have 10 of the 12 glaciers on Mount Adams fluctuated since ~1900 A.D.; 2) what factors were responsible for causing these fluctuations; and 3) what are the historic, current, and possible future effects of glacier change on streamflow originating from Mount Adams' glaciers.

Significance

This research is significant in that regional climate impacts on Mount Adams' glaciers will, in turn, affect the capacity for water storage and runoff used for salmon habitat and power generation. With an understanding of the relationship between climate change and glacier fluctuations on Mount Adams, prediction of local runoff becomes possible and management will be better able to accommodate the needs of the area's

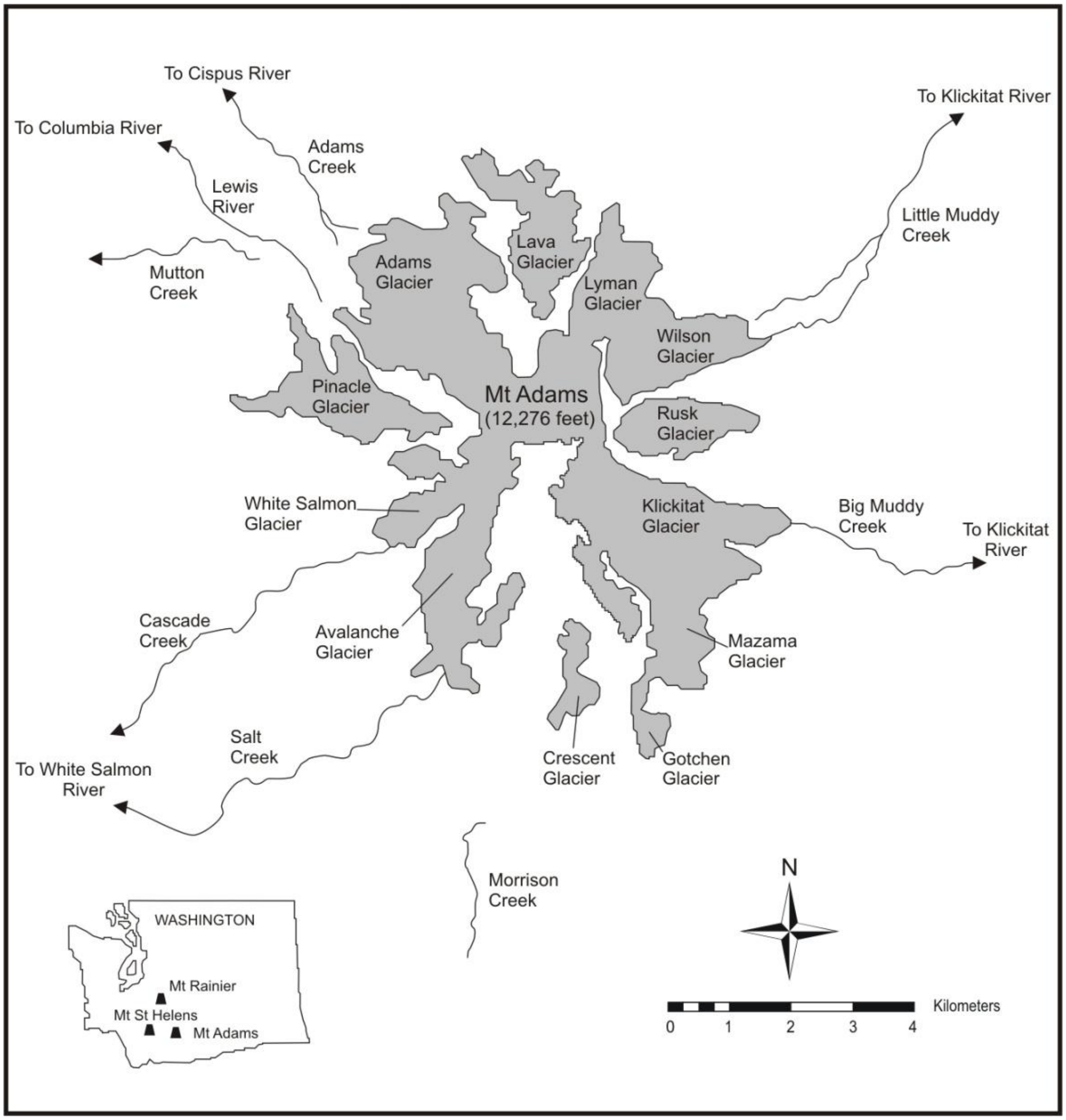


Figure 1. Mount Adams' glaciers and selected tributary drainages. Adapted from Vallance (1999).

population and aquatic ecosystems. In addition to the research being conducted in other regions of the state, the results of this investigation will further our knowledge of regional impacts of climate variability, the corresponding glacier responses, and the resulting changes to our Pacific Northwest water supplies.

CHAPTER II

LITERATURE REVIEW

Glacier Monitoring

Worldwide Glacier Monitoring

Collection of worldwide glacier change data first began in 1894 when the Council of the sixth International Geological Congress created the International Glacier Commission in Zurich, Switzerland. Their primary goal was to collect long-term observations of changes in the sizes of glaciers to understand the processes of climate change (Radok, 1997). Since then, the monitoring process has evolved and a large source of data on glacial change has been built. In 1986, the Permanent Service on Fluctuations of Glaciers and the Temporary Technical Secretariat for the World Glacier Inventory were combined to form the World Glacier Monitoring Service (WGMS). The WGMS now continues the collection of glacier change data with standardized observations and a worldwide database. Today, their duties include publishing data on glacier fluctuations every 5 years, publishing data on mass balance of selected reference glaciers every 2 years, managing the existing inventory of glaciers, and stimulating satellite observations of remote glaciers in order to reach global coverage (WGMS Tasks, 2008).

The information produced by the WGMS now supports decision makers involved in climate system monitoring and hydrological modeling. Furthermore, data provided by the WGMS is beneficial to those operating within the fields of glaciology, climatology, hydrology, and Quaternary geology. The World Glacier Inventory (WGI) that was published in 1989 listed 67,000 glaciers with related data and is a compilation from over 80 separate inventories from each continent. Today, the WGI contains information on over 100,000 glaciers worldwide. This extensive work for over one century by the WGMS has revealed a common theme of shrinking mountain glaciers on a global scale (Haeberlie, 2006; National Snow and Ice Data Center, 2007).

Glacier Monitoring in the United States

Within the United States, the U.S. Geological Survey has an ongoing Glacier Monitoring Program, established in the late 1950s, that is coordinated with the WGMS. Beginning with just the South Cascade Glacier in 1958, the USGS program’s focus was on water resource potential of glaciers. The early years of this program brought a standardized system of terminology and methodology for taking direct measurements of mass balance. However, the intensive field work and costs led to new methods for monitoring (Fountain et al., 1997).

The USGS adopted and now utilizes a three-tiered system of surveillance. One glacier, called a “benchmark” glacier, is chosen in each glacierized region to be intensely measured for mass balance, stream flow, and meteorological information. These benchmark glaciers are selected for their similarity to other local glaciers, ease of access, and significant amounts of available previous information. The second level of monitoring involves the measurement of several glaciers in each of the regions for mass balance and terminus position only. The third level of this monitoring program defines the changing areal extent of a large number of glaciers through remote sensing and aerial photography. Changes found within the “benchmark” and secondary glaciers are extrapolated into the large number of these third-tier glaciers (Fountain et al., 1997).

Specifically within the Pacific Northwest, several monitoring programs have been established. These have primarily been focused on the Olympic Range, Mount Rainier, and the North Cascades of Washington, and at Mount Hood and the Three Sisters in Oregon (University of Washington, 2005). Within the Olympic Range, the Blue Glacier has been the focus of research by University of Washington, where monitoring has been occurring since the International Geophysical Year (IGY), 1956-1957. Results from this long-term study show a rapid retreat of the terminus following the Little Ice Age up through the 1950s. This was followed by a period of advance through the mid 1970s, and returning to an episode of retreat through the early 2000s. From the start of active monitoring with the IGY 1956-1957, the Blue Glacier had a total retreat of 2% by 1997 (Conway, Rasmussen, & Marshall, 1999).

Glacier terminus position measurements at Mount Rainier began in 1918 by the U.S. Geological Survey, now with continuing support by the National Park Service (Driedger, 1993; Pelto & Riedel, 2002; Riedel, 2006). A database constructed of historic changes in glacier area, length, and volume of Mount Rainier's glaciers illustrates a similar regional pattern. While total glacier area and volume decreased between 1913 and 1994, several periods of advance and retreat can be seen within the last century. Between 1913 and the mid-1950s, most of Mount Rainier's major glaciers were retreating with an average loss of 1,318 m (4,324 ft). These same glaciers then advanced up through the early 1980s. Since then, all but three of Mount Rainier's glaciers have been in a phase of retreat. While most of the glaciers showed similar patterns over the last century, the magnitude of response to climatic changes varied spatially around the mountain (Nylen, 2004).

The North Cascades Glacier climate Project annually monitors 47 glaciers in the North Cascades and measures the mass balance of eight. Research of terminus behavior following the LIA has shown similarities between climate phases and periods of glacial activity. Pelto has categorized each of the studied glaciers into one of three types depending on its response: Type 1) Retreat from the LIA to 1950, advance from 1950 to 1976, and moderate to rapid retreat since 1976; Type 2) Rapid retreat from the LIA to 1950, followed by slow retreat or equilibrium to 1976, and moderate to rapid retreat since 1976; and Type 3) Continuous retreat from the LIA to present (Pelto & Hedlund, 2001).

Within the Oregon Cascades, the Mazamas began most of the glacier monitoring programs early in the 20th century, and currently support research through their Research Committee's grants. With focus on Mount Hood, Lillquist and Walker (2006) assessed historical changes of glacier termini through measurements of repeat aerial and ground photographs along with field and GPS surveys. Demonstrating a similar pattern to regional glaciers of the Cascade Range, results show two periods of retreat and advance. Between 1901 and 1946 and again from the late 1970s to the mid-1990s, Mount Hood glaciers retreated due to rising temperatures and decreased precipitation. Alternatively, advances occurred between 1947 and 1976, and again in the late 1990s (Lillquist & Walker, 2006).

Each of these studies and monitoring programs indicate a general trend of glacier recession during the past century, mixed with lesser periods of advance and equilibrium.

While many of these similarities can be seen as a result of large-scale climate fluctuations in the Pacific Northwest, spatial and geographic variations produce differing responses within the glaciers. Up until recently, no monitoring programs have focused on the glaciers of Mount Adams and few studies have been completed on each of the mountain's 12 glacier termini.

Glacier Monitoring at Mount Adams

Monitoring of Mount Adams' glaciers began early, concurrently with those of Mount Hood and Mount Rainier. However, less attention has been paid in recent years than its regional counterparts. The earliest documented research of the glaciers of Mount Adams was in 1895, when members of the Mazamas visited the White Salmon, Klickitat, and Mazama glaciers. Although no quantitative measurements were taken of these glaciers at that time, each was described in a physical context and related to the much more accessible glaciers of Mount Hood. The glaciers of Mount Adams were observed to be much larger and not so regular or typical in form due to the enormous surface exposure of the mountain (Lyman, 1896).

In 1901, Harry Fielding Reid visited Mount Adams with another member of the Mazamas, C.E. Rusk. On August 10^{th}, Reid noted that snow cover was so abundant that observations of equilibrium lines were impossible and determinations of glacier termini could not be accomplished for two glaciers. During this visit, 10 glaciers were recorded and each placed into one of four categories based upon the way in which it was fed. Expanding on the research by Lyman, rough calculations were made of each glacier's length and terminus position. A map was produced (Figure 2) showing each glacier and its relative positions and elevation on the mountain (Reid, 1905, 1906).

The U.S.G.S produced a map of Mount Adams in 1904, including the locations of several glaciers. This map, however, was published showing primarily the eastern half of Mount Adams. Two key glaciers, the Pinnacle and Adams, were drawn with indeterminate terminus locations. A map of Mount Adams' western flank, including the Pinnacle and Adams Glacier, was then completed in 1926 by the U.S.G.S. These maps show glacial extents in greater detail than what was revealed by Reid's 1906 map.

Since these early reports, few have returned to Mount Adams for the purpose of glacial research. In 1981, however, Mahaney dated late Quaternary glacial deposits in the Hell Roaring Valley on the mountain's southeast flank identifying three major glacial advances. On the basis of morphology, position, weathering characteristics, lichenometry, and tephrochronology, Mahaney found distinct soil profiles correlating with the Garda and Burroughs Mountain stades and Fraser Glaciation similar to that found on Mount Rainier (Mahaney, Fahey, & Lloyd, 1981).

The most recent research of Mount Adams' glaciers consisted of measuring areal extents of all 12 glaciers for four time periods between 1904 and 2006. Sitts, Fountain, and Hoffman (2010) found a 49% loss of total glacier area during the last century. From 1904 to 1969, Sitts et al. show all 12 glaciers in a phase of retreat, followed by a slowing rate of retreat or advance to 1998. Since then, their results indicate that all Mount Adams' glaciers, except the Lyman, have decreased in total area. These data were then

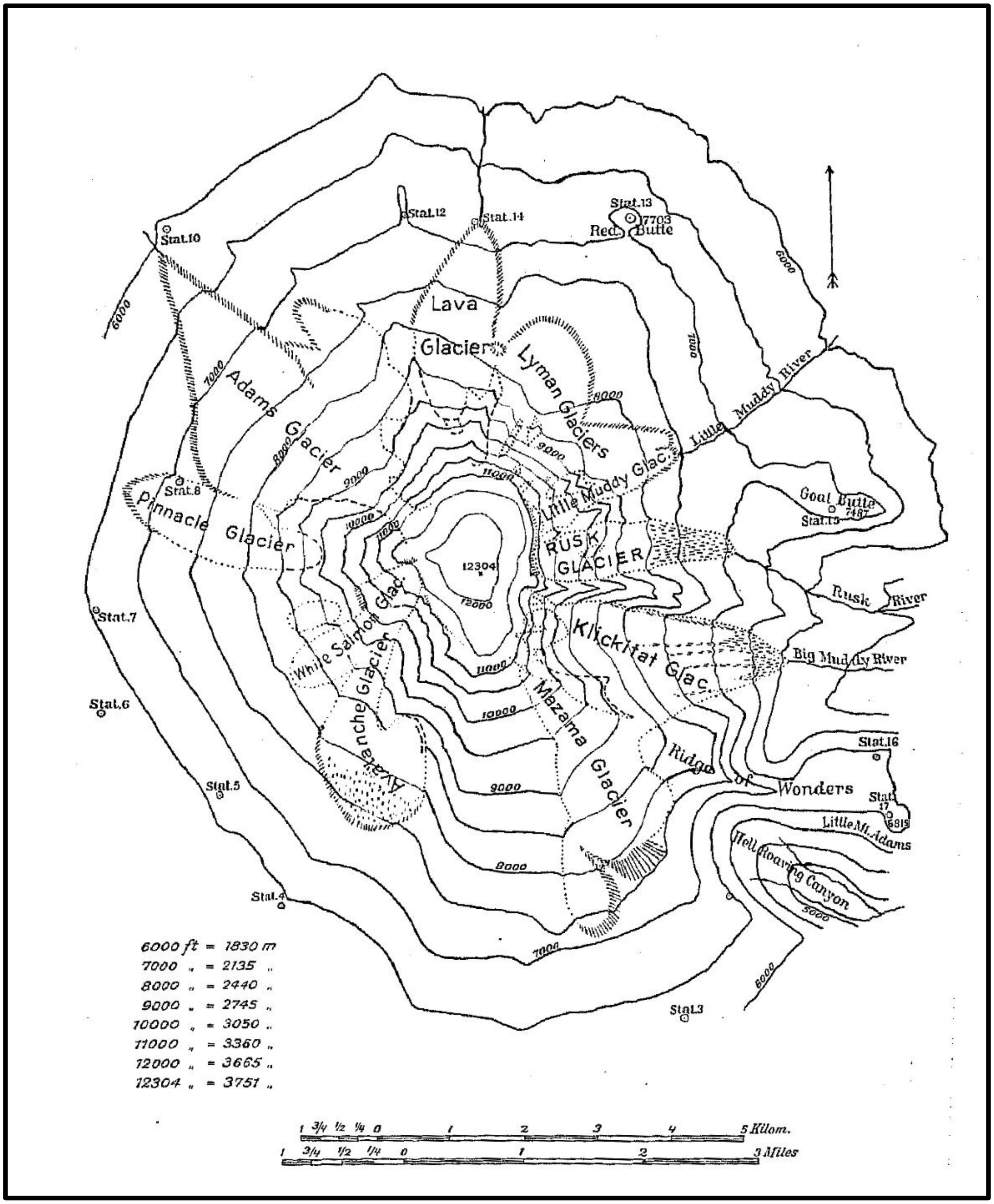


Figure 2. Early map of Mount Adams' glaciers drawn by Harry Fielding Reid (1906).

qualitatively compared to the climate record, concluding that glacier recession at Mount Adams has been driven by summer air temperatures.

Pacific Northwest Glacier Dynamics

As weather and climate patterns continually shift, so do glaciers in an attempt to achieve a state of equilibrium. Typically, glaciers will retreat as climate warms and snowfall decreases, while colder temperatures and increased snowfall cause positive mass balance and glacial advance. Since the beginning of the Holocene approximately 11,500 BP, several periods of glacial advance can be identified in the Pacific Northwest beginning with the Neoglacial period lasting from 3,500 to 2,500 BP. More recently, the Little Ice Age brought substantial glacial advances from 1500-1850 A.D., nearly equaling those of the Neoglacial (Hubley, 1956; Mann, 2002). Mean annual temperatures were up to 1.5° C cooler than present during both these periods (Porter, 1981).

In addition to the previous Holocene advances, observations from the monitoring programs in Washington State (Burbank, 1982; Fountain et al., 1997; Pelto & Hedlund, 2001) and research conducted at Oregon's Mount Hood (Lillquist & Walker, 2006) show a general pattern of alpine glacier terminus change in the last century of the PNW. This pattern begins with retreat from the end of the Little Ice Age to the mid-1940s. In 1944, a sharp rise in winter precipitation and a decline in summer temperatures led to an approximate 30 year period of advance from the mid-1940s to the mid-1970s. In 1977, Pacific Northwest climate shifted, decreasing winter precipitation, leading to another phase of retreat until the mid-1990s (Lillquist & Walker, 2006; Pelto, 2007; Mantua & Hare, 2002). An advance was observed in many North Cascade glaciers between 1995 and 2000 (Pelto & Riedel, 2002). Since 2000, the cumulative mass balance of all measured North Cascade glaciers has been negative, leading to further retreat (Pelto, 2007).

In addition to terminus fluctuations, ice thicknesses throughout the longitudinal profile of several glaciers in the North Cascades have also been shown to be substantially decreasing over the last century (Pelto & Hartzell, 2004). While the general pattern can be seen in most areas of the Cascade Range, some variations occurred due to varying spatial and topographic characteristics of each glacier (Granshaw, 2002).

Glacier-Climate Correlations

As noted above, glacier mass balance responds to and reflects climatic conditions by becoming more positive or negative. The accumulation and ablation that determine mass balance are primarily determined by the region's climate patterns (Benn & Evans, 1998). Many studies of glacier fluctuations have therefore looked at the correlations with regional climate variations. Correlations in the Pacific Northwest have historically been linked to several recurring trends: winter climate being either relatively cool and wet or warm and dry. These climate patterns are associated with several coupled oceanic-atmospheric processes occurring in the Northeast Pacific Ocean (JISAO/SMA Climate Impacts Group, 1999) including the Pacific Decadal Oscillation (PDO), typically lasting 20-30 years, and the El Niño-Southern Oscillation (ENSO), having a typical cycle lasting 6-18 months (Mantua, Hare, Zhang, Wallace, & Francis, 1997; Wallace & Vogel, 1994).

Pacific Decadal Oscillation

The PDO is a climate index that is based on the differences in sea level air pressure (slp) and the sea surface temperature (sst) over the subtropical north Pacific Ocean and western North America. Fluctuations in PDO correspond with changes in the precipitation and temperature patterns in the Pacific Northwest. These patterns have been historically consistent with glacier fluctuations on a 20-30 year cycle (Figure 3). Periods of positive PDO, or "warm phases," are times with above average October through March air temperature, below average precipitation and below average PNW spring snow pack. During a cool phase, the jet stream is steered further north so that the Pacific Northwest is stormier with below average air temperatures and increased precipitation. Four PDO phases have been identified in the last century. Two cooling phases occurred, one from 1890 to 1928 and another from 1947 to 1976. Warm phases occurred from 1925 to 1946 and again from 1977 to 1997 (Figure 3) (Mantua, 1999).

The impacts of the PDO on Pacific Northwest climate can indirectly be seen in the glacial record. This is the result of the PDO affecting local precipitation, a crucial factor that has been positively correlated with the net winter balance of Cascade glaciers (Bitz & Bittisti, 1999). Additionally, the PDO can shift temperatures up to 2 °C above or below the long-term mean for a period of 20 to 30 years (Maxwell, 2002). When positive shifts in mean temperature occur during the accumulation season, more snow is likely to fall as rain, while this same increase during the ablation season increases the rate of mass

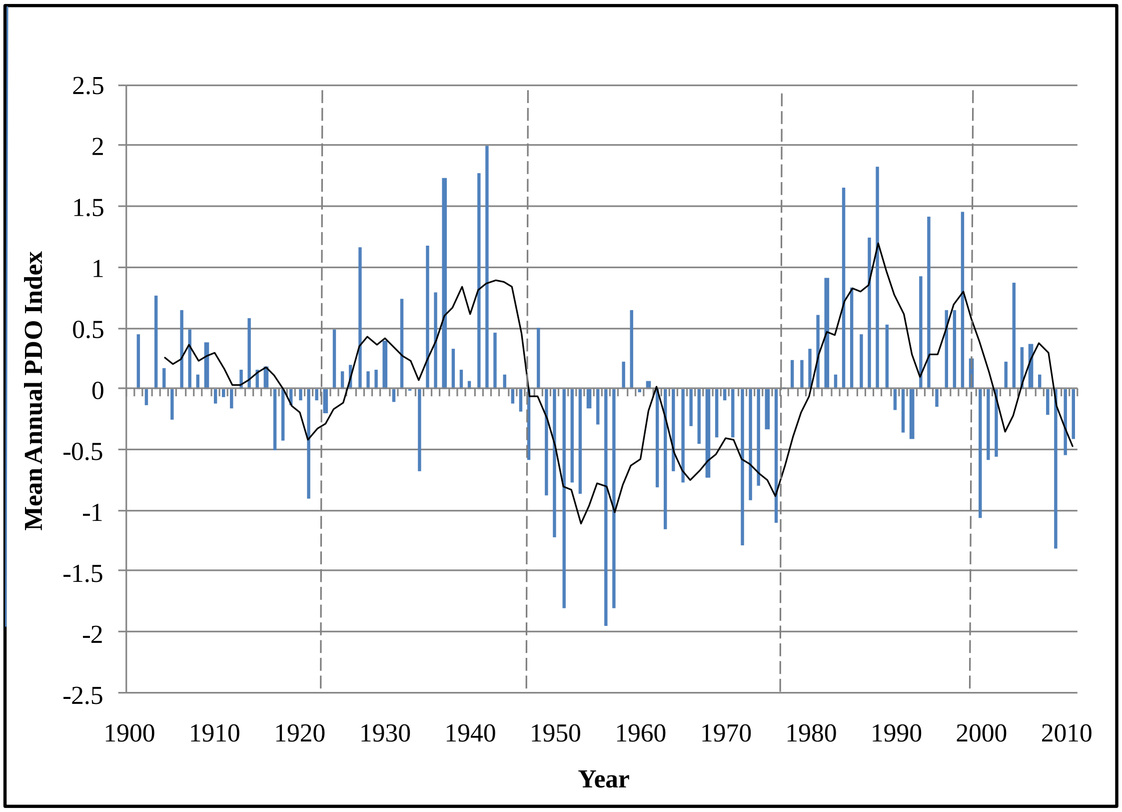


Figure 3. Mean annual PDO index, 1900-2010 shown with 5-year running average. Vertical dashed lines represent PDO phase shifts (JISAO, 2011b).

loss. The combination of these shifts in temperature and precipitation patterns has been positively correlated with glacier fluctuations throughout the Pacific Northwest. Typically, each warm phase of the PDO triggered a negative mass balance response, while each cool phase has led to equilibrium or advance in studied glaciers (Harper, 1993; Pelto & Hedlund, 2001; Lillquist & Walker, 2006).

El Niño-Southern Oscillation

El Niño-Southern Oscillation is a recurring cycle originating in the tropical Pacific Ocean linked to anomalies in sea-level pressure, surface winds, and sea-surface temperatures and typically last between 6 and 18 months (Figure 4). These fluctuations are based on departures from long-term averages of ocean temperatures. Typically, during non-El Niño conditions (La Niña), trade winds drive surface waters of the tropical Pacific westward leading to progressively warmer water as it is exposed longer to solar heating. During a warm El Niño event, weaker easterly trade winds lead to a drop in the normal sea level pressure gradient across the Pacific, leading to a deepening of the eastern thermocline. Warm waters of the western Pacific migrate eastward and eventually reach the South American Coast (Alverson, Bradley, & Pedersen, 2003; Wallace & Vogel, 1994)

The opposite of El Niño is La Niña, when cooler than usual ocean temperatures occur in the tropical Pacific. During these events, stronger trade winds diminish the eastern Pacific thermocline by pushing ocean water away from the equator, producing a stronger, colder upwelling. With the increased sea surface temperature gradient, trade winds are strengthened, causing more upwelling in a positive feedback. This feedback mechanism results in cooler sea surface temperature anomalies in the eastern Pacific (Alverson et al., 2003; Wallace & Vogel, 1994).

While not every region of the United States is affected by ENSO, the Pacific Northwest is affected opposite to that of the Pacific Southwest for each event. During El Niño years, rain is more abundant with cooler temperatures in the U.S. Southwest, creating a deeper snowpack in higher elevations. In the Pacific Northwest, however, El

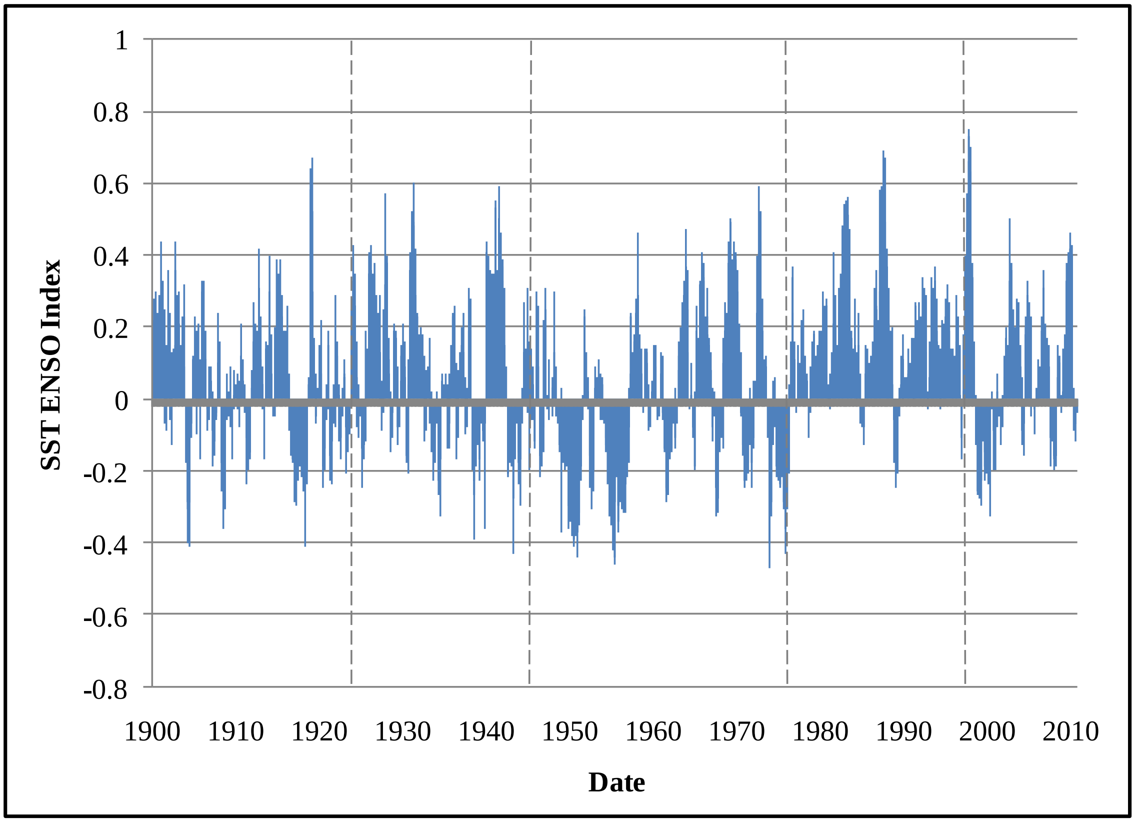


Figure 4. Monthly SST ENSO index, 1900-2010. Vertical dashed lines represent PDO phase shifts (JISAO, 2011a).

Niño winters are characteristically warmer and drier than usual. The combination of less precipitation and higher freezing levels in Washington lead to a smaller snowpack accumulation and typically negative mass balance for many glaciers. The opposite holds true in La Niña events with cold, snowy winters in the northern Cascades of Washington and dry winters in the Southwest (JISAO/SMA Climate Impacts Group, 1999; Gedalof, Peterson, & Mantua, 2004). The extent to which each event extends north and south along the West Coast differs; however, Northern California typically receives moisture from both the northern end of an El Nino and the southern end of a La Niña. The primary effect ENSO events have on glaciers are their roles in determining interannual variations of mass balance. ENSO events can significantly amplify or minimize the effects of interdecadal climate variability, such as the Pacific Decadal Oscillation (Hodge, Trabant, Krimmel, Heinrichs, March, & Josberger, 1998).

ENSO / PDO Relationship

The effects of a negative PDO phase have been shown to be amplified during times of concurrent cool ENSO events. During a coupled La Nina/negative PDO event, frequencies of normal to above normal precipitation are more predominant in the Pacific Northwest. Normal to below normal temperature patterns become more consistent and stable, extending the accumulation season and allowing more precipitation to be stored in the snowpack. The same holds true during synchronized times of positive PDO and warm ENSO. Barton and Ramirez found that warm ENSO events occurring during a positive PDO causes a shift in precipitation and temperature patterns in the Cascades and eastern Washington. Slightly below normal precipitation and above normal temperatures were observed in the fall with a much stronger shifts in the winter and spring months (Barton & Ramirez, 2004). These shifts in climate affect the glaciers in the Cascade Range by decreasing the amount of snow falling during the accumulation season with more precipitation falling as rain (JISAO/SMA Climate Impacts Group, 1999). When the two patterns are out of sync, however, a dampening effect occurs in terms of the amount of precipitation (Gershunov & Barnett, 1998).

Glacier Lag Time

When determining the effects of a shift in climate on the terminus position of a glacier, such as those produced by ENSO and PDO events, it is important to take into consideration the time between the climatic event and the initial observed terminus response. This period, known as the lag time or reaction time (Figure 5), is a result of glacial flow taking several years for accumulated snow and ice to transfer through the glacier to the ablation area and be reflected in the terminus position (Benn & Evans, 1998). Lag times vary as a result of several properties of the individual glacier such as slope, thickness, and accumulation-ablation area ratios. Small temperate glaciers will typically have the shortest lag times ranging from 10 to 20 years for both positive and

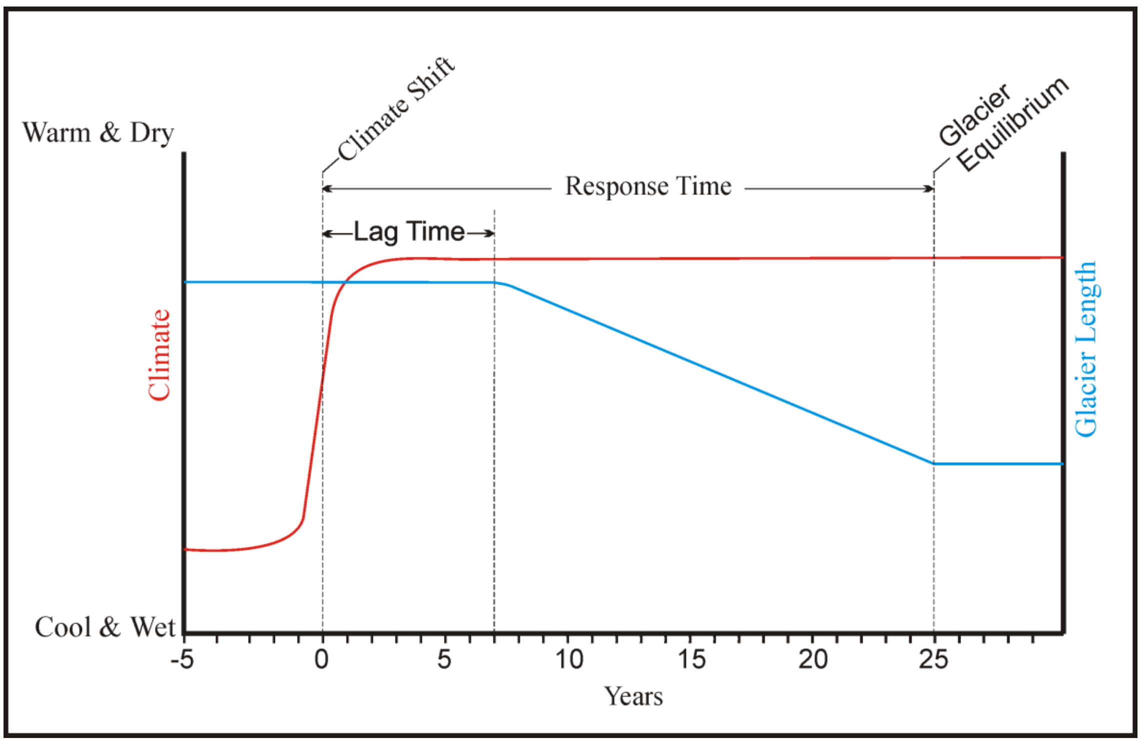


Figure 5. Relationship between a shift in climate and glacier terminus lag and response times.

negative shifts in mass balance (Pelto & Hedlund, 2001; Jóhannesson, Raymond, & Waddington, 1989; Benn & Evans, 1998). Additionally, once a shift in climate has occurred, the time required to reach a new steady-state or equilibrium is the glacier's response time. While this equilibrium is never truly reached with a continually changed climate, research on the magnitude of both lag and response times are crucial in predicting future change (Pelto, 2001; Schwitter & Raymond, 1993).

