GLACIAL CHANGES BETWEEN 1985-2009 AND IMPLICATIONS FOR VOLCANIC HAZARDS AT MT. RAINIER, WASHINGTON

By

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GLACIAL CHANGES BETWEEN 1985-2009 AND IMPLICATIONS FOR VOLCANIC HAZARDS AT MT. RAINIER, WASHINGTON

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CHAPTER I

INTRODUCTION

Glaciers throughout the world have shown decreases in size in recent years (WGMS, 2008). Because of their sensitivity to temperature and precipitation changes, glaciers are good indicators for climate change (Nylen, 2001). Glaciers located in temperate areas are especially sensitive to warming due to their relatively quick flow and high mass turnover (WGMS, 2008). In areas with significant amounts of glaciation, a warmer climate can have a considerable effect.

A ~0.6ºC increase in the mean global temperature is responsible for the overall retreat of mountain glaciers since the early 20th century (Hock et al., 2005). Further decreases are expected due to increased global warming as predicted by General Circulation Models (Hock et al., 2005). Several potentially active volcanoes with rapidly thinning glaciers are located in Mexico, Columbia, Chile, and Tanzania (Tuffen, 2010). Tuffen (2010) estimates that if the current rate of thinning continues glaciated volcanoes would lose a large portion of ice. At Popocatépetl in Mexico, this has already happened. The amount of ice on Popocatépetl decreased 53% from 1996-2001, which was partially due to eruptive activity (Julio-Miranda et al., 2008). Other mountain glaciers around the world have also experienced decreases in areal extent. The World Glacier Monitoring Service (WGMS) reports that annual melting rates of mountain glaciers have doubled since the turn of the century (WGMS, 2008). New records for ice loss were also set in 2003, 2004, and 2006 (WGMS, 2008). Significant glacier changes could affect local hazards due to the decrease in glacial coverage and the increase in melt water. Glaciers, ice caps, and ice sheets cover approximately 10% of Earth's surface and contain 75% of its freshwater (UNEP, 1992; Nylen, 2001). Hazards in volcanic regions that could occur as a result of melting glaciers include lahars, debris/ice avalanches, eruptions, and jökulhlaups (glacier outburst floods) (Hoblitt et al., 1998). Recent changes in glacial extent on Mt. Rainier could increase hazard risks due to the increase in melt water and steep exposed slopes (Crandell, 1971). The large amounts of loose debris, along with slopes that have been weakened as a result of hydrothermal alteration, also increase hazard risks at Mt. Rainier (Reid et al., 2001). The amount and rate at which Mt. Rainier glaciers are retreating is important for determining risks from hazards such as lahars, debris avalanches, eruptions, and jökulhlaups.

Remote sensing provides an alternative method of monitoring glaciers changes as opposed to ground surveys or aerial photographic surveys. Glacier mapping using satellite images is generally less expensive and involves a smaller amount of labor than ground and aerial surveys (Sidjak and Wheate, 1999). Many studies have used Landsat images to map and interpret glacier changes around the world in places such as Iceland, British Columbia, Austria, and Peru (Williams et al., 1997; Sidjak and Wheate, 1999; Paul, 2002; Silverio and Jaquet, 2005). They show that satellite images are useful for collecting data on glacier extent, which can then be used for water management and climate monitoring purposes (Sidjak and Wheate, 1999). They are especially useful in places like the Tibetan Plateau, where areas with rugged terrain and lack of access make ground surveys very difficult or impossible (Zhen et al., 1998).

This study concentrates on the changes in glacier areal extent that have occurred at Mt. Rainier and some of the possible consequences of those changes in terms of volcanic hazards. The first objective of this study is to measure the changes in glacier area from 1985-2009 at Mt. Rainier with satellite images. This study maps the areal extents of glaciers and groups of glaciers on Mt. Rainier as a function of time and then examines the rate of ice loss or gain for each glacier/glacier group as well as the rate of total ice loss or gain. These measurements are compared with measurements made by the United States Geological Survey (USGS) and the

Global Land Ice Measurements from Space (GLIMS) project. The second objective is to determine the possibility of an increased risk for eruptions at Mt. Rainier due to the removal of glaciers from its slopes. This study examines the relationship between glacier change and eruption rates in the past by comparing the modeled glacier area at Mt. Rainier for the last 10 ka to the eruptive history of Mt. Rainier and other Cascade volcanoes during the same period. Any correlations between times of deglaciation and increases in eruption rates could help in predicting future volcanic activity resulting from continued glacial retreat at Mt. Rainier

CHAPTER II

STUDY SITE

Mt. Rainier is a stratovolcano that is located in the state of Washington, United States (46° 51’ N, 121° 45’ W). It is part of the Cascade Range, which extends from northern California to southern British Columbia. At 4,392 m, it is the tallest volcano in the Cascade Range (Hoblitt et al., 1998). Mt. Rainier is primarily composed of andesite along with pyroclastic flow deposits and minor tephra deposits (Reid et al., 2001). The geologic history of Mt. Rainier began approximately 500 ka ago when it began forming on top of granite and metamorphic basement rocks of Tertiary age as well as a heavily eroded volcanic edifice of Pleistocene age (Lescinsky and Sisson, 1998). Volcanism at Mt. Rainier is a result of the subduction of the Juan de Fuca Plate beneath the North American Plate (Brantley, 1994).

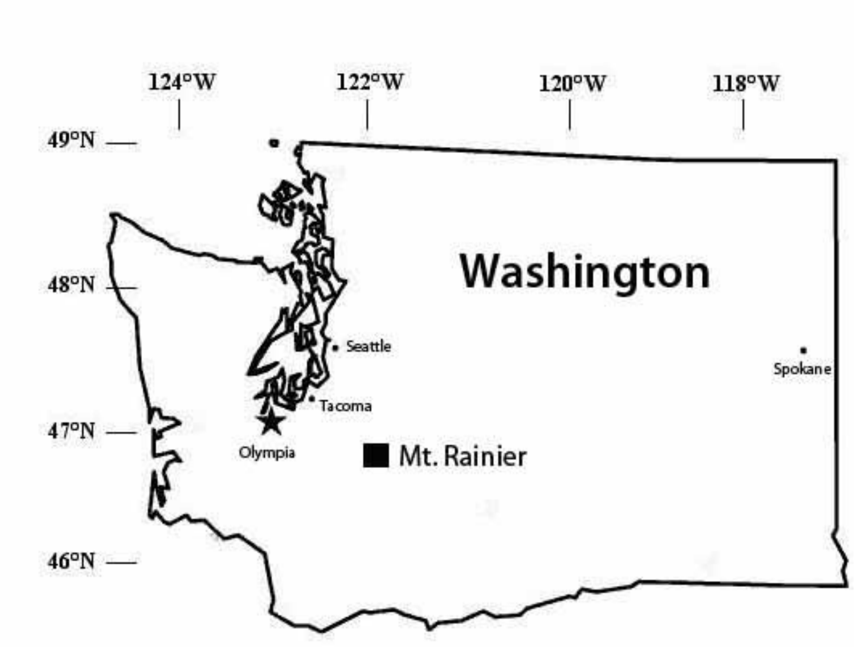
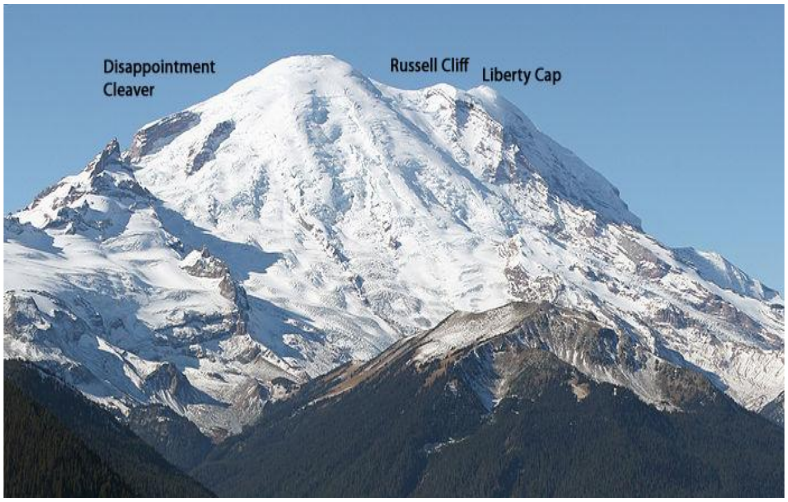


Figure 1: Location of Mt. Rainier

Mt. Rainier contains the greatest amount of glacial ice of any mountain in the conterminous United States (Hoblitt et al., 1998). There are numerous valleys radiating from the summit that contain glaciers. During the last ice age, these valleys were filled with glaciers as well as the majority of the surrounding areas (Crandell, 1969). There are 26 named glaciers on Mt. Rainier, which cover an area of ~87 km^2 and have a volume of ~4.1 km^3 (Driedger, 1993). The glaciers range from ~0.2 km^2 to ~11.2 km^2 in area (Nylen, 2001). The largest glacier in terms of area is Emmons Glacier (Nylen, 2001). However, Carbon Glacier has the greatest volume at ~0.8 km^3 (Nylen, 2001). Glacial meltwater contributes to five major rivers and their tributaries, which drain the slopes of Mt. Rainier (Crandell, 1971). These rivers are located in deep canyons 304-914 m below adjacent divides and 2,743-3,352 m below the nearby summit (Crandell, 1971). The stream gradients range from 30.5-244 m within Mt. Rainier National Park (Crandell, 1971). The steep slopes and glaciers of Mt. Rainier along with its proximity to population centers make it one of the most dangerous volcanoes in the United States. Mt. Rainier is only about 65 km southeast of Tacoma, Washington (Lescinsky and Sisson, 1998) (Figure 1). There are also more than 100,000 people in the area that lives on top of ash and mudflow deposits originating from Mt. Rainier (Moran et al., 2000).

During the last 10 ka, at least eleven eruptions have occurred (Hoblitt et al., 1995). One of these eruptions occurred ~5.6 ka and is believed to have removed a large portion of the summit (Reid et al., 2001). It also caused the Osceola Mudflow, which is the largest mudflow at Mt. Rainier during the last 10 ka (Hoblitt et al., 1998). The eruption and mudflow is estimated to have removed ~500 m of the summit resulting in a semicircular depression opening to the northeast (Fiske et al., 1963; Vallance and Scott, 1997). The outline of the previous summit is currently defined by Russell Cliff, Liberty Cap, Point Success, and Disappointment Cleaver (Vallance and Scott, 1997) (Figure 2). The volume removed is calculated to have been ~2.0-2.5 km^3 and the depression is estimated to have been 0.6 km deep and 1.8-2.0 km across (Vallance and Scott, 1997). This would make the size of the depression similar to the crater formed during the May 18, 1980 eruption of Mt. St. Helens (Vallance and Scott, 1997). Subsequent lava flows and ice have since filled the depression forming a new summit cone (Reid et al., 2001).

A.



B.

Figure 2: Views of Mt. Rainier: (A) View from the SW of Liberty Cap and Point Success (Modified from photo by Lee Siebert, 1969 (Smithsonian Institution), Retrieved February 10, 2011. http://www.volcano.si.edu/ world/volcano.cfm?vnum=1201-03-&volpage =photos&photo=045066), (B) View from the NE of Disappointment Cleaver, Russell Cliff, and Liberty Cap (Modified from photo by Walter Siegmund, Retrieved September 1, 2010. http://en.wikipedia.org/wiki/File:Mount_Rainier_5917s.JPG)

CHAPTER III

BACKGROUND INFORMATION

Hazards

Hazards associated with Mt. Rainier can have many different effects. This mostly depends on the location and distance away from the volcano. Hazards other than eruptions that are present are debris avalanches, lahars, and jökulhlaups. Debris avalanches occur due to the failure of an unstable slope. They can result from a magma injection similar to what occurred at Mt. St. Helens in 1980 (Hoblitt et al., 1998). They can also result from slopes weakened by glacial erosion and hydrothermal alteration (Hoblitt et al., 1998). The result is a rapidly moving landslide, which can transform into a lahar if it incorporates enough water (Hoblitt et al., 1998).

Lahars, also called volcanic mudflows, are mixtures of water and at least 60% sediment by volume (Hoblitt et al., 1998). They are likely to occur at Mt. Rainier for several reasons. These include fairly steep slopes at the summit, the presence of glaciers, and altered volcanic rock. Lahars are especially dangerous because they can move quickly downstream and have limited warning times. Some lahars can travel over 70 km at speeds of tens to hundreds of km/hour (Hoblitt et al., 1998; Reid et al., 2001). Lahars can be initiated in several ways and can have different compositions. Small lahars typically result from small debris avalanches, heavy rain, or the sudden release of glacial melt water (Hoblitt et al., 1998). Large lahars usually result from the rapid melting of glacial ice and snow during a volcanic eruption (Dyurgerov and Meier, 2005).

Lahars that contain large amounts of water and altered rock, such as clay, are known as cohesive lahars (Hoblitt et al., 1998). This type of lahar results from the relatively high amounts of water located within hydrothermally altered clay-rich rock (Hoblitt et al., 1998). Non-cohesive lahars result from water mixing with loose rock (Hoblitt et al., 1998). At Mt. Rainier, volcanism is the cause for large non-cohesive lahars (Hoblitt et al., 1998). These large non-cohesive lahars result from rapid melting of glacial ice during an eruption resulting in a massive amount of water that incorporates rock and sediment (Hoblitt et al., 1998). An important variable in the extent of lahars is the amount of water present. If there is a large amount of water available, then a greater volume of material can liquefy and travel greater distances (Hoblitt et al., 1998).

Because of the large areas they can cover, lahars are perhaps the greatest hazard to those living near Mt. Rainier. There have been at least 60 lahars at Mt. Rainier during the last 10 ka (Hoblitt et al., 1998). As mentioned earlier, the largest was the Osceola Mudflow, ~5.6 ka, which traveled over 120 km to the north and west and covered an area of at least 200 km^2 (Vallance and Scott, 1997). It flowed all the way to the Puget Sound and filled valleys to depths of over 100 m (Vallance and Scott, 1997). The Osceola Mudflow was a cohesive lahar that resulted from a large hydrothermally altered debris avalanche likely caused by magma injection (Hoblitt et al., 1998). Since the Osceola Mudflow, there have been at least 6 other lahars caused by debris avalanches (Hoblitt et al., 1998). The largest of which was the Electron Mudflow, which does not appear to be related to an eruption (Crandell, 1971). It occurred due to slope failure on the west side of Mt. Rainier ~600 years ago and flowed west and north along the Puyallup River valley (Crandell, 1997). In the Puget Sound Lowland, deposits from the Electron Mudflow cover an area of about 36 km^2 and are up to 7.9 m thick (Crandell, 1971).

Jökulhlaups are somewhat common on the slopes of Mt. Rainier. They are not inherently related to volcanic activity and result from the "sudden release of water stored at the base of glaciers or within the glacier ice" (Hoblitt et. al., 1998). Many jökulhlaups incorporate sediment from channel walls and become lahars (Hoblitt et al., 1998). Although the timing of jökulhlaups is unpredictable, they usually occur when there is a large input of melt water during times of unusually warm weather or when there are heavy rains (Hoblitt et al., 1998). Peak discharge from some jökulhlaups can exceed 100-year flood levels for a given valley (Hoblitt et al., 1998). In the past 100 years there have been at least 36 jökulhlaups (Hoblitt et al., 1998). Roads, buildings, and bridges have been destroyed or damaged ten times by jökulhlaups from Mt. Rainier since 1926 (Hoblitt et al., 1998). Jökulhlaups pose the greatest risk to the slopes and river valleys near Mt. Rainier. Hazards from jökulhlaups are rare beyond Mt. Rainier National Park (Hoblitt et al., 1998).

Glaciers

The previous location and age of Mt. Rainier glaciers have been estimated using tree rings, lichens, tephra, and moraine locations (Harrison, 1956; Burbank, 1981). Burbank (1981) found that all Mt. Rainier glaciers were fairly synchronous in recessional behavior and were at or near Neoglacial maximums during the Little Ice Age up to the early 1800's. After 1850, glaciers slowly retreated until about 1920 (Driedger, 1993). Glaciers then retreated rapidly until 1950 (Driedger, 1993). By 1950, the length of Mt. Rainier glaciers was reduced by ~25% from their Little Ice Age maximums (Driedger, 1993). Many glaciers then advanced until the early 1980's due to cooler temperatures (Driedger, 1993). Since the early 1980's, advances slowed followed by thinning and retreat (Driedger, 1993). The overall recession since the early 19th century is attributed to a mean annual temperature rise of about 1.0°C (Burbank, 1981).