Other Factors Affecting Glacier Distribution and Extent

Climate plays the largest role in governing the distribution and activity of glaciers throughout the world, primarily summer temperatures and winter precipitation. However, climate is not the single controlling factor. A variety of other variables can play a significant role in determining the amount of snow and ice that will accumulate and melt at a particular location including aspect, altitude, slope, radiational shading, continentality, and debris cover.

Aspect, Latitude, Slope, and Radiational Shading

The aspect of a glacier plays a significant role in ablation at a local scale. This is especially true in marginal areas of alpine glaciation where the snowline (i.e., the area or zone between seasonal snow and permanent snow) is just below the mountain summit and slight changes in temperature or precipitation will have a large, observable effect (Evans, 1969). Aspect influences glaciers by exposing them to varying degrees of direct solar radiation. This radiation provides the primary source of energy used for melting and sublimating snow and glacial ice. A percentage of this incoming solar radiation can be reflected off the surface, and is termed the albedo. Glaciers with a higher albedo reflect a greater portion of the radiation, thereby absorbing less energy and losing less mass to ablation effects. Additionally, mountains and other barriers provide increased radiational shading, reducing ablation rates. This is the basis for most glaciers being poleward-oriented. In areas where glaciers are insufficiently oriented to protect them from this radiation, equilibrium lines (i.e., the point/altitude at which yearly accumulation equals ablation) will be substantially higher in comparison (Evans, 1969; Benn & Evans, 1998).

The amount of radiation that comes in contact with a glacier is also affected by latitude and time of year. The amount of incoming radiation received by the glacier surface depends on the angle at which the sun’s rays are received. High latitude glaciers have a low solar angle in comparison to mid-latitude glaciers, reducing the overall solar radiation received. Additionally, solar radiation is least in the northern hemisphere in December, while the southern hemisphere solar radiation is at a minimum in June (Benn & Evans, 1998).

In a similar fashion to latitude, the slope angle of the glacier surface will determine the intensity of incoming radiation. A south-facing glacier in the mid-latitude northern hemisphere with a steep slope will receive a far greater amount of incoming radiation as opposed to a flat lying surface. Given that reflectivity of a glacier increases with increased solar angle, those surfaces approaching an angle of 90° to incoming radiation will be more susceptible to mass loss during the summer ablation season. These variations in slope can result in significantly different rates of ablation on adjacent glaciers (Benn & Evans, 1998).

Continentality

With solar radiation producing the energy for ablation on a glacier, continentality (i.e., the location of the glacier in respect to an ocean or other significant water source) plays a role in determining the amount of precipitation received during the winter accumulation season. Typically, coastal regions experience moderate temperatures with an abundance of precipitation, while interior regions experience extremes in temperature and less precipitation. As a result of these climate differences, the mass balance of Coast Range glaciers will be influenced more by winter precipitation, whereas glaciers further toward the interior of a continent will be influenced more by summer temperatures (Pelto, 1989; Benn & Evans, 1998).

On account of the differences in climate between coastal and interior locations, snowlines increase with increased distance from a water source (Benn & Evans, 1998). The glaciation level in Washington's Cascade Range was determined to rise inland at a rate of 10 to 12 m/km with increased variability of 7 to 25 m/km in topographic depressions along the crest as moisture is permitted to move further eastward (Porter, 1977). Resulting from Mount Adams' location east of the Cascade Crest, it has a more continental climate regime with hot summers, cold winters, and less precipitation than its regional counterparts. Snowlines on Mount Adams are likely elevated in response to its more continental location (Porter, 1977; Pelto, 1993).

Debris Cover

In alpine settings, the source of supraglacial debris can come from several sources. The most common form of debris is material falling down directly onto the glacier from the cliffs and cirque headwall above. If the debris is deposited within the accumulation area of the glacier, it will be transported englacially, eventually re-emerging and concentrating on the surface of the ablation area. Additionally, this englacial material can compose subglacial material brought up from the bed of the glacier (Sharp, 1949).

Supraglacial debris cover is often seen on many small, temperate glaciers. The occurrence of debris on glacial ice can have a significant effect on its albedo, ultimately changing the ablation rates of the glacier. The rate at which ice under a debris cover melts is a function of the thickness of the debris. Because the albedo of a rocky surface is typically lower than that of the underlying ice, the surface debris will absorb more incoming short-wave solar radiation and heat up. If this debris cover is thin enough, it will release long-wave radiation to the adjacent ice and increase the rate of ablation. When the layer of debris cover becomes sufficiently thick, it will protect the underlying ice from incoming radiation and essentially delay the ablation process. This typically occurs when a continuous layer of debris cover thickens to approximately 1 to 2 cm (0.4 to 0.8 in) (Benn & Evans, 1998; Lundstrom, 1992; Nakawo & Rana, 1999). The relationship of ablation to the thickness of the debris cover is not always the same, however, but will also depend upon the properties of the debris and local meteorological conditions (Nakawo & Rana, 1999). In a comparison of adjacent, debris covered glaciers in the North Cascades, ablation rates in late summer were slowed up to 40% (Pelto, 2000).

Ablation rates under a debris cover can vary largely as a result of their highly heterogeneous surface. Within the debris covered area, ablation can continue at a normal rate in areas too steep to support debris such as crevasses, moulins, and ice cliffs. In this differential ablation process, the surface of the glacier will become even more diverse, forming debris mantled ridges, mounds, and a generally hummocky topography (Benn & Evans, 1998; Sharp, 1949). At the interface between the covered and debris-free area, ablation will happen at the fastest rate. In doing so, a depression will form, often creating a supraglacial lake (Konrad, 1998). If ice melt continues at different rates, the debris covered tongue can even disconnect itself, creating a new terminus and stagnating the lower lobe.

Geothermal Activity

Geothermal and volcanic activity beneath glacial ice can have a significant impact on termini fluctuations and rate of ice melt. Subglacial eruptions in Iceland have been shown to rapidly melt ice and release great quantities of water. Additionally, basal geothermal heat can melt ice at the glacier bed, flowing through subglacial channels to the glacier margin or accumulating in subglacial lakes. Sudden release of subglacially stored water in the form of an outburst flood (jökulhlaup) can be devastating to both environment and mankind. These forms of non-climatic glacier melt ultimately decrease mass balance and glacier length. However, this release of water has the potential to enhance basal sliding by lubricating the ice-bedrock interface (Björnsson, 2002; Jarosch & Gudmundsson, 2007).

The location of Mount Adams within the Mount Adams Volcanic Field and greater Cascade arc provide a high likelihood for its glaciers to be affected by volcanic and geothermal activity. In addition to increasing the potential for glacial melt, geothermal activity at Mount Adams releases hydrogen sulfide from fumaroles and crevasses on the summit cap and steep glacial headwalls. This gas has chemically altered the numerous stacks of thin lava flows and fragmental andesite surrounding the crater. As a result, small volume debris avalanches are common, continually depositing material onto the Klickitat, Rusk, Wilson, Lava, Adams, and Avalanche glaciers, and to a lesser extent the Mazama and Lyman glaciers (Figure 3) (Hildreth & Fierstein, 1995). This debris can cover and insulate these glaciers, dramatically reducing ablation rates, increasing load, and ultimately increasing glacier length (Frank & Krimmel, 1978; Reid, 1969; Sturm, Hall, Benson, & Field, 1991).

Glacier Runoff Studies

Streamflow contributions made by glacier runoff provide many regions of the world with critical water supplies by storing winter precipitation and releasing it during hot, dry summer months (Willis & Bonvin, 1995). These glaciers provide a constant source of potential streamflow, used for hydroelectric power generation (Tangborn, 1984), agricultural irrigation, fisheries, recreation, and human habitation (Gedalof, Peterson, & Mantua, 2004). With growing demands for water, prediction of runoff has increasingly become the focus of research.

One of the earliest studies of glacial runoff in the Pacific Northwest was performed in 1933. This early report noted that in areas where water originated from glacierized regions, the annual variation in flow was decreased, producing more water during warm and dry years than in cool wet ones (Fountain & Tangborn, 1985; Henshaw, 1933; Meier & Tangborn, 1961). Since then, the field of glacial hydrology has slowly been advancing. It was found that the liquid flow through the entire glacial system behaves as though the glacier were a porous medium and obeying the Darcy Flow Law (Campbell & Rasmussen, 1973). This runoff was also found to be greatest during sunny weather, whereas non-glacial runoff tends to be greatest during times of storminess. In areas with partial glacial coverage, it has been shown that variability in streamflow is decreased due to the mixing of the two systems (Krimmel & Tangborn, 1974). Since these early studies, glacial meltwater research has detailed the movement of water from the glacial surface to intragranular passageways and subglacial channel networks (Shreve, 1972).

Building on this research, efforts have been made to determine the effects glaciers have on runoff. By comparing runoff from glaciated regions to unglaciated regions, studies have shown that glaciers influence streamflow in discharge magnitude and timing (Fountain & Tangborn, 1985; Kuhn & Batlogg, 1998; Mayo, 1984; Pelto, 1993).
The presence of glaciers within a drainage basin delays the timing of maximum seasonal runoff by storing spring meltwater within the glacier, to be released later in the summer

(Fountain & Tangborn, 1985). The timing of release across western North America, however, has been shifting earlier in the water year, although the mean annual flows have remained constant or increased slightly. Studies of streamflow timing since 1948 indicate a 10-50% decrease in spring and summer streamflow, now occurring during winter. The cause for the trend to an earlier snowmelt and peak streamflow has been shown to be the result of a broad-scale increase in winter and spring temperatures by approximately 1-3 °C over the last 50 years. This has partially been the product of positive phases of the Pacific Decadal Oscillation (Stewart, Cayan, & Dettinger, 2005).

While glacial melt can have positive effects on streamflow, outburst floods from these same glaciers can be catastrophic. While there are several modes for water to be stored within a glacier, research at Mount Rainier suggests that water can be retained within several large cavities formed in the lee of bedrock steps. These voids form when the glacier ice separates from the bedrock at the step. If the glacier characteristics, such as crevasses and moulins, permit water to flow into these spaces, the cavity will enlarge to an impressive size (Driedger & Fountain, 1989). Additionally, water storage within a glacier can be supported by debris cover on the surface of the glacier. As a debris-covered glacier enters the ablation zone, the rate of melting and thinning of the glacier decreases. Since the highest rate of ablation is shifted to the lowest area of the glacier that is debris-free, depressions will form up-glacier of the debris cover. A subglacial reservoir will then form beneath this depression, beginning the process of outburst flooding (Konrad, 1998). Once the pressure increases to initiate the release of water, frictional heat from the flowing water will often expand the passageways until all the water is released.

This release of stored water has been found to have a high correlation with atypical weather, such as extremely hot or rainy conditions, when the rate of water input to the glacier exceeds its storage (Walder & Driedger, 1995).

In addition to determining both positive and negative effects on streamflow, researchers have been attempting to predict runoff from glacierized regions (Braun et al., 2000; Martinec & Rango, 1986; Tangborn, 1984). While research on the effects of climate change on non-glacierized regions shows that streamflow responds primarily to changes in precipitation rather than to rising mean summer temperatures, in highly glacierized basins, rising mean ablation season temperatures play an important role. Increasing temperatures have been shown to initially enhance glacial melt and runoff, creating glaciers with negative mass balance. Continued years of strongly negative mass balance can in-turn increase diurnal variations in runoff. After the initial increase in runoff, if glacier mass loss continues, glacial contributions to summer streamflow will be diminished and eventually eliminated (Braun et al., 2000).

To date, most of these models account for historic trends in climate such as temperature and precipitation, while incorporating the percentage of snow and ice cover of the watershed. However, debates over model complexity/simplicity and incorporation of other geographic and hydrologic parameters have resulted in no single model being universally accepted. Difficulty arises when attempting to accurately predict streamflow as there is still no certainty in the accuracy of current climate models.

CHAPTER III

STUDY AREA

Location

Mount Adams (46.206 N, 121.49 W), rising to 3,742 m (12,276 ft) along the crest of the Washington's South Cascades, is the second tallest mountain in the Pacific Northwest, second only to Mount Rainier. It is situated 50 km (31 mi) north of the Columbia River and 50 km (31 mi) due east of Mount St. Helens. The summit of this stratovolcano lies within the southwestern corner of Yakima County, with the western flank extending into Skamania County. Lands along the northeastern portion of the mountain lie within the Yakama Indian Reservation, while the western and southern sections are managed by the U.S. Forest Service. The massive size of this volcano is set within the Mount Adams, Indian Heaven, and Simcoe Mountains volcanic fields, covering an area of approximately 1,250 km^2 (483 ft^2) (Figure 6). Over 60 smaller volcanoes are scattered throughout this area, many sitting within broad lava flows (Hildreth, 1990; Hildreth & Fierstein, 1997; U.S. Geological Survey, 1970).

Climate

The PDO and ENSO patterns that dominate the climate of the Pacific Northwest both take into account changes in oceanic and atmospheric temperature, precipitation, and wind patterns. Changes in these components and patterns essentially affect the climate of the Pacific Northwest and Mount Adams by influencing the overall patterns of

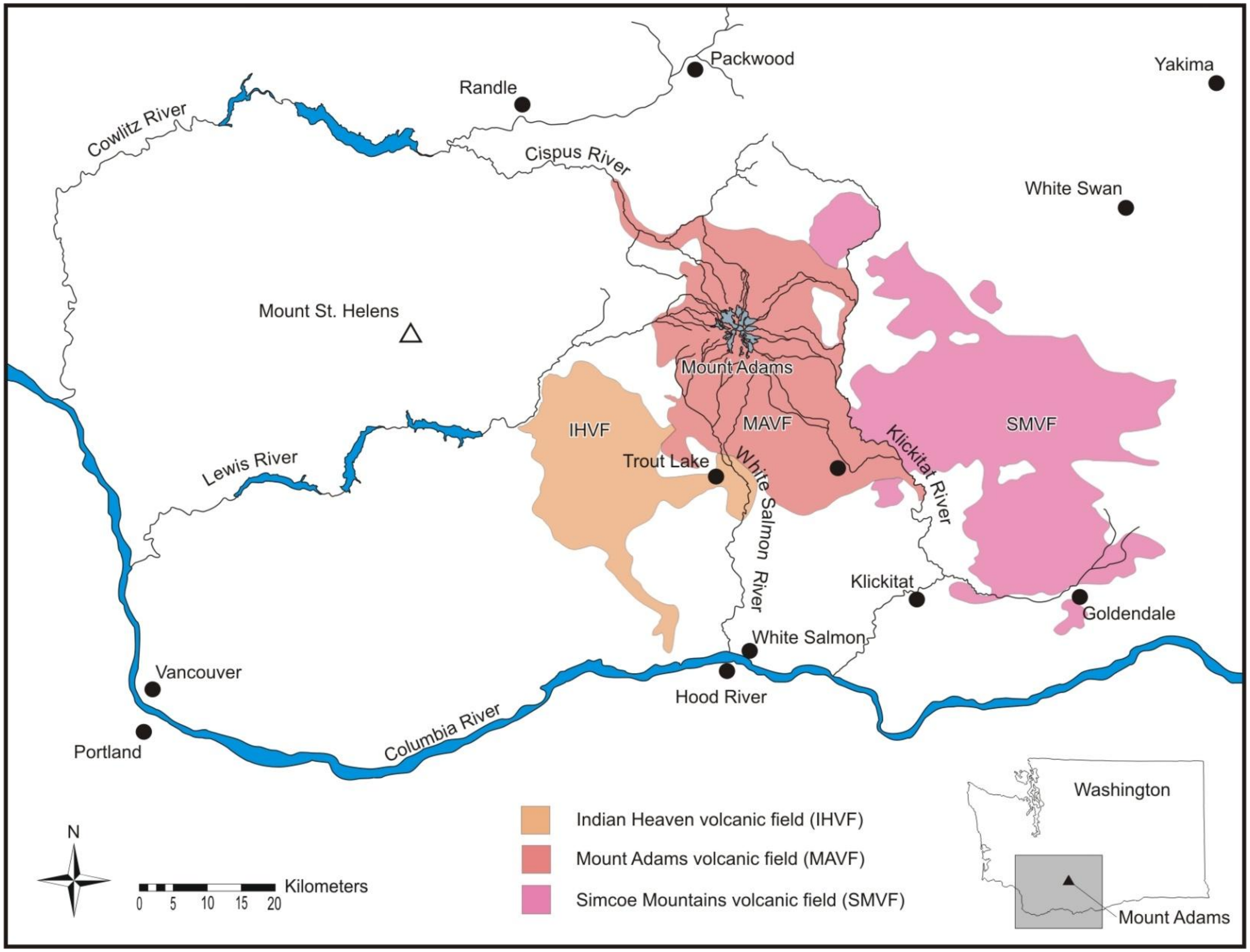


Figure 6. Mount Adams location map and volcanic field. Adapted from Hildreth and Fierstein (1995).

atmospheric circulation (JISAO/SMA Climate Impacts Group, 1999). The two primary, semi-permanent systems in the North Pacific influencing climate are a low-pressure area known as the Aleutian Low that originates near the Aleutian Island chain and the Hawaiian High pressure system, residing southwest of California. The manner in which these opposing pressure cells converge is largely what determines temperature, precipitation, and wind (Western Regional Climate Center, 1985).

During spring and summer months, the counter-clockwise circulating Aleutian Low is weak and shifts north. The Hawaiian High during these same months strengthens, extending further into the North Pacific Ocean. Dry, stable, westerly and north-westerly winds blowing off the high-pressure system move across the Pacific Northwest, becoming warmer and drier as they move inland. Alternatively, during the fall and winter months the high pressure system weakens, allowing the strengthened Aleutian Low to move southward. The convergence during these months typically brings moist air across the Pacific Northwest, often falling as snow as it rises over the Cascade Mountains (Western Regional Climate Center, 1985).

As a result of Mount Adams' remoteness and limited access, direct long-term climate records are unavailable. In 1980, a Snowpack Telemetry (SNOTEL) system was put into service at Potato Hill, approximately 15 km (9.3 mi) north of Mount Adams at an elevation of 1,371 m (4,500 ft). While this location is not specifically located on the mountain, it is the closest available site and can be used as a sufficient proxy. On the south side of the mountain and at a considerably lower elevation, Mount Adams Ranger

Station has been keeping records since 1948. This site is located in Trout Lake and sits approximately 22 km (13.7 mi) south of the summit at an elevation of 597 m (1,960 ft).

The temperature patterns surrounding Mount Adams are influenced by its latitude, altitude, and continentality. At 46.2° north, the mountain's mid-latitude location creates hot summer temperatures as a result of longer days and moderate sun heights and cooler winters associated with shortened daylight hours. With the base of Mount Adams at an approximate elevation of 1,828 m (6,000 ft) and rising up to 3,742 m (12,276 ft), cooler temperatures are accentuated during winter months while keeping summer temperatures significantly cooler than surrounding lowlands. Standing astride the Cascade Crest, Mount Adams is also subject to its continentality. Temperature patterns here reflect a more continental climate with hot summers and cool winters. Average annual temperatures at Potato Hill from 1995-2005 were 2.5 °C (36.5 °F). January averages were -2.7 °C (27.1 °F), while July averages were 11.3 °C (52.3 °F) (Natural Resources Conservation Service, 2008). South of Mount Adams at the Mount Adams Ranger Station average monthly temperature for January and July from 1971-2000 were -0.8 °C (30.6 °F) and 18.4 °C (65.2 °F) respectively (Figure 7).

Temperature measurements taken at both the Potato Hill and Trout Lake locations can be used in conjunction with the environmental lapse rate to establish likely values at different elevations on the mountain. Using the recommended lapse rate of 6.49 °C /1,000 m. (Benn & Evans, 1998), temperatures can then be determined for the average elevation of Mount Adams' glacier termini, approximately 2,253 m (7,392 ft). Applying the lapse rate to the temperature records taken at Mount Adams Ranger Station, 1,656 m

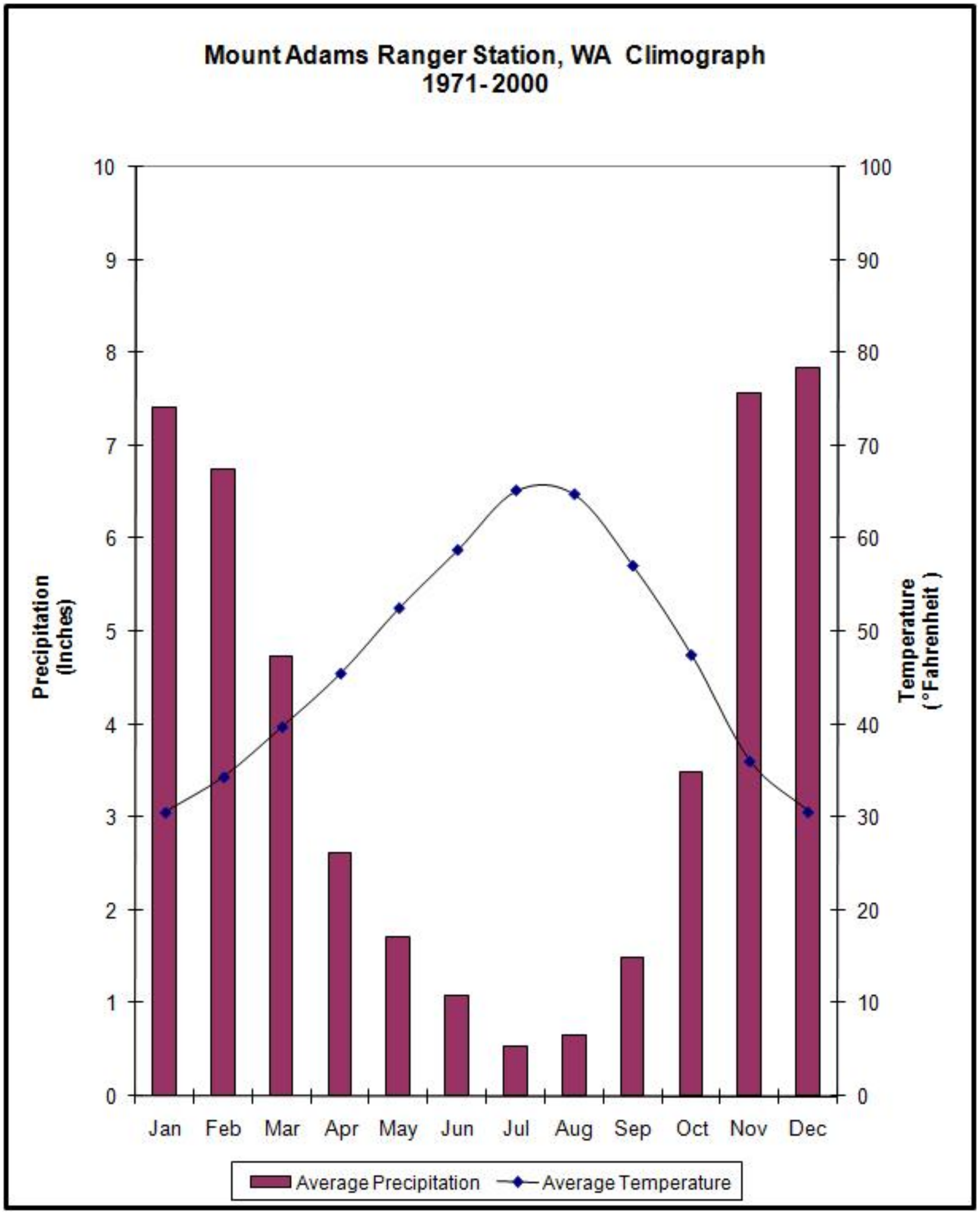


Figure 7. Climograph of Mount Adams Ranger Station, WA, 1971-2000 (Western Regional Climate Center, 2008)**.**

lower, glacier termini should typically have an average January temperature of -11.6 °C (11.1 °F), rising to 7.7 °C (45.9 °F) in July.

Precipitation patterns at Mount Adams are primarily affected by the atmospheric circulation in the North Pacific. While the Hawaiian High pressure system dominates the North Pacific in late spring and summer months, the storm jet from the north is blocked, creating a drought condition in much of the west. When this high pressure diminishes in fall months, westerly and south-westerly winds bring the majority of annual precipitation to Mount Adams. At Potato Hill, average annual precipitation was 175 cm (68.9 in) from 1995-2005. January average precipitation was 30 cm, while July averaged only 1.8 cm (0.7 in) (Natural Resources Conservation Service, 2008).

Patterns of wind at Mount Adams also play an important role in the development of glaciers. With wind direction typically only changing from southwesterly in the winter to northwesterly in the summer, the value lies with its impacts on snow accumulation and distribution. Ridges and exposed slopes, receiving the highest velocity of wind, will often be blown free of snow, depositing it on the leeward slopes. The north-south trending Suksdorf Ridge and North Cleaver are two such ridges often exposed to prevailing westerly winds. Leeward glaciers, Mazama and Lava, are subsequently the recipients of increased quantities of drifting snow.

Geology

Mount Adams is one of twelve major stratovolcanoes of the Cascade Range (Figure 5). Although not the highest in elevation compared to other Cascade volcanoes, the main cone exceeds 200 km^3 (48 mi^3) greater than the taller Mount Rainier and only

2nd to that of Mount Shasta in California. It stands within the center of a 1,250 km^2 (483 mi^2) Quaternary volcanic field, comprised of several smaller fields of varying ages in southern Washington (Scott, Iverson, Vallance, & Hildreth, 1995). This zone of volcanism is the product of subducting oceanic lithosphere under the continental crust of North America, forming the Cascade Arc, stretching from southern British Columbia to north California (Figure 8). The Mount Adams volcanic field (0.9-0 Ma) is centered between the Simcoe Mountains volcanic field (4.5-0.6 Ma) to the east and the Indian Heaven volcanic field (0.8-0 Ma) to the west (Figure 6). Approximately 23 km (14 mi)

Figure 8. Location of major Cascade stratovolcanoes.

north of the mountain lays a Quaternary volcanic center near Walupt Lake, separating the area from the Goat Rocks stratovolcano. To the south, lies a 50 km-wide (31 mi) area near White Salmon and Gilmer, WA. with scattered basaltic centers (Hildreth & Fierstein, 1995; Scott, Iverson, Vallance, & Hildreth, 1995).

The development of Mount Adams began approximately 940 ka with scattered basaltic eruptions around the Mount Adams volcanic field (Figure 6). By about 460 ka, eruptions became more focused at the present day cone, forming the relatively large area of andesite-dacite lavas surrounding the mountain. Activity at the site continued for the next 420,000 years, having three major cone-building episodes. During these active volcanic periods, ~315 ± 84 km^3 (75 ±20 mi^3) of andesite, basalt, and dacite were released in the volcanic field. One hundred and thirty two volcanic eruptive sites have been distinguished since then (Hildreth & Fierstein, 1995), most notably, Bunnel Butte, Snipes Mountain, Little Mount Adams, Mulligan Butte, Glaciate Butte, Potato Hill, and Red Butte. While the majority of eruptions within the Mount Adams volcanic field were basaltic, the eruptions forming Mount Adams mainly consisted of andesite, making up the bulk of its volume. The last major mountain building activities occurred between 40 and 15 ka, forming the uppermost 1,300 m (4,265 ft) of the current summit (Hildreth & Fierstein, 1997). The main cone today exceeds 200 km^3 (48 mi^3) in volume, built through successive volcanic flows through multiple vents (Wood & Kienle, 1990). While this impressive size is far more than adjacent mountains of the Cascade Range, it is estimated that the summit was once some 2,500 m (8,202 ft) higher than its current altitude, containing an additional 100 km^3 (24 mi^3) of material (Hildreth & Fierstein, 1997).

Volcanic mountain building activity slowed near the end of the Pleistocene; however, several vents have remained active (Wood & Kienle, 1990). Since the beginning of the Holocene, nine vents on the flanks of Mount Adams have produced lava flows, with the summit vent showing some minor activity as well. The majority of these vents originate at the break in slope below the main cone at an elevation of 2,100-2,600 m (6,890-8,530 ft)(Figure 9)(Hildreth & Fierstein, 1997) with lava flows covering an area of approximately 50 km^2 (20 mi^2) (Scott et al., 1995). The eruptions that originated from these vents have predominately been effusive and originated within 6 km (3.7 mi) of the summit. The lava emanating from the vents typically flowed into valleys and travelled less than 20 km (12 mi). These slow moving flows often developed steep fronts with thicknesses between 1 and 35 m (3-115 ft) (Hildreth & Fierstein, 1995; Hildreth & Fierstein, 1997).

The volcanic activity of Mount Adams volcanic field differs from that of other stratovolcanoes of the region in its distinct lack of pyroclastic material. Unlike the dacite eruptions seen at Mount St. Helens with regionally distributed pumice and ash, the less explosive activity at Mount Adams has primarily been mafic andesite and basalt (Figure 9)(Table 1). These eruptions result in shield-style flows, scoria and spatter cones, and effusive lava, forming long tongues (Hildreth & Fierstein, 1995).

Figure 9. Geologic map of Mount Adams. Adapted from Hildreth and Fierstein (1995).

Table 1

Description of Geologic Map Units for Geologic Map of Mount Adams. Adapted from Hildreth and Fierstein (1995).

Map unit	Description
Surficial deposits	
i	Glacial ice - Present-day glaciers and summit icecap. Many contacts with ice-cored till and perennial snowfields.
daf	Debris avalanche and debris flow deposits - Unconsolidated, poorly sorted sheets of andesitic rubble from failure of glacial headwalls.
gn	Neoglacial deposits (Holocene) - Till and outwash with many steep, sharp crested moraines dating to the last few centuries.
gy	Younger glacial deposits (late Pleistocene) - Till and outwash with steep, heavily forested moraines emplaced during glacial episode of 25-11 ka.
yal	Younger alluvium (Holocene and late Pleistocene) - Unconsolidated, water transported mud, sand, gravel, and coarse debris near present day streams and lakes.
Primary volcanic	
aas	Andesite of Mount Adams summit - Upper 250 m of fumarolically altered andesite of Mount Adams summit, overlying app flows.
app	Andesite of Pikers Peak - Andesite lava flows and scoria of the summit cone, Pikers Peak, The Pinnacle, glacial cleavers, and headwalls.
ask	Andesite of Suksdorf Ridge (late Pleistocene) - Leveed flows of lava from effusive vents on lower Suksdorf Ridge. Typically blocky and scoriacious, overlying app flows.
Other volcanic	
abl	Andesite of Bird Lake
acg	Andesite of Crooked Creek-Gotchen Creek divide
acr	Andesite of Crofton Ridge
adg	Andesite of Devil's Gardens
ahc	Andesite of High Camp
aht	Andesite of Highline Trail
ahv	Andesite of Hellroaring Valley
akc	Andesite of Killen Creek
asb	Andesite of South Butte
atm	Andesite of Takh Takh Meadow
dbc	Dacite of Bird Creek Meadows
dcc	Dacite of Cascade Creek
dth	Dacite tuff of Heallroaring Creek
rg	Rock glacier

Volcanic activity on the mountain has slowed in the last few thousand years; however, fumaroles still emit hydrogen sulfide (H_2S) from within crevasses on the summit icecap. These vents are likely remnants of Holocene conduits (Hildreth & Fierstein, 1995). When H_2S-laden vapor seeps up through the thin lava flows and scoriaceous breccias near the summit and glacial headwalls, chemical reactions decompose and alter the surrounding rock, creating surfaces prone to failure (Hildreth & Fierstein, 1997). Rockfall and small debris avalanches can regularly be seen originating from the headwalls of most of Mount Adams' glacial cirques.

Within the last 10,000 years, Mount Adams has produced multiple large debris avalanches and flows from its upper slopes. The largest and most notable postglacial event has been the Trout Lake mudflow, occurring approximately 5.2 ka. Originating from the cirque high on the southwest side, above the present day White Salmon and Avalanche glaciers, the slope failure took nearly 0.07 km^3 (0.02 mi^3) of debris and covered approximately 14 km^2 (3.4 mi^3) of the Trout Lake lowlands. Again in 1921, a debris avalanche originated from this same location and transported 4,000,000 m^3 (141,000,000 ft^3) of hydrothermally altered material, and covered approximately 4 km^2 (1.5 mi^2) of the southwest face with debris (Hildreth & Fierstein, 1997; Scott et al., 1995; Vallance, 1999).

Glaciers and Hydrology

Twelve glaciers currently exist on the slopes of Mount Adams, five of which originate from the summit cap at approximately 3,600 m (11,811 ft) (Figure 1). Ice covers approximately 18 km^2 (6.9 mi^2) of the mountain, having a total volume of approximately 0.7 km^3 (0.17 mi^3), and extends to elevations of 1,994 m (6,541 ft) at their lowest point on the Klickitat glacier. The largest glacier, Adams, drops over 1,615 m (5,300 ft.) and travels approximately 4.2 km (2.6 mi) to the northwest of the summit. Average terminus elevation of all the mountains' glaciers, however, is 2,253 m (7,391 ft).

Drainage from Mount Adams occurs through four major rivers, fed by multiple tributaries originating from its 12 glaciers (Figure 1). The southwest side of the mountain is drained by the White Salmon River, fed by the White Salmon and Avalanche glaciers. The Lewis River on the western flank drains the Pinnacle glacier, along with runoff stemming from the left lateral margin of the Adams Glacier. Several smaller tributaries draining the Adams, Lava, and Lyman glaciers flow northwest and drain into the Cispus River. Little Muddy Creek, Rusk Creek, Big Muddy Creek, and Hellroaring Creek are all tributaries of the Klickitat River that drain the Wilson, Rusk, Klickitat, and Mazama glaciers respectively. Drainage from each of these glaciers eventually turns to the south and drain into the Columbia River (Hildreth & Fierstein, 1997; Vallance, 1999).

Much of the meltwater and precipitation at Mount Adams percolates into the porous surface and interior of the mountain, reemerging at lower on the flanks. This outflow of groundwater typically takes place on the lower lava apron surrounding the mountain, comprised of Quaternary andesite and basalt. More than 100 of these springs have been recorded on the stratocone and lower flanks. One major discharge zone crops up approximately 15 km (9 mi) to the east of Mount Adams along the Klickitat River.

The majority of these springs are relatively cool, with temperatures below 10 °C (50 °F) (Cline, 1976; Hildreth & Fierstein, 1995).

Historic Use

Human use of Mount Adams can be dated back 9,000 years when several Native American tribes used the site for resource gathering, fishing, hunting, and as a permanent settlement location. Although written records of Mount Adams do not appear until the exploration by Lewis and Clark in 1805, Yakama tribal legends explain how the mountain came to be. Originally referred to as Pahto, Mount Adams took what she wanted from the mountains south of her. Pahto brought back wildlife, roots, and berries to be release and be planted in the rivers and fields around her. Wyeast, Mount Hood, fought with Pahto, knocking Pahto's head off, scattering rocks a half-mile north of Mount Adams. The Great Spirit eventually restored Pahto's head with a red eagle and a white eagle with Pahto promising to never have hard feelings toward the other mountains (Clark, 2003).

Mount Adams acquired its current name in the 1830's when Hall J. Kelly proposed to name each major peak in the Cascades after a former President of the United States and have the mountain range renamed the "President's Range." Kelly's intention was to have the name "Adams" placed on the current Mount Hood. Instead, the cartographer misplaced the name in the approximate location of present day Mount Adams is today. Coincidentally, the name Mount Adams stuck in the same location when the Pacific Railroad Survey put that name on their map in 1853 (Thomas, Cowperthwait & Co., 1853).

Early trips to Mount Adams in the late 1800's and early 1900's were made for the purposes of exploration, adventure, research, and mapping. Numerous members of the Mazamas, a mountaineering organization, made the journey from Portland to see the grandeur of the mountain. Professor W.D. Lyman accompanied the group on several occasions, conducting some of the first research, taking measurements, and making notes on the condition of the glaciers. During Lyman's earliest trips, he examined and photographed three glaciers: the White Salmon, Mazama, and Klickitat. Other significant trips to the mountain made by Harry Fielding Reid and Claude Ewing Rusk early in the 20th century added to the growing knowledge of its glaciers. The two traveled to each of the 12 glaciers, taking notes and producing a map of each terminus location (Reid, 1905; Rusk, 1978).

While individuals were visiting Mount Adams for adventure and research, several local sheepherders used the flanks of the mountain for grazing. During a visit in 1902 with the Mazamas, W.D. Lyman noted the vast degradation of land in and around Bird Creek Park on the southeast side of the mountain. In his report, he noted that some 200,000 sheep had been witnessed pasturing on the flanks of the mountain, with more than double that number during peak grazing periods. While Mount Adams had been declared a government reserve in 1897 (Plummer, 1900), laws governing the sheep industry were often violated. Witnessing the changes occurring to the parklands, Lyman noted "To one who saw it twenty years ago it seems sadly degenerate" (Lyman, 1903).

Soon after the creation of the U.S. Forest Service in 1905, President Theodore Roosevelt signed the executive order forming the Columbia National Forest. This was later renamed the Gifford Pinchot National Forest to honor the first chief of the Forest Service. Included in the National Forest were over 60% of Mount Adams and its western flanks. The east side, however, was within the boundaries of the Yakama Indian Reservation, set aside by the Treaty of 1855. With these two entities governing the use of the area, Mount Adams has been protected from excessive and damaging uses.

Despite the fact that Mount Adams has been under the protection of the Forest Service and the Yakama Indian Nation for over 100 years, human use at the site has still had impacts. As a result of the Yacolt Fire of 1902, the state's largest fire in recorded history, the Forest Service constructed the highest fire lookout in the country on Mount Adams summit. The lookout proved to be unsuccessful and was only staffed through 1924 (McCoy, 1987). In addition to the constructed lookout, the Glacier Mining Company was granted a mining claim in 1929 to obtain sulfur at the summit. The company explored the crater for several years until the operation stopped in the mid-1930s. During the few short years that the mining operation was in business, 168 pack trips were made to the summit with the support of mules and horses. Ultimately, little progress was made and their claim expired in 1959 (McCoy, 1987).

As part of the Wilderness Act of 1964, the Mount Adams Wilderness Area was created within the National Forest, encompassing 46,353 acres (18,758 ha) of land surrounding the mountain, not including lands within the Yakama Indian Reservation. This Act was established to further manage human-caused impacts to the area in order to protect the wilderness character for the future use and enjoyment of others. Specifically, restrictions were placed on motorized equipment, stock use, and campsite locations, as well as creating a mandatory permit system for entry into the wilderness (Wilderness Act, 1964).

Since the passage of the Wilderness Act, Mount Adams has maintained its pristine nature. Hiking and climbing in the area continue to be the most popular activities today with over 100 miles (161 km) of trails on the flanks of the mountain. Presently, over 4,000 permits are issued each year to individuals attempting to climb the mountain (USDA Forest Service, 2006).

CHAPTER IV

METHODS

To accomplish the objectives of this research, three steps were taken: 1) historic air photos were assessed, along with satellite imagery and on-site terminus measurements to determine glacier terminus fluctuations from 1900-2005; 2) historical and present climate within the study area was evaluated in terms of seasonal magnitude of temperature and precipitation to determine correlations with terminus fluctuations; and 3) streamflow measurements were collected to determine the effects of glacier meltwater on streamflow.

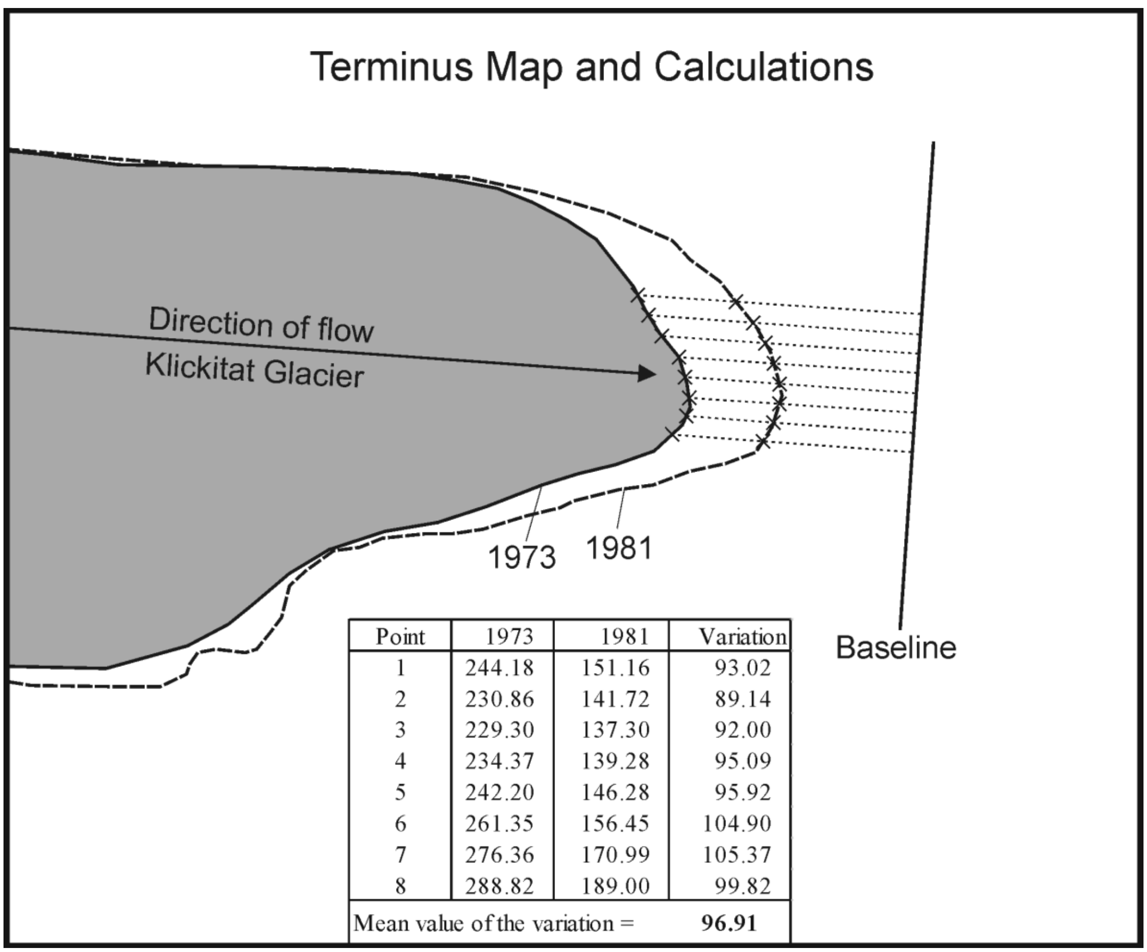
Step 1 - Glacier Terminus Measurements

Initial assessment of historic fluctuations of Mount Adam's glacier termini was accomplished with repeat air photos obtained from Central Washington University Geography Department in Ellensburg, WA, and the Mazamas office in Portland, Oregon. Seven sets of 1:12,000 – 1:24,000-scale vertical air photos were acquired from Central Washington University's Geography Department, from 1949, 1958/1959, 1967, 1973, 1981, 1994, and 2000, along with 1 m (3 ft) resolution 2003 orthophotos from the U.S.G.S.

All air photos were then scanned at 900 dpi, rectified, and georeferenced to the 2003 USGS orthophotos using ArcGIS 9.1 software. A minimum of 20 control points were applied to each rectification using a third-order polynomial model. To achieve this number, approximately 30 to 40 control points were initially selected, removing anything with a residual greater than 10 root mean square error (RMSE) (Hughes, McDowell, & Marcus, 2006). As a result of the high relief of the study area, a significant amount of distortion was involved. The acceptable RMSE limit was therefore set at 10.

After each of the air photos were georectified, terminus position maps were created in ArcGIS. Construction of the terminus map consisted of overlaying the air photos onto the 2003 orthophoto and digitizing glacial extents and termini for each year of record. Precise location of the termini from aerial photographs was often difficult to identify as a result of cloud cover in 1949, late-lying or perennial snow-covered areas, and significant debris cover over a majority of the glaciers. A glacier whose terminus is covered with debris is often indistinguishable from proglacial till and morainal material. Differentiation between an active terminus and stagnant ice or ice-cored morainal material is also essential for avoiding erroneous conclusions of terminus activity. Criteria used to determine the termini location included: 1) having a distinct lobate form, 2) abrupt change in relief, 3) soil/debris color change between wet and dry, 4) having active glaciation upslope (i.e. movement/crevassing), and 5) terminus visibly connected to the accumulation area (Lillquist & Walker, 2006).

With glacial extents and terminus positions digitized, changes in length of 10 glaciers were measured between periods of record. Two glaciers, Avalanche and White Salmon, were intentionally left out of this process because the 1921 debris avalanche and continued rockfall onto these glaciers left their termini indistinguishable. Massive quantities of rock and debris now cover the majority of the ablation zones of each glacier. Measurements for the remaining ten glaciers were taken to the general specifications laid out during the International Hydrological Decade and set forth by the World Glacier Monitoring Commission (Kasser, 1967). This methodology calculates an average change over the entire terminus, rather than just the most down valley extent of ice or the point at which a glacial stream emerges. This procedure calls for reference points to be set on the earliest photos within 100 meters (328 ft) of the glacier termini (Figure 10). Measurements of distance between the reference points and the glacier front are made parallel to one another and at a given azimuth perpendicular to the glacier terminus. The same reference points are then used for each successive set of aerial photos with distances



Point	1973	1981	Variation
1	244.18	151.16	93.02
2	230.86	141.72	89.14
3	229.30	137.30	92.00
4	234.37	139.28	95.09
5	242.20	146.28	95.92
6	261.35	156.45	104.90
7	276.36	170.99	105.37
8	288.82	189.00	99.82
Mean value of the variation =		**96.91**	

Figure 10. Terminus map created using modified parameters set by the World Glacier Monitoring Commission.

recorded. The mean value of the variation is then calculated referring to the horizontal change in distance (Kasser, 1967).

Additionally, historic documents, oblique air photos, and ground photos were obtained from the Mazamas in Portland, Oregon. While not accurate within an acceptable amount of error for use in statistical evaluation of glacier change, historic documentation was used in determining approximate locations of 1901 termini.

A global positioning system (GPS) survey was conducted in the summer of 2006. Each glacier was visited, taking GPS measurements using a Trimble GeoXM for terminus locations and prominent features to be used as control points for georeferencing.

Step 2 - Glacier Climate Relationships

Climate data was obtained from the Natural Resources Conservation Service (NRCS) in cooperation with the Spatial Climate Analysis Service (SCAS) in the form of a GIS Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset. This model utilizes a multitude of geographic datasets to generate gridded data sets of monthly estimates of climatic parameters such as precipitation, temperature, and snowfall back to 1895. The high resolution (800 m x 800 m) grid cell was chosen that surrounds Mount Adams' summit (Lat: 46.202, Long: -121.491). Monthly gridded data of temperature and precipitation was then separated into a water-year format, Oct 1 – Sept 30.

Relationships between the terminus position of Mount Adams' glaciers and climate were assessed through a variety of statistical measures. A 5-year running average of temperature and precipitation was calculated for each year to reveal general climate patterns at Mount Adams and compare with terminus positions. A Spearman Rank test was then applied to test significant correlations between each of Mount Adams' cumulative terminus position records. Spearman Rank was additionally used to test terminus fluctuations with the monthly gridded climate data such as average monthly temperature (Tavg), minimum monthly temperature (Tmin), maximum monthly temperature (Tmax), and monthly precipitation (Ppt). Other parameters tested include: accumulation and ablation season temperatures (Tavg, Tmin, Tmax), accumulation and ablation season precipitation, and mean monthly deviations for temperature and precipitation. Each test was conducted using a significance value of 0.05 (Figure 11)(Harper, 1993; Lillquist & Walker, 2006).

To utilize a Spearman rank correlation, temperature and precipitation data were collapsed into single points to facilitate the rank ordering of data. This was accomplished by using the 10-year mean previous to the corresponding air photo date. Spearman rank was also used to test values between terminus fluctuations by using the mean value of temperature or precipitation since the previous period of record.

Each parameter tested was then tested again, readjusting for varying lag times associated with terminus advance and retreat. The time required for a small alpine glacier to respond to climatic events or broad shifts can vary, and will be unique for each glacier. This initial reaction time has typically been shown to be <16 years for glaciers of the Cascade Range (Harper, 1993; Pelto & Hedlund, 2001). With the air photo record at Mount Adams only occurring once per decade, precise lag times are difficult to determine. As a result, all parameters were checked at multiple lag times including: 0 lag

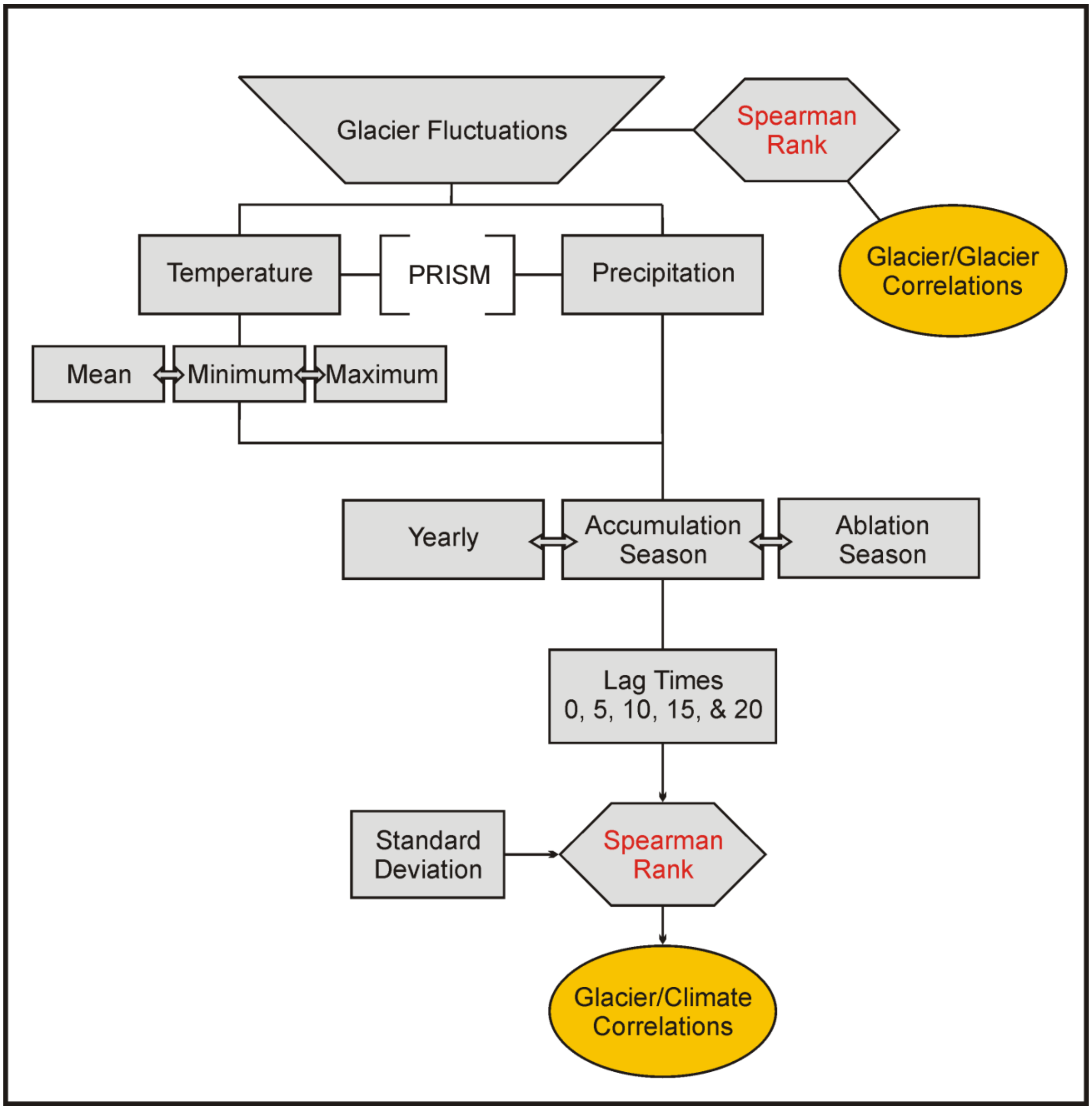


Figure 11. Flowchart of correlation tests based on glacier-climate fluctuations.

(terminus response occurring the first year after a climate shift or event), 5 years, 10 years, 15 years, and 20 years. Lastly, a standard deviation of the 105-year mean was calculated to determine any considerable outliers within the data set.

In addition to testing for correlations with climate, terminus fluctuations were qualitatively analyzed to determine relationships with local factors such as aspect, source area, subglacial topography, and debris cover. Similarities between glacier terminus advance and retreat, for time periods such as PDO phases and the air photo record, were examined for comparable or similar local characteristics.

Step 3 – Glacier Runoff Measurements

Streamflow was obtained in close proximity to glacier termini from stream gauges of the Hydroclimatic Data Network (U.S.G.S.). These datasets contain daily streamflow observations that are considered to be relatively unaffected by anthropogenic influences and land-use changes. Draining four glaciers on the eastern flanks of Mount Adams, the Klickitat River was analyzed for two trends. First, monthly and seasonal flows were defined as their percentage of the streamflow in that month or season to the total streamflow in the water year. Rates were then checked to determine if any linear trends were visible in the annual and monthly maximum flows.

Secondly, changes to streamflow timing was calculated by first determining the date on which 50% of the water-year flow was equaled or exceeded (Julian day) for each of the recorded years. The presence of linear trends was analyzed to determine if the seasonality of peak spring flow was changing. These types of analyses have been used several times in the Pacific Northwest to determine timing and magnitude variations in streamflow over broad regions (Regonda et al., 2005; Stewart et al., 2005).

CHAPTER V

RESULTS AND DISCUSSION

Glacier Terminus Results

In the following pages, I will describe results of each of the 10 glaciers studied on Mount Adams in a counterclockwise approach beginning with Klickitat Glacier. Based on 2006 records, results of each glacier include details on horizontal length, width, accumulation zone, and terminus elevation, and historic terminus change (Tables 2 & 3) (Figure 12). Additionally, historic descriptions of each glacier are given based on written records, ground photographs, and Reid's 1906 map.

Klickitat Glacier

The Klickitat Glacier originates high on the eastern edge of Suksdorf Ridge between Pikers Peak and Mount Adams' summit cap (Figure 1). Bound on the north edge by the steep Battlement Ridge, the Klickitat Glacier flows over 3.3 km (2 mi) to the east, draining into the headwaters of the Big Muddy River. Steep, unconsolidated andesite deposits surrounding the summit icecap often break loose from the glacial headwalls of the Klickitat Glacier. This rock can be seen and heard daily falling from the upper accumulation zone, frequently causing debris avalanches. Currently, debris covers over 90% of the lowest 1,600 m (5,249 ft) of the Klickitat Glacier.

As a result of the heavy debris cover, terminus positions from air photo records can easily be confused with proglacial till and moraine. Visiting the Klickitat Glacier in

Table 2

Terminus Position Change (meters) of Mount Adams' Glaciers Based on Previous Period of Record.

	Year							
Glacier	1949	1959	1967	1973	1981	1994	2000	2003
Klickitat	0	42	233	34	97	5	-22	-12
Rusk	N/A	0	212	73	153	166	-7	8
Wilson	0	-95	58	19	29	28	21	4
Lyman	N/A	0	-96	-2	11	29	-45	-20
Lava	N/A	0	-208	54	81	-34	6	-29
Adams	N/A	0	48	-3	-2	-24	-22	3
Pinnacle	0	-1	27	9	-30	13	19	-29
Crescent	0	-27	24	-6	-19	25	-6	-8
Gotchen	0	-42	62	-68	39	68	-98	-108
Mazama	N/A	0	38	42	-10	-2	8	-69

Table 3

Cumulative Terminus Position Change (meters) of Mount Adams' Glaciers Based on 1949 Dataset Where Applicable.

	Year							
Glacier	1949	1959	1967	1973	1981	1994	2000	2003
Klickitat	0	42	275	309	406	411	389	377
Rusk	0	0	212	284	437	603	597	605
Wilson	0	-95	-37	-17	12	40	61	65
Lyman	0	0	-96	-98	-87	-59	-104	-124
Lava	0	0	-208	-154	-72	-106	-100	-129
Adams	0	0	48	45	43	19	-2	1
Pinnacle	0	-1	26	34	5	18	37	8
Crescent	0	-27	-3	-9	-29	-4	-10	-18
Gotchen	0	-42	20	-48	-8	60	-38	-147
Mazama	0	0	38	80	70	68	75	6

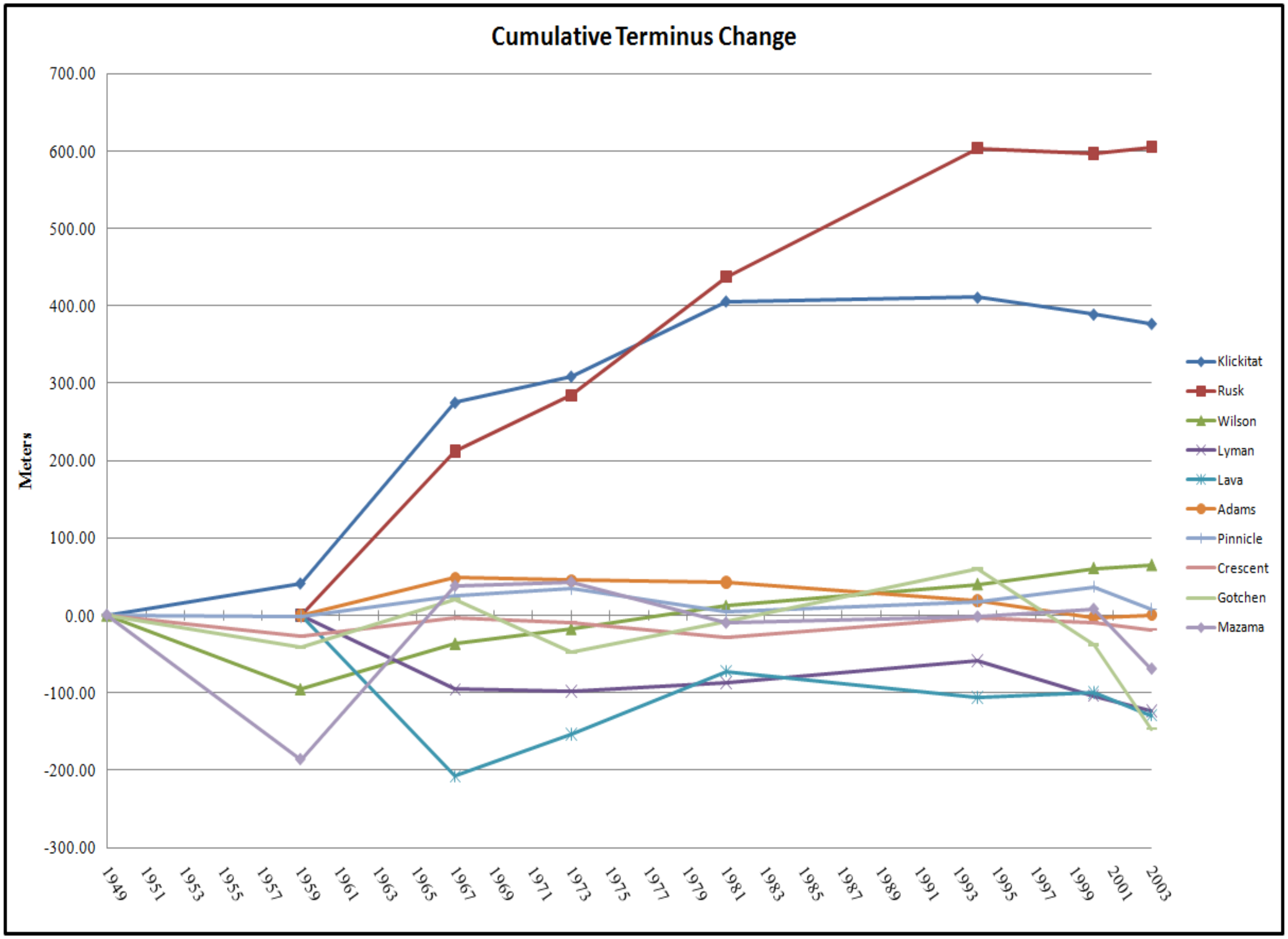


Figure 12. Mount Adams cumulative terminus change, 1949 -2003.

1895, Prof. W.D. Lyman made notes on the glacier, stating it was “three miles long” with a terminus “indistinguishable from the terminal moraine” (Lyman, 1896). In 1901, Harry Fielding Reid visited Mount Adams with C.E. Rusk, recording the length of the glacier to be “about three and a half kilometers” (1906). During their trip, the lower half of the glacier was said to be covered with several moraines, brought down from the cliffs above. In his report to the Mazamas, Reid also made note of the extent of debris cover stating “so much covered, indeed, with debris that we could not determine from a short distance where the ice ends. It [debris cover] is about a mile long” (1905).

During C.E. Rusk’s circuit of Mount Adams in 1890, he noted “the Klickitat Glacier ended close against the great south wall of the canyon, and here was the source of the Big Muddy” (Rusk, 1978). The terminus of the glacier during this trip approached the ridge obliquely, stopping just short of the 1,000 ft (305 m) ridge on the south. The thickness of the terminus was measured to be approximately 12-15 m (40-50 ft) thick, but increased to a depth up to 91 m (300 ft) a short ways upglacier (Rusk, 1978). Written records and maps drawn by Harry Fielding Reid in 1906, place the Klickitat Glacier’s terminus at an elevation of approximately 1,829 m (6,000 ft)(Figure 13 & 14), further confirming Rusk’s observations. A moraine currently exists just below this point at an elevation of 1,768 m (5,800 ft), validating early 20th century positions.

With the end of the LIA, regional warming trends brought about a significant recession of the Klickitat Glacier. During Rusk’s last trip to the Klickitat Glacier in 1921, he noted that the terminus had retreated at least a quarter mile (~400 m). Additionally, the glacier had retreated far back from the southern wall it had once come in contact with

(Rusk, 1978). Air photo records for 1949 show an indistinguishable terminus position, resulting from cloud cover, late lying perennial snow, and heavy debris cover. While the terminus position for this year may be hazy, a glacial stream can be seen emerging at an elevation of 1,981 m (6,500 feet)(Figure 13), giving a rough estimate of a location. That being the case, warming since the LIA brought a little over 1,000 m (3,281 ft) of

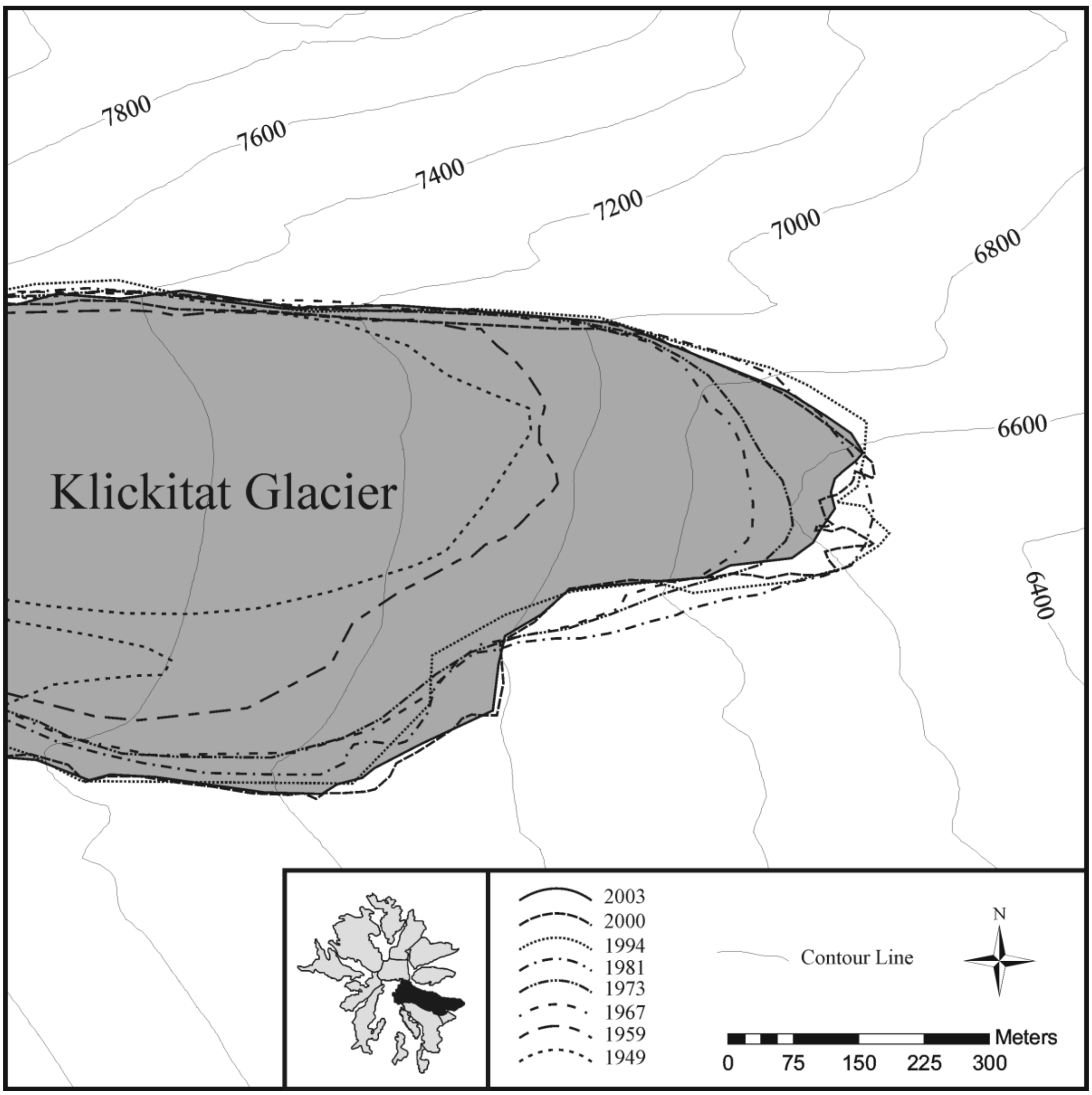


Figure 13. Klickitat Glacier termini changes 1949-2003.