Glacier monitoring at Mt. Rainier has been taking place since the late nineteenth century. The USGS was the first to map Mt. Rainier glaciers in 1898 (Nylen, 2001). Nisqually Glacier is one of the best-observed glaciers because of its accessibility. Harrison (1956) analyzed the change in the location of Nisqually Glacier terminus from 1750 to 1955. His study showed that the front of Nisqually Glacier retreated ~1750 m during this time despite a few minor advances (Harrison, 1956). More recently, three advances and retreats of Nisqually Glacier occurred between 1965 and 1992 (Driedger, 1993). A period of retreat began in 1985 and resulted in a loss of 15.85 m between 1985 and 1991 (Driedger, 1993). Also, the terminus position of 12 Mt. Rainier glaciers have retreated an average of 1129 m from 1913 to 1994 (Nylen, 2001). The total glacier area decreased 23.9 km^2 during the same period (Nylen, 2001).

The cumulative net mass balance is a comparison between the amount of snow that accumulates during the winter compared to the amount of snow remaining at the end of the summer (Pelto, 2010). These measurements of snow accumulation and melt allow for the calculation of the cumulative net mass balance. The National Park Service has monitored the annual mass balances on Nisqually and Emmons glaciers since 2003. The areas and volumes are also recorded for all of Mt. Rainier's glaciers on a 20-year cycle. Measurements are taken three times a year and record the snow depth, density, and snow and ice melt (Riedel and Wenger, 2009). The cumulative net mass balance for both the Emmons and Nisqually Glaciers is negative (Riedel and Wenger, 2009). In 2003, Emmons and Nisqually Glacier each had a net mass balance of -2.0 m.w.e. (meters water equivalent) (Riedel and Wenger, 2009). The overall trend is for an increasing negative net mass balance. From 2003-2008, the net balance of Emmons Glacier went from -2.0 m.w.e. to -6.0 m.w.e. and the net balance of Nisqually Glacier went from -2.0 m.w.e. to -8.0 m.w.e. (Riedel and Wenger, 2009).

Eruptions Caused By Deglaciation

Several studies have recognized a correlation between volcanic eruptions and glacial unloading. Some of the strongest evidence for a link between deglaciation and increased volcanism comes from Iceland. Iceland is unique because it is the location of an upwelling mantle plume beneath the Mid-Atlantic Ridge (Maclennan et al., 2002). There have been numerous studies on the effects of deglaciation on volcanism in Iceland that have shown an increase in mantle melting due to decreased pressure (Sigvaldason, 1992; Jull and McKenzie, 1996; Slater et al., 1998; Maclennan et al., 2002). It has been estimated that the average eruption rate was 20-30 times greater than today following the retreat of ice after the last glacial maximum around 11 ka (Slater et al., 1998). This increase in eruption rate is attributed to increased mantle melting caused by deglaciation (Slater et al., 1998). The volume of deposits also show that the amount of magma erupted was 30-50 times greater ~1.5 ka after deglaciation (Maclennan et al., 2002). This indicates that the magma was transported to the surface rather quickly. The glaciers' thickness is estimated to have been ~1,000 m in central Iceland, which caused up to 300 m of subsidence (Sigvaldason et al., 1992). The high rate of isostatic rebound that accompanied glacial retreat likely caused decreased lithostatic pressure and weaknesses in the crust, which could have triggered volcanism (Sigvaldason et al., 1992).

Slater et al. (1998) also found differences in the compositions of interglacial and glacial lavas. Compared to the glacial lavas, the interglacial lavas were depleted in trace element concentrations (Slater et al., 1998). This is interpreted to be a result of mantle melting at shallow depths as the ice retreated (Slater et al., 1998). Using measurements of (^{226}Ra/^{230}Ra) ratios in the basalt, melt transport times were found to be consistent with the increased eruption rates seen 1-3 ka after deglaciation (Slater et al., 1998).

Retreating glaciers in Iceland seem to be having a possible ongoing effect on volcanic activity. Pagli and Sigmundsson (2008) studied the effect of retreating glaciers on volcanism at the Vatnajökull ice cap. They found that from 1890-2003; a total volume loss of ~435 km^3 of ice was indicated by mass balance measurements (Pagli and Sigmundsson, 2008). However, the overall melt production due to deglaciation is much less than in the past. The ice cap at Vatnajökull is over 3 times smaller and is currently thinning at ~0.5 m/yr compared to ~2 m/yr during the time following the last glacial maximum (Pagli and Sigmundsson, 2008). Pagli and Sigmundsson (2008) indicate that the loss of ice at Vatnajökull can increase mantle melting at a rate of 0.014 km^3/yr. This relates to an increased magma production of around 10% (Pagli and Sigmundsson, 2008).

Another area that has been studied is located in eastern California. Glazner et al. (1999) found that over the last 800 ka there is a relationship between decreases in volcanism and glacial maximums. This relationship is explained to be a result of an increase in lithostatic pressure caused by glaciers, which inhibits dike formation (Glazner et al., 1999). Dike formation is subsequently caused by a decrease in confining pressure and increasing decompression melting as a result of glacial unloading (Jellinek et al., 2004). Jellinek et al. (2004) also showed that there is a connection between the rate of change in ice volume and the frequency of eruptions. Therefore, they theorize that the rate of change of ice volume controls dike formation instead of the total volume of ice and that "volcanism is a response ultimately controlled by the dynamics of dike formation" (Jellinek et al., 2004). Furthermore, they calculated the time lags between glacial unloading and volcanism. The results show a marked difference between different types of volcanism. Their calculated time lags for silicic volcanism are 3.2 ± 4.2 ka, and 11.2 ± 2.3 ka for basaltic volcanism (Jellinek et al., 2004).

Ice cores from Greenland show a record of past volcanic eruptions. For example, Zielinski et al. (1994) found that there were three times as many volcanic events between 7 ka and 9 ka as compared to the last 2 ka based on SO_4^{2-} concentrations in the top 1,468 m of ice. This could provide additional evidence of increased global volcanism caused by deglaciation following the end of the last glacial maximum. It is also possible that layers of ice with higher concentrations of SO_4^{2-} result from eruptions at high latitudes such as in Alaska and Iceland (Zielinski et al., 1994). These areas would have been heavily glaciated and would be the most likely areas to have had increased volcanism in the early Holocene (Zielinski et al., 1994).

One factor that could affect the possibility of an eruption due to decompression is the depth of Mt. Rainier's magma chamber. Although the exact depth is unknown, earthquake activity provides an indication to the possible depth of the magma chamber. Mt. Rainier averages one to two earthquakes each month, which makes it the most seismically active Cascade volcano (Moran et al., 2000). Unger and Decker (1970) studied microearthquake activity beneath Mt.

Rainier and found that ~8% of the earthquakes measured had epicenters beneath the summit at depths of 0.3 km to 20 km. Approximately 75% of the microearthquakes measured had depths that were <5 km (Unger and Decker, 1970). Moran et al. (2000) measured earthquakes beneath Mt. Rainier and found that the majority were located 0.0 km to 0.8 km below sea level or ~4-5 km beneath the summit. Tomography results also show a low velocity anomaly of hot/partially molten bodies >6 km beneath the summit (Moran et al., 2000). These studies suggest that the top of the magma chamber could be ~4-6 km beneath the summit. However, magmatic gases and fluids could be the cause of some of the earthquakes beneath the summit (Moran et al., 2000).

Climate

Large-scale atmospheric circulation is the primary control on glaciers around the world (Meier et al., 2003). Therefore it is important to consider the climate and climate change when studying Mt. Rainier glaciers. Mt. Rainier receives a large amount of precipitation and has previously held several records for snowfall, including 28.5 m in 1971-1972 at the Paradise Ranger Station (Leffler et al., 2001) (See Appendix E for additional information) . The Paradise Ranger Station is located at 1,652 m and averages greater than 15.24 m of snow each year (Leffler et al., 2001). The greatest amount of snow typically falls from 1,219-2,438 m in elevation because the freezing line in the area is typically ~1,219 m (Leffler et al., 2001). The large amount of precipitation at Mt. Rainier results from its topography and location. Storm systems move in from the Pacific Ocean and bring moist air, which is forced to rise as it hits the Cascade Range causing abundant precipitation (Leffler et al., 2001).

Since 1850, the amounts of carbon dioxide in the atmosphere and global temperatures have steadily increased (Mote, 2003). Global surface temperatures rose 0.6º±0.2ºC during the twentieth century (Mote, 2003). In the Pacific Northwest, temperatures have also been increasing. Evidence that glacier decreases at Mt. Rainier could be the result of climate change comes from measured temperature trends and snow water equivalent measurements. Ninety-one percent of weather stations located in Washington and Oregon had an increasing trend in annual temperature (Mote, 2003). Warmer temperatures could cause snow to begin melting earlier in the spring and lead to a longer period for melting to occur. The majority of rivers in the Pacific Northwest show a trend for earlier snowmelt timing (Stewart et al., 2004). These changes in snowmelt runoff are mostly connected to warmer spring air temperatures (Stewart et al., 2004).

CHAPTER IV

GLACIER CHANGE

Data Sources and Description

To determine recent changes in the area and terminus locations of Mt. Rainier's glaciers, seven Landsat thermal infrared scenes from 1985-2009 were used. The four scenes from 1985-1998 are from Landsat 5, which have a spatial resolution of 120 m for Band 6 (thermal infrared band). The three scenes from 2005-2009 are from Landsat 7, which have a spatial resolution of 60 m for Band 6. The Landsat 7 scenes contain data gaps caused by a failure of the scan line corrector in 2003. The failure of the scan line corrector caused duplicated scan lines. As a result, data gaps occur when the duplicated scan lines are removed. Landsat data was downloaded from the USGS using EarthExplorer at http://edcsns17.cr.usgs.gov/NewEarthExplorer/. The Landsat scenes are from August 1985, August 1988, September 1991, September 1998, August 2005, August 2007, and September 2009 (Table 1); these datasets represent all late summer Landsat datasets covering the study area that were suitable for analysis. Thermal infrared images were used instead of visible satellite images because thermal infrared images show the emitted radiation. Therefore glaciers appear much darker than surrounding areas of bare, vegetated, and snow-covered ground, making glacier boundaries easier to detect when compared to visible satellite images. To get the best view of the glaciers, all of the satellite images are from either August or September when seasonal snow cover is at a minimum. Each scene was also selected based on the least amount of cloud cover and are intended to provide a good representation of glacier change from 1985-2009.

Table 1: Details for each Landsat scene used in this study

Year	Satellite	Date Acquired	Band 6 Resolution
1985	Landsat 5	August 23	120 m
1988	Landsat 5	August 31	120 m
1991	Landsat 5	September 25	120 m
1998	Landsat 5	September 12	120 m
2005	Landsat 7	August 6	60 m
2007	Landsat 7	August 28	60 m
2009	Landsat 7	September 18	60 m

Measurements were made to characterize twenty glaciers on Mt. Rainier. Some of the glacier boundaries were difficult to distinguish on the upper slopes of Mt. Rainier. As a result, only eleven measurements were made for each year because several glaciers that are connected or adjacent to each other were grouped together. Many of the glacier boundaries near the summit remain stationary for each scene. These boundaries were determined using previous glacier maps and aerial photographs along with satellite images. Aerial photographs from 2007 were downloaded from Portland State University's website: Glaciers of the American West (http://glaciers.us/). The individual glaciers that were mapped are the Winthrop, Carbon, Inter, Kautz, and Emmons Glaciers. The glaciers that were grouped together are the North Mowich/Edmunds, Puyallup/South Mowich, Tahoma/South Tahoma, Nisqually/Wilson, Cowlitz/Ingraham/Paradise, and Whitman/Ohanapecosh/Fryingpan Glaciers (Figure 3).

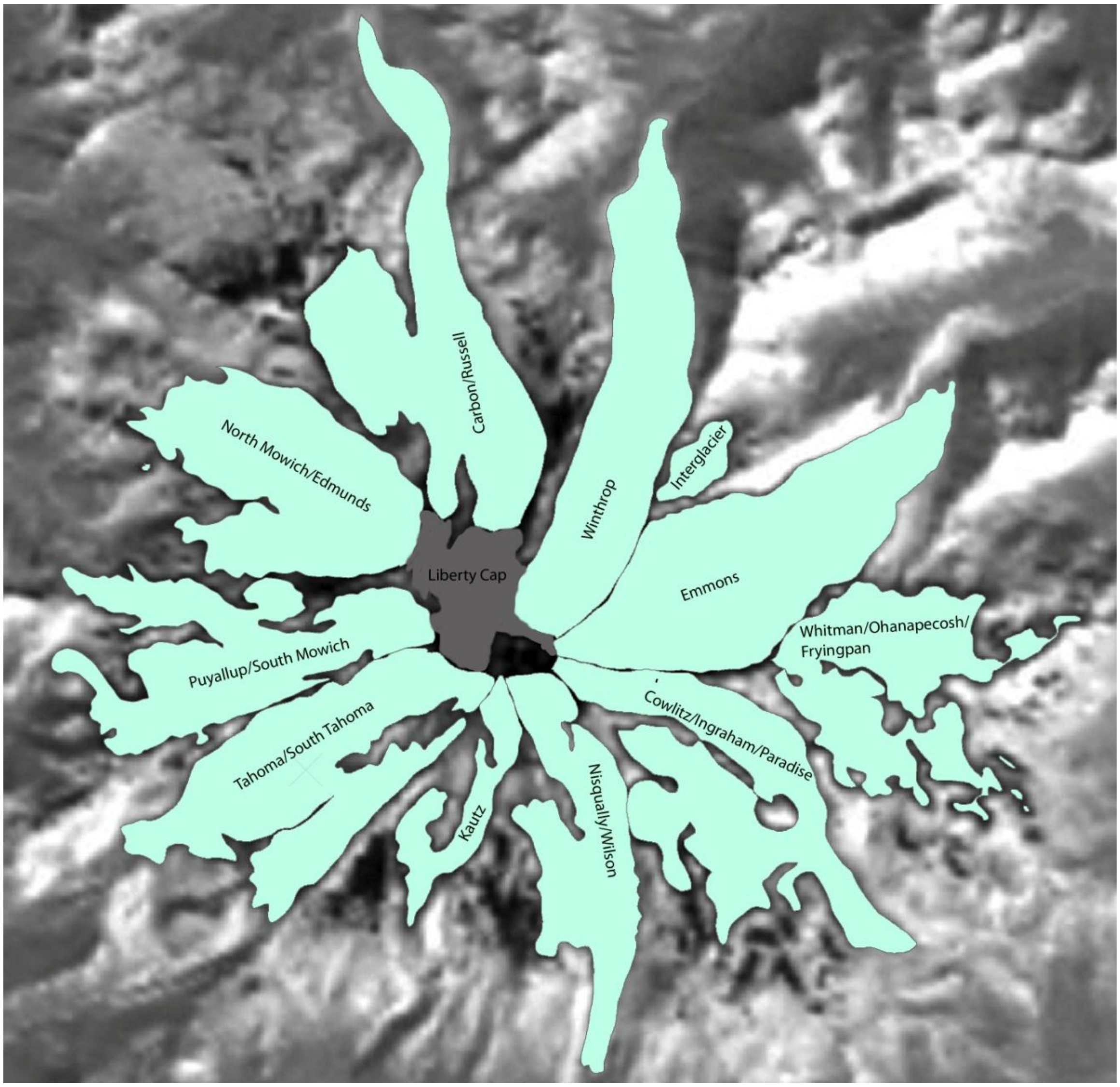


Figure 3: Individual and grouped glaciers measured in this study

Methods

ArcMap was used to analyze the images, including mapping the extent and measuring the area of each glacier/glacier group in each Landsat scene. First, the extent of each glacier was mapped for each year. Then the area of each glacier/glacier group was calculated in ArcMap. Glacier area measurements were made in square kilometers and were rounded to three decimal places. The change in glacier extent and area was calculated for the time periods of 1985-1988, 1988-1991, 1991-1998, 1998-2005, 2005-2007, and 2007-2009. Then the change in area was calculated for the entire time period from 1985-2009. From the glacier area measurements, the rate of glacier change (both as area and as percent) was calculated and compared for each time period. Data for glacier area and the rate of change in area was then used in several ways. First, the measured glacier areas found in this study were compared to glacier area measurements taken by the USGS to identify any differences. Glacier measurements by the USGS were made in 1994. To compare the glacier areas measured by the USGS to the glacier areas measured in this study, the areas for 1994 were interpolated using the average change in area between 1991 and 1998. Then a comparison was made between the total glacier area and rate of change between USGS measurements from 1971-1994 and this study's measurements from 1985-2009. Finally, glacier area measurements for 2005 were compared to area measurements that were available from the GLIMS database for the same year.