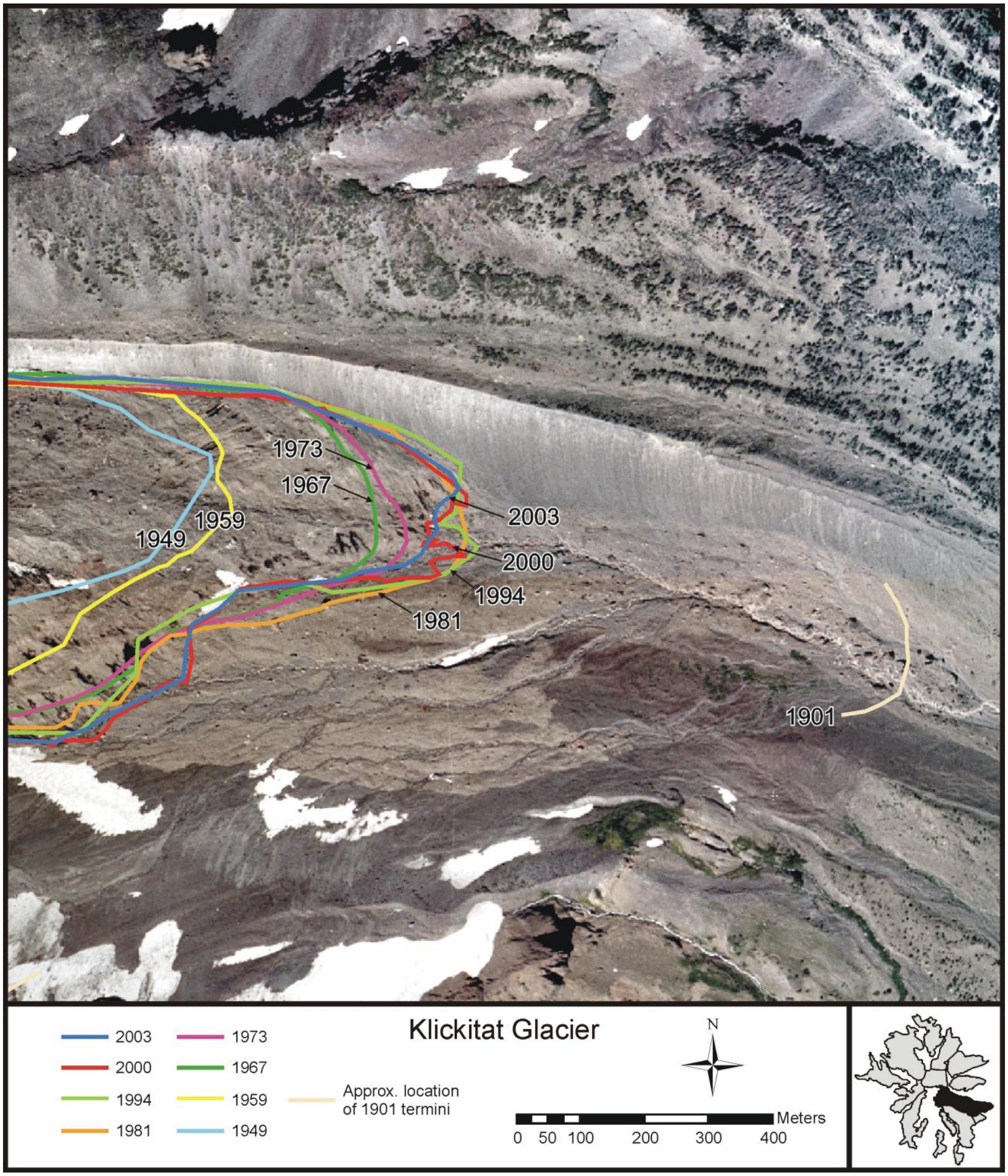


Figure 14. Orthophoto of Klickitat Glacier (2003) shown with historic terminus positions.

retreat since the late 19th century. During the 1949-1959 period, the glacier continued its retreat from the point at which the stream emerged in 1949, to a position another 390 m (1,280 ft) upslope (Figure 9). Klickitat Glacier reversed its trend and advanced 369 m (1,211 ft) from 1959 through at least 1994 with the largest advance occurring between 1959 and 1967 with an advance of 233 m (732 ft). Following this advance, Klickitat Glacier has been in slow retreat, receding 34 m (112 ft) from 1994 to 2003. As of 2006, the terminus of Klickitat Glacier sits at an elevation of 2,008 m (6,587 ft) with a total cumulative advance of 377 m (1,236 ft) since 1949 (Figure 12)(Table 2 & 3).

Rusk Glacier

North of the Klickitat Glacier and directly east of Mount Adams' summit lies the Rusk Glacier, bounded by Battlement Ridge to the south and Victory Ridge to the North (Figure 1). The Rusk Glacier originates high in a cirque directly below the Roosevelt Cliffs, gaining much of its accumulation from avalanches off the summit cap. The unstable nature of the Roosevelt Cliff and surrounding ridges deposit large quantities of rocky debris onto the surface of the glacier, completely covering the lowest 1,000 m (3,281 ft).

The Rusk Glacier was visited as early as 1895 by W.E. Lyman and then again in 1901 by Reid and Rusk, accompanied by the Mazamas. Early reports by these explorers described the terminus as located just below the 7,000 ft (2,134 m) level with an overall length of 1.75 km (1.09 mi) (Lyman, 1896; Reid, 1905; Reid, 1906). A map of the glacier by Reid (1906) also depicts debris cover completely covering the glacier below the 8,000 ft (2,438 m) level. Air photos from each year of record since 1959 additionally show a heavy debris cover beginning at that same general elevation. Similar to the Klickitat Glacier, unconsolidated andesite deposits of the Roosevelt Cliff and the steep confining ridges deposit large quantities of debris onto the surface of the glacier. This debris resurfaces in the ablation zone, considerably slowing the rate of melt.

Using the descriptions of the Rusk Glacier terminus made by Reid and Lyman at the turn of the century, the Rusk Glacier extended over 2.7 km (1.7 mi) downslope to an elevation of 2,103 m (6,900 ft). A prominent left lateral moraine still exists at this position. Since these early observations, the Rusk Glacier retreated. This trend continued through 1959 at the latest, when the glacier retreated over 800 m (2,625 ft) to an elevation of 2,316 m (7,600 ft). This trend may have ended earlier; however cloud cover, late lying perennial snow patches, and heavy debris cover in the air photo record for 1949 obscure the view of the glacier. As a result, a clear determination of the terminus position could not be made. It should be noted, however, that there is no visible relief change, lobate form, or active glaciation in the 1949 air photo at the point where the glacier terminates in 1959. This suggests that the retreat to 1949 was greater than what can be observed on the air photos. By 1959, the retreat had ended and the Rusk Glacier went into a phase of advance for the next several decades. By 1994 the glacier had advanced a total of 603 m (1,978 ft), with the largest advance occurring between 1959 and 1967 when the glacier advanced 212 m (696 ft) (Figure 15 & 16). This period of rapid growth ended in 1994, but has not shown a trend in either direction since. A small retreat of 7 m (23 ft) occurred between 1994 and 2000, but again advanced 8 m (26 ft) by 2003. As of 2006, Rusk

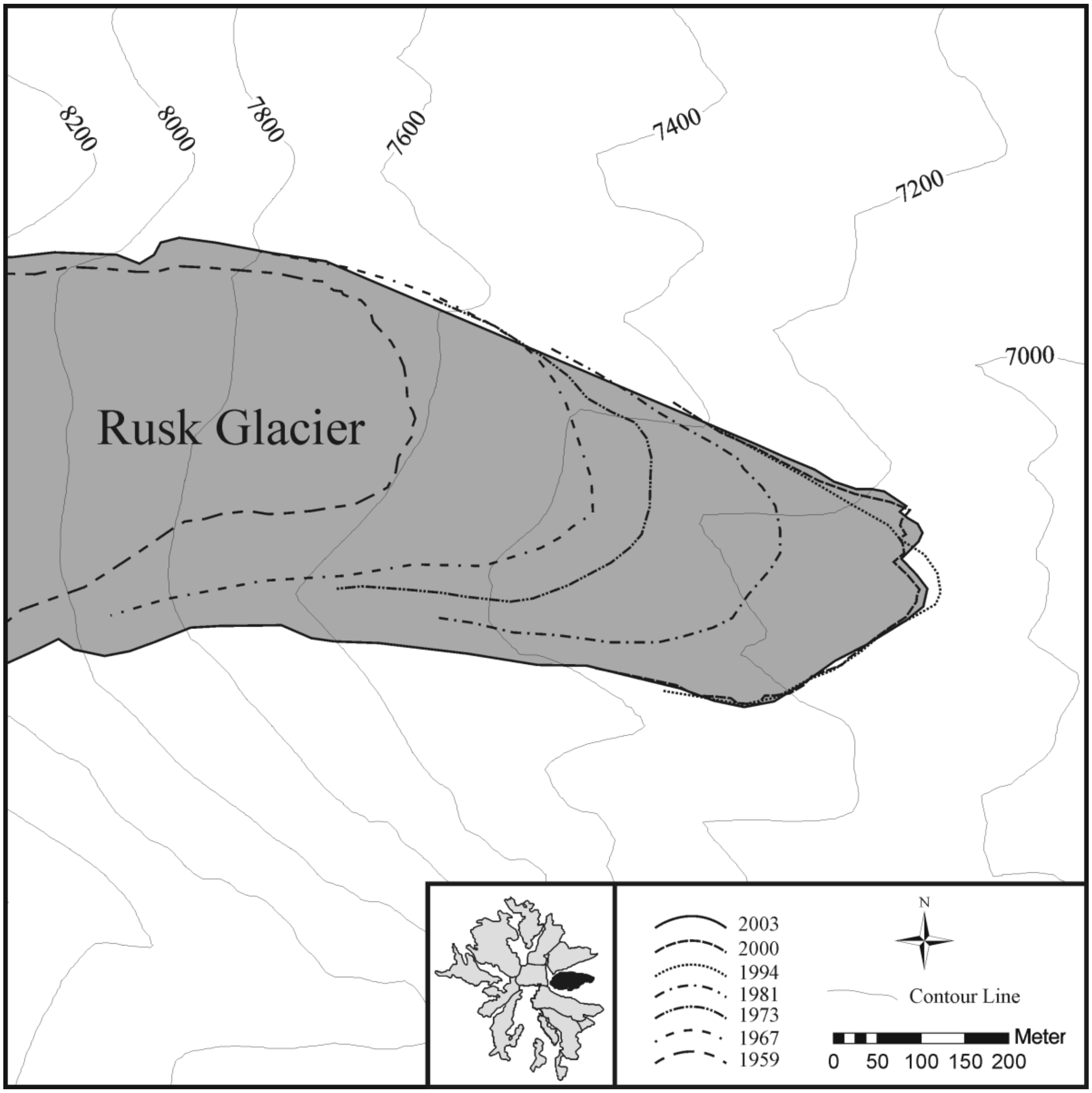


Figure 15. Rusk Glacier termini changes 1949-2003.

Glacier's terminus has advanced 605 m (1,984 ft) since 1959. It is currently located at an approximate elevation of 2,161 m (7,090 ft) elevation, only slightly upslope from the documented position in 1895 (Figure 12)(Table 2 & 3).

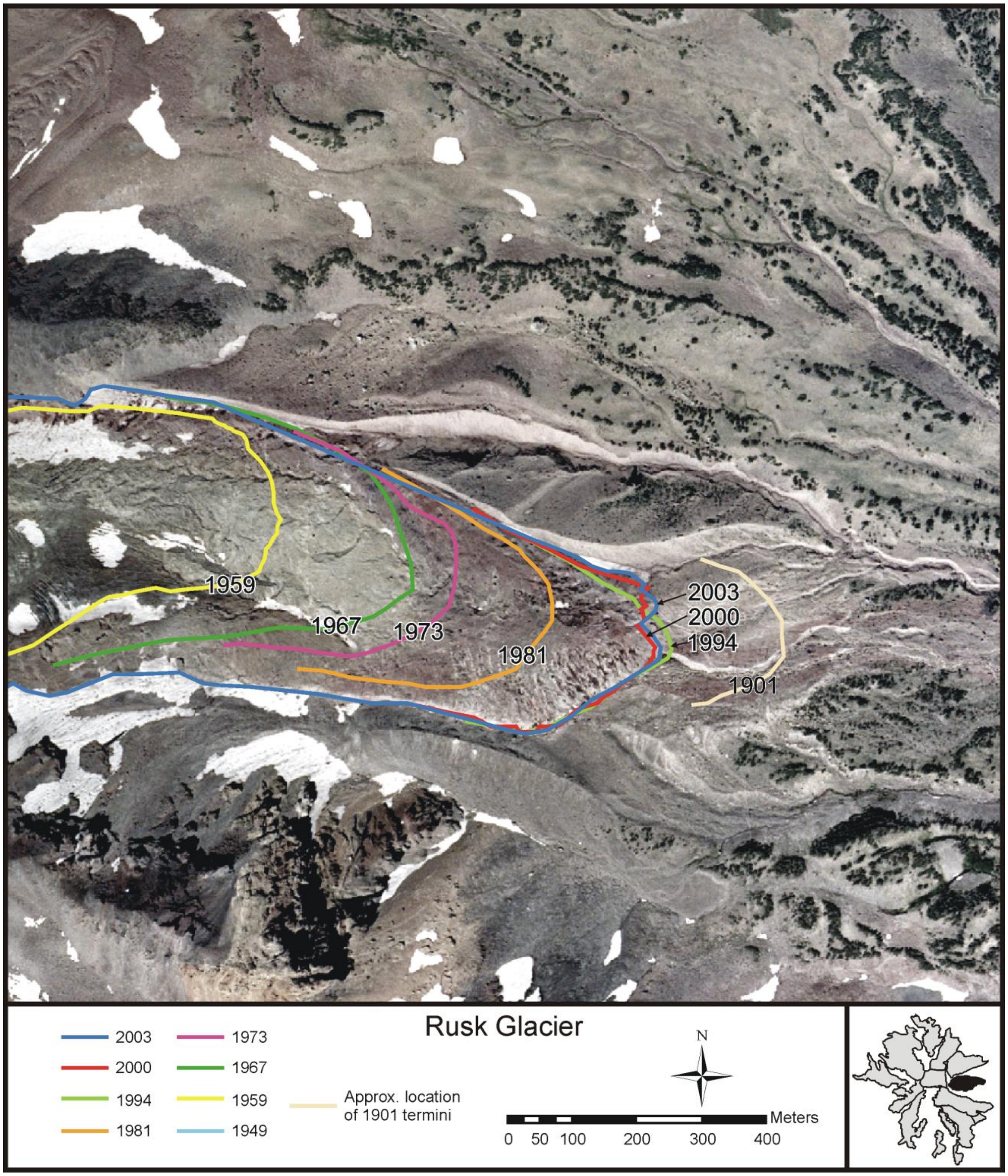


Figure 16. Orthophoto of Rusk Glacier (2003) shown with historic termini positions.

Wilson Glacier

Wilson Glacier originates northeast of Mount Adams' summit cap in a cirque below the Roosevelt Cliff. The glacier is right laterally bound on the south by Victory Ridge, but unconfined on the northern edge, spilling over into the Lyman Glacier. Similar to the Rusk Glacier, much of the accumulation is seen in avalanches off the summit cap. It extends approximately 2.2 km (1.4 mi) northeast within the boundary of the Yakama Indian Reservation, ending approximately 600 m (1,969 ft) above timberline at an elevation of 2,290 m (7,513 ft). The unconsolidated andesite structure of Roosevelt Cliff deposits substantial amounts of debris into the accumulation zone of Wilson Glacier, reemerging in the ablation zone. Currently, the lowest 1 km (0.6 mi) of the glacier is completely debris covered.

Observations and documentation of Wilson Glacier dating back to the early 20th century and late 19th century are limited. Studying Mount Adams' glaciers during his early trips, C. E. Rusk often bypassed the Wilson Glacier, commenting only of its location and unnamed status (Rusk, 1978). During the 1901 expedition to the mountain, in the company of C. E. Rusk, H. F. Reid (1905) only stated, "To the south of the Lyman glacier is another small glacier which has not been named and is not very important." In a separate report made by Reid the following year, the "unnamed glacier" was formally called the "Little Muddy Glacier," in reference to the glacial stream formed below. Terminus observations of the Wilson Glacier (Little Muddy) only indicate that it was significantly debris covered and somewhat smaller than the Rusk Glacier to the South (Reid, 1906).

A map of the glacier by Reid (1906) indicates the terminus was at approximately 2,301 m (7,550 ft) in 1901. Using the early descriptions of Wilson Glacier and the map created by Reid, the 1901 terminus was approximately 30 m (98 ft) upslope from its current position in 2006 (Figure 17 & 18). Despite regional warming trends following the

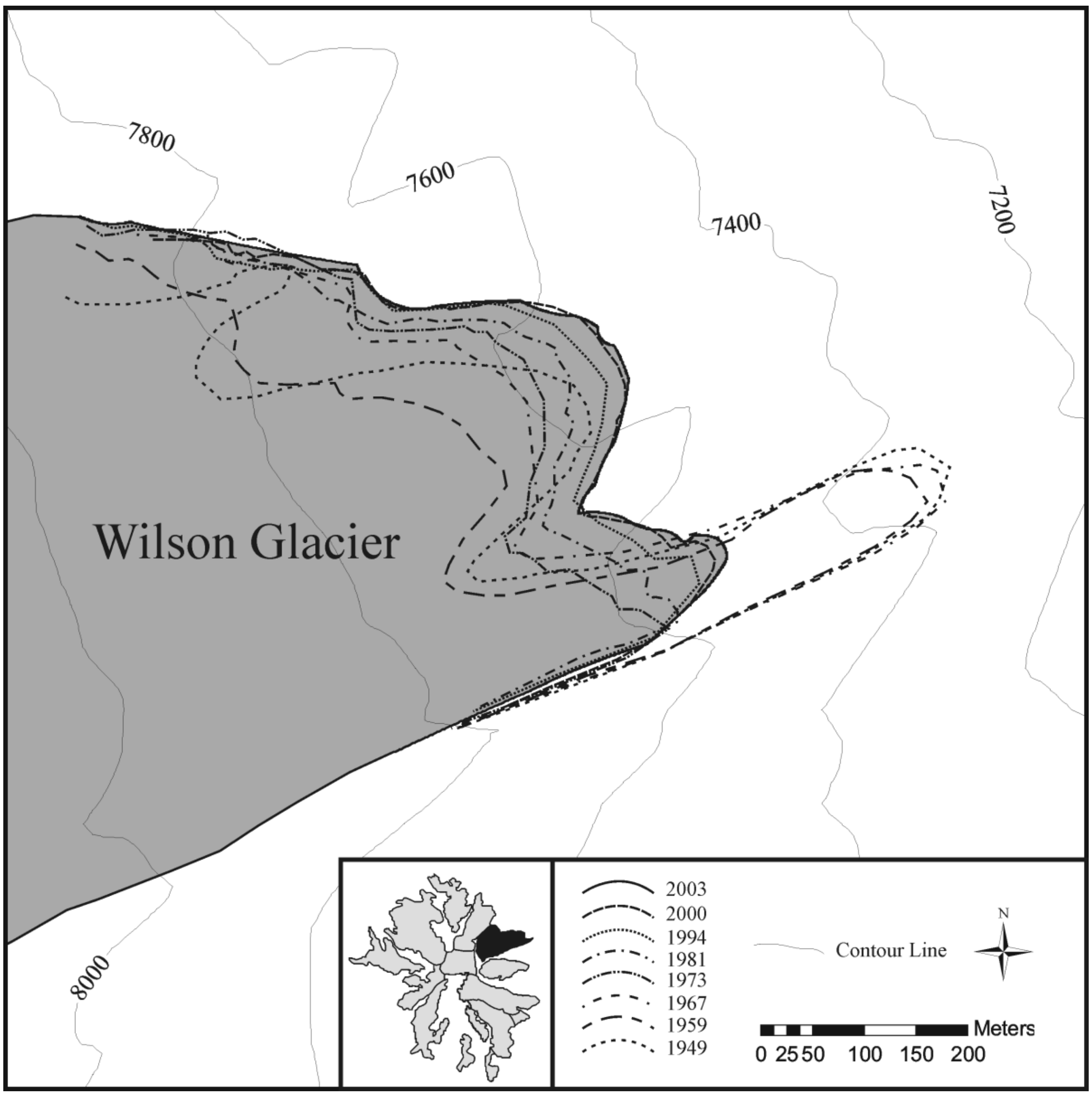


Figure 17. Wilson Glacier termini changes 1949-2003.

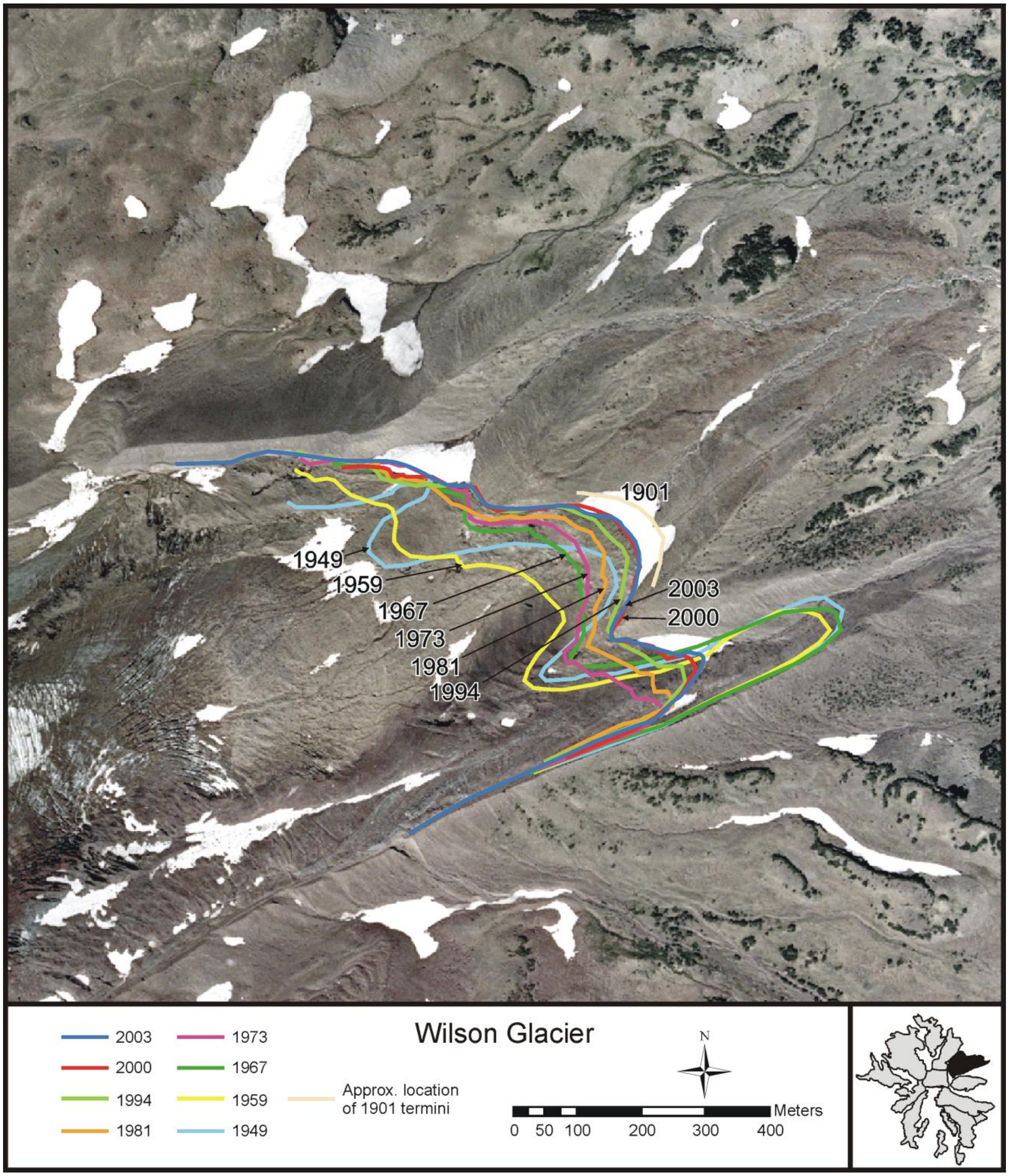


Figure 18. Orthophoto of Wilson Glacier (2003) shown with historic termini positions.

LIA, Wilson Glacier showed no significant change in its terminus position through 1949. By 1959, however, the terminus retreated 94 m (308 ft) to its furthest point upslope since the turn of the 20th century. This short-lived retreat reversed itself and by 1967 the Wilson Glacier began advancing again. This period of advance continued through the rest of the century. By 2003, Wilson Glacier advanced a total of 159 m (522 ft) with the largest advance (58 m) occurring between 1959 and 1967. While this positive growth of the glacier has continued through the present, the rate of advance has begun to slow down. As of 2006, the terminus of Wilson Glacier sits at an elevation of 2,290 m (7,513 ft) (Figure 12)(Table 2 & 3).

Lyman Glacier

Lyman Glacier originates directly from the northern edge of Mount Adams' summit cap and flows approximately 2.3 km (1.4 mi) to the north (Figure 1). The upper reaches of the glacier flow down through several steep andesitic cleavers, forming two distinct couloirs with a third flow spilling over from the Wilson Glacier to the southeast. The ablation zone is confined on the east by the andesitic flows of the Devils Garden shield which rises approximately 100 m (328 ft) above the glacial surface (Hildreth & Fierstein, 1995). A sharply crested left-lateral moraine extends down the lower western edge of the glacier, confining it to its present day location. While much of the glacier surface above 2,438 m (8,000 ft) is clean, rockfall from the steep cliffs and unstable cleavers above supply an ample amount of material to cover much of the ablation zone. Currently, the lowest 600 m (1,969 ft) of glacier surface is debris covered.

First visited by C. E. Rusk in 1890 during his circuit of Mount Adams, Lyman glacier was only briefly observed by Rusk, making note of its steep ice falls and sharp cleavers. The northern side of Mount Adams was said to present “an aspect of stupendous Alpine grandeur” (Rusk, 1978). Lyman Glacier was later named during a mapping exploration trip made by Rusk and Reid in 1901. Rusk requested that the glacier be named after W. D. Lyman, a Professor of History at Whitman College in Walla Walla for being one of the earliest researchers of Mount Adams (Rusk, 1978). During the same trip, Reid observed the Lyman Glacier’s terminus area, noting specifically the extensive moraines extending great distances from where the ice spread out on the gentle slopes below the steep projecting ridges. Neither Reid nor Rusk was able to determine the exact location of the terminus as a result of the great quantity of snow persisting late into the summer that year (Reid, 1906).

The position of Lyman Glacier’s terminus in 1901 can be roughly estimated by the map created by Reid. While it was suggested in both Reid and Rusk’s reports that the terminus could not be identified, Reid’s description and drawing indicate it to be in the general vicinity of where the terminus can be clearly identified in the 1959 air photo. Although this location is not entirely accurate, the width of the glacier is shown to extend from one side of the valley to the other, much greater than in the recent air photo record (Reid, 1906). Furthermore, the uncertainty in Lyman Glacier’s terminus position is not clarified with the emergence of the air photo record in 1949. Late-lying, perennial snow masks the location at that time. Not until 1959 can the position of Lyman Glacier’s terminus be identified (Figure 19 & 20), showing itself to be considerably less in width than the early 20th century observations. Since 1959, the terminus has alternated between periods of advance and retreat several times. Between 1959 and 1973, Lyman Glacier retreated 98 m (322 ft), with the majority of that (96 m) occurring between 1959 and

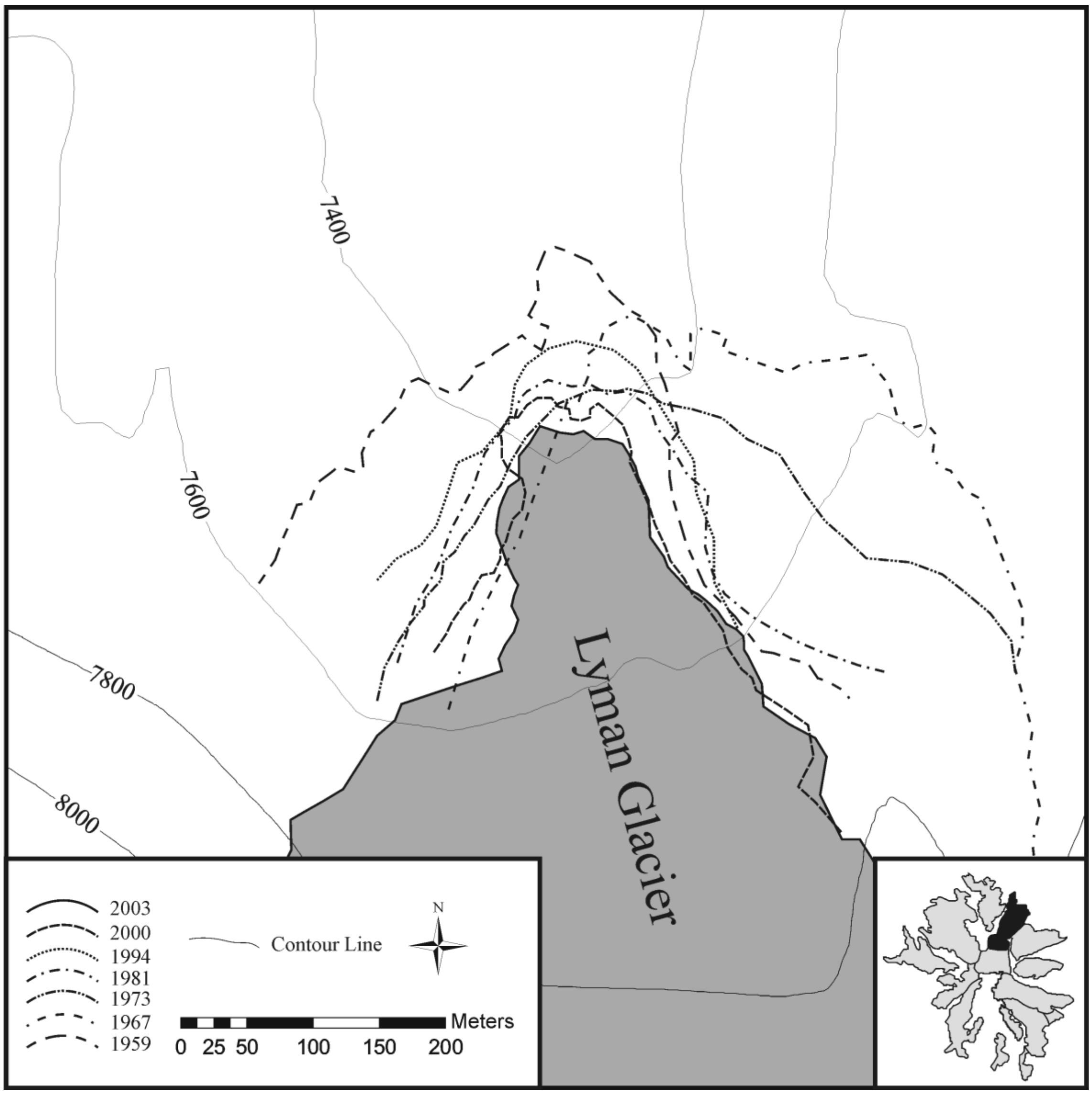


Figure 19. Lyman Glacier termini changes 1949-2003.

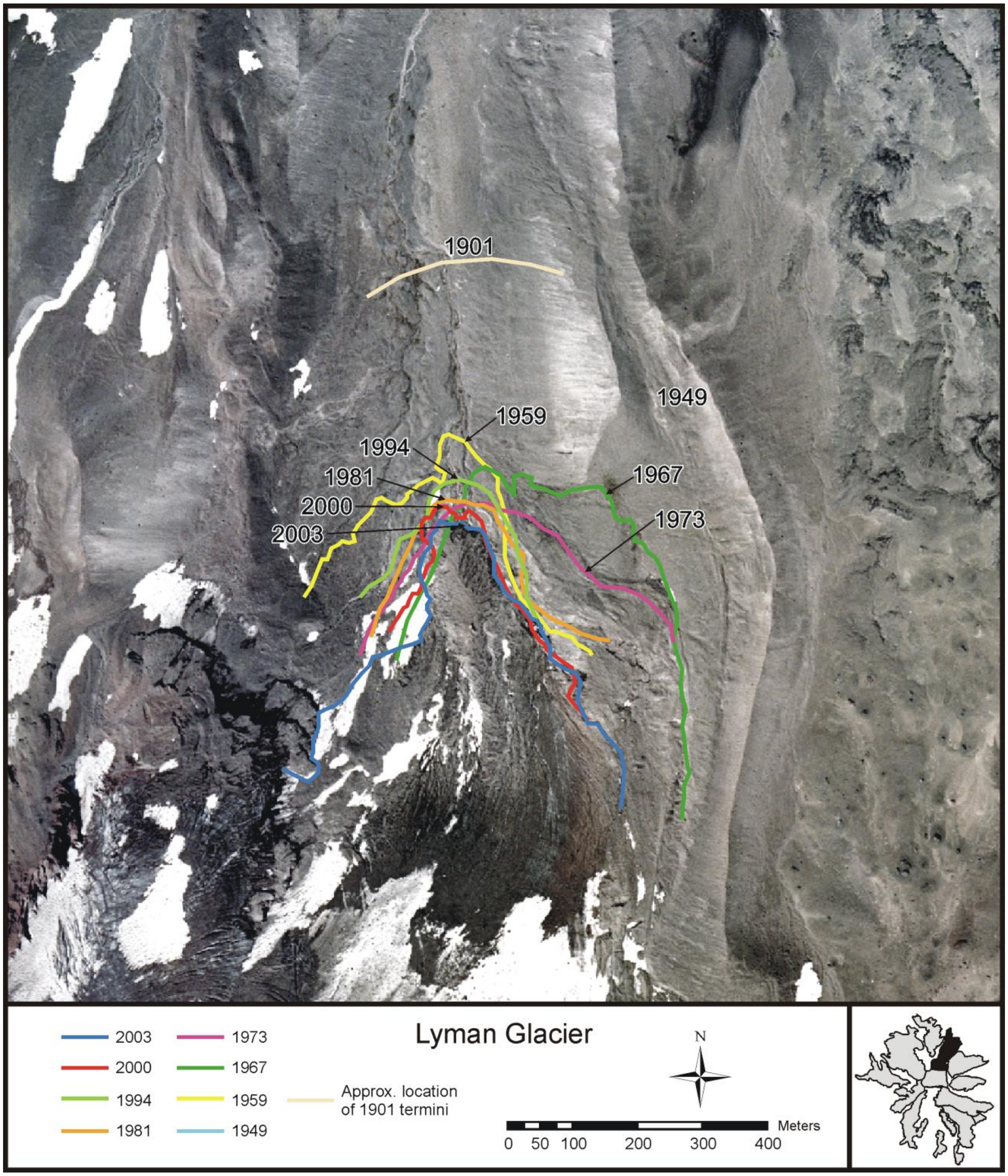


Figure 20. Orthophoto of Lyman Glacier (2003) shown with historic termini positions.

1967. Following this period, Lyman Glacier advanced 39 m (128 ft) between 1973. Since 1994, Lyman Glacier has again gone into a period of retreat, receding 65 m (213 ft) by 2003. As of 2003, the terminus of Lyman Glacier has had a cumulative retreat of 124 m (407 ft) since 1959, now positioned at an elevation of 2,245 m (7,365 ft) (Figure 12) (Table 2 & 3).

Lava Glacier

Lava Glacier originates high in a steep cirque on the north face of Mount Adams just west of Lyman Glacier, flowing 1.7 km (1 mi) to the north (Figure 1). Unlike the Lyman Glacier, most of the accumulation occurs through snow drift and snow directly deposited onto the upper regions of the glacier. The accumulation zone of Lava Glacier is bounded on the western edge by North Cleaver and by another unnamed cleaver on the east, additionally separating it from Lyman Glacier. With over 300 m (984 ft) of steep unstable headwall above Lava Glacier, ample amounts of debris are deposited within the accumulation zone. The heavily debris-covered terminus of Lava Glacier currently sits at an elevation of 2,312 m (7,585 ft) with the lowest 500 m (1,640 ft) being covered by approximately 75% debris.

Early records of Lava Glacier generally begin with visits by C.E. Rusk in 1890, and again later in 1901 accompanied by H.F. Reid. Most accounts of the glacier are brief and have little in terms of a clear description. Despite the lack of a detailed written description of Lava Glacier’s terminus, Reid spent some time mapping it. Estimates of the terminus position in 1901 locate it at approximately 2,072 m (6,800 ft) elevation, well below its present day location (Figure 21 & 22). The most notable of these early records state that Lava Glacier had a relatively low accumulation zone, approximately 2,750 m (9,022 ft), with the terminus being debris-covered and surrounded by large moraines (Reid, 1906). Currently a large, steeply crested, left lateral moraine exists directly at this elevation, rising approximately 50 m (164 ft) high. Additionally, multiple smaller ice-cored moraines can be found between this early documented terminus location and Lava Glacier's current position.

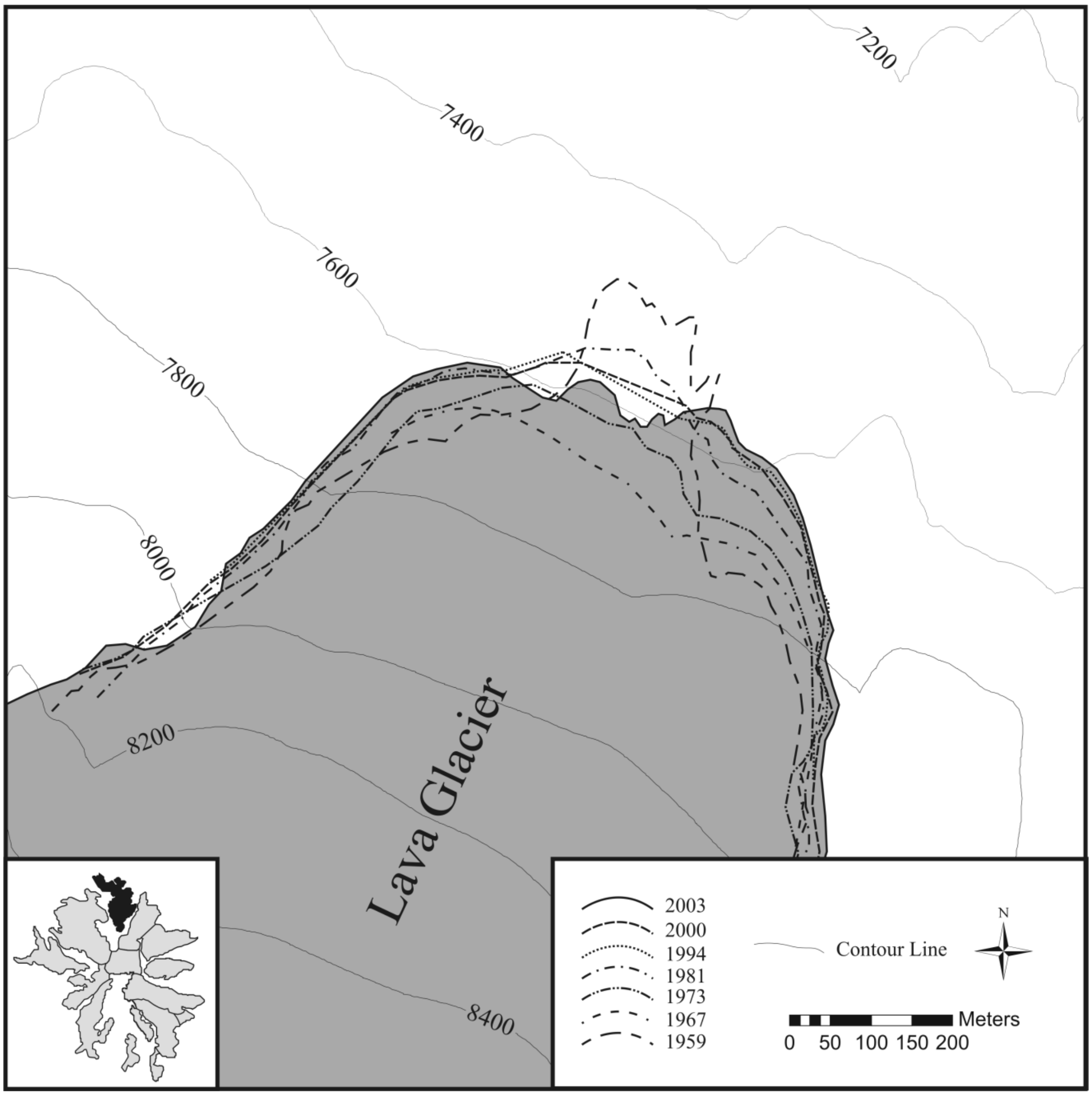


Figure 21. Lava Glacier termini changes 1949-2003.

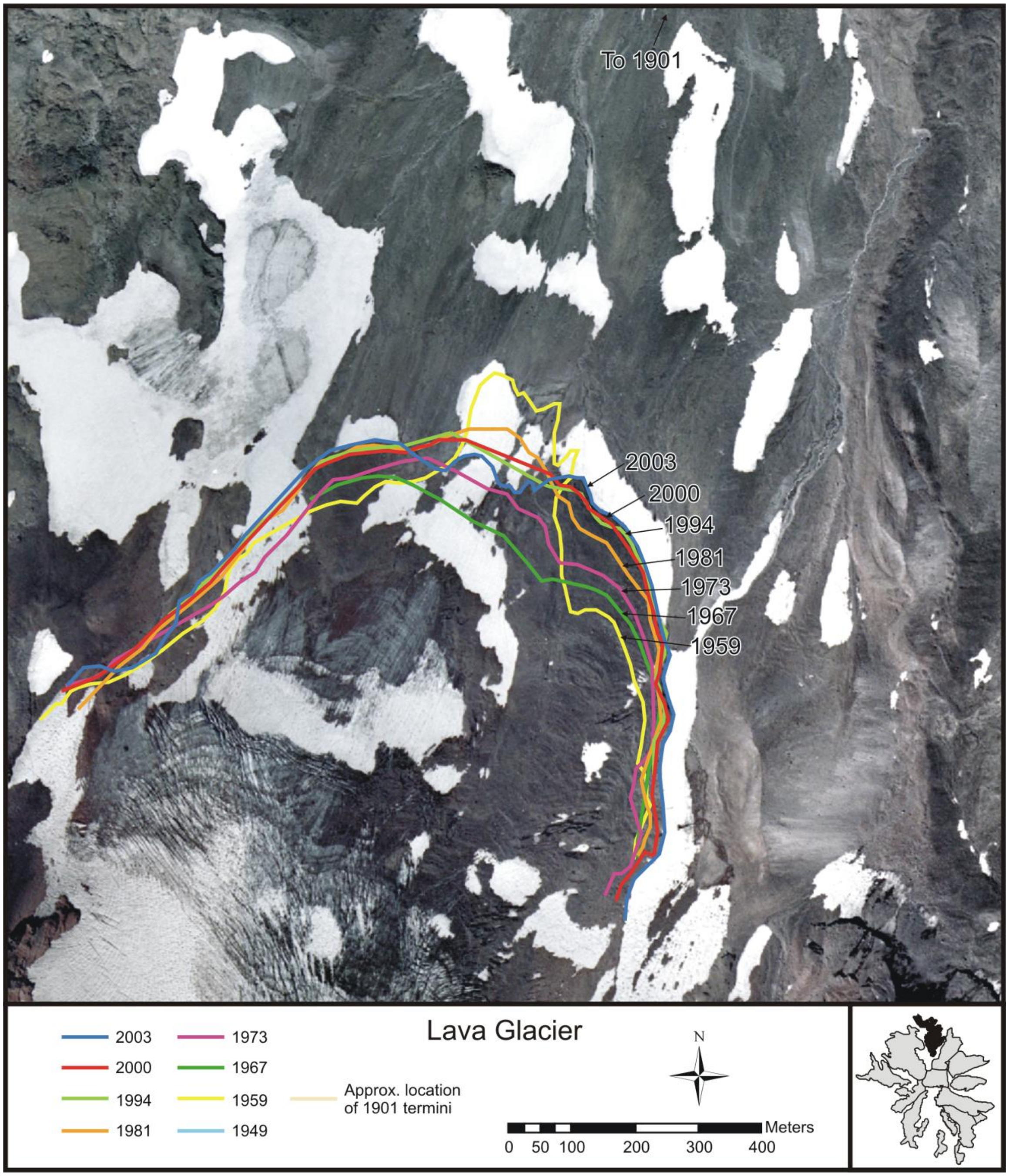


Figure 22. Orthophoto of Lava Glacier (2003) shown with historic termini positions.

Taking into account Reid's observation of Lava Glacier's terminus in 1901, regional warming trends since the LIA brought about ~1,050 m (3,445 ft) of recession up through 1959. The exact time frame of this retreat is undetermined as a result of few documented observations of the Lava Glacier in the first half of the 20th century. Additionally, air photo records for 1949 are inconclusive, as late lying perennial snow patches cover much of the surface around the terminus. This exceptionally large retreat of the Lava Glacier can possibly be attributed to the topography of the area below the present day terminus. Unlike many of Mount Adam's glaciers, Lava Glacier's terminus region has a relatively large unconfined area, causing it to spread itself thinner without achieving any significant depth. Lava Glacier continued this retreat through 1967 when it retreated an additional 208 m (682 ft). By 1967, however, the retreat had ended and Lava Glacier stabilized. A 15-year advance followed, with the terminus advancing 135 m (443 ft) by 1981. Since then, Lava Glacier has generally retreated, losing 57 m (187 ft) by 2003. As of 2006, the terminus of Lava Glacier sits at an elevation of 2,312 m (7,585 ft) (Figure 12)(Table 2 & 3).

Adams Glacier

Adams Glacier, the largest of all 12 glaciers on Mount Adams, originates directly from the northwest corner of the summit cap. Cascading off the summit, snow and ice falls over 800 m (2,625 ft) down a relatively narrow icefall 300 m (984 ft) wide, creating the most prominent feature on Mount Adams western face. Below this icefall the glacier rapidly spreads out onto the lower flanks, reaching a width of over 2 km (1.2 mi) at its widest point. The total length of Adams Glacier is approximately 3.5 km (2.2 mi), ending at an elevation of 2,149 m (7,050 ft). Multiple smaller lobes extend out on both the north and south sides of the main lobe, separated by steep, sharp-crested moraines dating back only a few centuries (Hildreth & Fierstein, 1995). The largest lobe of the Adams Glacier is currently positioned on top of a small rock outcrop, with the lowest 1 km (0.6 mi) being approximately 50% heavily debris covered.

The earliest reports of Adams Glacier come from C.E Rusk's exploration of the mountain and its glaciers in the late 1800s. While his circuit of the mountain in 1890 describes many of Mount Adams' glaciers in detail, the Adams Glacier is only briefly mentioned. It was not until 1901 when Rusk returned to the mountain with H.F. Reid and conducted a more thorough examination of the glacier and its terminus. Before this exploration, Adams Glacier remained nameless. Rusk, being the first to see the glacier several years prior, named it Reid Glacier. However, because Professor Reid was making a map of the mountain, he wished to avoid placing his own name on it. Rusk reluctantly named it Adams Glacier, hoping that the original name would eventually stick (Rusk, 1978).

The Adams Glacier in 1901, as observed by Rusk and Reid, was the longest glacier on Mount Adams with an approximate length of 5.5 km (3.4 mi). The glacier surface was said to be debris-free all the way to the terminus where a moraine 40 m (131 ft) high surrounded it. The map produced by Reid shows the Adams Glacier terminus to be located at an elevation of ~1,890 m (6,200 ft) (Reid, 1906). Currently, a large moraine approximately 20 m (66 ft) high exists at an elevation of 1,920 m (6,300 ft), with another twice as high at an elevation of 1,951 m (6,400 ft.) Assuming this location is that described and witnessed by Rusk and Reid, the Adams Glacier experienced significant retreat in the years following the LIA. In the time period between 1901 and 1959, Adams Glacier retreated ~1,500 m (4,921 ft) to a point atop a small rocky outcrop (Figure 23 & 24). The full extent of the retreat may have been greater; however, the air photo record

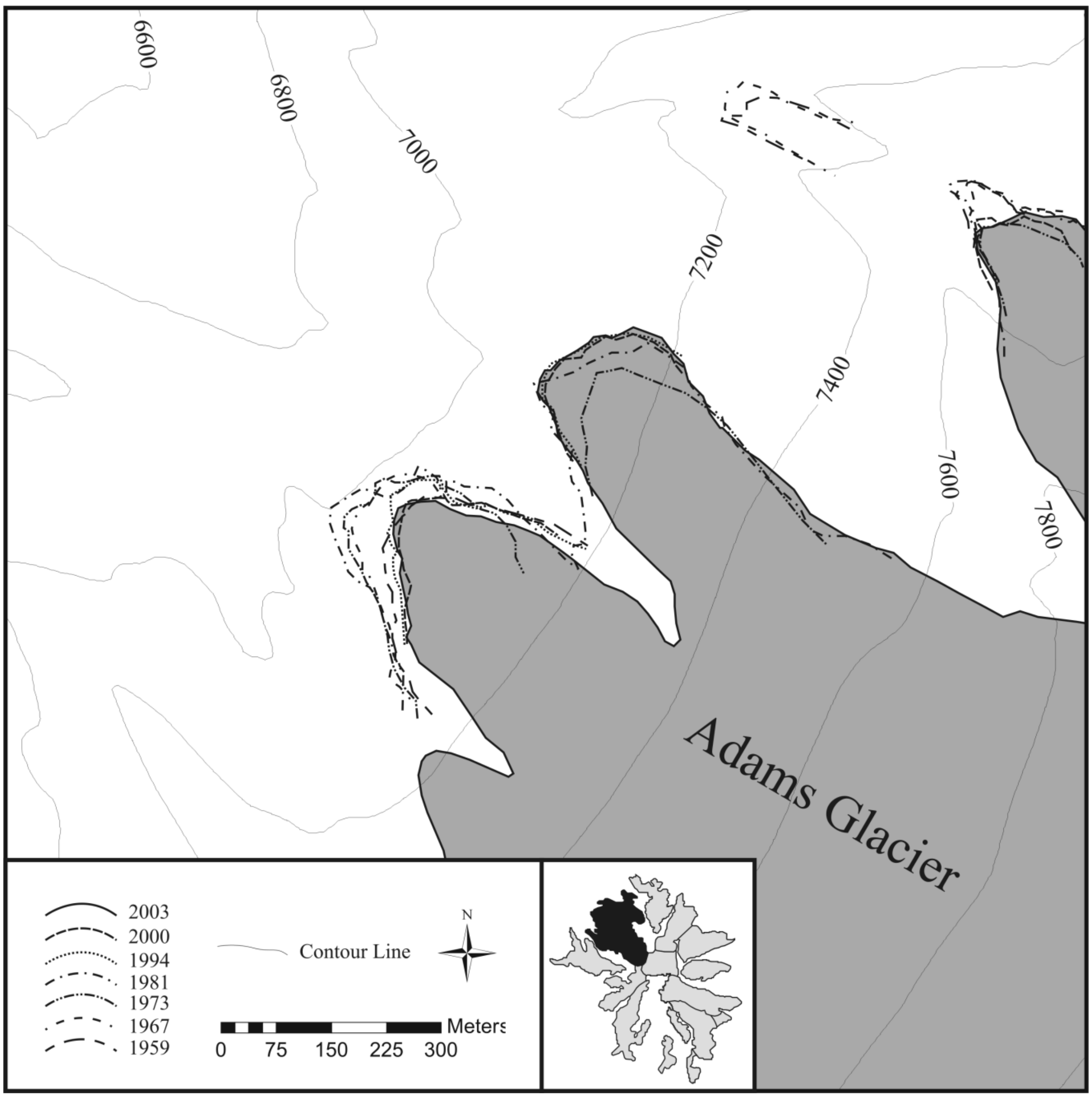


Figure 23. Adams Glacier termini changes 1949-2003.

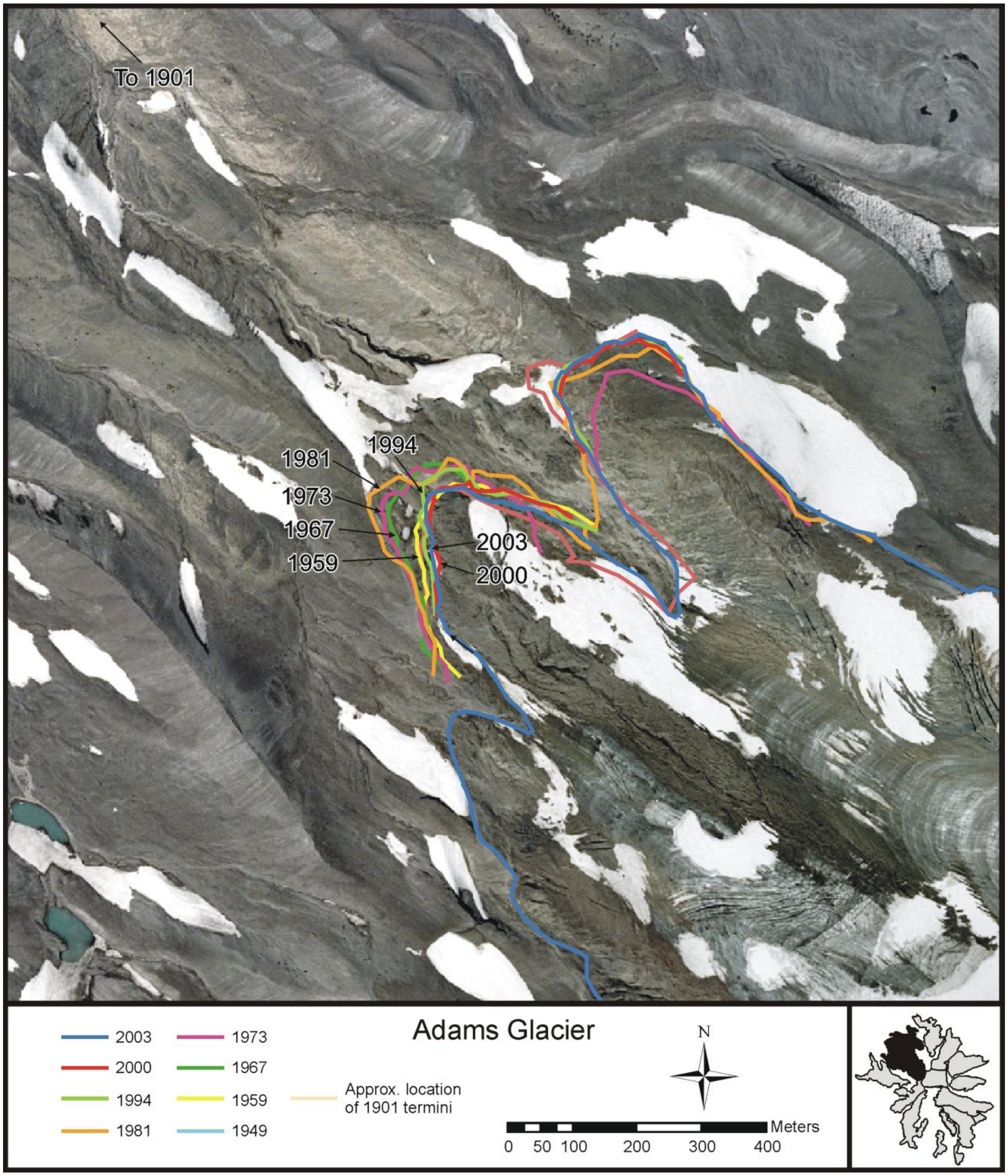


Figure 24. Orthophoto of Adams Glacier (2003) shown with historic termini positions.

for 1949 is largely covered with late-lying snow patches, masking the location of the terminus. Following this climate change and subsequent glacial retreat, Adams glacier shifted into a positive phase for the next eight years, advancing 48 m (157 ft) by 1967. This period of advance was short-lived and Adams Glacier began retreating again through 2000. While the total extent of this retreat was only 50 m (164 ft), 90% of the loss occurred between 1981 and 2000. Since 2000, no significant change in the terminus position has been recorded (Figure 12)(Table 2 & 3).

Pinnacle Glacier

Pinnacle Glacier, located just south of Adams Glacier, originates west and below the steep cliffs of The Pinnacle. The majority of accumulation is derived from snow and ice avalanching off the unconsolidated cliffs above and direct deposits on the upper reaches. Pinnacle Glacier is left-laterally bound by the east/west trending ridge stemming from the peak above and right-laterally bound in the ablation area by the Neoglacial moraines (Hildreth & Fierstein, 1995). The total length to the main terminus of Pinnacle Glacier is 2.3 km (1.4 mi), ending at an elevation of 2,137 m (7,011 ft) (Figure 25 & 26). While much of the glacial surface extending down to the main terminus is debris free, large amounts of debris fall and avalanches from the unstable cliffs below The Pinnacle have covered much of the north half of the glacier. With the thickness of debris being upwards of 2 m (6.6 ft), differential ablation rates have allowed the northern half of the glacier to persist throughout the years, being less affected by short-term climate change. With much of the north side of Pinnacle Glacier being heavily debris covered, terminus positions become vague. For the purposes of this research, only the southern, debris-free half of the glacier was measured for terminus change.

First documented by C.E. Rusk in 1890 during his circuit of Mount Adams, Pinnacle Glacier has seen few people return for the sole purpose of research. Reports of the glacier dating back to the late 1800s and early 1900s are scarce. Rusk's account of Pinnacle Glacier during his first trip was that "it is probably the least interesting side of the great peak." On Rusk's return trip in 1901 with H.F. Reid, the only mention of Pinnacle Glacier was that it was considerably smaller than both the White Salmon and Avalanche Glaciers (Rusk, 1978). Although little is known about the condition of the terminus in these early years, Reid set up a camp at the terminus to complete his Mount Adams map. The Pinnacle Glacier, as mapped by Reid in 1901, is shown to have a terminus located at an elevation of ~6,700 ft (2,042 m) (Reid, 1906). Matching the position of the terminus documented by Reid with a current location is unlike that of the other glaciers on Mount Adams and brings up several problems. The elevation band that is said to be the position in 1901 crosses many Neoglacial moraines, ice-cored moraines, and stagnant debris covered ice. Similarly, much of the current terminus is under several meters of debris, brought down from the steep, unconsolidated cliffs below The Pinnacle. This debris has concealed much of the current terminus. As a result, it would be unacceptable to make any determination between active debris-covered glacier, ice-cored moraine, and stagnant glacier for this time period.

This debris-free section of glacier has remained relatively stable over the years. After the retreat from the LIA maximum, Pinnacle Glacier retreated less than 2 m (6.6 ft) from 1949 to 1959. The glacier then moved into a positive phase for the next 14 years advancing 36 m (118 ft) by 1973. This short advance was followed up by a retreat of 30 m (98 ft) between 1973 and 1981. Another positive phase through 2000 allowed Pinnacle Glacier to advance 22 m (72 ft). Most recently, Pinnacle Glacier saw a 29 m (95 ft) retreat within the short period between 2000 and 2003 (Figure 12)(Table 2 & 3).

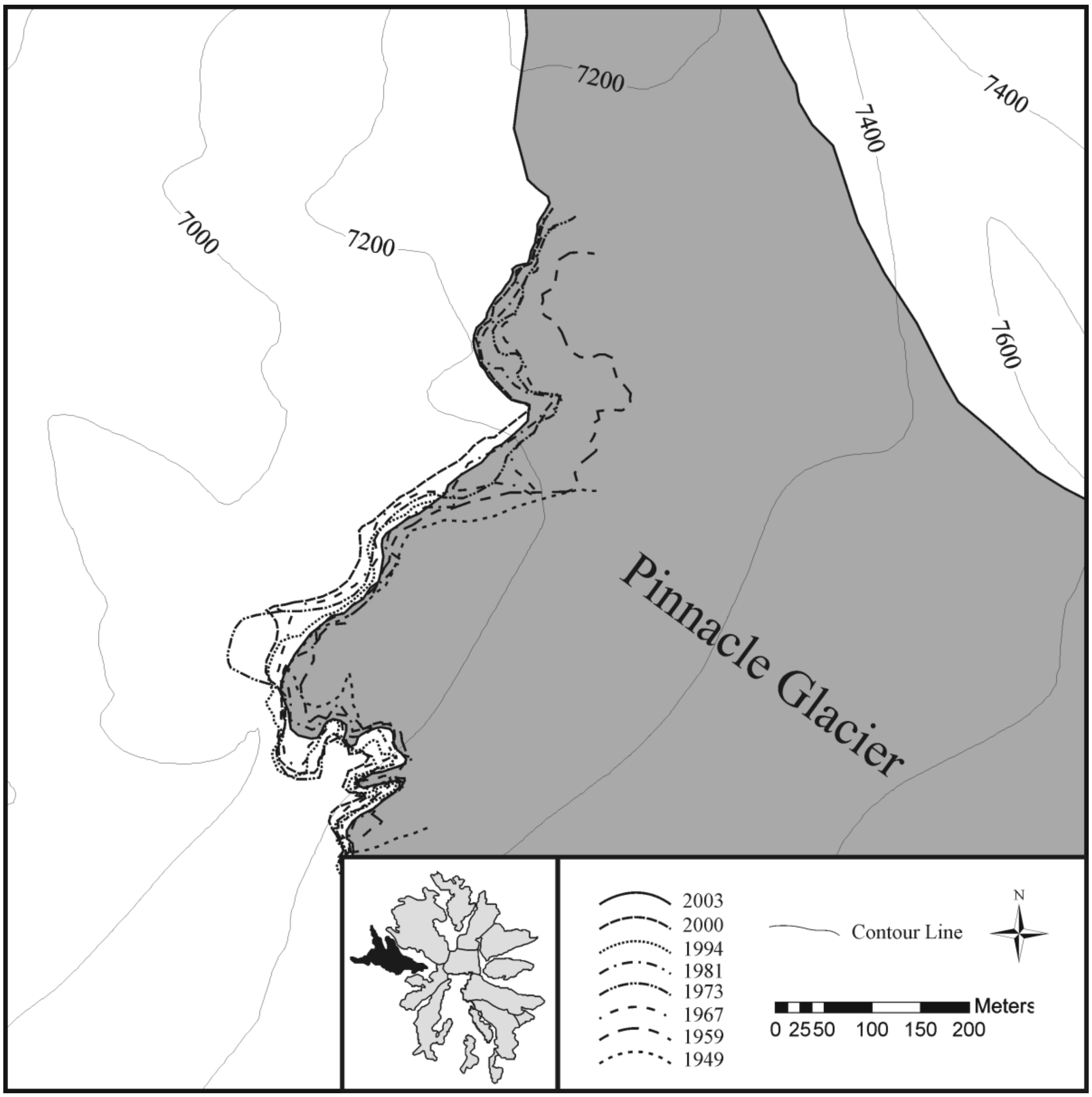


Figure 25. Pinnacle Glacier termini changes 1949-2003.

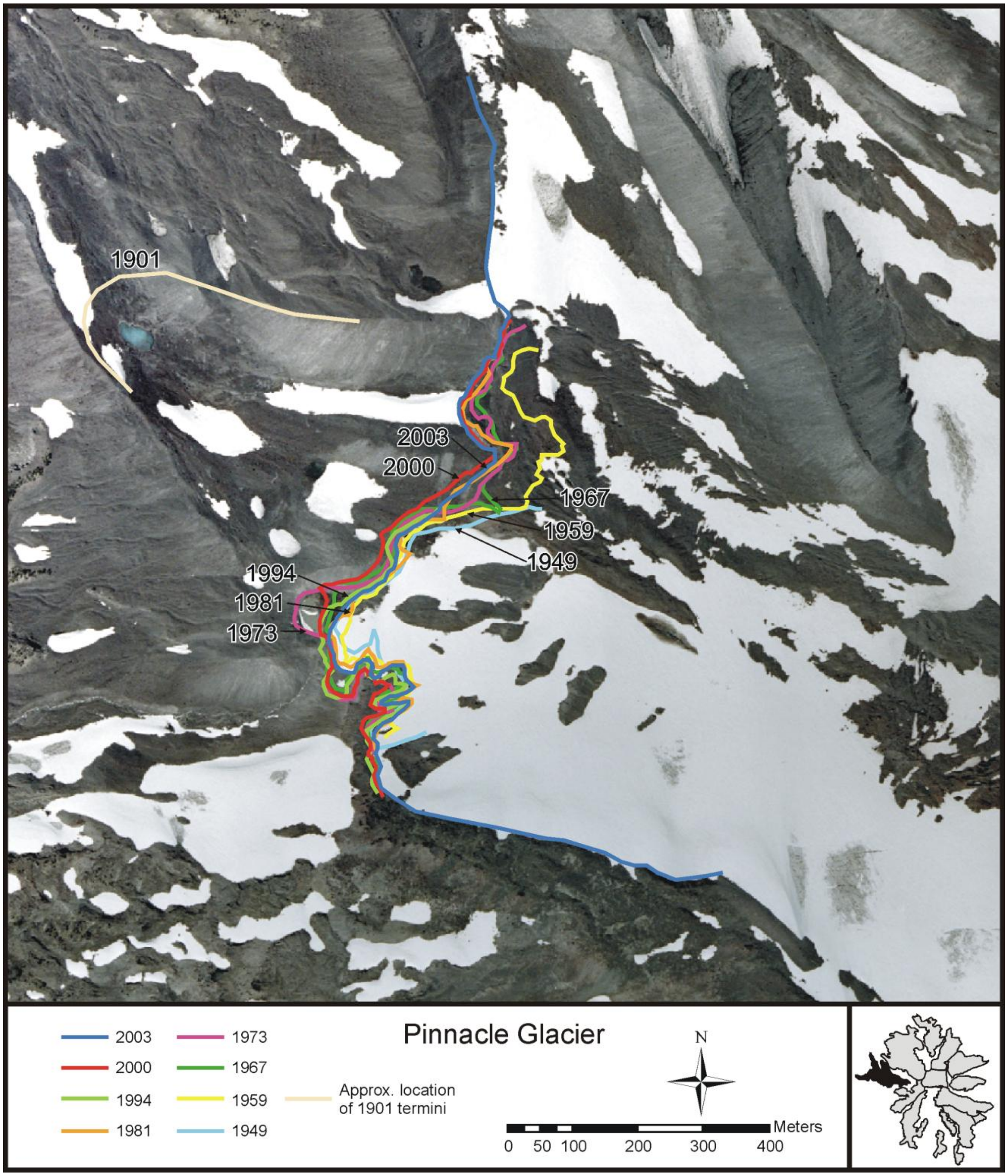


Figure 26. Orthophoto of Pinnacle Glacier (2003) shown with historic termini positions.

Crescent Glacier

Crescent Glacier is located west of the Suksdorf Ridge on the lower southern flanks of Mount Adams. Originating in a small cirque at an approximate elevation of 2,560 m (8,399 ft), Crescent Glacier is bound on the east by Suksdorf Ridge and by an unnamed spur ridge on the west. The accumulation zone of Crescent Glacier is relatively low, only extending up to 2,560 m (8,400 ft). Resulting from its small accumulation zone, the glacier has a total length scarcely reaching 0.5 km (0.3 mi), and only reaching 400 m (1,312 ft) at its widest point. While its total area only reaches 0.11 km^2 (0.04 mi^2), Crescent Glacier's terminus is bound by a large moraine several hundred feet high. Largely bound on all sides, Crescent Glacier has seen little horizontal movement in recent history.

Early research of Mount Adams' glaciers, specifically by Rusk, Reid, and Lyman, typically failed to recognize the presence of Crescent Glacier. The reason behind this lack of acknowledgement is yet to be determined. Whether the relatively small area of this glacier proved to be too insignificant or it failed to meet their classification standards for glacial ice, Crescent Glacier was not identified in early literature. The southern climbing route which passes directly alongside Crescent Glacier has not significantly changed courses from the time of these early explorers, all of which used the route to ascend to the summit. As a result, it is unlikely that Crescent Glacier was overlooked or passed by undetected, but rather just unacknowledged.