Results

Area Changes

The measured glacier/glacier group areas show a consistent trend of decreasing area from 1985-2009 (Table 2). The total glacier area decreased during all six time periods (Appendix A). During this time, the observed area of Mt. Rainier glaciers decreased from 85.590 km^2 to 81.355 km^2, which is 4.235 km^2 or 5.32% (Figure 4). The area also decreased for the majority of each individual glacier/glacier group for each Landsat scene. Only one glacier/glacier group increased in area during any of the time periods. This was Emmons Glacier from 1988-1991 and 1991-1998. However, the increases that are seen are small. The largest increase was 0.013 km^2 or 0.004 km^2 per year, and occurred from 1988-1991. Inter Glacier did not increase in area but had a decrease of less than 0.003 km^2 from 1991-1998 and a decrease of 0.0003 km^2 from 1998-2005. Pictured below are Landsat scenes showing area comparisons between 1985 and 2009 (Figure 5, 6) (See also Appendix B, C).

Table 2: Glacier/glacier group areas and total area measured for each Landsat scene

Glacier Name	**Total Glacier Area (km^2)**						
	1985	**1988**	**1991**	**1998**	**2005**	**2007**	**2009**
Carbon/Russell	11.426	11.261	11.062	10.920	10.828	10.746	10.664
Cowlitz/Ingraham/Paradise	9.437	9.212	9.193	9.071	9.021	8.992	8.929
Emmons	11.164	11.161	11.174	11.178	11.125	11.115	11.108
Inter	0.806	0.801	0.790	0.787	0.787	0.784	0.780
Kautz	2.244	2.217	2.214	2.163	2.119	2.098	2.075
Nisqually/Wilson	6.094	6.072	5.974	5.969	5.912	5.883	5.846
North Mowich/Edmunds	9.440	9.261	9.070	8.919	8.811	8.784	8.733
Puyallup/South Mowich	8.365	8.199	8.107	7.950	7.823	7.794	7.762
Tahoma/South Tahoma	9.688	9.585	9.427	9.339	9.293	9.266	9.261
Whitman/Ohanapecosh/ Fryingpan	7.613	7.415	7.307	7.251	7.166	7.162	7.128
Winthrop	9.312	9.252	9.214	9.127	9.089	9.087	9.067
Total	**85.590**	**84.437**	**83.533**	**82.674**	**81.975**	**81.711**	**81.355**

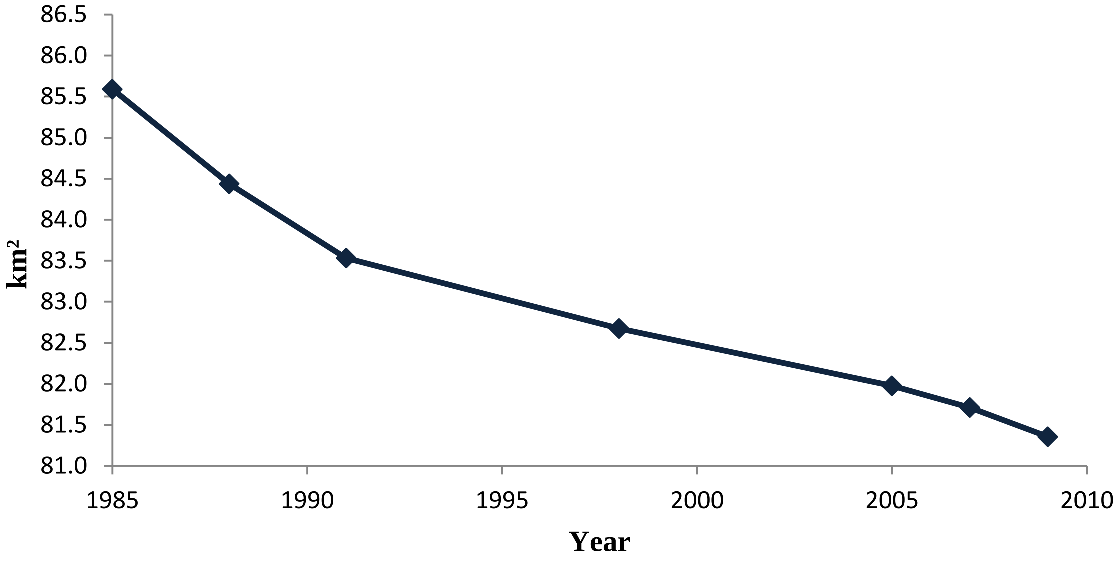


Figure 4: Change in the total glacier area measured in this study from 1985-2009

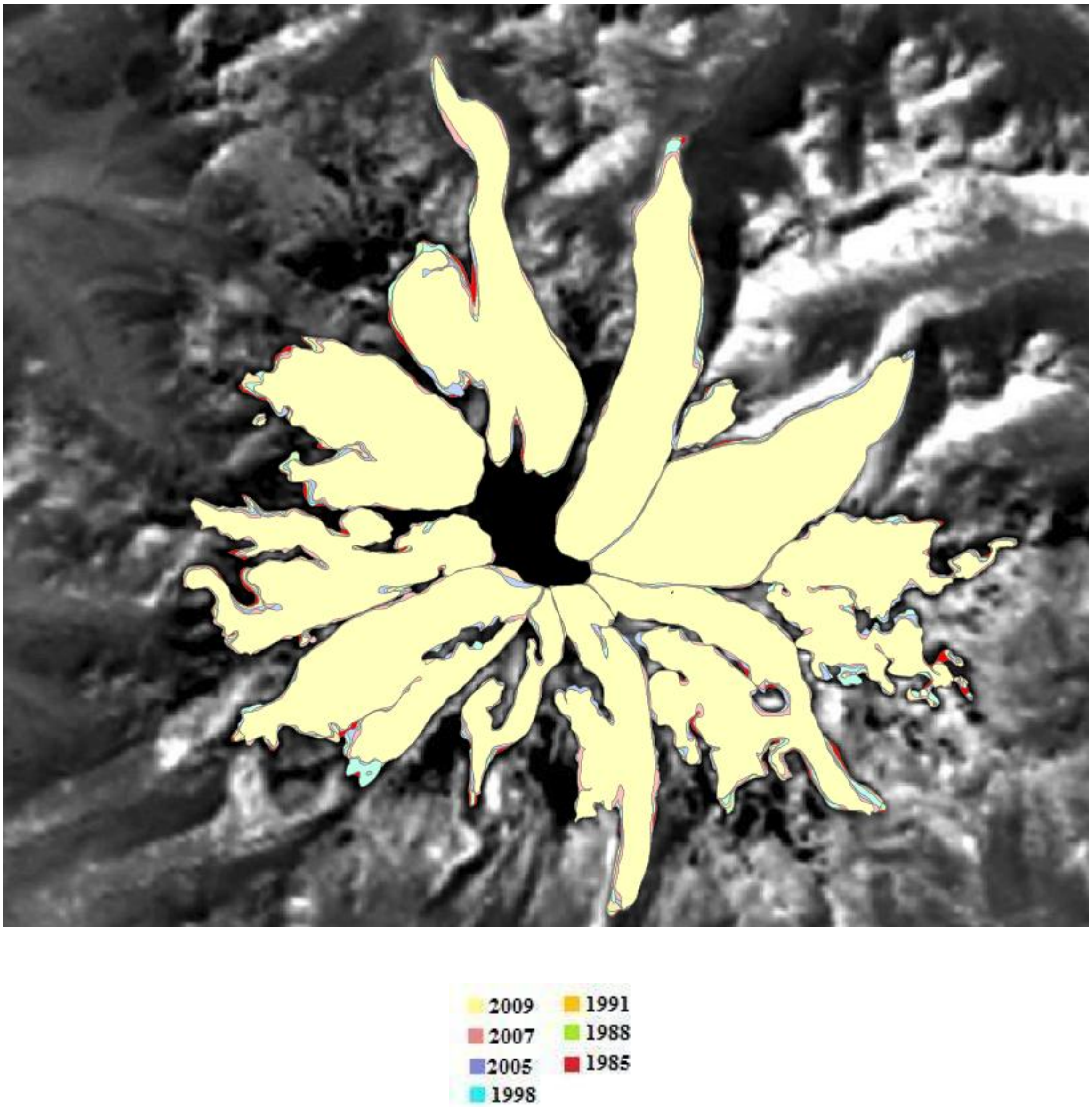


Figure 5: Measured glacier areas from 1985-2009

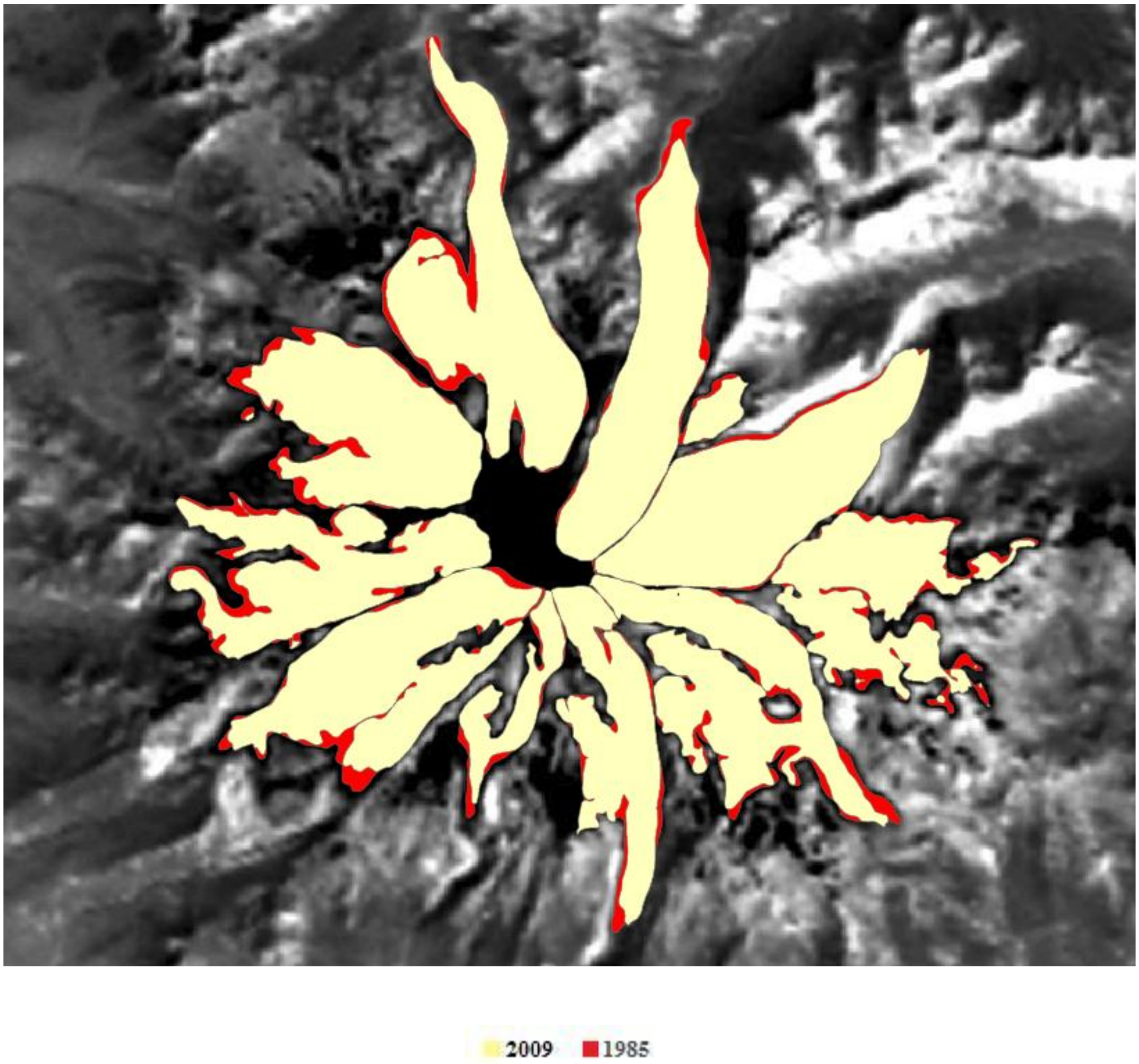


Figure 6: Measured glacier areas from 1985 and 2009

Decreasing area trends also appear when looking at the total rate of change and percent change per year for each period. The total change in area per year and percent change in area per year show an overall decrease in area and is negative for all six time periods (Figure 7). The largest average change in area occurred from 1985-1988, when the total glacier area decreased an average of 0.385 km^2 or 0.449 % per year. The rate of change in total area then decreased during the time periods of 1988-1991, 1991-1998, and 1998-2005. During the time period of 1998-2005, the smallest rate of change per year was measured with an average decrease of 0.100 km^2 or

0.121% per year. The rate of change in area then rose to -0.132 km^2 or -0.161% per year from 2005-2007. The rate of loss continued to increase from 2007-2009 with an average change in area of -0.178 km^2 or -0.218% per year.

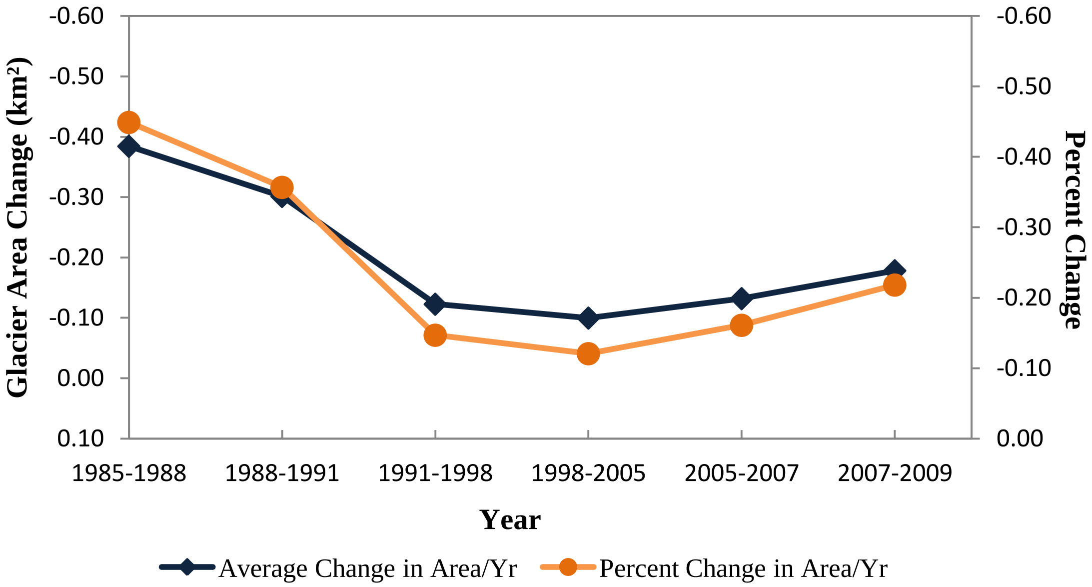


Figure 7: Average change and percent change in the total glacier/glacier group area per year for six time periods between 1985 and 2009

The Cowlitz/Ingraham/Paradise Glaciers had the highest average change in area per year, which was -0.075 km^2 per year from 1985-1988 (Table 3). That time period also had the highest rate of loss in total area with an average loss of 0.384 km^2 per year. The overall trend is for higher rates of loss during the time periods of 1985-1988 and 1988-1991 (Figure 8). This is followed by a decrease in rates of loss from 1991-1998 and 1998-2005 and an increase in rates of loss from 2005-2007 and 2007-2009. Only Emmons Glacier and the Tahoma/South Tahoma Glaciers did not show increases in the rate of area loss from 2005-2007 to 2007-2009.

Table 3: Average change in area per year for each glacier/glacier group (km^2)

Glacier Name	**1985-1988**	**1988-1991**	**1991-1998**	**1998-2005**	**2005-2007**	**2007-2009**
Carbon/Russell	-0.055	-0.066	-0.020	-0.013	-0.041	-0.041
Cowlitz/Ingraham/Paradise	-0.075	-0.006	-0.017	-0.007	-0.015	-0.031
Emmons	-0.001	0.004	0.001	-0.008	-0.005	-0.004
Inter	-0.002	-0.004	0.000	0.000	-0.001	-0.002
Kautz	-0.009	-0.001	-0.007	-0.006	-0.011	-0.012
Nisqually/Wilson	-0.007	-0.033	-0.001	-0.008	-0.014	-0.018
North Mowich/Edmunds	-0.060	-0.064	-0.022	-0.015	-0.014	-0.025
Puyallup/South Mowich	-0.055	-0.031	-0.022	-0.018	-0.015	-0.016
Tahoma/South Tahoma	-0.034	-0.053	-0.013	-0.007	-0.013	-0.002
Whitman/Ohanapecosh/Fryingpan	-0.066	-0.036	-0.008	-0.012	-0.002	-0.017
Winthrop	-0.020	-0.013	-0.012	-0.005	-0.001	-0.010
Total	**-0.384**	**-0.301**	**-0.123**	**-0.100**	**-0.132**	**-0.178**

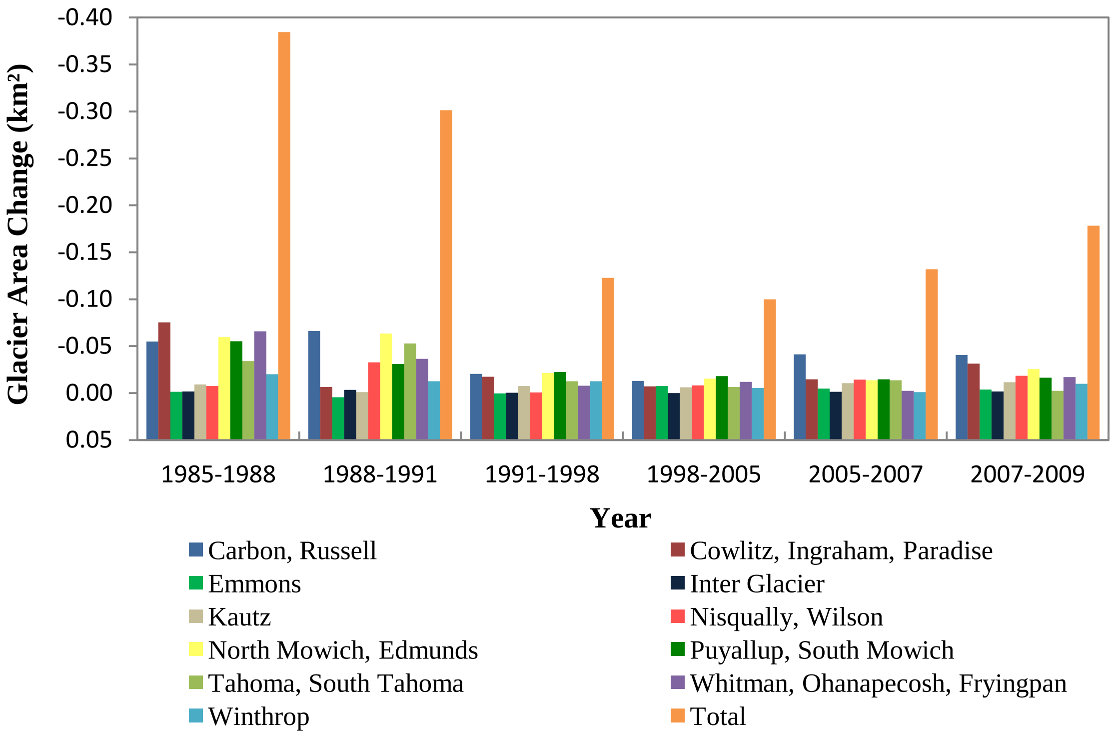


Figure 8: Average change in area per year for each glacier/glacier group for six periods from 1985-2009

The majority of the glaciers/glacier groups show similarities when comparing percent changes per year (Figure 9). The largest percent decreases per year occurred from 1985-1988. Percent decreases were greatest at the Whitman/Ohanapecosh/Fryingpan and Cowlitz/Ingraham/Paradise Glaciers which experienced decreases of 0.86% and 0.80% per year, respectively (Table 4). Then from 1988-1991, six glaciers/glacier groups experienced a decrease in percent loss per year while 5 glaciers/glacier groups experienced increases in percent loss per year. From 1991-1998 and 1998-2005, the percent loss per year for nearly all glaciers/glacier groups either remained fairly constant or showed a decrease in percent loss per year. Then from 2005-2007 and 2007-2009, there is an overall increase in the rate of percent loss. Only Emmons, Tahoma/South Tahoma, and the Carbon/Russell Glaciers do not show an increase in percent loss over that same period.

Table 4: Average percent change in glacier/glacier group area per year

Glacier Name	**1985-1988**	**1988-1991**	**1991-1998**	**1998-2005**	**2005-2007**	**2007-2009**
Carbon/Russell	-0.48%	-0.59%	-0.18%	-0.12%	-0.38%	-0.38%
Cowlitz/Ingraham/Paradise	-0.80%	-0.07%	-0.19%	-0.08%	-0.16%	-0.35%
Emmons	-0.01%	0.04%	0.00%	-0.07%	-0.04%	-0.03%
Inter	-0.22%	-0.44%	-0.06%	-0.01%	-0.19%	-0.22%
Kautz	-0.40%	-0.05%	-0.33%	-0.28%	-0.50%	-0.55%
Nisqually/Wilson	-0.12%	-0.54%	-0.01%	-0.14%	-0.24%	-0.31%
North Mowich/Edmunds	-0.63%	-0.69%	-0.24%	-0.17%	-0.15%	-0.29%
Puyallup/South Mowich	-0.66%	-0.38%	-0.28%	-0.23%	-0.19%	-0.21%
Tahoma/South Tahoma	-0.35%	-0.55%	-0.13%	-0.07%	-0.14%	-0.03%
Whitman/Ohanapecosh/Fryingpan	-0.86%	-0.49%	-0.11%	-0.17%	-0.03%	-0.24%
Winthrop	-0.22%	-0.14%	-0.14%	-0.06%	-0.01%	-0.11%
Total	**-0.45%**	**-0.36%**	**-0.15%**	**-0.12%**	**-0.16%**	**-0.22%**

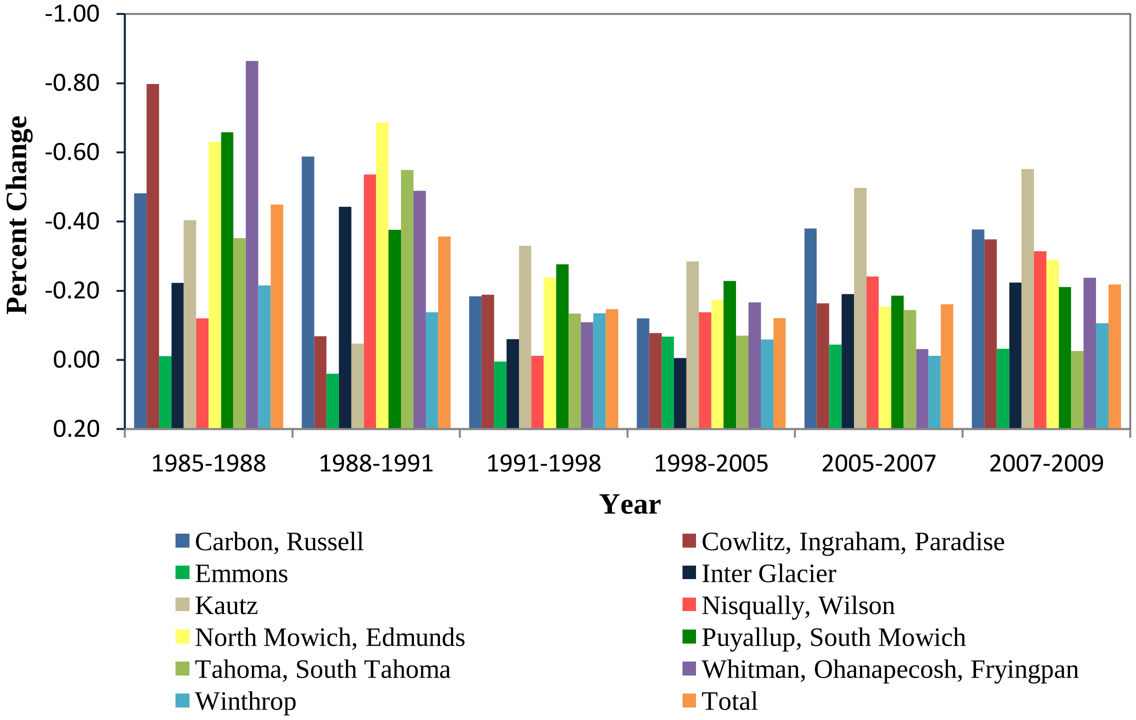


Figure 9: Average percent change per year for each glacier/glacier group during six time periods from 1985-2009

Area Comparison

Interpolated glacier areas for 1994 from this study were compared to glacier areas measurements made by the USGS in 1994 (Table 5). The majority of the measurements are similar. All but two of the glaciers/glacier groups have an area difference equal to or less than 0.07 km^2. The measurements from this study were larger overall; with a total difference in area of +1.675 km^2. However, six of the eleven glacier/glacier group areas measured were smaller than U.S. Geological Survey measurements. The largest differences are seen in the North Mowich/Edmunds and the Cowlitz/Ingraham/Paradise Glaciers. They show a difference of +1.396 km^2 and +0.330 km^2 respectively, which is significantly larger than any differences seen with the other glaciers/glacier groups. The total difference in area measurements is only -0.051 km^2 if those two glacier groups are removed from the calculation.

Table 5: Comparison between the areas measured by the USGS in 1994 and the areas interpolated for 1994 from the areas measured in this study

Glacier Name	**USGS (1994)**	**This Study (1994)**	**Difference (km²)**
Carbon/Russell	11.010	11.001	-0.009
Cowlitz/Ingraham/Paradise	8.810	9.140	0.330
Emmons	11.210	11.176	-0.034
Inter	0.790	0.789	-0.001
Kautz	2.160	2.192	0.032
Nisqually/Wilson	6.010	5.972	-0.038
North Mowich/Edmunds	7.610	9.006	1.396
Puyallup/South Mowich	7.980	8.040	0.060
Tahoma/South Tahoma	9.460	9.390	-0.070
Whitman/Ohanapecosh/Fryingpan	7.240	7.283	0.043
Winthrop	9.210	9.177	-0.033
Total	**81.490**	**83.165**	**1.675**

The total glacier area measured by the USGS ranged from 82.17 km^2 in 1971 to 81.49 km^2 in 1994, whereas the total glacier area measured in this study ranged from 85.590 km^2 in 1985 to 81.355 km^2 in 2009. The calculated rate of change in total glacier area from this study was also greater than that of the USGS measurements. Using USGS measurements, the total glacier area decreased 0.68 km^2 or 0.028 km^2 per year from 1971-1994. Meanwhile, the measurements from this study show an overall decrease of 4.235 km^2 or 0.169 km^2 per year from 1985-2009.

Glacier area data for 2005 was available from the GLIMS project database for nine of the glaciers/glacier groups mapped in this study. The overall difference in area of these nine glaciers/glacier groups when compared to areas from this study is -1.693 km^2 or -2.5% (Table 6). Six out of the nine measurements from this study were smaller than the GLIMS data. However, the majority of measurements were similar. Only two glacier group measurements had differences greater than 0.45 km^2. These were the North Mowich/Edmunds Glaciers, which had a difference of 1.246 km^2 (~15.1%), and the Tahoma/South Tahoma Glaciers, which had a difference of -1.845 km^2 (~16.6%).

Table 6: Comparison between GLIMS data and data from this study for glacier areas in 2005

Glacier Name	**GLIMS data (2005)**	**This Study (2005)**	**Difference (km^2)**
Carbon/Russell	11.231	10.828	-0.402
Emmons	11.042	11.125	0.083
Inter	0.841	0.787	-0.054
Kautz	1.826	2.119	0.294
North Mowich/Edmunds	7.565	8.811	1.246
Puyallup/South Mowich	8.247	7.823	-0.423
Tahoma/South Tahoma	11.138	9.293	-1.845
Whitman/Ohanapecosh/Fryingpan	7.608	7.166	-0.442
Winthrop	9.238	9.089	-0.149
Total	**68.735**	**67.042**	**-1.693**

Discussion

In the twentieth century, glaciers worldwide have shown significant decreases (WGMS, 2008). Consistent glacier retreat occurred during the 1940’s and again from the mid 1980’s to present (WGMS, 2008). This corresponds well to glacier research at Mt. Rainier, which indicates that major glaciers advanced from the 1950’s to the early 1980’s followed by retreat since the mid-1980’s (Nylen, 2001). Other Cascade glaciers also experienced similar glacial advances from the 1950’s to the 1980’s (Nylen, 2001). Beginning in the mid-1970’s, most Cascade glaciers began retreating (Nylen, 2001). By 1988, only 3 out of 107 monitored Cascade glaciers were advancing and all of the glaciers were retreating by 1992 (Nylen, 2001).

The data suggests a continuing trend of decreasing glacier area at Mt. Rainier. Measurements from the seven Landsat scenes show that the total area of Mt. Rainier glaciers included in this study decreased 4.235 km^2 from 1985-2009. The rate of glacier loss also increased over the last decade. Between 2005 and 2009, the average decrease in total area rose -0.012 km^2 per year. When comparing the glacier loss between north and south facing glaciers/glacier groups, south facing glaciers had a greater total percent decrease in area (Figure 10) (See also Appendix D). The trends for north and south facing glaciers/glacier groups are similar. However, south facing glaciers/glacier groups had greater decreases in area from 1985-1988 and 2005-2009. This corresponds with a previous study that showed larger decreases in area and greater retreat in terminus positions of south facing glaciers compared to north facing glaciers (Nylen, 2001).

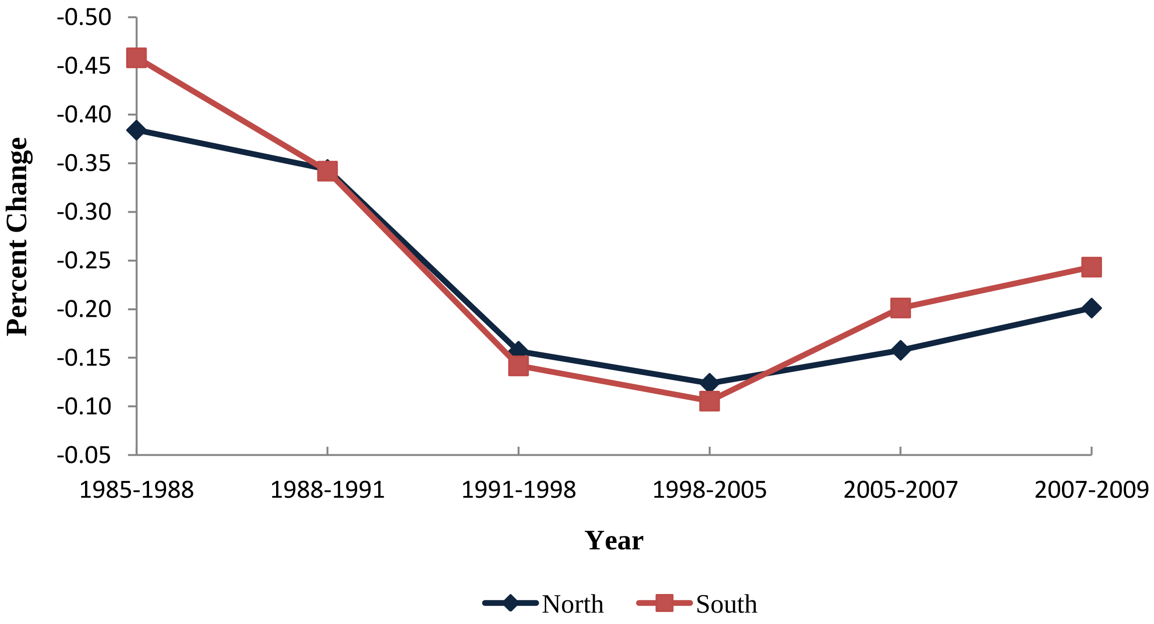


Figure 10: Comparison of percent change in area between north and south facing glaciers of Mt. Rainier

Comparisons between area measurements made in this study show many similarities to those from the USGS and the GLIMS database. The total difference in area of the glaciers/glacier groups compared to GLIMS measurements was -1.693 km^2. This study complements the work done through the GLIMS project by providing a detailed analysis of glacier change from 1985-2009. A comparison of the change in total area of Mt. Rainier glaciers to USGS measurements shows that the total area measured in this study is larger than that which was previously measured by the USGS. In this study, a decrease of 4.235 km^2 was measured from 1985-2009. According to USGS measurements, the same glacier/glacier groups experienced a decrease of 0.68 km^2 from 1971-1994 (Figure 11). However, the majority of glacier/glacier group area measurements are very similar to those made by the USGS. Much of the discrepancy, in 1994 at least, is due to the much larger areas of the North Mowich/Edmunds and the Cowlitz/Ingraham/Paradise glaciers that were measured in this study.