With no written documentation of Crescent Glacier prior to 1949, the location of its early terminus is unknown. However, with the presence of the large terminal moraine directly below the present day terminus, it is likely that the late 1800s terminus was in approximately the same location as that in 1949 (Figure 27 & 28). Since 1949, Crescent Glacier has undergone very little horizontal movement, resulting from the glacier still being in contact with its moraine. Much of the movement can be attributed to the vertical

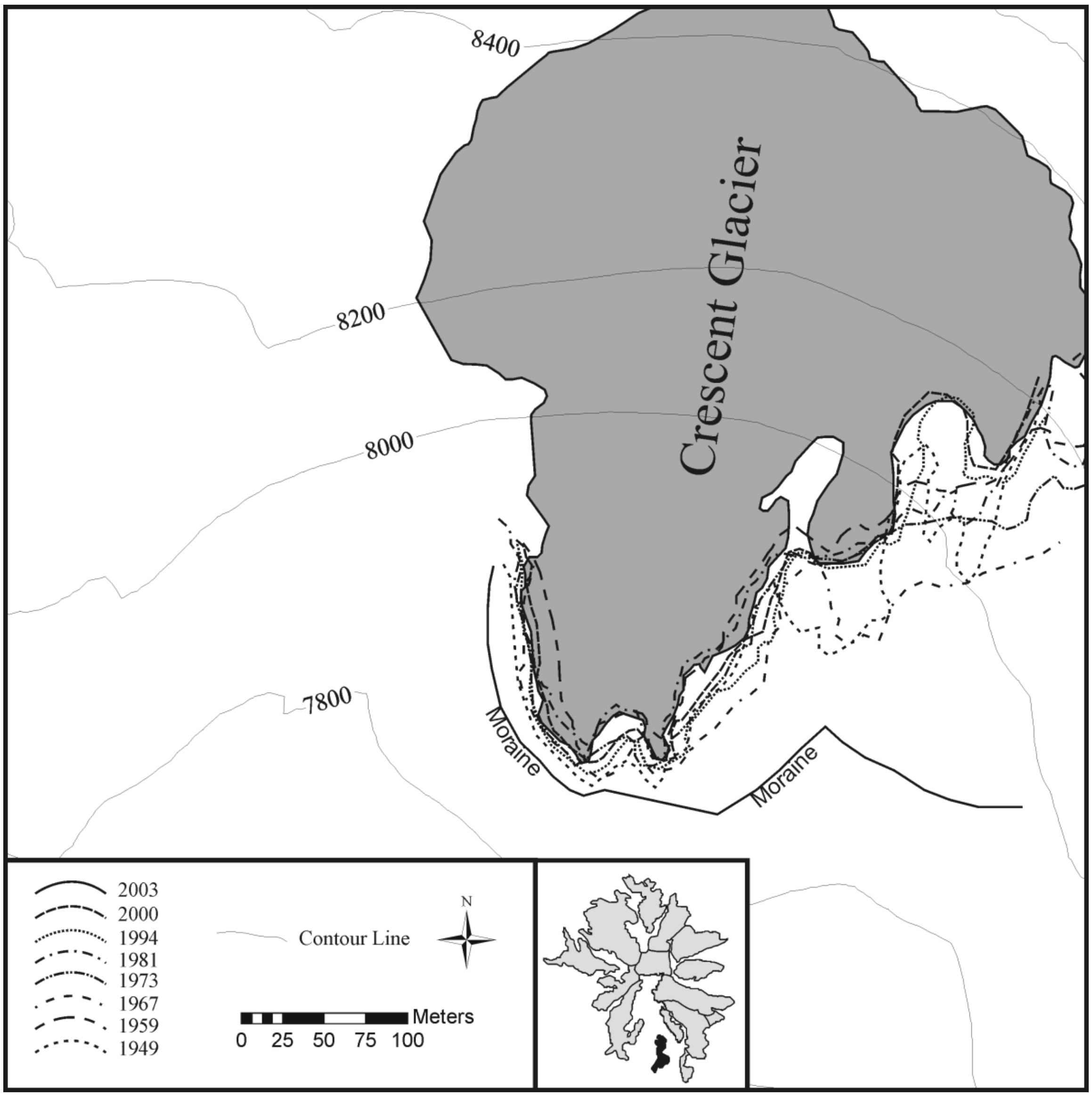


Figure 27. Crescent Glacier termini changes 1949-2003.

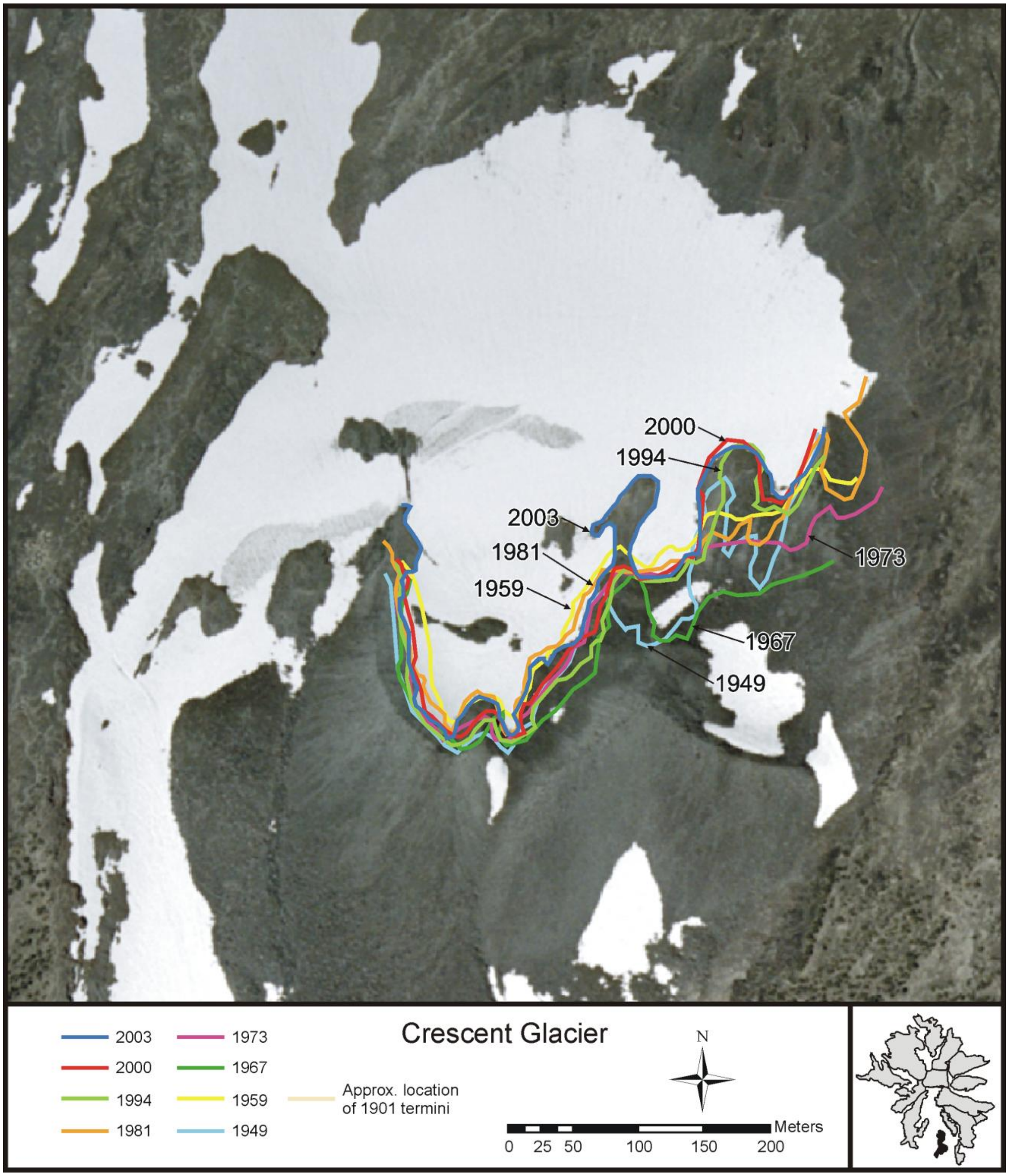


Figure 28. Orthophoto of Crescent Glacier (2003) shown with historic termini positions.

movement up and down the moraine. Not until recently has it pulled back away from this moraine and began receding upslope. Alternating advances and retreats of Crescent glacier have occurred nearly every decade since 1949. Following the first air photo on record in 1949, Crescent Glacier retreated 27 m (89 ft) through 1959. By 1967, however, the glacier readvanced 24 m (79 ft). Another retreat occurred between 1967 and 1981 with a 26 m (85 ft) loss. By 1994, Crescent Glacier saw a 25 m (82 ft) advance, followed only by a 14 m (46 ft) loss through 2003 (Figure 12)(Table 2 & 3). Today, Crescent Glacier's terminus has thinned to a point where further ablation will cause a significant retreat upslope, rather than just down its terminal moraine.

Gotchen Glacier

Gotchen Glacier, another relatively small glacier, is located east of the Suksdorf Ridge on the lower southern flanks of Mount Adams. Gotchen Glacier does not originate in a cirque or from the summit cap, but on the leeward side of Suksdorf Ridge, gaining much of its accumulation from drifting snow. As a result, Gotchen Glacier is as wide as it is long, 400 m (1,312 ft) being both its greatest length and width. Similar to the Crescent Glacier, Gotchen has a relatively low elevation, spanning from 2,438 m (8,000 ft) down to 2,255 m (7,400 ft). Without a large quantity of debris falling or avalanches in the upper reaches of the accumulation zone, the glacier remains relatively debris free. However, a large moraine approximately 70 m (230 ft) high currently encloses the glacier on three sides (Figure 29 & 30).

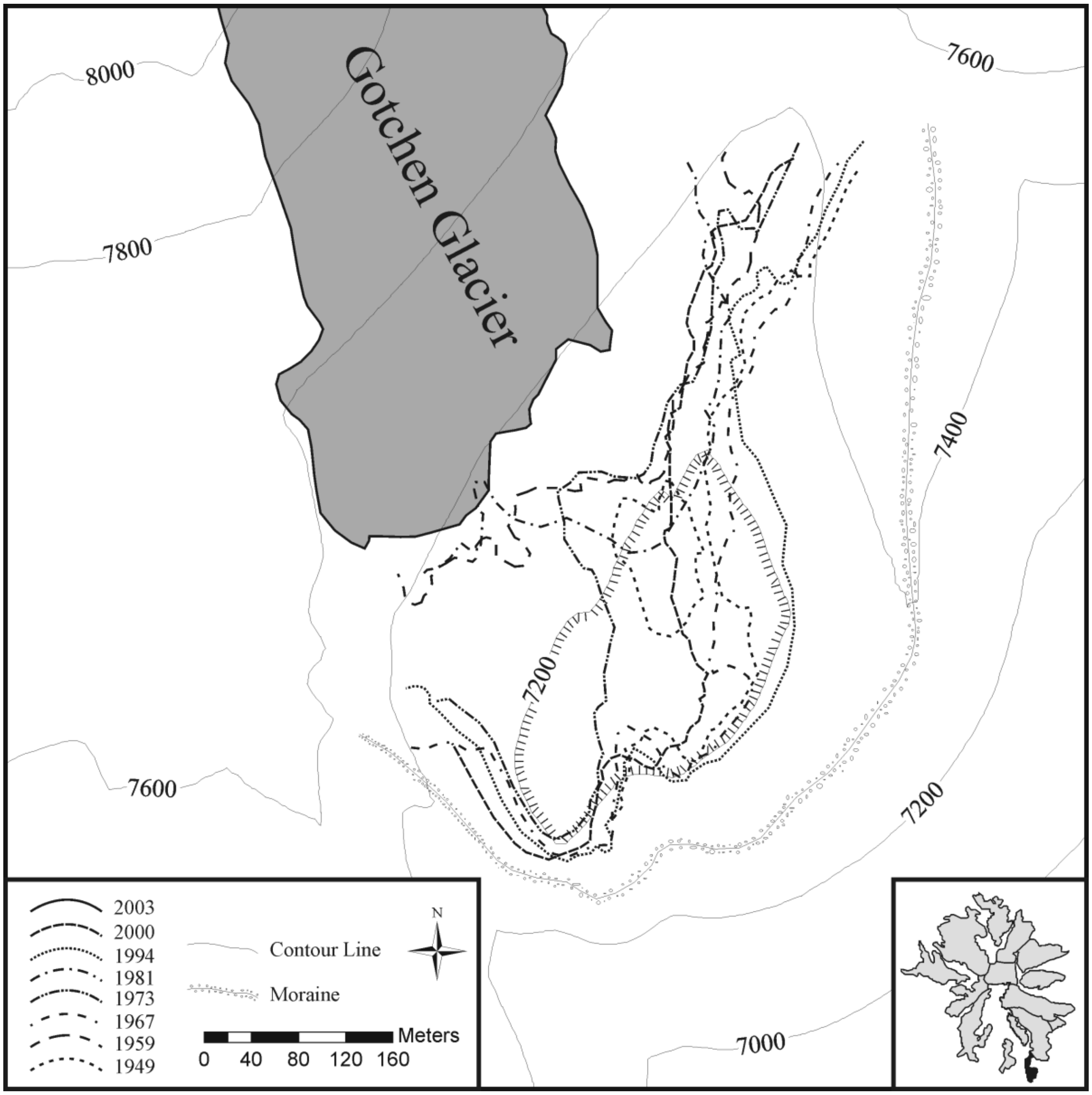


Figure 29. Gotchen Glacier termini changes 1949-2003.

Similar to Crescent Glacier, most early researchers of Mount Adams' glaciers failed to name or mention the location of Gotchen Glacier. Several possibilities exist that may explain this lack of acknowledgement. The relatively small area of Gotchen glacier may have proved to be too insignificant to justify research time. Alternatively, it may

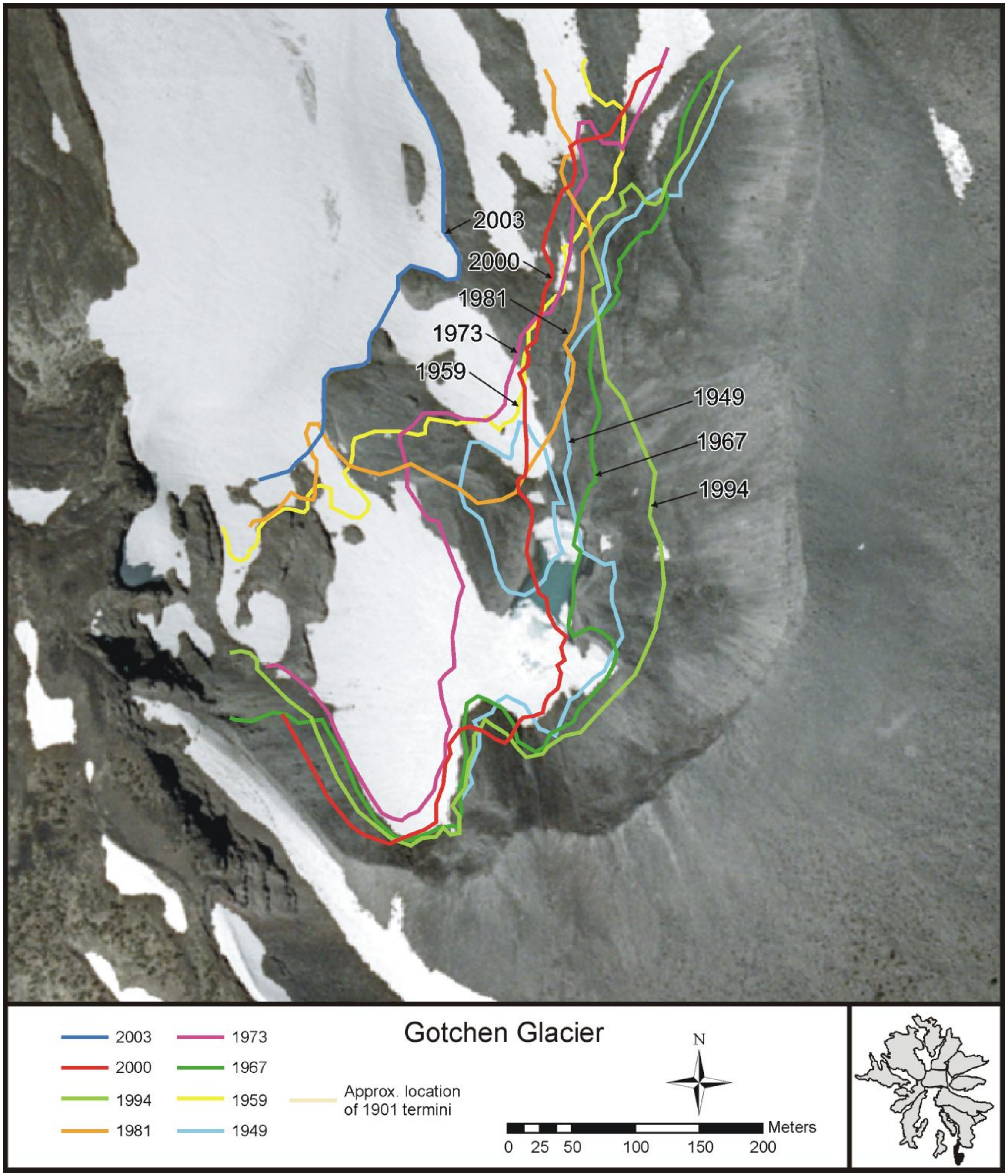


Figure 30. Orthophoto of Gotchen Glacier (2003) shown with historic termini positions.

have simply failed to meet their classification standards for glacial ice. While there is no written documentation or reason, H.F. Reid did sketch the position of it on his 1901 map, indicating that this glacier wasn't just overlooked.

Historic locations of the Gotchen Glacier terminus can initially be seen by interpreting the 1901 map. Reid shows the terminus positioned at an elevation of ~2,195 m (7,200 ft), directly adjacent to the large terminal moraine (Figure 29 & 30). With the presence of this large moraine, horizontal movement of the glacier is greatly diminished, as the glacier will advance and retreat up and down the moraine. As a result, very little change in the horizontal position of Gotchen Glacier has occurred though the beginning of the air photo record in 1949. By 1949, Gotchen Glacier's terminus had pulled away slightly from its moraine and by 1959 had retreated 42 m (138 ft). The next 8 years brought 62 m (203 ft) of glacier advance, followed by a loss of another 68 m (223 ft) between 1967 and 1973. From 1973-1994, Gotchen Glacier advanced 107 m (351 ft), again retreating 206 m (676 ft) by 2003. As of 2003, Gotchen Glacier's terminus has had a cumulative retreat of 147 m (482 ft) since 1949, now sitting at an elevation of 2,249 m (7379 ft) (Figure 12)(Table 2 & 3).

Mazama Glacier

Mazama Glacier originates in a small cirque high on the east side of Suksdorf Ridge, above Crescent and Gotchen Glaciers. Formerly bound by the walls of Hellroaring Valley and the Ridge of Wonders, Mazama Glacier currently flows ~1,700 m (5,577 ft) east, terminating above the great Neoglacial moraines lining the upper valley. The current ablation area is neither bound on its right or left, but fans out to a thin terminus, now disconnected from the lobe below Suksdorf Ridge to the south. With no major precipices or other unstable cliffs to deposit debris, Mazama Glacier's main stem remains relatively debris free. The disconnected portion of glacier, however, beginning below the steep cliffs of Suksdorf Ridge, accumulates a considerable amount of material.

Historic research of Mazama Glacier began in 1901 when C. E. Rusk and H. F. Reid visited the glacier on their circuit of the mountain. While Rusk had visited the glacier on several earlier occasions, this was the first for the sole purpose of research and mapping (Rusk, 1978). During this visit, Reid was unable to put a precise location on the terminus of the Mazama Glacier as a result of heavy snowfall that persisted late into the summer. However, an estimate was made for inclusion on his Mount Adams map. In his 1906 report, Reid states that the Mazama Glacier no longer extended down into the Hell Roaring canyon, but just touched the head of the canyon. Additionally, Reid mentions the Mazama Glacier was supported on the south by a large moraine 30 m (98 ft) high and underlain with ice. At the time of his research, the moraines at the top of Hell Roaring canyon were said to be free from vegetation, suggesting a recent origin (Reid, 1906).

Using Reid's glacier map and description of Mazama Glacier, the terminus in 1901 was located at an elevation of ~2,134 m (7,000 ft). The large moraine formerly bounding the southern edge of Mazama Glacier currently ends right at the same location, reinforcing Reid's description. By 1949, Mazama glacier had retreated over 1,000 m (3,281 ft); however, as a result of cloud cover and late lying perennial snow in the air photo record, the exact location of the terminus does not become visible until 1959.

By 1959, Mazama Glacier had receded ~1,300 m (4,265 ft), and also the furthest point upslope in the 20th century (Figure 31 & 32). The phase of retreat reverses and advances 80 m through 1973. The time period between 1973 and 1994 showed little movement of the terminus, with only a slight retreat of 12 m. Following a small 8 m advance between

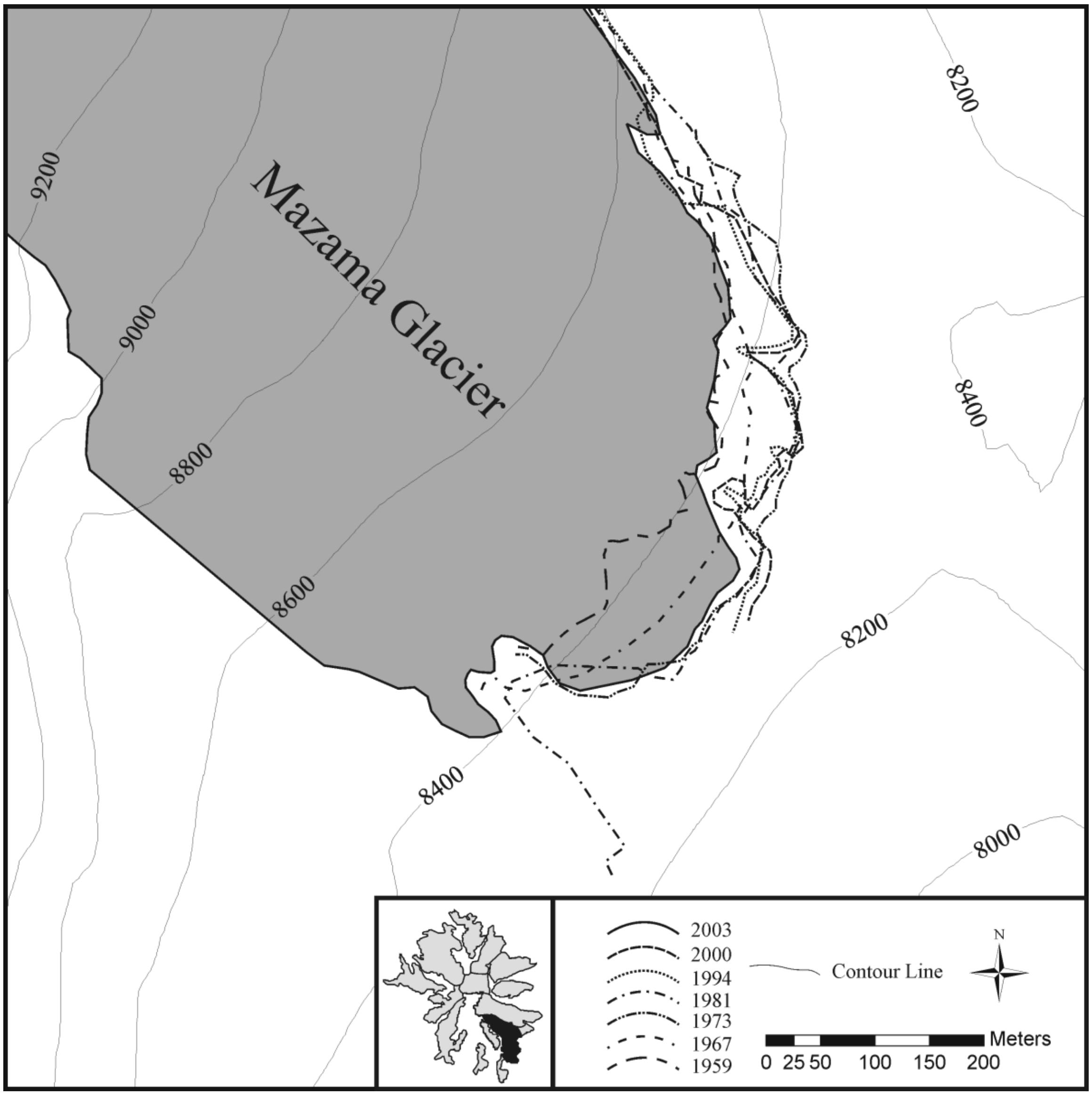


Figure 31. Mazama Glacier termini changes 1949-2003.

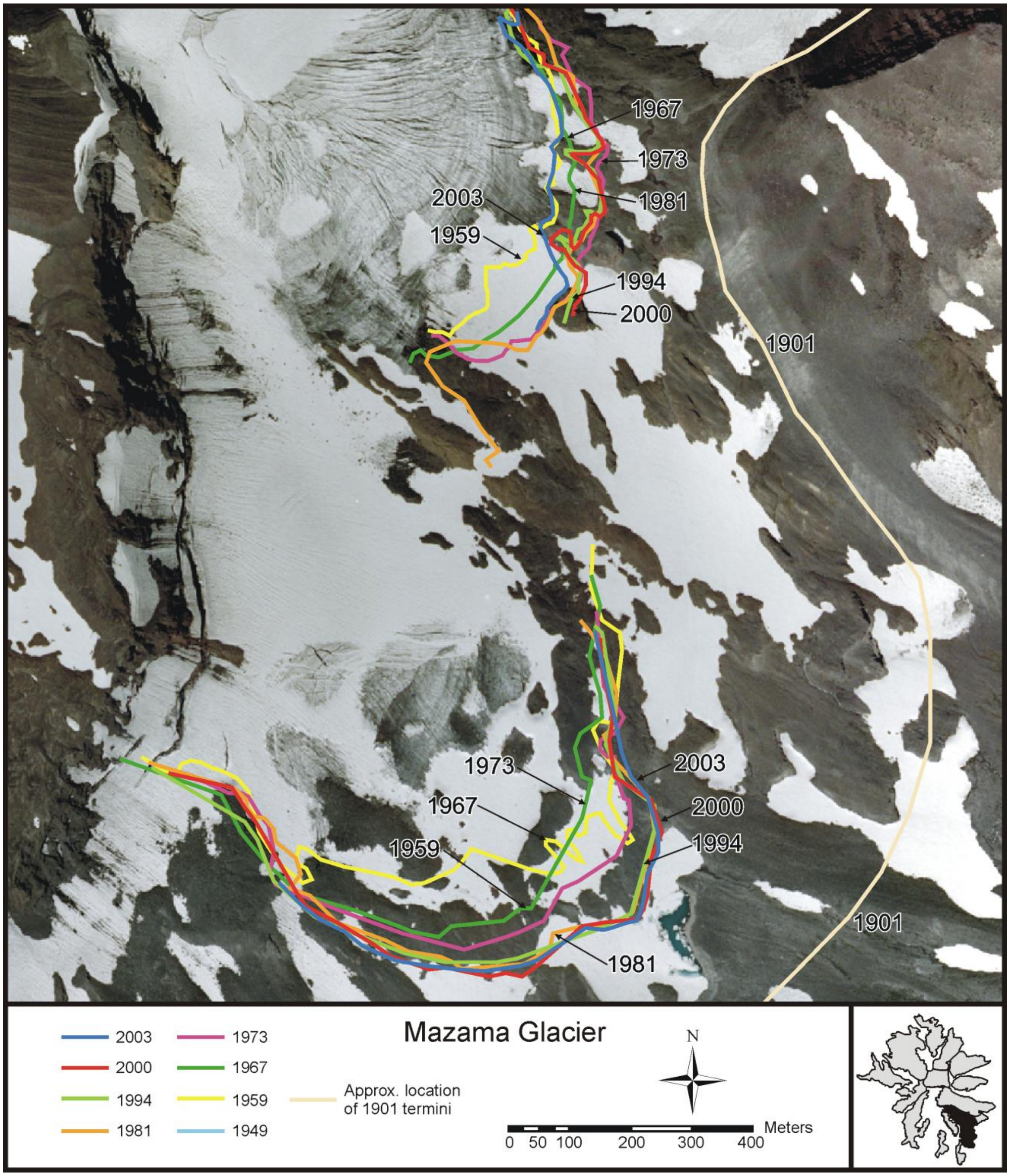


Figure 32. Orthophoto of Mazama Glacier (2003) shown with historic termini positions.

1994 and 2000, The Mazama Glacier switched to a rapid negative phase, retreating 69 m (226 ft) by only 2003. Currently the terminus sits at an elevation of ~2,560 m (8,400 ft), with a very thin front (Figure 12)(Table 2 & 3).

The retreat of Mazama glacier's terminus during the first half of the 20th century has subsequently split the glacier into two reasonably distinct termini. The largest and most well-defined terminus lies directly below the main stem at an elevation of 2,550 m (8,366 ft), being primarily debris-free and having a distinct lobate form. A secondary terminus to the south now exists at an elevation of 2,337 m (7,667 ft), being heavily debris covered and fed only through the accumulation below the steep cliffs of Suksdorf Ridge.

Historic Climate Patterns

Patterns of climate at the summit of Mount Adams (Lat: 46.202, Long: -121.491) since 1900 follow a similar timeframe as the PDO (Figure 33). These patterns, persisting between 20 and 30 years, generally follow the same phases with cool and wet periods lasting from the turn of the century to 1924 and from 1947 to 1976. Warm phases persisted from 1925 to 1946 and from 1977 to the mid-1990s. Five-year running average (RA) temperatures increased by 0.46 °C (0.83 °F) in the accumulation season and by 0.63 °C (1.13 °F) in the ablation season from 1900 to 2005. Five-year RA accumulation season precipitation increased ~211 mm (8.3 in) over the 105-year period of record, 1900-2005.

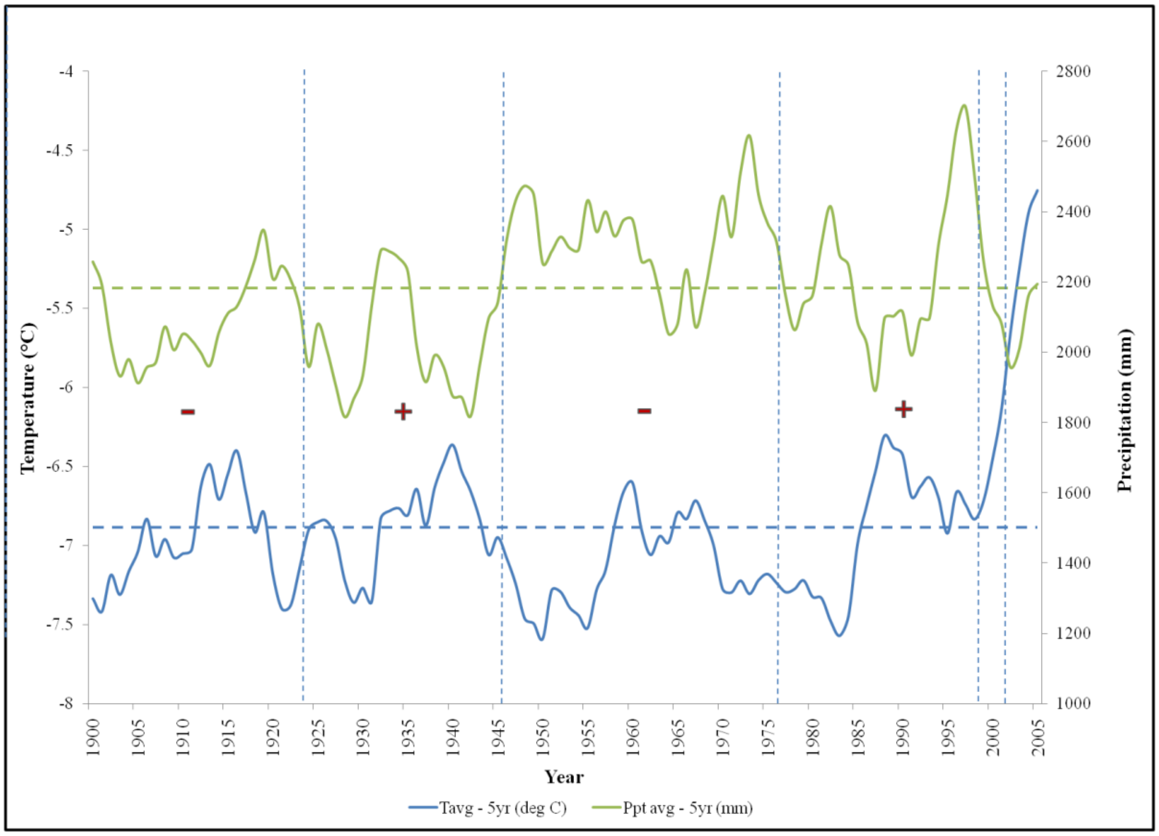


Figure 33. Five-year running average of temperature and precipitation with vertical dashed lines representing PDO phases (Daly et al., 2008).