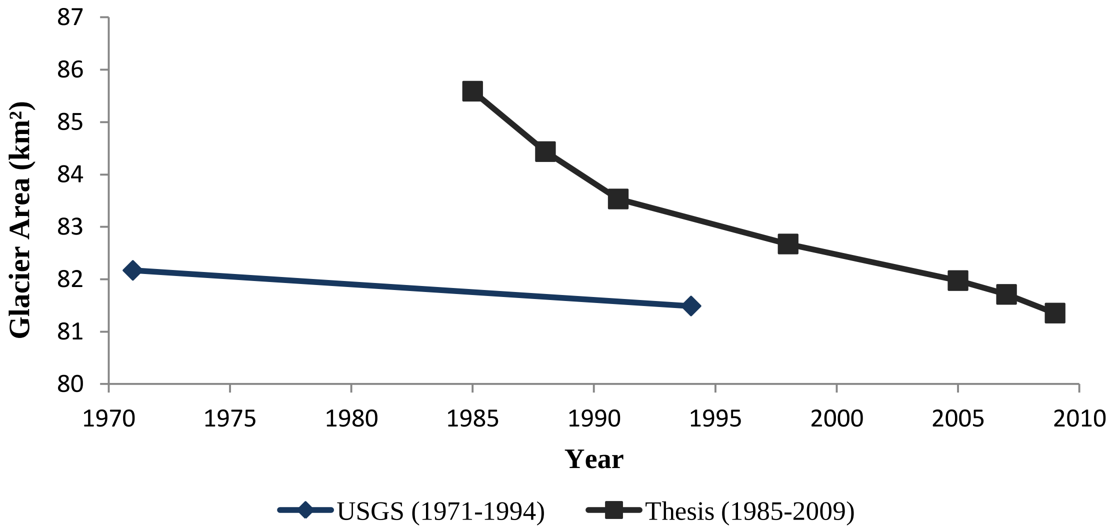
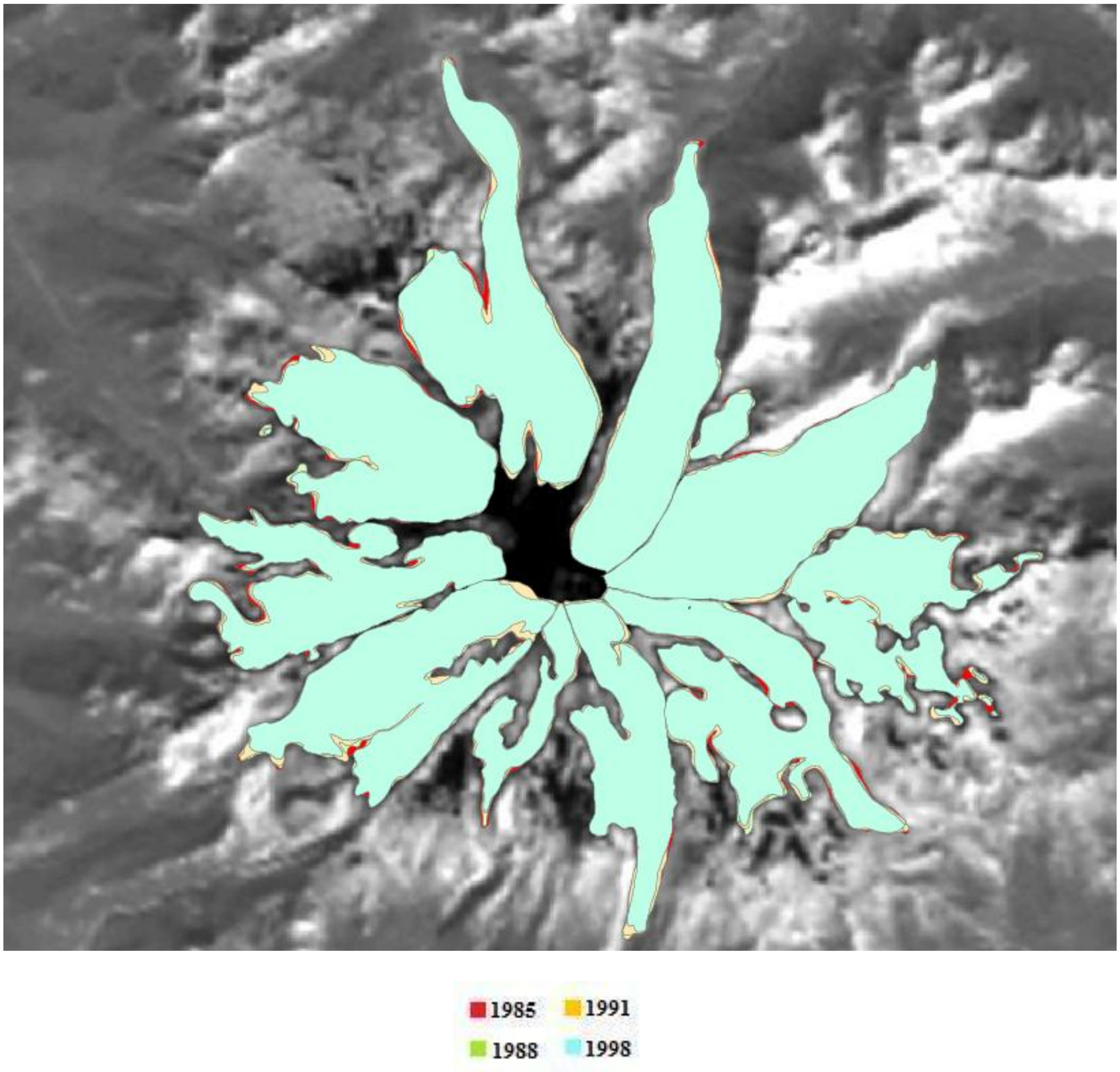


Figure 11: Comparison of glacier area measurements from this study to USGS measurements

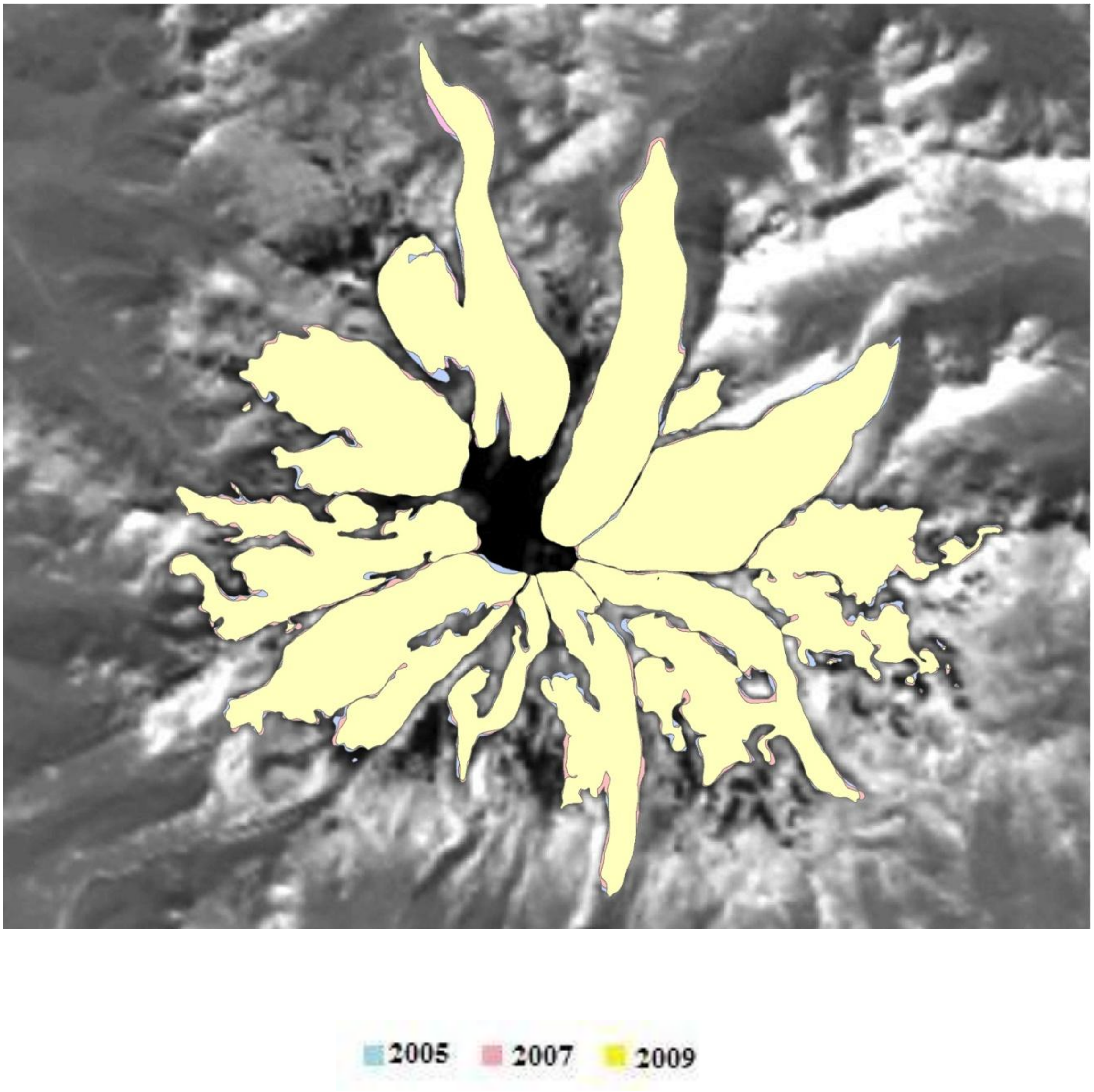
However, there are several possible explanations for the disparities seen in the area and in the rate of change in area between the earlier measurements made in this study and measurements made by the USGS. One potential reason for the discrepancy is differences in the placement of boundaries between glaciers, which would affect measurements for individual glaciers but not total glacier area. Measurements made in this study also may include snow patches or permanent ice that is not included in USGS measurements.

It appears that Landsat 7 scenes provide a more accurate image in which to manually delineate glacier area than Landsat 5 scenes. The total area and rate of change in area measured with Landsat 7 scenes is much more similar to measurements made by the USGS. One explanation is the difference in the spatial resolution between Landsat 5 and Landsat 7 images. The maximum spatial resolution of Landsat 7 images (60 m/pixel) is double that of Landsat 5 images (120 m/pixel). The areas that were measured in this study using Landsat 5 images were generally larger and had greater rates of decrease than the areas measured using Landsat 7 images (Figure 12). Some of the dissimilarities could be attributed to error differences (based on resolution) between Landsat 5 and Landsat 7 images. The error in associated with measuring glacier extents in this study is estimated to be ≤50% for each pixel. Therefore, Landsat 5 images could have a higher percent error compared to Landsat 7 images due to the larger pixel size. However, it is likely that most of the differences are an accurate representation of the glacier areas. The area measurements using Landsat 5 scenes (1985-1998) show a total decrease of 2.916 km^2, which results in an average loss in area of 0.224 km^2 per year during that time period. The Landsat 7 scenes (2005-2009) show a total decrease of 0.62 km^2, which results in an average decrease of 0.155 km^2 per year. However, the rate of decrease in area is still higher than the 0.028 km^2 per year calculated from USGS measurements from 1971-1994.



A.

Figure 12a: Measured glacier areas for 1985, 1988, 1991, and 1998



B.

Figure 12b: Measured glacier areas for 2005, 2007, 2009

CHAPTER V

ERUPTION HAZARDS

Methods

Hekkers (2009) produced two different models that reconstructed glacier area at Mt. Rainier during the Holocene. Model 1 uses the current mass balance conditions of Emmons and Nisqually Glaciers for equilibrium line altitude (ELA) reconstruction (Hekkers, 2009). Model 2 is based on the best fit to the extent of glacier during the Garda advance (160 cal yr BP), and has adjusted mass balance parameters to fit Garda moraines (Hekkers, 2009). The results of the two models were averaged for the time period of 11 ka to 160 cal yr BP (Table 7). Two more recent measurements for glacier area were also used. Those areas are from USGS measurements from 1913 and 1994 (Nylen, 2001).

The eruptive history for Mt. Rainier and other Cascade volcanoes was compiled (Appendix F). This data came from deposits such as lava flows and ash layers that have been identified and dated in previous studies (Ewert et al., 1994; Hildreth and Fierstein, 1997; Kovanen et al., 2001; Harris, 2005; Sisson and Vallance, 2009). The eruptions of Mt. Rainier were compared to the modeled glacier area over the last 10 ka. It is assumed that the glacier coverage at Mt. Rainier can reasonably be used as a good proxy of glacier coverage throughout the Cascades. A cumulative curve for Cascade eruptions was then created to compare eruptions to modeled glacier area to see if any correlations exist.

Table 7: Mt. Rainier modeled glacier area and average modeled area, along with two more recent USGS area measurements

Cal Yr BP	**Hekkers (2009) Modeled Glacier Area**		**Glacier Area Data**
			USGS Glacier Area Measurements
17			87.4
98			111.3
	Model 1	**Model 2**	**Average Modeled Area (km^2)**
160	192.7	123.8	158.3
550	192.7	123.8	158.3
2,130	161.5	99.1	130.3
2,790	192.7	123.8	158.3
3,450	265.8	233.9	249.9
4,890	253	176	214.5
5,520	161.5	92.3	126.9
6,490	265.8	212.3	239.1
7,940	118.5	71.5	95.0
8,200	173.2	115.7	144.5
8,600	67.8	58.7	63.3
9,260	73.5	64.7	69.1
10,050	29.4	12.4	20.9
10,170	193.7	131.5	162.6
10,400	36.3	20.1	28.2
10,990	327.3	303.8	315.6
11,150	26.7	11.8	19.3
11,490	173.2	123.8	148.5

Results

The earliest eruption of Mt. Rainier during the last 10 ka occurred ~9.8 ka (Figure 13). At this time glaciers covered less than 50 km^2, which according to the glacier area models is one of the lowest glacier extents following the last ice age (~1.2 ka prior to the eruption). A period of activity then occurred from ~7.4-5 ka. There were at least eight eruptions during this time. For this 2.4 ka period, the modeled glacier area fluctuates several times resulting in no obvious correlations between glacier area and the timing of eruptions during that time frame. However, the increase in activity begins ~3.5 ka following the last glacial maximum. Two more recent periods of volcanic activity occurred ~2.2 ka and ~150 cal yr BP At the time of each of these eruptions, the average modeled glacier area is similar. The average modeled glacier area 2.2 ka is ~133 km^2 and the average modeled glacier area 150 cal yr BP is ~157 km^2. The eruption 2.2 ka occurred near a low point in the average modeled glacier area and was ~1.25 ka after the last peak in glacier area 3.45 ka. The eruption ~150 cal yr BP occurred ~3.3 ka after the last peak in the average modeled glacier area.