Trends in these seasonal temperatures show the coolest ablation season on record occurred in ~1900 (Figure 34). Ablation season temperatures then generally increased through 1925, while accumulation season temperatures decreased to the second coldest 5-year period on record. The period between 1925 and 1946, ablation season temperatures remained relatively consistent with the 105-year mean, while the accumulation season temperatures increased ~0.7°C (1.3 °F) above normals. The negative phase of the PDO occurring between 1947 and 1976 brought about cooling in both the accumulation and ablation seasons. With ablation season temperatures fluctuating ~0.2 °C (0.4 °F) below the 105 year mean, five-year RA accumulation season temperatures fell 1.2 °C (2.2 °F)

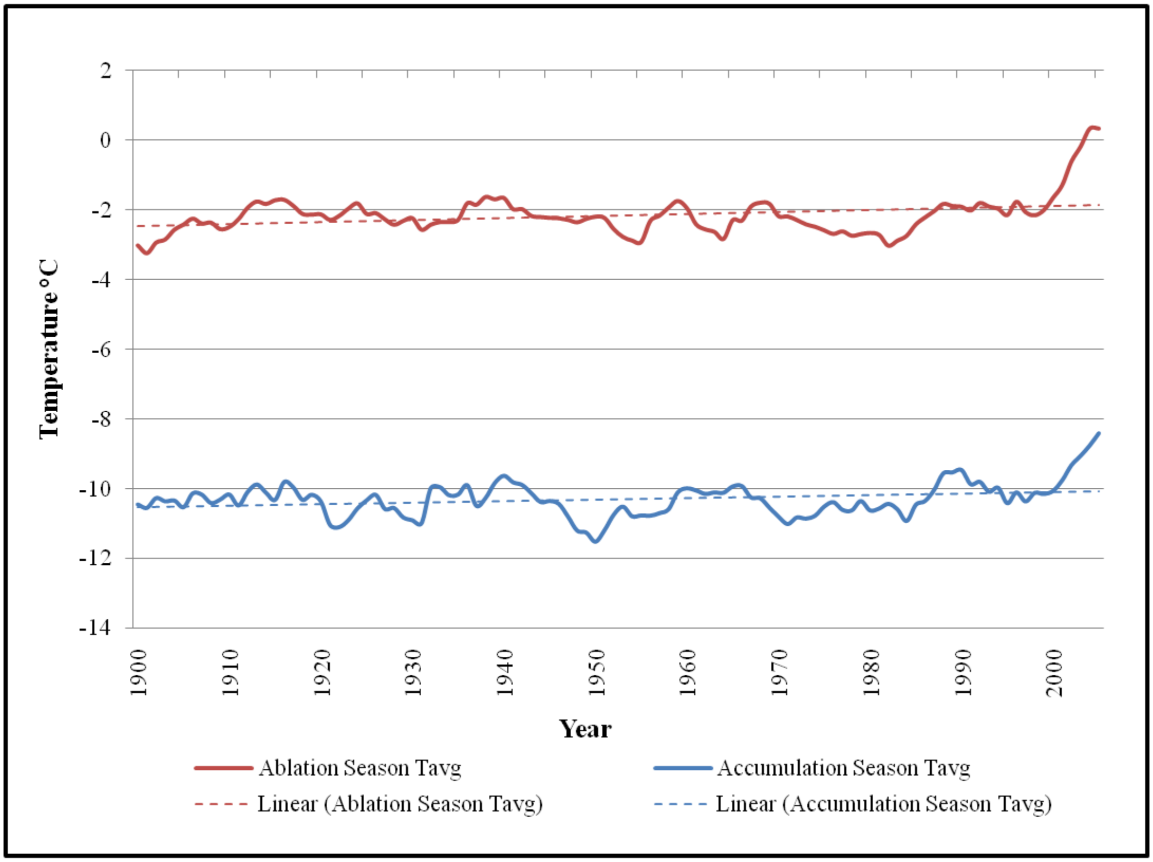


Figure 34. Five-year running average of accumulation and ablation season temperature with linear trendlines (Daly et al., 2008).

below the mean. While there has been only a minor increase in mean annual temperatures at the summit of Mount Adams since 1900, much of this is seen in both accumulation and ablation season temperatures from 1977 to 2005. The warmest 5-year period on record occurred in 2005 with an increase of 1.9 °C (3.4 °F) in the accumulation season and 2.5 °C (4.5 °F) in the ablation season (Daly et al., 2008).

While the general trend for the accumulation season precipitation was positive gains, five-year RA ablation season precipitation remained relatively constant with only a ~15 mm (0.6 in) increase over the same period (Figure 35). Within this trend, lower than average accumulation season precipitation during the 1900-1924 PDO phase were steadily increasing. This trend soon reversed itself and precipitation remained below normal through 1946, reaching the lowest 5-year period of the last century in 1942. The 1947 shift in the PDO to a negative phase brought about a sharp increase in precipitation, lasting for 30 years. After the 1977 shift in PDO to a positive phase, precipitation levels fell back to the 105-year mean but have steadily been increasing.

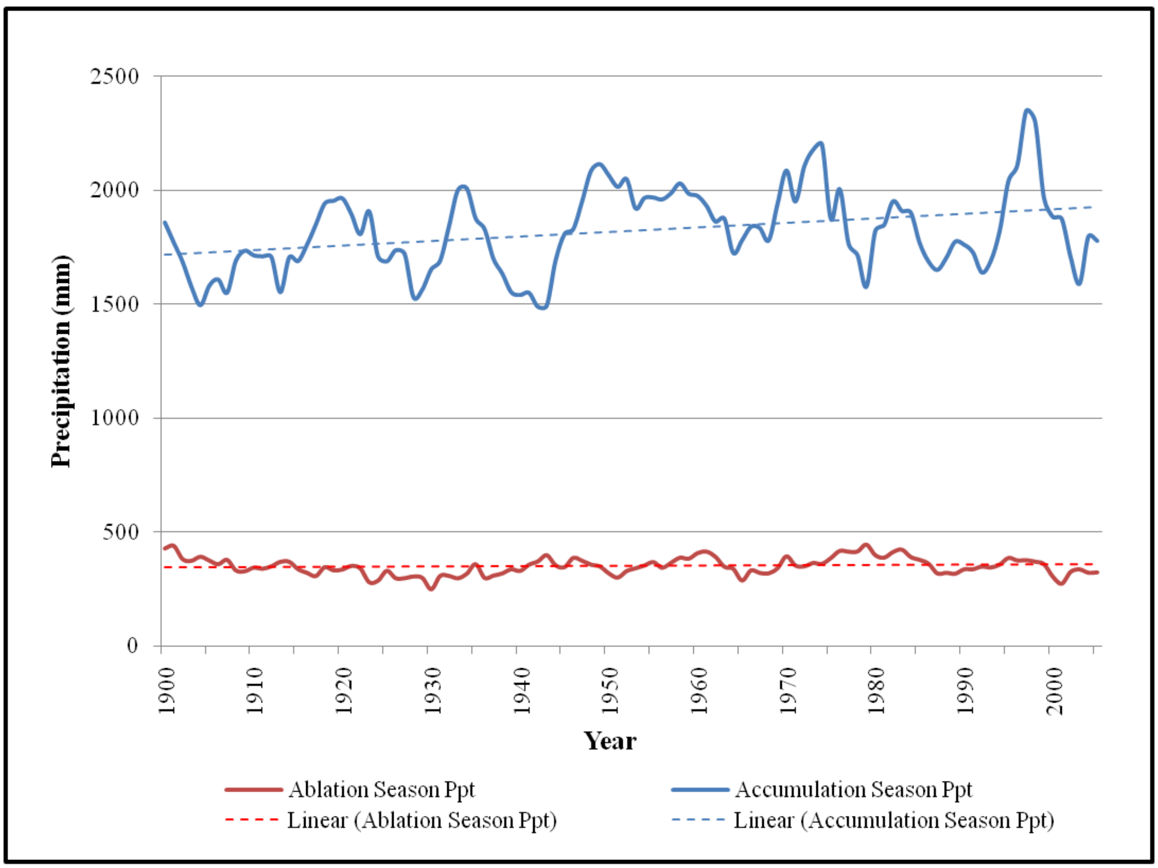


Figure 35. Five-year running average of accumulation and ablation season precipitation with linear trendline (Daly et al., 2008).

Factors Influencing Terminus Fluctuations

Glaciers respond to variables in climate such as temperature and precipitation through their fluctuating terminus positions. Mount Adams' glaciers have advanced and retreated through multiple PDO phases in the past century. However, the 12 glaciers did not all respond in similar fashion; some glaciers were in phases of retreat while during the same period, others were advancing. Because of these dissimilar responses, no correlations were found between glacier termini fluctuations at Mount Adams. With climate being the primary factor influencing glacier behavior, other geographic characteristics such as aspect, accumulation source, glacier length, and debris cover have all had substantial impacts on terminus positions of Mount Adams' glaciers as indicated by the asynchronous glacier terminus fluctuation record.

Klickitat Glacier

Temperature Analysis

While Spearman rank correlation analysis of cumulative glacier terminus change can only be applied to the 1949-2003 record of known terminus locations, patterns following the LIA through ~1930 suggest that above average ablation season temperatures were a likely source for the ~1,000 m (3,281 ft) retreat of the Klickitat Glacier. Applying the Spearman rank correlation with a significance level of .05 to the known record (1949-2003), the terminus position of Klickitat Glacier showed several correlations with the temperature record (Table 4). Strong negative correlations can be seen with mean annual temperatures and minimum annual temperatures, both with

Table 4

Select Klickitat Glacier r Values and p Values.

	Value	
Variable	*r*	*p*
Mean annual temperature, 5-year lag	-.89	.03
Minimum annual temperature, 5-year lag	-.89	.03
Mean ablation season temperature, between years	-.89	.03
Mean annual precipitation, 5-year lag	.83	.03
Mean accumulation season precipitation, 5 year lag	.79	.04

r values of -.89 ($p = .03$) at a 5-year lag time. These strong correlations suggest that the terminus position of Klickitat Glacier, between 1949 and 2003, responded greatest to the mean annual and minimum temperatures 5-15 years previous to the terminus fluctuation. Using the Spearman rank correlation to further test values specifically within the accumulation and ablation seasons resulted in strong negative correlations for ablation season temperature for time periods in-between air photo records. This suggests that terminus position also responded to ablation season temperatures for the time period dating back to the previous air photo record, typically 10 years.

Precipitation Analysis

In addition to temperature, the other primary climate factor influencing glacier change is precipitation. Following the LIA, precipitation levels at Mount Adams were significantly below the 105-year mean through both the 1900-1924 and 1925-1946 PDO cool and warm phases. Together with the above average ablation season temperatures, lower than average mean annual precipitation was a likely source for the ~1,000 m (3,281 ft) retreat of the Klickitat Glacier.

Beginning in 1949 with the air photo record and known terminus position of Klicktat glacier, Spearman rank analysis shows a strong positive correlation (*r* value of .83, $p = .03$) with terminus position and mean annual precipitation at a 5-year lag (Table 4). Further strengthening of the relationship between precipitation and terminus position can be seen within the accumulation season with an *r* value of .79 ($p = .04$). With both temperature and precipitation showing strong relationships with terminus positions, climate can be seen as being a primary forcing mechanism of Klickitat Glacier's terminus fluctuations.

Other Contributing Factors

Among the factors influencing glacier advance and retreat, debris cover on Klickitat Glacier has likely played an important role in its fluctuations over the past century. In 1949, air photos show debris covering the lowest 800 m (2,625 ft) of glacier, beginning just below the rocky outcrop at an elevation of ~2,434 m (8,000 ft) and extending down to its terminus. Currently, the lowest ~1,600 m (5,249 ft) of Klickitat Glacier is heavily covered in debris, fed from the unstable cliffs of Pikers Peak and the Ridge of Wonders above. While several of Mount Adams' glaciers have advanced and retreated during these same time periods, drastically reduced ablation rates from the excessive debris cover has likely preserved the glacier through times of typical glacier retreat (Mattson, Gardner, & Young, 1993; Wei, Tandong, Baiqing, & Hang, 2010).

Supplementing the debris that emerges in the ablation zone through rockfall in the upper reaches of the glacier, debris avalanches commonly extend down to the terminus itself. On October 20, 1997, one such debris avalanche originating at ~3500 m (11,483 ft) on the south face of The Castle at the head of Battlement Ridge traveled ~2 km (1.24 mi) down below the terminus. With a total volume exceeding 1 million m^3 (35.3 million ft^3), deposits from this event alone covered the entire ablation zone with upwards of 20 m (66 ft) of rocky debris (U.S. Geological Survey, 1997).

Rusk Glacier

Temperature Analysis

Following the LIA, Rusk Glacier proceeded into a period of retreat, lasting through the mid-20th century and losing over 800 m (2,625 ft) from its terminus. While no quantitative record of Rusk Glacier's terminus is available prior to 1959, and cloud cover obscuring the location of the terminus in the 1949 air photo record, the increased ablation season temperatures at Mount Adams were a likely source for the extended period of retreat during the first half of the twentieth century.

Utilizing a Spearman rank correlation analysis with a significance level of .05 to test the known terminus locations (1959-2003) of Rusk glacier for correlations with annual temperatures, several significant relationships are revealed (Table 5). A strong negative correlation can be seen with mean annual temperatures and minimum annual temperatures, with r values of -.89 (p = .03) and -.82 (p = .04) respectively at 10-year lag times. This suggests that Rusk Glacier's terminus responded to mean and minimum

Table 5

Select Rusk Glacier r Values and p Values.

Variable	Value r	p
Mean annual temperature, 10-year lag	-.89	.03
Minimum annual temperature, 10-year lag	-.82	.04
Mean accumulation season temperature, 10-year lag	-.94	.02
Minimum accumulation season temperature, 10-year lag	-.94	.02
Maximum accumulation season temperature, 10-year lag	-.89	.03

annual temperatures greatest from 10-20 years prior to the fluctuation. Using the Spearman rank correlation to further test the temperature variables specifically within the accumulation and ablation season resulted in multiple strong relationships. Both the mean and minimum accumulation season temperatures produced negative correlations at a 10-year lag time, resulting in r values of -.94 (p = .02), while maximum accumulation season temperatures correlated at -.89 (p = .03).

Precipitation Analysis

In addition to temperature, precipitation at Mount Adams was tested using Spearman rank. Similar to Klickitat Glacier, the Rusk Glacier retreated following the LIA up through the mid-20th century. This time period was characterized by precipitation levels that were significantly below the 105-year mean, continuing through both cool and warm phases of the PDO. Coupled with higher than normal ablation season temperatures, these two factors likely played a large part in the approximate 800 m (2,625 ft) retreat of the Rusk Glacier.

Beginning in 1959 with the air photo record and known terminus locations, Spearman rank analysis showed no direct relationship with precipitation within either the accumulation or ablation season, and yearly mean precipitation for all lag times up to 20 years. While Klickitat Glacier showed similar relationships between both temperature and precipitation, it is unknown why Rusk Glacier only responded to temperature despite being adjacent and having similar characteristics.

Other Contributing Factors

In addition to the climate factors influencing glacier advance and retreat on Rusk Glacier, heavy debris cover has likely been a contributing factor to the delayed reactions over the past century. Similar to the terminus of Klickitat Glacier, the lowest 1,000 m (3,281 ft) of Rusk glacier is heavily covered in debris, brought down from the unstable Roosevelt Cliffs and steep surrounding ridges. While much of the ablation zone of Rusk Glacier is covered, varying amounts of debris, crevasses, and differential ablation above an elevation of 2,300 m (7,546 ft) has produced characteristic hummocky topography with numerous scarps and gullies. This localized thermokarst development is a likely cause for a lowering of the glacier surface at this elevation.

Wilson Glacier

Temperature Analysis

Prior to the air photo record of Wilson Glacier’s terminus, warming patterns following the LIA produced ablation season temperatures greater than the 105-year mean. While no quantitative record of Wilson Glacier’s terminus exists prior to the 1949 air photo record, this warming trend is presumed to be a contributing factor to the retreat from the roughly mapped 1906 location observed by Reid.

Beginning in 1949 with known terminus locations, a Spearman rank analysis was applied utilizing a significance level of .05 (1949-2003), testing for correlations with annual temperatures. Unlike the other eastern slope glaciers, Klickitat and Rusk, the Wilson Glacier showed no correlations with annual temperature within the acceptable level of significance at lag times up to 20 years.

Precipitation Analysis

Precipitation patterns at Mount Adams were also tested using a Spearman rank analysis with the known terminus locations of Wilson Glacier. Similar patterns can be seen when comparing periods of advance and retreat to both the Klickitat and Rusk glaciers, all being on the eastern slope and having similar characteristics. However, much like the temperature record, no correlation could be found. With neither temperature nor precipitation showing any correlations with the terminus record, other factors must have contributed to the delayed reactions to each change in climatic conditions.

Other Contributing Factors

Similar to that of both Klickitat and Rusk glaciers, Wilson Glacier's lowest 1,000 m (3,281 ft) of terminus is heavily covered in up to 10 m (33 ft) of debris, brought down from the northern edge of Roosevelt Cliffs and Victory Ridge. The 600 m (1,969 ft) wide ablation zone of Wilson Glacier is covered with such heavy debris that it is often indistinguishable as a glacier. With this condition making surface ablation negligibly small, it is the likely cause for a significantly delayed response to climatic changes.

In addition to debris cover, ablation rates on Wilson Glacier are lessened from a northwest-facing aspect. Much of the incoming solar radiation on bare ice is either reflected during hours of high solar angle or completely shaded by the summit cap and Roosevelt Cliffs by late-afternoon. This combination of radiational shading and debris cover has allowed the Wilson Glacier to persist longer into periods of warmer climate than similar glaciers in the region.

Lyman Glacier

Temperature Analysis

With glacial cycles showing periods approximately equal to PDO phases, temperature patterns were tested using a Spearman rank analysis against the known terminus locations from 1959 to 2003. At a significance level of .05, Lyman Glacier showed no correlations with annual temperature for lag times up through 20 years.

Precipitation Analysis

Precipitation patterns at Mount Adams were also tested against the known terminus locations of Lyman Glacier from 1959 to 2003. Since late lying snow cover in the 1949 air photo record prevented an accurate calculation of the terminus position, it was not used. Comparable to the results of the temperature record, no significant correlations could be made with precipitation. With both tested climate variables showing no correlations with glacier change for common lag times, other geographic factors are accountable for the variations in terminus position.

Other Contributing Factors

With a lack of correlation between Lyman Glacier's terminus and climate at typical lag times, other local geographic features such as debris cover must be considered as contributing factors for the abnormal response. Currently, the lowest 550 m (1,804 ft) of terminus are covered in rocky debris, although, not as heavily as each of the eastern slope glaciers. With upwards of 1 m of debris covering the terminus, surface ablation has been significantly reduced, allowing more stability during periods of climate change. However, by having other similar characteristics as the adjacent advancing glaciers such as source area and length, it is likely that Lyman Glacier has a lag time greater than what was tested and may still be responding to the LIA climate shift.

Lava Glacier

Temperature Analysis

Temperature patterns at Mount Adams were tested using a Spearman rank analysis against the known record of terminus change for Lava Glacier. With heavy cloud cover and substantial amounts of late-lying snow, the 1949 air photo was not used as the terminus location could not be accurately determined. However, beginning in 1959 with a known location of Lava Glacier's terminus, Spearman rank analysis was applied with a significance level of .05. Despite having similar patterns as PDO phases, results of multiple tests for correlation with annual temperature, ablation season temperature, and accumulation season temperature, no significant correlations were found.

Precipitation Analysis

In addition to temperature, precipitation patterns at Mount Adams were tested for correlation with the terminus locations of Lava Glacier from 1959 to 2003. Similar to that of Lyman Glacier for the same time periods, all but one Spearman rank test resulted in p values outside the acceptable level of significance for all lag times up through 20 years. The only test returning a significant value was ablation season precipitation tested for periods in-between air photo records (Table 6). With a lack of significant correlations between both tested climate variables and glacier change for common lag times, other contributing factors have been crucial to the variations in terminus position.

Table 6

Select Lava Glacier r Values and p Values.

Variable	Value	
	r	*p*
Ablation season precipitation between years of air photo records	.83	.03

Other Contributing Factors

Debris cover on Lava Glacier has likely played an important role in its terminus fluctuations over the last century. Currently, the lowest 800 m (2,625 ft) of glacier is approximately 80% covered in varying depths of debris, brought down from the steep cirque headwall and North Cleaver. While bare ice is visible in several sections of the western half of the ablation zone, the eastern half is buried with up 10 m (33 ft) of large rocky debris. The differential coverage of debris over the last 50 years clearly shows its effects on ablation. Since 1959, the center line of the terminus retreated through 1967, advanced through 1981, and is now in a current state of retreat. With a deep layer of debris protecting Lava Glacier's eastern half of the ablation zone, the terminus has slowly but steadily advanced during each of these same time periods. Resulting from this inconsistent coverage of debris, terminus measurements may not reflect accurate responses to climate change. Additionally, unlike other glaciers on the east slopes of Mount Adams, Lava Glacier is not fed directly from the summit cap, but rather from a large cirque at approximately 2,900 m (9,514 ft). With a significantly smaller accumulation zone, Lava Glacier's terminus will not react in a similar fashion.

Adams Glacier

Temperature Analysis

With general trends indicating climate patterns paralleling terminus movements, temperature patterns at Mount Adams were checked using a Spearman rank analysis. Correlation tests were performed utilizing the air photo record from 1959 to 2003. While the 1949 record was available, it was not used as late lying snow and cloud cover prevented accurate location of the terminus and subsequent measurements. No correlations were found despite showing similar patterns to warm and cool phases of the PDO.

Precipitation Anyalysis

In addition to Spearman rank analysis of temperature and glacier change, precipitation patterns were tested against the known terminus locations from 1959 to 2003. Only mean annual precipitation returned a *p* value within the acceptable level (Table 7). With both climate variables being tested and having only one correlation, lag time of Adams Glacier is either greater than normal or other variables having played an important role in its' terminus fluctuations.

Table 7

Select Adams Glacier r Values and p Values

Variable	Value	
	r	*p*
Mean annual precipitation 5-year lag	.89	.02

Other Contributing Factors

Advance and retreat of Adams Glacier, while being driven by climate, has been influenced by other processes such as debris cover. Currently the lowest 500 m (1,640 ft) of the ablation zone is completely covered in rocky debris, with a large debris ridge extending another 900 m (2,953 ft) upslope. While the majority of Mount Adams' Glaciers have shown significant advance and retreat over the last 50 years, Adams glacier has been relatively stable. Following the extreme retreat of over 1,500 m (4,921 ft) since the early 1900s, Adams Glacier has not significantly advanced or retreated since the 1950s. This stability can partially be attributed to the large amounts of rocky debris drastically reducing the ablation rate of the terminus. Additionally, the rock outcrop at Adams Glacier's terminus may further be stabilizing its current position. Subglacial topography that rapidly changes the slope of a glacier, such as outcrops and cliffs, increases the speed at which a glacier flows. This extending flow thins ice and often disconnects a glacier's snout in years of retreat. Once a glacier has been disconnected from a portion of its ablation zone, the new terminus above will often remain in place for many years until ablation processes thin the ice, allowing for continued retreat (Benn & Evans, 1998).

Pinnacle Glacier

Temperature Analysis

Quantitative analysis of temperature patterns and terminus fluctuations at Mount Adams was performed using a Spearman rank analysis for the period of known terminus locations (1949-2003). Results show two correlations (Table 8). First, a strong negative correlation, having an *r* value of -.82 ($p = .04$), can be seen for maximum temperatures within the accumulation season at a 15-year lag time. Additionally, minimum temperatures in the ablation season at a 10-year lag showed strong negative correlations with an *r* value of -.89 ($p = .03$). While Pinnacle Glacier's lag time is assumed to be between 10 and 15 years from the correlation analysis, all times were checked for up through 20 years, with other time periods returning no P-values within the acceptable level of significance.

Table 8

Select Pinnacle Glacier r Values and p Values

	Value	
Variable	*r*	*p*
Maximum accumulation season temperature, 15-year lag	-.82	.04
Minimum ablation season temperature, 10-year lag	-.89	.03

Precipitation Analysis

With precipitation being so closely related to temperature in determining the effects on glacier change, a Spearman rank analysis was used to test correlations between precipitation and the known record of terminus locations from 1949 to 2003. While some similarities can be seen between the advance and retreat of the terminus and PDO cycles, results for each of the correlation tests with precipitation produced no *p* values within the acceptable level of significance. Only one correlation connecting climate with terminus advance and retreat, other mechanisms such as debris cover have likely altered the response and lag times of Pinnacle Glacier.

Other Contributing Factors

Debris cover on Pinnacle Glacier is split laterally down its centerline, rather than uniformly over the ablation zone. The steep, unstable cliffs of the Pinnacle frequently deposit large amounts of rocky debris onto the glacier's upper accumulation zone. This debris covers the northern half of the glacier, extending its entire length down through the terminus. As a result, very little exposed ice is visible, drastically reducing ablation rates throughout the glacier's entire northern edge.

South of Pinnacle Glacier's headwall, the southwest ridge extends down from the Pinnacle, containing the glacier's left lateral margin. Extending for the entire length of Pinnacle Glacier, this ridge allows for additional debris-free accumulation to be supplemented to the glacier. This unique landscape clearly shows the effects of debris cover on a glacier's terminus with an unmistakable division between debris-free and complete debris coverage. The left lateral terminus, being primarily free of debris cover, has advanced and retreated several times throughout the past century, while the right lateral terminus has continued to advance through the same periods (Figure 22).

With debris cover altering the effects of climate change on terminus behavior of Pinnacle Glacier's northern extent, the measured terminus to the south has only experienced minor fluctuations despite being completely free of debris. One explanation for the relatively insignificant terminus response of Pinnacle Glacier is the existence of a steep, sharply crested terminal moraine immediately below the present day terminus. Since 1959, with the known record of terminus positions, Pinnacle glacier's downslope movement has been inhibited by this 50 m (164 ft) tall moraine, but has rather moved vertically up and down its face.

Crescent Glacier

Temperature Analysis

Quantitative analysis of the temperature record and Crescent glacier's terminus was accomplished by using a Spearman rank correlation. Testing the known record of Crescent glacier's terminus position (1949-2003) at a significance level of .05 shows several significant correlations (Table 9). A strong negative correlation can be seen with both minimum and maximum ablation season temperatures at a 10-year lag time, with r values of -.89 (p = .03). Additionally, the mean deviation of minimum annual temperatures at a 10 year lag time produced a strong negative correlation with an r value of -.82 (p = .04). With Crescent glacier exhibiting three strong negative correlations, terminus behavior is shown to be strongly influenced by temperature patterns at a 10-year lag time.

Table 9

Select Crescent Glacier r Values and p Values

	Value	
Variable	*r*	*p*
Abl Tmin 10-year lag time	-.89	.03
Abl Tmax 10-year lag time	-.89	.03
Mean Dev Tmin 10-year lag time	-.82	.04

Precipitation Analysis

In addition to the temperature record, Crescent Glacier's terminus record was tested against precipitation patterns using a Spearman rank correlation analysis. Results returned no p values within the acceptable level of significance of .05 for all lag times up through 20 years. While terminus positions of Crescent Glacier responded strongly with temperature, but not precipitation patterns, it is likely that other factors contributed to the individual responses to climate change since the mid-1900s.

Other Contributing Factors

Although climate patterns can be viewed as the primary contributing factor to a glacier's terminus fluctuations, other geographic features can significantly impact terminus movements. Unlike the majority of glaciers tested, Crescent Glacier has little to no debris cover at its terminus, thus having minor impact on ablation rates. One noticeable feature, however, is the relatively large (~30 m high) end moraine encompassing all sides of the terminus. Over the past 50 years, Crescent Glacier's fluctuations have been bound by this moraine, only advancing and retreating several meters vertically up and down the face. This alone has diminished the downslope movement of the glacier and subsequently the results of correlation tests. Presently, thinning of the terminus has reached a point where rapid retreat will soon follow. If current climate trends persist, Crescent Glacier will likely recede back to a point where it no longer can sustain itself and its classification as a glacier.

Gotchen Glacier

Temperature Analysis

As climate mutually affects glacier health through both temperature and precipitation, Gotchen Glacier's known terminus fluctuations (1949-2003) were first tested for correlations with temperature using a Spearman rank analysis. Testing lag times up through 20 years at a significance level of .05, several correlations can be seen with annual temperature (Table 10). At a 10-year lag, both mean and maximum annual temperatures displayed strong negative correlations with r values of -.89 (p = .03) and -.94 (p = .02) respectively. Further testing of accumulation and ablation season temperatures, similar results can be seen. Maximum temperatures within the accumulation season showed a strong negative correlation at a 10-year lag time, while

Table 10

Select Gotchen Glacier r Values and p Values

Variable	Value	
	r	*p*
Mean annual temperature, 10-year lag	-0.89	.03
Maximum annual temperature, 10-year lag	-0.94	.02
Maximum accumulation season temperature, 10-year lag	-0.89	.03
Mean ablation season temperature, 5-year lag	-0.89	.03
Minimum ablation season temperature, 5-year lag	-0.89	.03
Maximum ablation season temperature, 5-year lag	-0.94	.02

minimum, maximum, and mean ablation season temperatures negatively correlated at a 5-year lag time. Annual and seasonal temperatures tested beyond a 10-year lag time produced no *p* values within the acceptable level of significance.

Precipitation Analysis

After showing strong correlations with temperature at 5-10 year lag times, precipitation patterns were tested for similar relationships using a Spearman rank analysis. While multiple correlations with temperature can be seen for Gotchen glacier, Spearman rank tests on precipitation resulted in no P-values within the acceptable level of significance of .05 for all tested lag times up through 20 years. With a total glacier length being less than 500 m (1,640 ft), lag times beyond this time frame are unlikely. Lack of correlation with precipitation suggests that temperature is the dominant climatic variable in determining the response of Gotchen Glacier.

Other Contributing Factors

Unlike the majority of Mount Adams' glaciers, Gotchen has little to no debris cover to affect ablation rates of the terminus. While some rockfall can be observed, there is no significant headwall or confining ridges to supply material to the glacier surface. Additionally, the large 60+ m (197 ft) moraine has relatively confined the glacier over the last century to a maximum length of 750 m (2,461 ft). Any advance of the glacier front during the last century would have been significantly diminished. With the lowest accumulation zone of all Mount Adams' glaciers, temperature changes likely have the greatest impact, with only slight variations determining whether precipitation falls as snow or rain, thus being the predominant climate variable in determining the glacier's response.

Mazama Glacier

Temperature Analysis

Testing of Mazama Glacier's main terminus for correlations with temperature was accomplished using a Spearman rank analysis. With late lying snow covering the terminus in the 1949 air photo record, testing of the known positions (1959-2003) resulted in negative correlations with both mean and minimum annual temperatures with *p* values of -.86 ($p = .03$) and -.93 ($p = .02$) respectively (Table 11). Additional tests of temperature specifically within the accumulation and ablation seasons resulted in negative correlations with mean, minimum, and maximum accumulation season temperatures at a 15-year lag. While temperature within the accumulation season showed multiple correlations, ablation season temperatures did not. Mazama Glacier's secondary terminus to the south was subsequently tested using the same statistical tests and lag times. Based on the temperature record since 1949, this smaller terminus showed no significant relationships or correlations.

Precipitation Analysis

Precipitation patterns at Mount Adams were also tested against the known terminus locations of Mazama Glacier from 1959 to 2003. Mean annual precipitation at a 10-year lag produced an r value of .89 ($p = .02$), while accumulation season precipitation

Table 11

Select Mazama Glacier r Values and p Values

	Value	
Variable	*r*	*p*
Mean annual temperature, 15-year lag	-.86	.03
Minimum annual temperature, 15-year lag	-.93	.02
Mean accumulation season temperature, 15-year lag	-.89	.03
Minimum accumulation season temperature, 15-year lag	-.89	.03
Maximum accumulation season temperature, 15-year lag	-.82	.04
Mean annual precipitation, 10-year lag	.89	.02
Mean accumulation season precipitation, 10-year lag	.82	.03
Mean accumulation season precipitation, 15-year lag	.89	.01
Mean deviation of precipitation, 10-year lag	.89	.02

significantly correlated at both 10- and 15-year lag times, producing r values of .82 (p = .03) and .89 (p = .01) respectively (Table 11). With results covering multiple lag times, precipitation was checked for correlations using the standard deviation at all lag times. At a 10-year lag time, the standard deviation of mean precipitation correlated with an r value of .89 (p = .02).

Precipitation trends at Mount Adams were also checked against Mazama Glacier's secondary debris covered terminus using the same statistical tests and lag times. Similar to the results with temperature, no significant correlations were found with annual precipitation, ablation season precipitation, or accumulation season precipitation since 1949.

Other Contributing Factors

With Mazama Glacier's two relatively close termini responding to climate change in dissimilar fashions, other geographic factors must be examined when determining the response. The most noticeable feature of the southern terminus is a thick layer of debris cover, absent at the main stem terminus. This debris, brought down from the steep cliffs of the Suksdorff Ridge above is visible in the air photo record beginning in 1959. Ablation at the terminus has significantly been reduced over the last 50 years and allowed the southern terminus to maintain a slow advance since 1967, while the main-stem terminus experienced several small advance and retreat phases. The amount of rock and debris supplied by the Suksdorff Ridge has been substantial enough to create a rock glacier between the Mazama and Gotchen glaciers, one of several on Mount Adams. Furthermore, being on the leeward side of Suksdorff Ridge, snow drift provides an additional source of accumulation, giving the main stem of Mazama Glacier more stability and the southern terminus enough additions to slowly advance.

Historic Streamflow Results

Streamflow contributions by Mount Adams' glaciers were tested using two U.S. Geological Survey stream gauges on the Klickitat River. With no historic streamflow measurements found on any of the outlet streams of Mount Adams' 12 glaciers, gauges were used on the Klickitat River above and below the addition of Big Muddy and Little Muddy Creek (Figure 36). On the eastern flanks of the mountain, these two creeks drain four glaciers, the Mazama, Klickitat, Rusk, and Wilson. To acquire approximate runoff from these glaciers, total flow above Little Muddy Creek was subtracted from the total

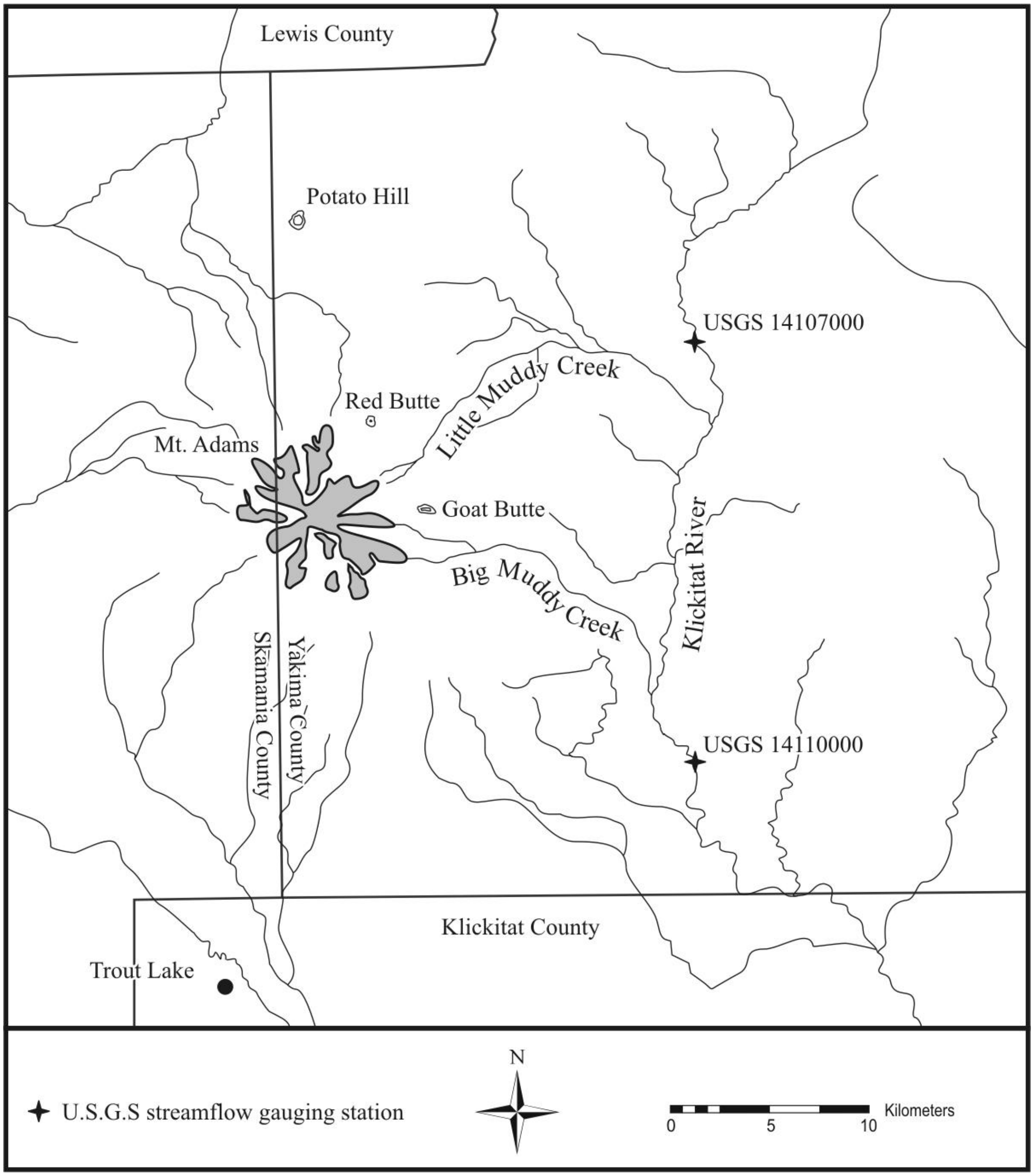


Figure 36. Mount Adams' drainages and Klickitat River streamflow gauges.

flow below Big Muddy Creek (Table 12). While this 20 km (12 mi) section of river has other streamflow contributions in addition to Little and Big Muddy Creeks, none are of equal magnitude. It is assumed that these two drainages account for greater than 75% of input along this section of the Klickitat River. It must be noted that for the water year 1957, no data was available in the record and was therefore omitted in the results.

Additions to the Klickitat River were first checked for changes in total flow from 1945 to 1971. Mean annual water year flow for the 26-year period was 4.66 x 10^6 ft^3, with its highest total flow of 6.2 x 10^6 ft^3 in 1958, and lowest total flow of 3.59 x 10^6 ft^3 in 1963. While interannual flows varied, no visible linear trends were seen in total yearly streamflow.

With mean annual flow determined, examinations were made for monthly flow and monthly percentage of total streamflow within the water year (Table 12) (Figure 37). Averages from water years 1945-1971 show peak streamflow occurs in May with 16.3%

Table 12

Average Monthly Streamflow Totals, 1945-1971. Measured Difference Between Stream Gauge 14110000 and 14107000 on the Klickitat River.

Month	Total ft^3	% of yearly flow
October	241,831	5.2
November	283,146	6.1
December	319,016	6.8
January	311,502	6.7
February	336,362	7.2
March	338,584	7.3
April	482,698	10.3
May	759,498	16.3
June	663,780	14.2
July	423,027	9.0
August	278,588	6.0
September	226,514	4.9
Total	4,664,546	100.0

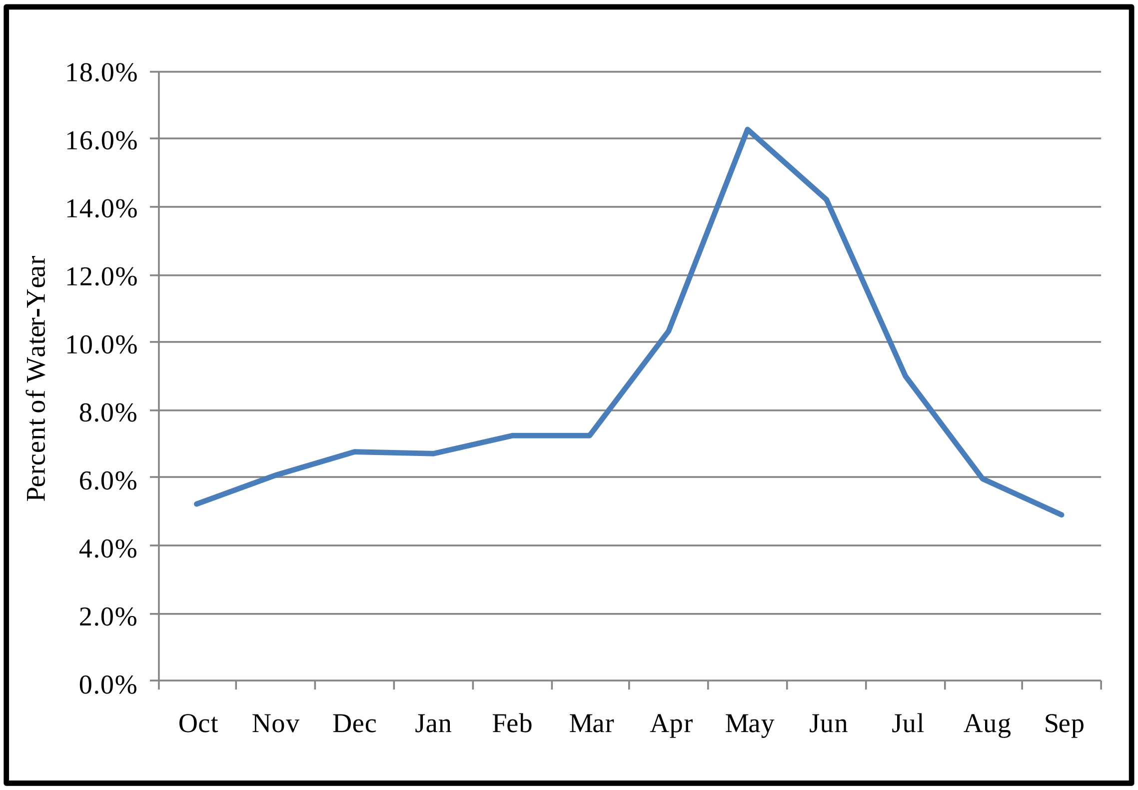


Figure 37. Average monthly percentage of total water year streamflow, Klickitat River, 1945-1971. Difference measured between gauge 14110000 and gauge 14107000.

of the total yearly flow and runs at a minimum in September with 4.9%. Mean springtime runoff (April–June) was checked to determine flow trends for the same period of time. In 1945, mean spring flow was at 42% of the total water year, decreasing to 40% by 1971. With a decrease in spring flow, percentages were calculated for winter months, November to March (Figure 38). During these months, total flow increased from approximately 32% in 1945 to 37% in 1971. Similar to spring, runoff during summer months (July-September) decreased from 21% of total water year flow in 1945 to 19% in 1971 (Figure 38). With trends showing decreased spring and summer runoff and increased winter runoff, climate patterns must be looked at for the origin of fluctuations.

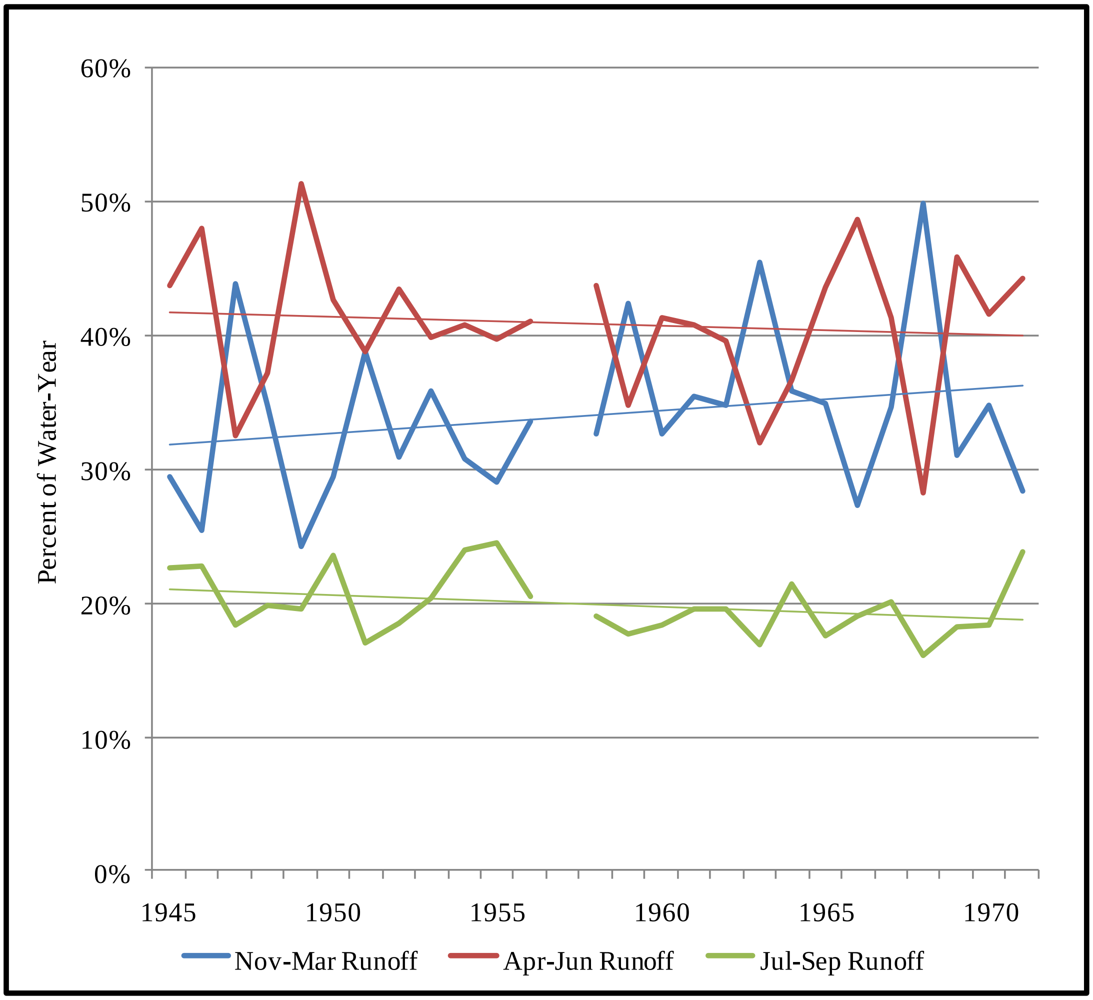


Figure 38. Comparison of seasonal runoff by percentage of total water year streamflow. Difference measured between gauge 14110000 and gauge 14107000.

During this time period, accumulation season temperature, while below the 105-year mean, was gradually increasing. Accumulation season precipitation was significantly higher than the 105-year mean. With rising temperatures and increased precipitation, more rain on snow events are likely to occur, enhancing melt. During the ablation season, temperatures were below the 105-year mean, while precipitation never significantly fluctuated away from the mean. These decreased temperatures were likely to slow the ablation process on Mount Adams glaciers, decreasing meltwater. In addition, heavy debris cover on each of the eastern flank glaciers further decreased the amount of melt during the ablation season.

Streamflow timing was calculated by determining the Julian Day within the water year on which 50% of that water year's total flow occurred, for each of the recorded years, 1945-1971 (Figure 39). These results show a change to an earlier Julian Day, from an average of May 3rd in 1945 to April 25th by 1971. This confirms the results of seasonal percentage shifts within the water year. With increases in winter streamflow and decreases during spring and summer, peak streamflows are occurring earlier in the year.

Since 1971, runoff has likely begun to decline from the glaciers on Mount Adams' eastern flank. While the termini have cumulatively advanced, downwasting of

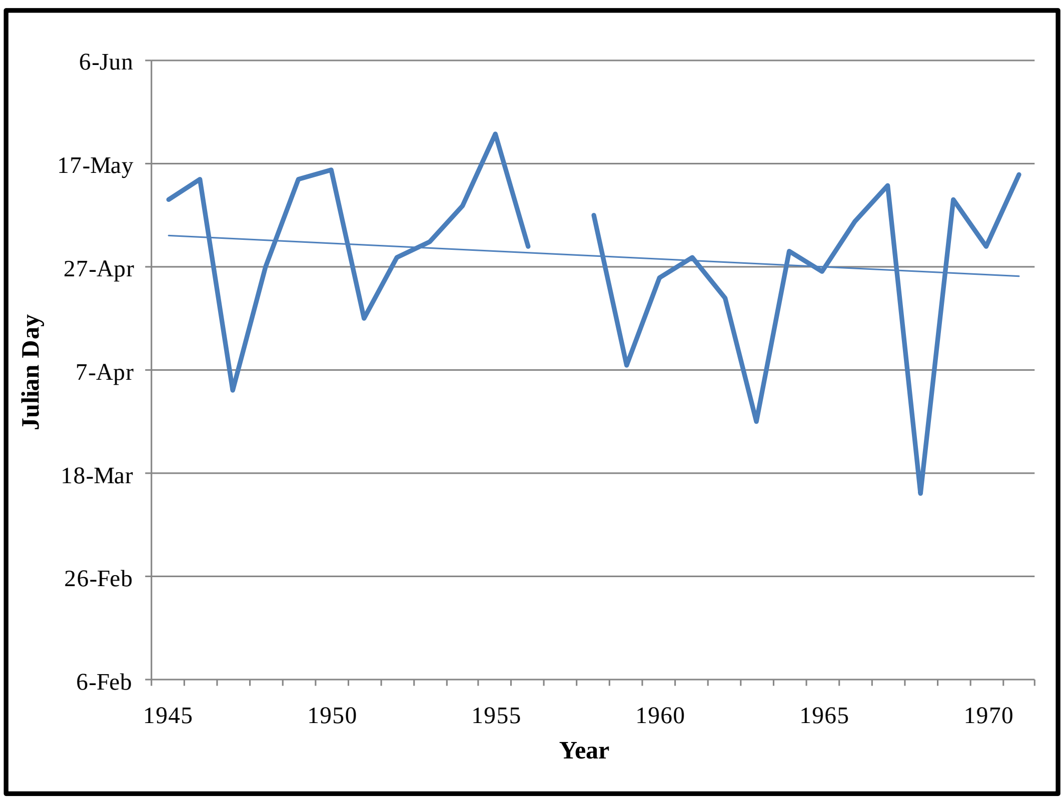


Figure 39. Julian day of runoff from Mount Adams east flank, 1945-1971.

the glacier surface above the debris covered areas can be seen on the Klickitat and Rusk glaciers. Additionally, the termini advances seen on the Klickitat, Rusk, and Wilson glaciers have slowed or stopped since 1971. Runoff from similar glaciers in the Pacific Northwest suggests that after an initial increase in runoff, decline in total streamflow soon follows (JISAO/SMA Climate Impacts Group, 1999; Pelto, 2007). Additionally, the timing of streamflow is expected to continue shifting. With increased temperatures, accumulation season precipitation is more likely to fall as rain rather than snow, reducing the amount of snowpack and storage for summer months.

CHAPTER VI

SUMMARY

The objectives of this research were to determine 1) how ten of the twelve glaciers on Mount Adams fluctuated since ~1900 A.D.; 2) what factors were responsible for causing these fluctuations; and 3) what were the historic, current, and possible future effects of glacier change on streamflow originating from Mount Adams' glaciers.

Glacier Terminus Fluctuations

Following the Little Ice Age, regional warming caused a cumulative retreat of all Mount Adams' glaciers to their positions observed by H. F. Reid in 1901. While no quantitative records are available through the first half of the 20th century, overall retreat can be seen between 1901 and 1949. Since 1949, however, this research reveals a diverse set of fluctuations for each of Mount Adams' glaciers.

Air photo analysis of the glaciers on the east slopes of the mountain, including the Klickitat, Rusk, and Wilson, shows cumulative advances between 1949 and 2003 (Table 3). While the Wilson Glacier continued to retreat through 1959, by 2003 it advanced to a position 65 m (213 ft) beyond its 1959 minimum. The Klickitat and Rusk glaciers, alternatively, showed continual advance between each year of record since 1949 with a total of 377 m (1,237 ft) and 605 m (1,985 ft) gained respectively. The advances seen at both of these glaciers have slowed or stopped, however, since 2000.

The two glaciers on the north side of Mount Adams, Lyman and Lava, both have generally retreated since 1949 (Table 3). Retreat can be seen at both termini between

1959 and 1967, followed by advances through 1981. The Lyman and Lava glaciers currently are in a phase of retreat, now with cumulative losses of 124 m (407 ft) and 129 m (423 ft) respectively since 1949.

Adams and Pinnacle glaciers, both located on the west slopes of Mount Adams, have generally been stable since 1949. While both cumulatively retreated in the first half of the century, current terminus movements have slowed or stopped (Table 2). The Adams Glacier terminus now rests atop a rock outcrop, currently stabilizing terminus movement. Pinnacle Glacier, however, presents a unique circumstance. While the measured terminus, located at a point behind a significantly large terminal moraine, has shown several brief cycles of advance and retreat since 1949, a heavily debris-covered section of the glacier to the north has continually advanced over the last 50 years.

Glaciers on the south and southeast side of Mount Adams were inconsistent in their fluctuations. While the Crescent and Gotchen glaciers both had cumulative retreat since 1949, the Mazama Glacier's terminus has remained in close proximity to its former location, showing only minor phases of advance and retreat. The net loss of 18 m (59 ft) by the Crescent and 147 m (482 ft) by the Gotchen were the result of thinning termini and retreat from their terminal moraines. Rocky outcroppings at the terminus of Mazama Glacier have helped maintain its current position; however, severe thinning at the terminus will eventually result in further retreat if warming trends continue.

The general trend of terminus fluctuations at Mount Adams shows a cumulative retreat from 1901 to 1949, followed by a mid-century advance of eight of the ten studied glaciers. During the second-half of the 20th century, however, terminus positions showed both advance and retreat through 1994. As of 2003, all 10 glaciers were retreating or had slowed in their advance. These fluctuations compare well to the changes in glacier area shown by Sitts et al. in 2010. Results from that study show a loss of total glacier area from 1904 to 1969, followed by a slower rate of decrease or advance to 1998. Between 1998 and 2006, all but the Lyman glacier decreased in area.

The pattern of glacier fluctuations seen at Mount Adams parallels that seen within other regions of the PNW. Glaciers at Mount Hood show a period of retreat during the first-half the 20th century, followed by an advance through the mid-1970s. Since the late-1970s, retreat was again the general trend at Mount Hood through the mid-1990s (Lillquist & Walker, 2006). At Mount Rainier, all the major glaciers retreated between 1913 and the late-1950s. This was followed by periods of advance through the early-1980s and retreat through the mid-1990s (Nylen, 2004). This general trend suggests an interdecadal-scale, regional weather and climate pattern influencing PNW glacier fluctuations.

Factors Influencing Glacier Fluctuations

Climate patterns at Mount Adams show increasing precipitation with decreasing temperatures from 1900 to 1925. This was followed by lower-than-normal precipitation and rising temperatures through 1946. A climate shift was then seen between 1946 and 1976, dominated by above-normal precipitation and below-normal temperatures. Since 1976, precipitation has remained relatively near the 105-year mean while temperatures have dramatically been on the rise. While the response of Mount Adams' glaciers showed similarities between aspects, no Spearman rank correlations were found between the glacier termini over the 1949-2003 period. The Klickitat, Rusk, Gotchen, and Mazama glaciers each showed correlations with mean annual temperature, while the Pinnacle and Crescent glaciers only responded to seasonal temperature extremes. Additionally, the Klickitat and Mazama glaciers were the only three to correlate with accumulation season precipitation (Table 13). The Wilson and Lyman glaciers did not show any correlations with either temperature or precipitation, seasonally or yearly, at any of the tested lag times. With such a varied response to climate, differences in terminus fluctuations at Mount Adams were the result of a variety of local factors such as aspect, source area, and debris cover (Table 14). The combined effect of these local glacier characteristics on accumulation and ablation rates likely obscured the climate correlation for many of Mount Adams' glaciers.

Comparing the aspect of each glacier to the recorded terminus fluctuations, we see several unusual similarities (Table 14). The three east and northeast facing glaciers cumulatively advanced between 1949 and 2003, while north- and south-facing glaciers retreated. Typically, glaciers with north-facing aspects are more stable as they receive less incoming solar radiation and have reduced ablation rates. However, the Lyman and Lava glaciers experienced the greatest amount of retreat for the measured time period. The Adams and Pinnacle glaciers, being west and southwest facing, saw little change over the last 50 years. Although aspect generally influences ablation rates, the measureable affects on Mount Adams' glacier termini are overshadowed by other characteristics such as debris cover.

Table 13.

Significant Temperature and Precipitation Correlations with Glacier Fluctuations at Mount Adams.

Temperature	Precipitation
Klickitat	Klickitat
Mean annual 5-year lag	Mean annual 5-year lag
Minimum annual 5-year lag	Mean accumulation season 5-year lag
Mean ablation season between years	
Rusk	~~Rusk~~
Mean annual 10-year lag	
Minimum annual 10-year lag	
Mean accumulation season 10-year lag	
Minimum accumulation season 10-year lag	
Maximum accumulation season 10-year lag	
~~Wilson~~	~~Wilson~~
~~Lyman~~	~~Lyman~~
~~Lava~~	Lava
	Mean ablation season between years
~~Adams~~	Adams
	Mean ablation season between years
Pinnacle	~~Pinnacle~~
Maximum accumulation season 15-year lag	
Minimum ablation season 10-year lag	
Crescent	~~Crescent~~
Minimum ablation season 10-year lag	
Maximum ablation season 10-year lag	
Gotchen	~~Gotchen~~
Mean annual 10-year lag	
Maximum annual 10-year lag	
Maxumum accumulation season 10-year lag	
Mean ablation season 5-year lag	
Minimum ablation season 5-year lag	
Maximum ablation season 5-year lag	
Mazama	Mazama
Mean annual 15-year lag	Mean annual 10-year lag
Minimum annual 15-year lag	Mean accumulation season 10-year lag
Mean accumulation season 15-year lag	Mean accumulation season 15-year lag
Minimum accumulation season 15-year lag	
Maximum accumulation season 15-year lag	

Note. Strikethrough name indicates no significant correlation.

Table 14

Physical Characteristics of Mount Adams' Glaciers

Glacier	Correlation with temperature	Correlation with precipitation	Aspect	Upper elevation (m)	Lower elevation (m)	Length (m)	Slope %	Debris cover	Change since 1949
Klickitat	Yes	Yes	E	3705	2008	3680	24.8	High	Advanced
Rusk	Yes	No	E	3705	2161	3251	25.4	High	Advanced
Wilson	No	No	NE	3655	2290	3132	23.6	High	Advanced
Lyman	No	No	N	3678	2245	3129	24.6	Medium	Retreat
Lava	No	Yes	N	2970	2312	1784	20.3	Low/High	Retreat
Adams	No	Yes	NW	3743	2100	4133	21.7	Medium	Little change
Pinnacle	Yes	No	W	3215	2158	2520	22.8	Low/High	Little change
Crescent	Yes	No	S	2594	2389	507	22.0	Low	Retreat
Gotchen	Yes	No	SE	2484	2249	464	26.9	Low	Retreat
Mazama	Yes	Yes	SE	3316	2550	1894	22.0	Low	Little change

The source area for the Klickitat, Rusk, Wilson, Lyman, and Adams glaciers is Mount Adams' summit cap. While the Roosevelt Cliffs prevent the Rusk Glacier from being directly connected to this large source area, snow and ice from the summit cap spill over the cliff face and provide additional accumulation for the glacier. Similarly, Wilson Glacier's accumulation zone appears to start just below the Roosevelt Cliffs; however, ice flowing down Lyman Glacier's eastern couloir spills over onto Wilson Glacier and over the cliff face itself. With the Klickitat, Rusk, and Wilson glaciers advancing since 1949, Lyman Glacier retreating, and the Adams Glacier showing little movement, source area cannot be the sole cause of the terminus fluctuations. These same five glaciers additionally represent the longest of Mount Adams' glaciers, each over 3 km (1.9 mi) in length.

Debris cover on Mount Adams' glaciers is varied, ranging from heavy coverage on the Klickitat, Rusk, and Wilson glaciers, to light or no coverage on the Crescent, Gotchen, and Mazama glaciers. Comparing this to the recorded terminus fluctuations, several similarities can be seen. The only glaciers that had cumulative terminus advance from 1949 to 2003 were the glaciers with large amounts of debris cover (Table 14). The three glaciers with little debris cover either retreated or showed no cumulative terminus change. The Lava and Pinnacle glaciers, with variable amounts of debris cover clearly show the effects of debris on ablation rates. Both glaciers have areas of heavy and light supraglacial debris. While the ablation zone of the Lava Glacier with bare ice retreated, the adjacent debris covered terminus advanced over the same time periods. Similarly, Pinnacle Glacier's bare ice terminus showed little change, while the debris-covered terminus slowly advanced. Although climate patterns are ultimately the source of a glacier's advance and retreat, each of these local characteristics play an important role in the extent and rate at which the fluctuations occur.

Effects on Streamflow

Runoff from Mount Adams' glaciers was measured as the difference between two stream gauges on the Klickitat River, one above and one below the contribution of meltwater from four glaciers. While long-term and consistent records for streamflow are scarce, measurements taken between 1945 and 1971 reveal several patterns. Meltwater from the Mazama, Klickitat, Rusk, and Wilson glaciers peaked in May, with minimum contributions occurring in September. Seasonal trends in meltwater during this 26-year period show a decrease in spring and summer runoff, from 42% to 40% of the water-year total and 21% to 19% respectively. Alternatively, winter runoff increased, from 32% to 37%. With shifting seasonal runoff, the Julian day in which 50% of the water-year flow is exceeded has been occurring earlier in the year, shifting from May 3rd in 1945 to April 25th by 1971.

In the 26-year period used in this research, no significant change in total glacial runoff was found, only a small change in the timing of that flow. While the timing shifts can possibly be attributed to shifting temperature and precipitation patterns, the lack of change in total streamflow is most likely the result of the minimal change in available area for melting. With streamflow measurements being taken for the contributions made by the Klickitat, Rusk, and Wilson glaciers, debris cover over these glaciers' ablation areas prevents much of the surface melt during the ablation season.

CHAPTER VII

IMPLICATIONS FOR RESOURCE MANAGEMENT

In the populated region downstream of Mount Adams, the impacts of climate change are likely to be amplified as the region depends on glacier-derived freshwater. In this area of Washington State, summer flows are supported by glacier melt, with the size of the glacier and rate of annual melt determining the glacier contribution. When the glaciers are in equilibrium, the amount of precipitation stored in winter is matched by summer melt. However, with global warming likely causing glaciers to retreat, flows are expected to initially increase during summer as a result of water being released from long-term storage. As these glaciers are reduced in size, summer flows will no longer be supported and will decline to below present levels. The duration of increased flows will depend largely upon the rate at which the glacier melts and its yearly accumulation (Braun et al., 2000). With rapidly increasing population in areas downstream of Mount Adams, and subsequent increases in water demand, managers will need to assess our current and future situations and determine when and how changes will be made (JISAO/SMA Climate Impacts Group, 1999).

Meltwater from Mount Adams' glaciers flows into several drainage basins, directly from runoff and indirectly through numerous springs on the lower flanks of the mountain. Originating from the south and east flanks of the mountain, water flows into the White Salmon and Klickitat Rivers. The western and northern flanks of Mount Adams drain into the Lewis and Cispus Rivers, all ultimately reaching the Columbia River. The downstream users include small agriculture and recreation-oriented towns such as Trout Lake and White Salmon, WA, to the larger metropolitan areas of Portland, OR. Potential use consists of agriculture and irrigation, hydroelectric power generation, municipal water supply, recreation, and fish migration. The rivers in this region are also primarily snowmelt-dominated, in which meltwater from accumulated winter precipitation feeds the river, having flows that typically peak in late spring and early summer. Late summer periods of low flow are then often fully allocated to the competing user groups and become sensitive to changes in supply (JISAO/SMA Climate Impacts Group, 1999).

To determine the impact of climate change on streamflow in this region, consideration must be given to the streamflow contributions made by Mount Adams' glaciers, and ultimately the impact climate has on these glaciers. This study shows the effects of a changing climate and other variables on ten glaciers and the corresponding runoff from four on Mount Adams' eastern flank. During the 26-year period of recorded streamflow contributions (1945-1971) made by the Mazama, Klickitat, Rusk, and Wilson glaciers, little change was seen in mean annual flows. As a result of heavy debris cover on three of these glaciers, their sensitivity to climate change has been decreased, allowing them to advance while similar debris-free glaciers in the region have retreated (Lillquist & Walker, 2006). As the percentage of debris cover increases, total yearly streamflow deceases. A recent study at Mount Hood has shown that a glacier with 42% debris cover will respond similar to that of a glacier 79% of its size (Nolin, Phillippe, Jefferson, & Lewis, 2010). As a result, impacts on streamflow contributions to the Klickitat River during warm PDO or ENSO phases should be significantly reduced.

While the glaciers on Mount Adams' eastern flank were cumulatively advancing, runoff measurements from 1945 to 1971 indicate that the timing of streamflow was still shifting to an earlier period in the year. With accumulation season temperatures rising through this same period, precipitation normally being accumulated in the winter was likely falling as rain, reducing the amount of storage for late-summer flow. If temperatures continue to increase, so will the amount of winter runoff. Consequently, when considering glacial meltwater contributions to streamflow, one must also consider the timing and availability of that water.

Unlike the glaciers on Mount Adams' eastern flank, the Lyman, Lava, Adams, and Pinnacle glaciers did not advance. Instead, retreat was seen on the Lyman and Lava, with the Adams and Pinnacle showing no significant change. These glaciers are far less debris covered, making them more vulnerable to climate change. Meltwater from these glaciers flows into the Cispus and Lewis rivers where it is used for hydroelectric power generation, reservoir storage, and fish migration; however, no direct measurements have been made for their contributions to streamflow.

The likely impact of a warming climate on streamflow for the Lyman, Lava, Adams, and Pinnacle glaciers will be similar to that seen in the North Cascades of Washington and at Mount Hood, Oregon (Nolin et al., 2010; Pelto, 2008). During the initial phases of a climate warming, monthly and annual water yields will be increased. If the warming continues, ablation rates will rise, leading to a significant reduction in the size of these glaciers. Corresponding with this loss in area and volume, there will be a reduction in total streamflow.

While the total contribution to streamflow made by glacier meltwater from Mount Adams may be relatively small, prior to draining into the Columbia River, the area is dependant up on glacier meltwater from additional glacierized regions such as the Goat Rocks, Mount Rainier, and Mount St. Helens. The combined flow from these areas, along with Mount Adams' western and northern slope glaciers, supply much of the late summer flow for the Lewis, Cispus, and Cowlitz rivers.

Resulting from a growing population downstream of Mount Adams' glaciers, an increase in demand for water is inevitable, even if future climate does not change. With an increase in demand for water and a potential reduction in supply, conflicts between users will certainly arise. To properly manage for future demand, an assessment of current supply needs to be completed. This can be in the form of direct measurements taken at a glaciers outlet stream, or predicted using a streamflow model (Tangborn, 1984; Chennault, 2004). By more accurately knowing our future supply of water, we can be more adaptable to climate change.

Further Research

While the effects on total yearly streamflow are buffered during climate change on Mount Adams' east flank, slight changes were seen in seasonal flow percentages. With an increase in winter runoff and corresponding decrease in summer runoff, close monitoring of these glaciers should continue. Because the Klickitat River is dominated by snowmelt, glacier meltwater in late summer becomes critical for downstream use. Any change in seasonal timing here would have the greatest effects on first and second-order watersheds, being used primarily for salmon habitat and irrigation.

Future monitoring of the effects of climate change on streamflow for Mount Adams eastern slopes needs to begin with a current assessment of glacier meltwater from the Mazama, Klickitat, Rusk, and Wilson Glaciers. Currently, the only data available is from the Klickitat River, and from only one phase of the PDO. Direct measurements of glacier meltwater from present day climate are unavailable. With no current information on daily or yearly streamflow directly from the outlet streams, gauges need to be implemented to begin a long-term monitoring program. Additionally, monitoring of glacier length, area, and debris cover will need to be continued at regular intervals.

Additional research on the effects of climate change on glacier-derived streamflow at Mount Adams should be considered to reduce the negative impacts of a future increase in demand and/or reduction in supply. In addition to updating our current glacier and streamflow monitoring at Mount Adams, a strategy for reducing demand should be considered. With the current system of prior appropriations being used in the downstream areas of Mount Adams, future increases in demand will require water managers to adapt to a growing population and changing needs. While improving the supply of water through expensive new storage projects is not always economically feasible, planning also becomes difficult when the magnitude, timing, and even the direction of the changes are unknown. Consequently, planning and adapting for future use should look into demand management. Potential use reduction and reallocation strategies could include the introduction of water markets, water banking, and encouraging water-use efficiency (JISAO/SMA Climate Impacts Group, 1999; WRIA 30 Water Resource Planning and Advisory Committee, 2008).

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