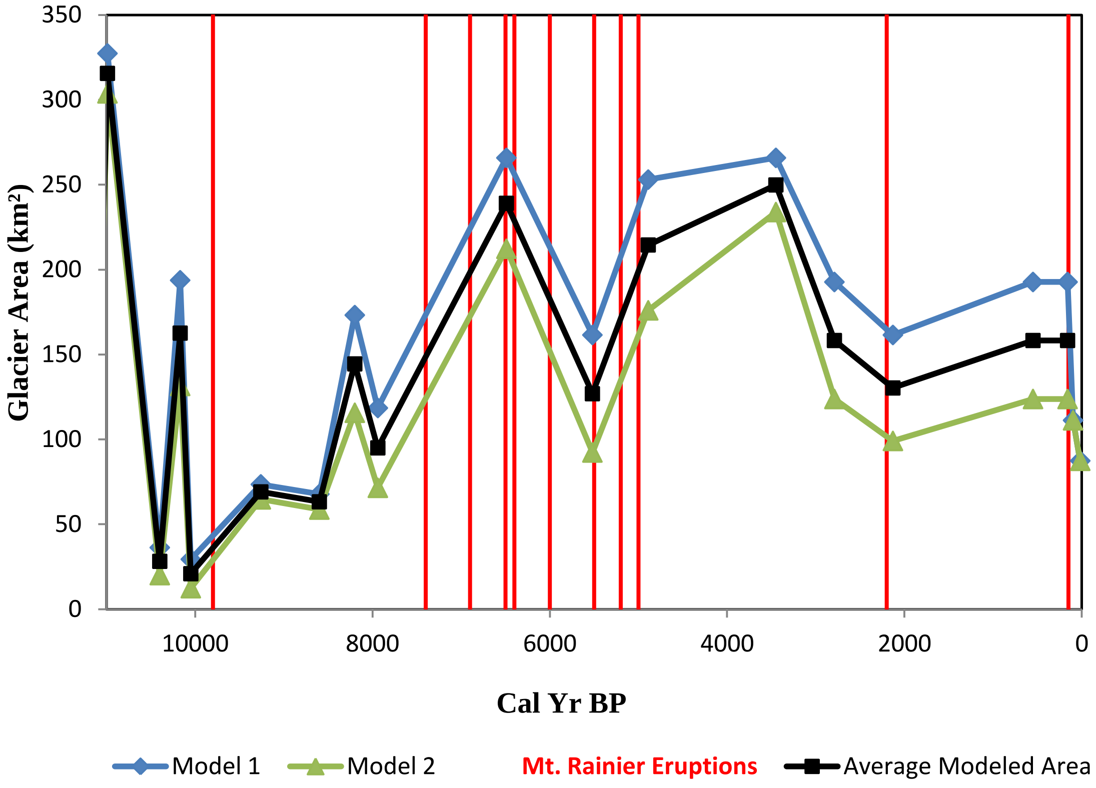


Figure 13: Modeled area of Mt. Rainier glaciers compared to timing of Mt. Rainier eruptions during the last 10 ka

A cumulative curve shows the number of Cascade eruptions compared to the modeled glacier area (Figure 14). The first eruptions within the last 10 ka for all Cascade volcanoes occurred from ~10-9.5 ka when there were 2 eruptions. They occurred at a low point in the modeled glacier area, which is ~1-1.5 ka following the last ice age. A low amount of volcanic activity is seen from 9.5-7.7 ka with only 2 eruptions occurring during this time. At that time, the modeled glacier area is ~150 km^2 and increasing. Then there is an increase in activity with an average of 1 eruption every 143 years from ~7.7-4.75 ka. During this time, the modeled glacier area increased to 239 km^2 at 6.49 ka before decreasing to a low of 215 km^2 at 5.52 ka. The eruption rate then decreased with the next eruption not occurring until ~3.8 ka. This is followed by an increase in the eruption rate at ~2.3 ka. At this time, the modeled glacier area decreases to below 150 km². The eruption rate remained fairly high between ~2.3-1 ka with an average of 1.7 eruptions every 100 years. Then the eruption rate decreased between ~1 ka-300 cal yr BP with only 3 eruptions occurring. During this time, the modeled glacier area increases to 158.25 km²; this is the largest glacier area during the last 2 ka. Finally, the eruption rate has increased during the last ~300 cal yr BP, with 10 eruptions occurring during this time. Meanwhile, during the last 300 cal yr BP, glacier area has decreased from a modeled area of 158.25 km² to the present area of ~87 km².

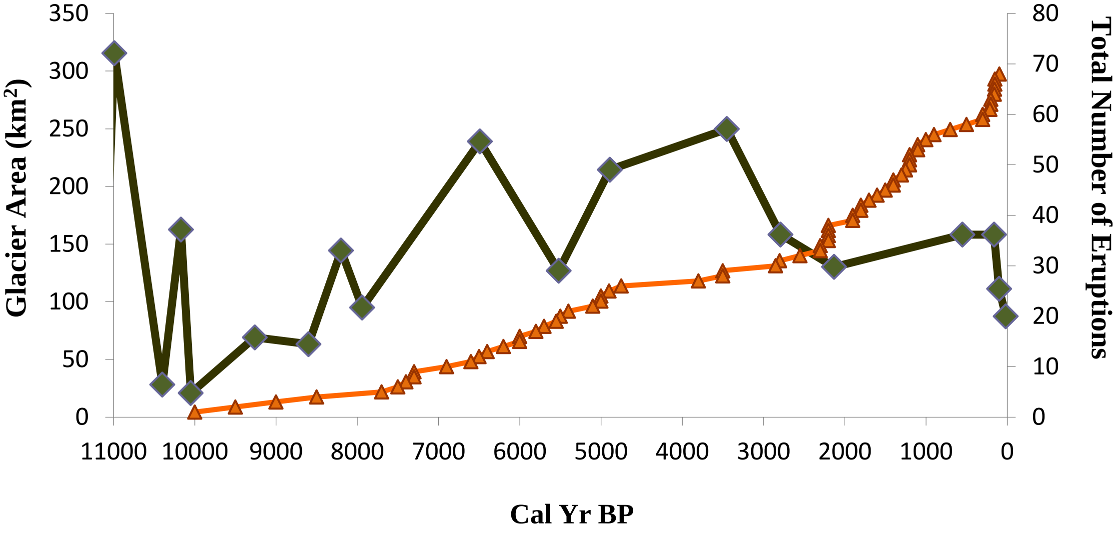


Figure 14: Modeled area of Mt. Rainier glaciers compared to a cumulative curve of the total number of eruptions of Cascade volcanoes during the last 10 ka

Discussion

The total average modeled glacier area at the time of the eleven eruptions of Mt. Rainier over the last 10 ka was 165.14 km². This is slightly higher than the overall average modeled area, which is 139 km². It is also greater than the current area of Mt. Rainer glaciers. Therefore, glacier area does not appear to have been significantly lower during times of eruptions during the past 10 ka. However, there is a period of increased activity between ~7.4-5 ka at Mt. Rainier. Eight of the eleven known eruptions during the last 10 ka occurred during this period. There is also a slight increase in the number of eruptions in the Cascade Range from ~7.7-4.75 ka. During that time, twenty-one eruptions occurred. The only other time period with a greater number of eruptions is during the last ~2.3 ka. This could suggest an increase in melting due to decompression of the magma chamber ~3.3-6.25 ka following the last glacial maximum. The time lag between the end of the glacial maximum and increased volcanic activity is greater than the 1.5 ka lag that occurred in Iceland following the last glacial maximum. However, because of the different geologic setting it is difficult to directly compare models for Iceland to deglaciation at Mt. Rainier. Icelandic volcanoes could have deeper magma chambers as a result of being located on a spreading center and hotspot. Iceland is also located on thinner oceanic crust whereas Mt. Rainier is located on thicker, continental crust. Also, increased volcanism in Iceland resulted from the removal of large ice sheets, which would likely result in much greater isostatic rebound and decompression compared to the removal of glaciers on the slopes of Mt. Rainier. However, a time lag of ~3.3-6.25 ka does fit into the range of 3.2±4.2 ka suggested by Jellinek et al. (2004) for silicic volcanism in California, which is more comparable to the geologic setting at Mt. Rainier.

There is also evidence that more recent eruptive patterns of Cascade volcanoes could correlate to glacial coverage. During the last ~2.3 ka, there have been two periods with an increased eruption rate for Cascade volcanoes. From ~2.3-1 ka, 22 eruptions occurred. This increase in eruptions coincides with a decrease in modeled glacier area, which decreased from 249.85 km^2 to 130.3 km^2 from 3.45-2.13 ka. An increase in the modeled glacier area to 158.25 km^2, 550 cal yr BP coincides with a decrease in eruptions from ~3-1 ka. Then, during the last 300 cal yr BP, the modeled glacier area decreased from 158.25 km^2 to the present glacier area of ~87 km^2. During which time the eruption rate increased. However, the modeled glacier area during the last ~2.3 ka is still larger than the glacier from ~10-8.5 ka, when the eruption rate was very low. Therefore, it is unclear if the recent increase in eruptions is solely related to glacier area. There is also the possibility that the large number of recent eruptions compared to the number of eruptions we are aware of during the last 10 ka could be a result of the erosion of volcanic deposits. This could cause some eruptions to go unnoticed due to the lack of preservation of older volcanic deposits.

CHAPTER VI

CONCLUSIONS

Mt. Rainier is the most glaciated volcano in the conterminous United States. Decreases in glacier coverage have been documented during several periods in the twentieth century. To measure glacier area from 1985-2009, seven Landsat scenes were used. Glacier areas measured in this study show a continuing trend of loss in glacier area, consistent with USGS and GLIMS measurements. The possibility of an increased risk for eruptions at Mt. Rainier due to the removal of glaciers from its slopes was then examined. This was accomplished by comparing past eruptions of Mt. Rainier and other Cascade volcanoes to the modeled glacier area of Mt. Rainier for the last 10 ka.

It is reasonable to presume that glacier area will continue to decrease in the short term based on the recent trends in glacier change at Mt. Rainier. The observed area of Mt. Rainier glaciers decreased from 85.590 km^2 to 81.355 km^2 (5.32%) from 1985-2009. Individual glacier areas also decreased continuously with only a couple exceptions during the same time period. The change in area per year and percent change in total area per year is negative for all six time periods studied. The rate of glacier loss also increased between 2005 and 2009. Therefore, if glacier loss continues, the risk of hazards such as jökulhlaups and lahars could be enhanced due to the increased amount of glacial melt. Decreases in glacier ice at Mt. Rainier could also lead to an increased risk of eruptions due to decompression of the magma chamber. A continuation of the glacier loss seen in this study could be enough to trigger decompression, especially if Mt. Rainier has a shallow magma chamber. However, it is unclear what the time lag would be between glacier loss and an eruption as well as the amount and rate of glacier loss that would be needed. An increase in eruptions occurred ~7.4-5 ka, which is ~3.6-6 ka following the last glacial maximum. During the last ~2.3 ka, eruption rates of Cascade volcanoes have increased during times when the modeled glacier area decreased. This strongly suggests a correlation between eruption rates and glacier coverage. However, more studies are needed at similar volcanoes with an extensive amount of glaciation on their slopes to confirm this relationship. Mt. Rainier's magma plumbing system also needs to be studied further to better understand its geometry and depth.

In conclusion, Mt. Rainier glaciers show continuous decrease in area from 1985-2009, and there is possibly a link between increased eruption rates and decreases in glacial ice. Glaciers at Mt. Rainier should therefore continue to be closely monitored in the future because of a possible increased risk of jökulhlaups, lahars, and eruptions. Satellite-based remote sensing, such as the Landsat scenes used in this study, can be a valuable tool for monitoring Mt. Rainier glaciers. Future monitoring through remote sensing would allow glacier areas to be consistently tracked and provide data needed to assess hazard risks.

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APPENDICES

Appendix A: Measured changes in glacier area (km^2)

Glacier Name	1985-1988	1988-1991	1991-1998	1998-2005	2005-2007	2007-2009	1985-2009
Carbon/Russell	-0.165	-0.199	-0.142	-0.092	-0.082	-0.081	-0.761
Cowlitz/Ingraham/Paradise	-0.226	-0.019	-0.122	-0.049	-0.030	-0.063	-0.508
Emmons	-0.004	0.0133	0.004	-0.053	-0.010	-0.007	-0.057
Inter Glacier	-0.005	-0.011	-0.003	0.000	-0.003	-0.003	-0.026
Kautz	-0.027	-0.003	-0.051	-0.043	-0.021	-0.023	-0.169
Nisqually/Wilson	-0.022	-0.098	-0.005	-0.057	-0.029	-0.037	-0.248
North Mowich/Edmunds	-0.179	-0.191	-0.151	-0.108	-0.027	-0.051	-0.706
Puyallup/South Mowich	-0.165	-0.093	-0.157	-0.127	-0.029	-0.033	-0.565
Tahoma/South Tahoma	-0.102	-0.158	-0.088	-0.046	-0.027	-0.005	-0.425
Whitman/Ohanapecosh/Fryingpan	-0.197	-0.109	-0.056	-0.085	-0.004	-0.034	-0.485
Winthrop	-0.060	-0.038	-0.087	-0.038	-0.002	-0.019	-0.333
Total	**-1.153**	**-0.904**	**-0.859**	**-0.698**	**-0.264**	**-0.356**	**-4.283**

Appendix B: Additional Landsat scenes and measured glacier areas of Mt. Rainier

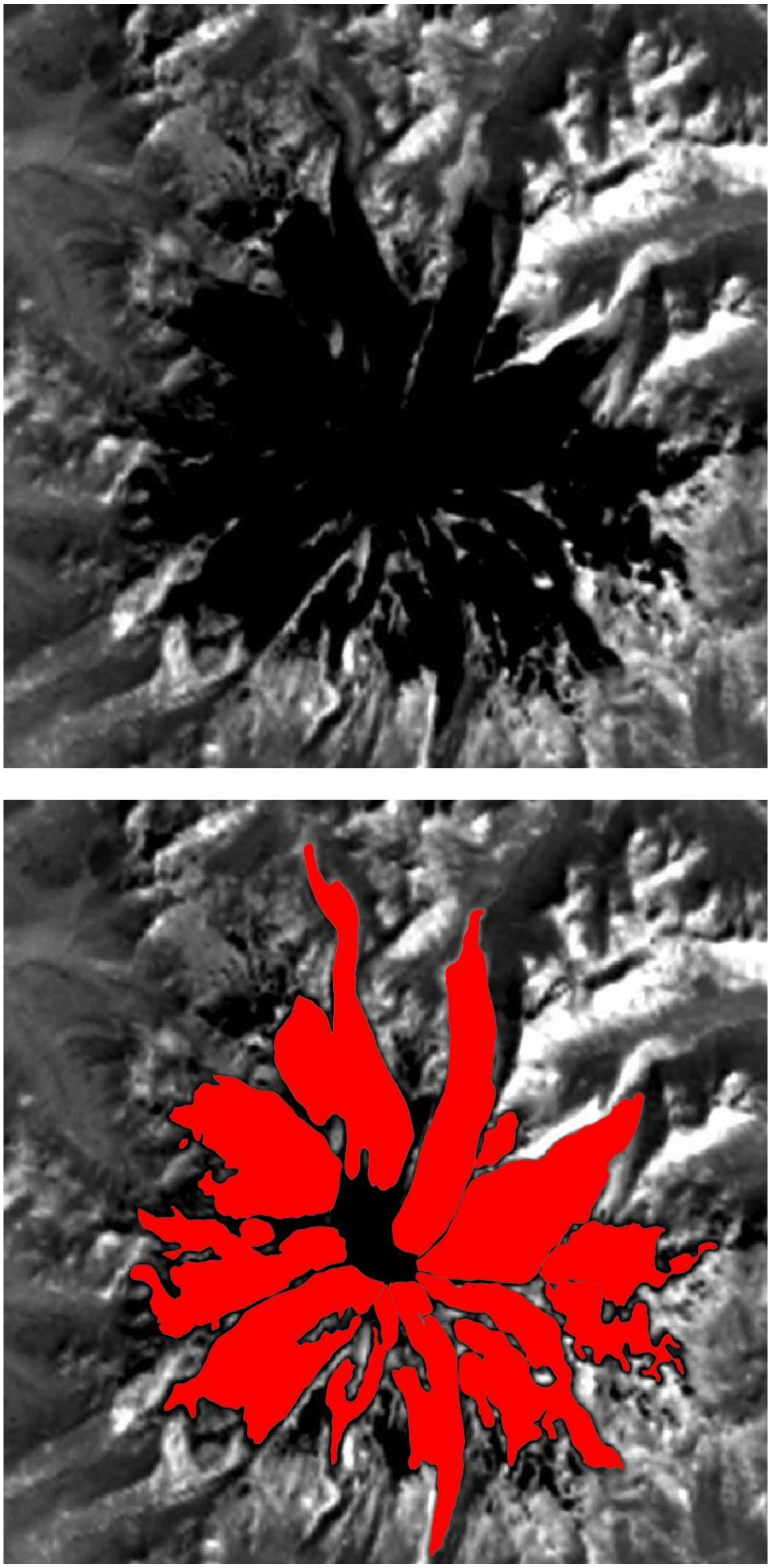


Figure B1: August 23, 1985

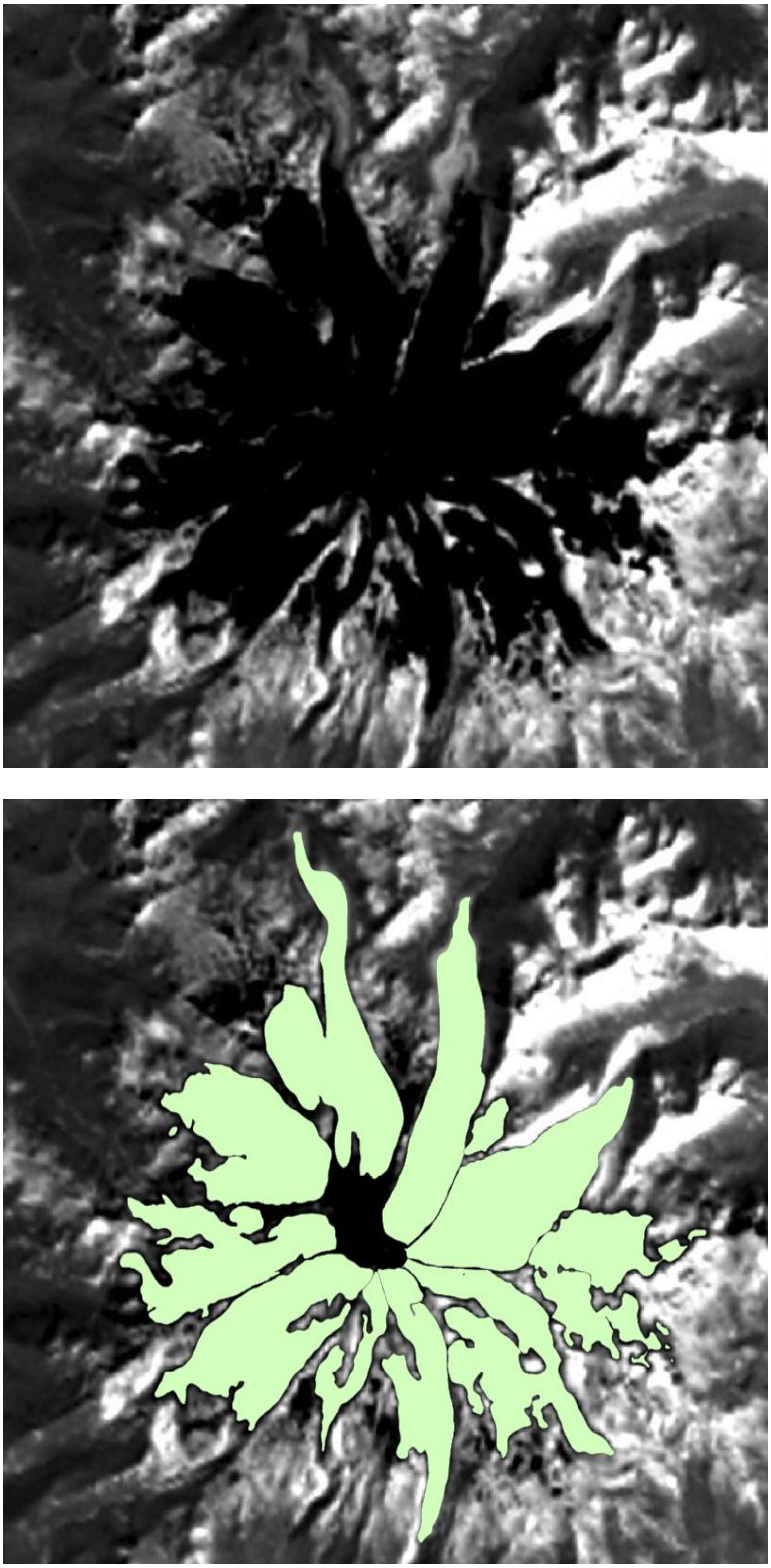


Figure B2: August 31, 1988

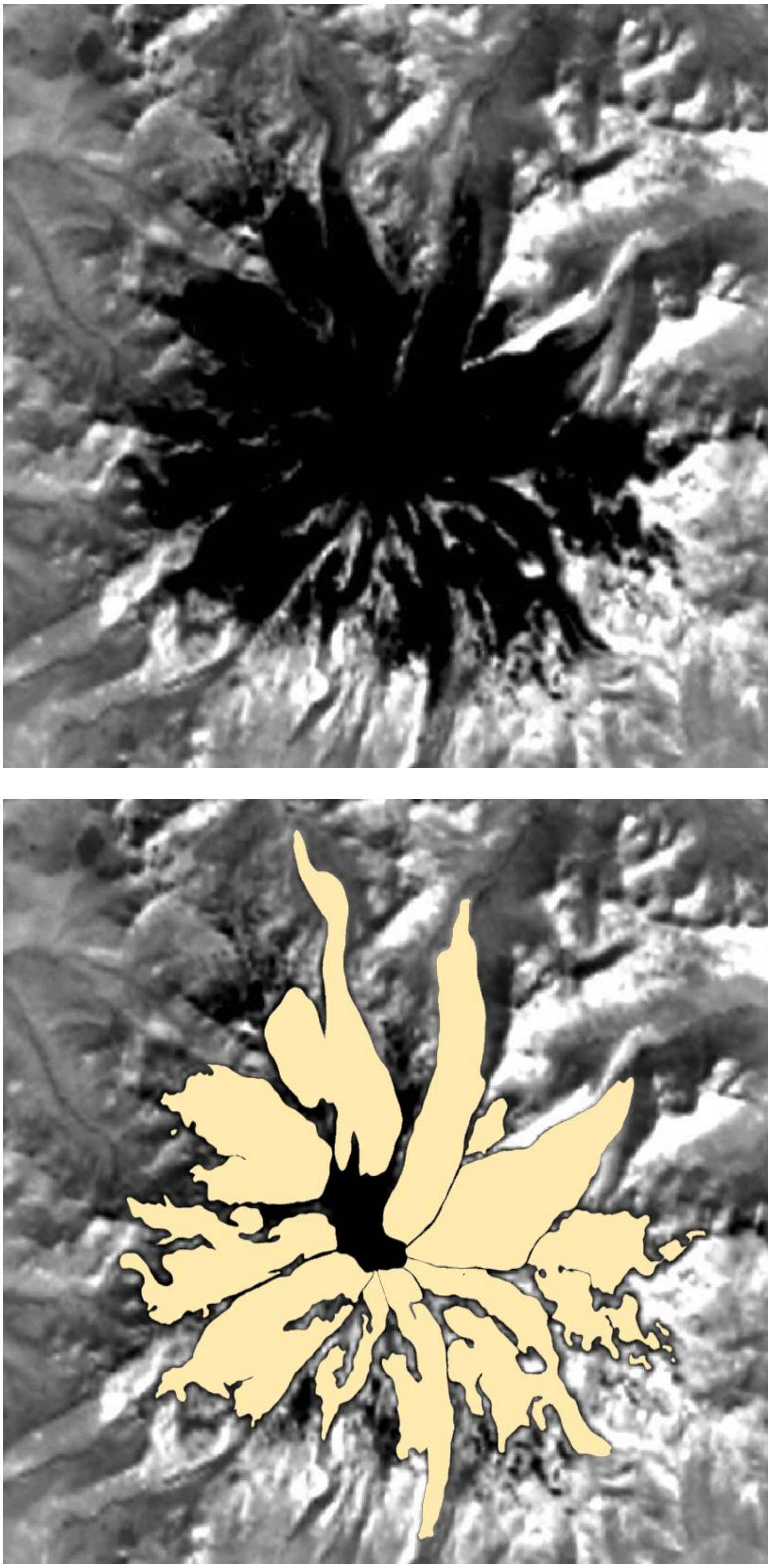


Figure B3: September 25, 1991

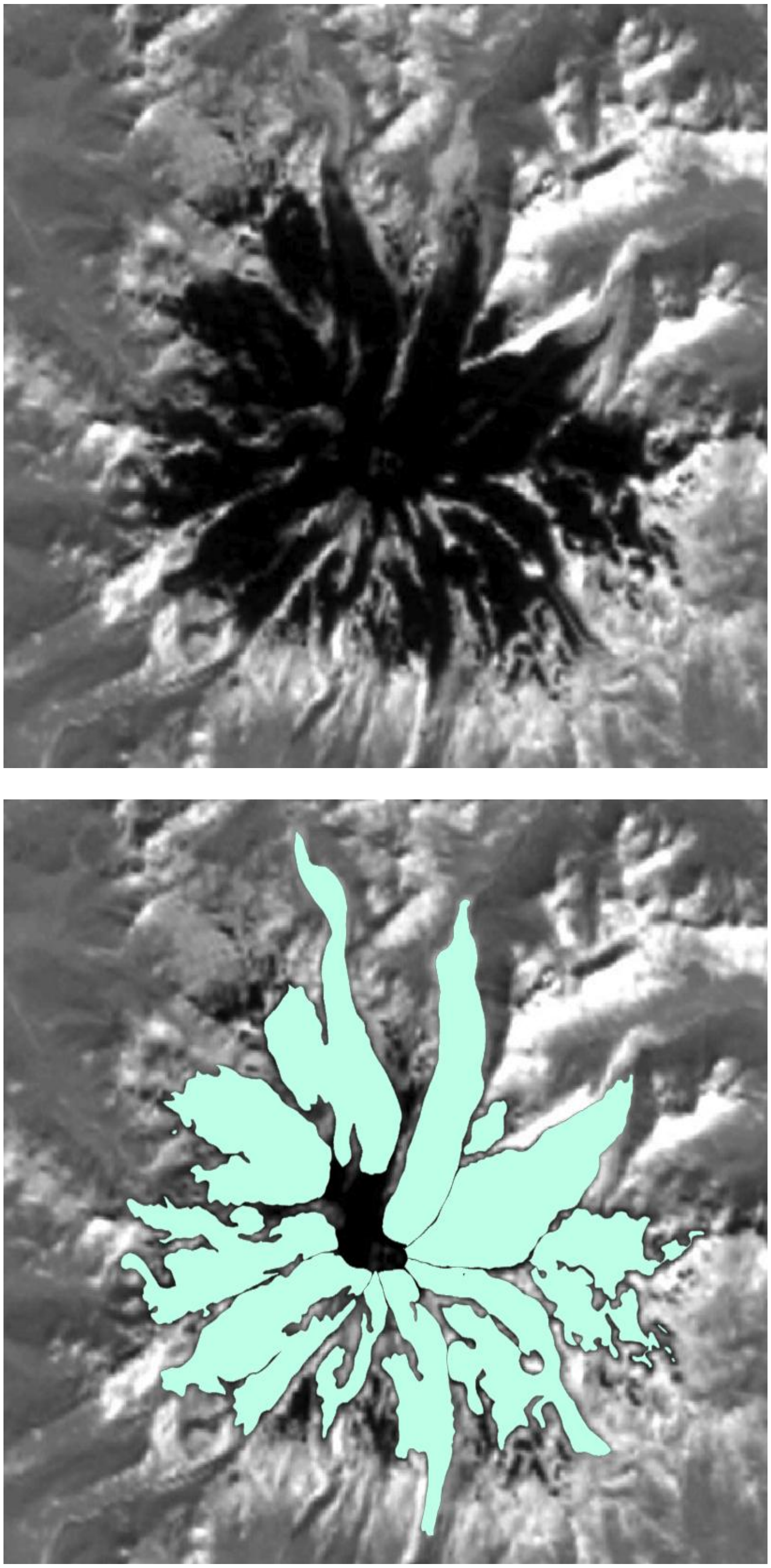


Figure B4: September 12, 1998

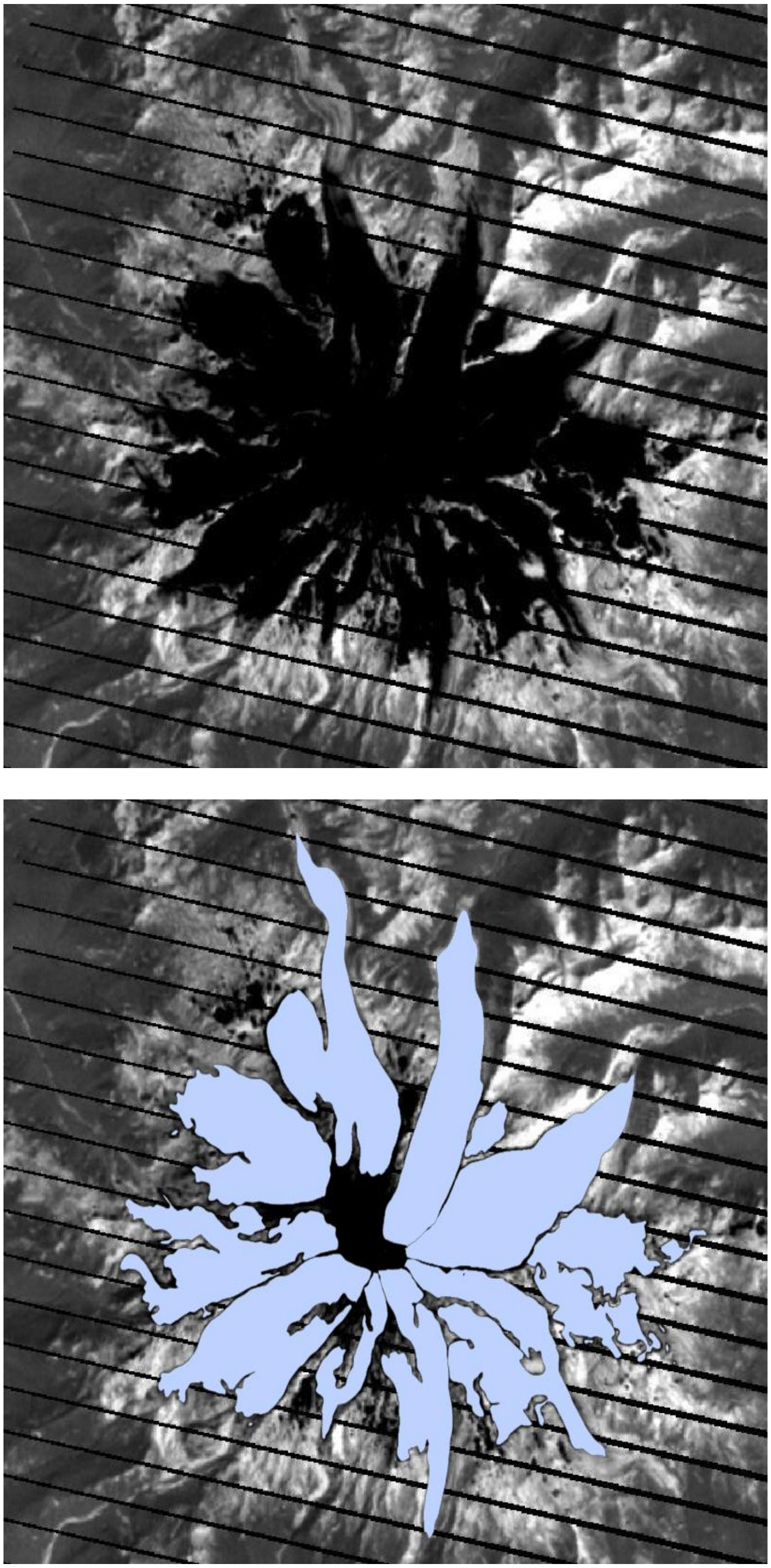


Figure B5: August 6, 2005

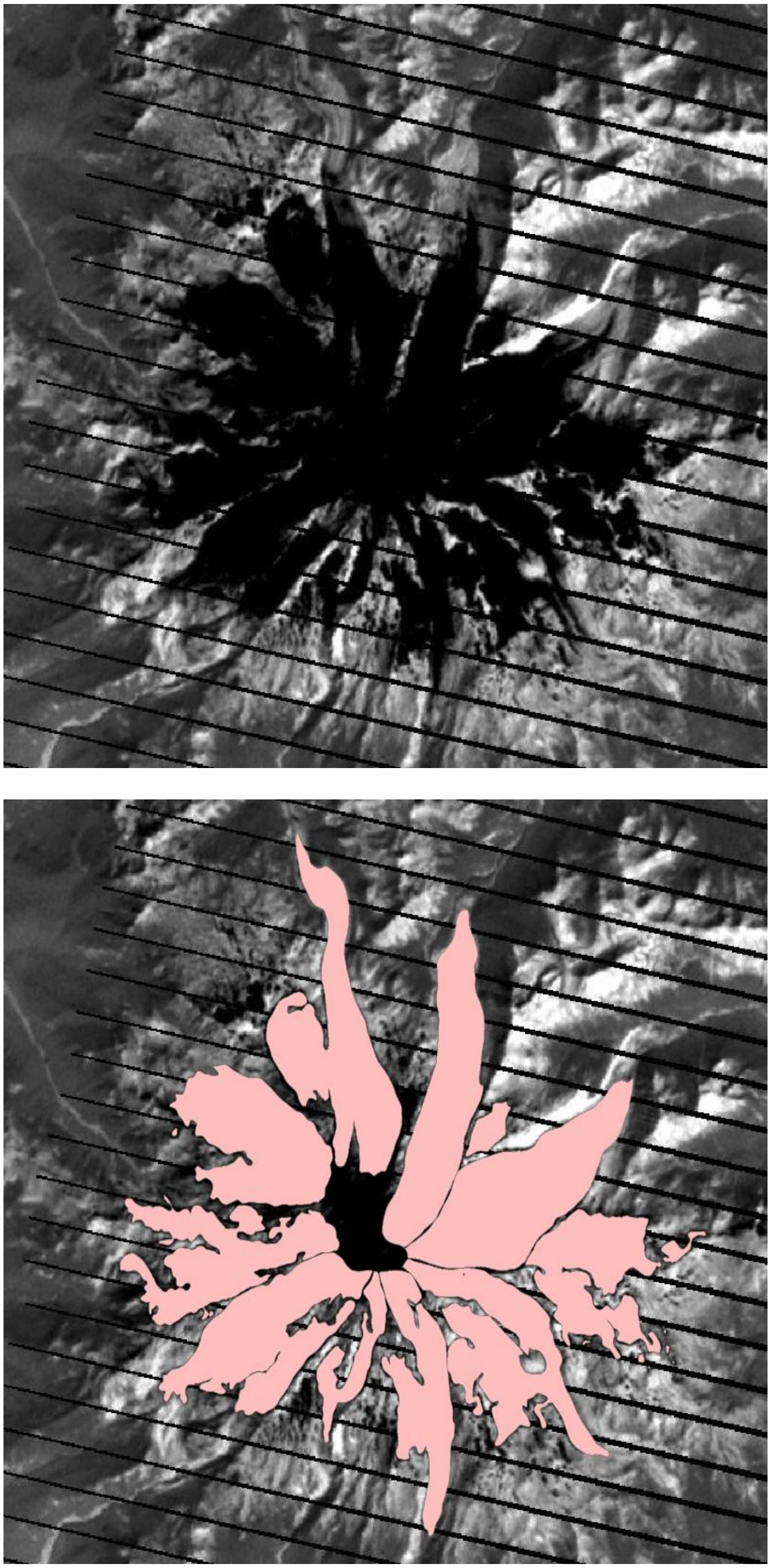


Figure B6: August 28, 2007

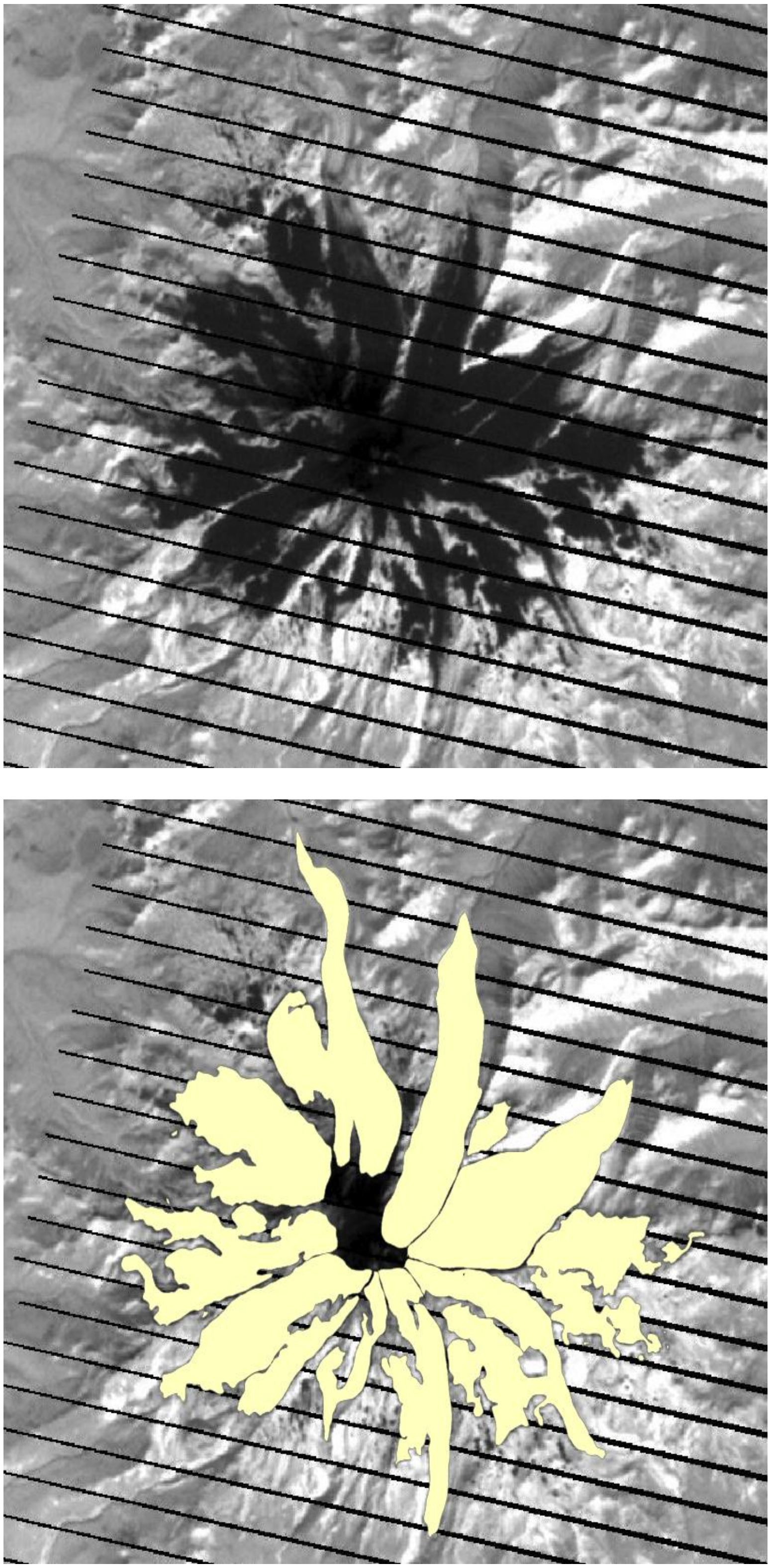
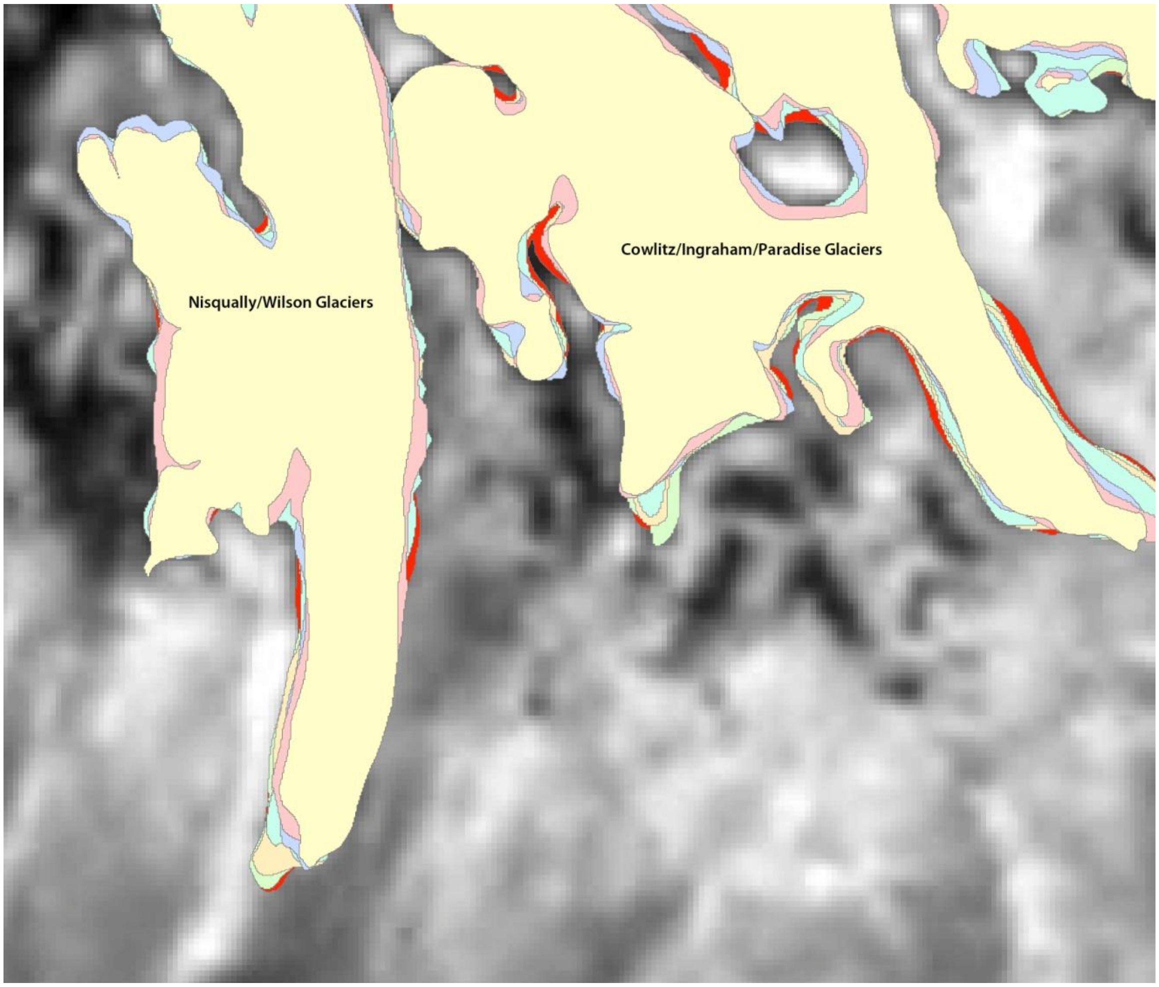


Figure B7: September 18, 2009

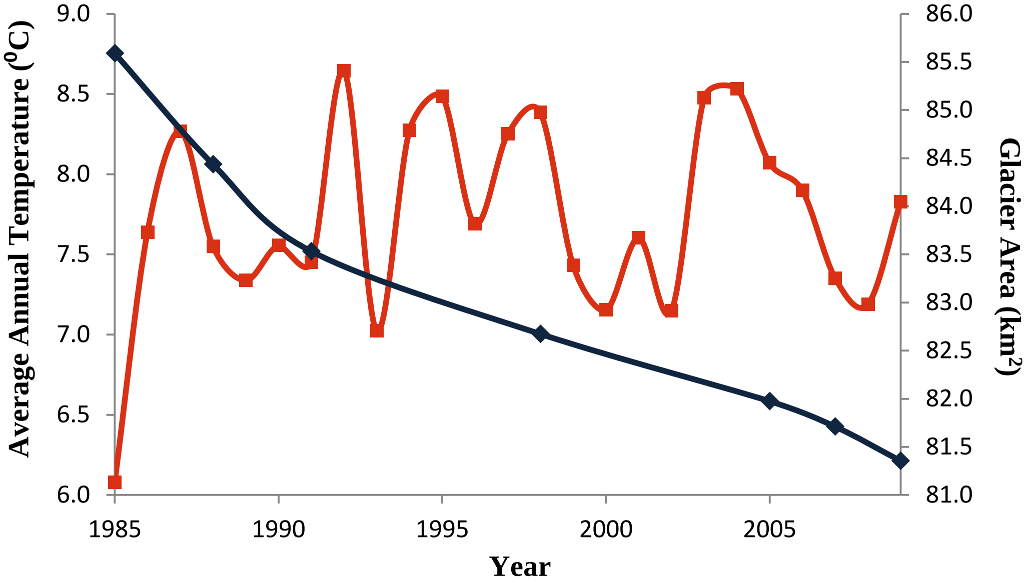
Appendix C: Zoomed in view of measured areas of Nisqually/Wilson and Cowlitz/Ingraham/Paradise Glaciers



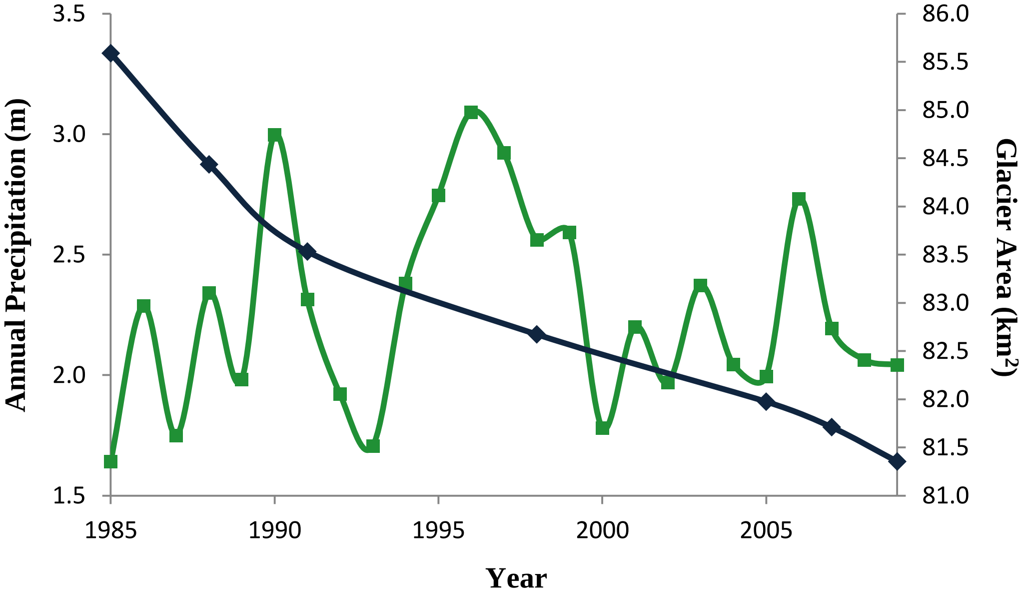
Appendix D: Percent Change in Area of North-Facing Glaciers (Carbon/Russell, Emmons, North Mowich/Edmunds, Puyallup/South Mowich, Winthrop) and South-Facing Glaciers (Cowlitz/Ingraham/Paradise, Kautz, Nisqually/Wilson, Tahoma/South Tahoma)

	1985-1988	**1988-1991**	**1991-1998**	**1998-2005**	**2005-2007**	**2007-2009**	**1985-2009**
North-facing	-0.384%	-0.344%	-0.157%	-0.124%	-0.158%	-0.201%	-0.199%
South-facing	-0.458%	-0.342%	-0.142%	-0.106%	-0.201%	-0.243%	-0.205%

Appendix E: (A) Comparison of average annual temperature and (B) annual precipitation recorded at the Paradise Ranger Station to the measured glacier area from 1985-2009



A.



B.

Appendix F: Approximate timing (cal yr BP) of Cascade eruptions during the last 10 ka

Mt. Adams	**Mt. Baker**	**Glacier Peak**	**Mt. Hood**	**Lassen Peak**	**Mt. Mazama**
1,250	157	300	150	95	5000
1,400	5,800	1,100	200	1,100	7,500
1,500	6,600	1,800	1,700		7,700
2,300	8,500	2,800			
5,000		3,800			
6,000		5,100			
9,000					

Medicine Lake	**Newberry Caldera**	**Mt. Rainier**	**Mt. St. Helens**	**Mt. Shasta**	**Three Sisters**
900	1,200	150	30	200	1,600
1,200	3,500	2,200	200	700	1,900
1,300	6,500	5,400	300	1,800	2,200
1,400	7,300	5,550	499	2,200	2,300
4,900		5,700	1,200	2,850	5,500
		6,200	1,900	3,500	
		6,400	2,200	4,750	
		6,900	2,550	6,000	
		7,300		9,500	
		7,400			

VITA

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Scope and Method of Study: Thermal Infrared Landsat scenes (Band 6) were collected and analyzed to quantify area changes and rates of change of Mt. Rainier glaciers between 1985 and 2009. Glacier change data was compared to measurements made by the United States Geological Survey (USGS) and the Global Land Ice Measurements from Space (GLIMS) project. The modeled glacier area at Mt. Rainier for the last 10 ka was then compared to the eruptive history of Mt. Rainier and other Cascade volcanoes to examine correlations.

Findings and Conclusions: Landsat scenes show a steady decrease in glacier area at Mt. Rainier, consistent with USGS and GLIMS measurements. The observed area of Mt. Rainier glaciers decreased from 85.590 km^2 to 81.355 km^2 (5.32%) from 1985-2009. If glacier loss continues, the risk of hazards such as jökulhlaups (glacial outburst floods) and lahars could be enhanced due to the increased amount of glacial melt. Decreases in glacier ice at Mt. Rainier could also lead to an increased risk of eruptions due to decompression of the magma chamber. A continuation of the glacier loss seen in this study could be enough to trigger decompression, especially if Mt. Rainier has a shallow magma chamber. However, it is unclear what the time lag would be between glacier loss and an eruption as well as the amount and rate of glacier loss that would be needed. Previous studies indicate that there was an increase in eruptions ~7.4-5 ka, which is ~3.6-6 ka following the last glacial maximum. During the last ~2.3 years, eruption rates of Cascade volcanoes have increased during times when the modeled glacier area decreased. This strongly suggests a correlation between eruption rates and glacier coverage. Glaciers at Mt. Rainier should therefore continue to be closely monitored in the future because of a possible increased risk of debris avalanches, lahars, jökulhlaups, and eruptions. Satellite-based remote sensing such as the Landsat images used in this study can be a valuable tool for monitoring Mt. Rainier glaciers. Future monitoring through remote sensing would allow glacier areas to be consistently tracked and provide data needed to assess hazard risks.

ADVISER'S APPROVAL: Dr. Jeffrey Byrnes