THESIS APPROVAL

The abstract and thesis of Thomas H. Nylen for the Master of Science in Geology presented October 25, 2001, and accepted by the thesis committee and the department.

COMMITTEE APPROVALS: ________________________________

Andrew G. Fountain, Chair

____

Scott F. Burns

____

Christina L. Hulbe

____

Keith S. Hadley
Representative of the Office of Graduate Studies

DEPARTMENTAL APPROVAL: ________________________________

Michael L. Cummings, Chair
Department of Geology

ABSTRACT

An abstract of the thesis of Thomas H. Nylen for the Master of Science in Geology presented October 25, 2001.

Title: Spatial and Temporal Variations of Glaciers (1913-1994) on Mt. Rainier and the Relation with Climate

Databases have been constructed for the purpose of studying glacier changes at Mt. Rainier. Glacier cover on Mt. Rainier decreased 18.5% (112.3 km^2 to 88.1 km^2) between 1913 and 1971 at a rate of about -0.36 km^2 a^{-1}. The total area in 1994 was 87.4 km^2, which equates to a rate of -0.03 km^2 a^{-1} since 1971. Glaciers with southerly aspect lost significantly more area than those with a northerly aspect, 26.5% and 17.5% of the total area, respectively. Measured and estimated total volumes for Mt. Rainier glaciers also decreased. From 1913 to 1971 the total volume decreased 22.7% from 5.62 km^3 to 4.34 km^3 and from 1971 to 1994 decreased 3.1% to 4.21 km^3. Nisqually Glacier shows three cycles of retreat and advance but an overall loss of 0.44 km^2 since 1931. Cross-correlation with snowfall suggests about a decade response time for the glaciers.

The pattern of terminus change through this century has been consistent between the glaciers. Between 1913 and the late 1950s, the major glaciers were

retreating, with an average retreat of 1,318 m. Following this period and up to the early 1980s the glaciers advanced an average distance of 390 m. Since 1980, the terminus positions of all but three glaciers, Emmons, Winthrop and Cowlitz, retreated.

Though the response has been similar, spatial variations exit in the magnitude of response. Southern glaciers, which are on average smaller decreased in area, volume and length more than the northern glaciers. The northern glaciers decreased in area by 17.5%, while the southern glaciers decreased by 26.5%. As for the terminus positions, the southern glaciers retreated on average 1,957 m, which is approximately three times as far as the average for the northern glaciers. The spatial variations in area and volume of the glaciers are caused primarily by differences in incoming solar radiation, size and elevation range. With more solar radiation the southern glaciers have smaller mass balances and over time cause spatial differences in the size of the glaciers. Smaller glaciers appear to be more sensitive to climate changes than larger glaciers because they have smaller elevation ranges.

SPATIAL AND TEMPORAL VARIATIONS OF GLACIERS (1913-1994) ON MT. RAINIER AND THE RELATION WITH CLIMATE

by

THOMAS H. NYLEN

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Table of Contents

List of Figures

List of Tables

I. Introduction

Glaciers are good gauges of climate in temperate alpine regions (Meier, 1998). Because temperatures of these glaciers are at the melting point, they are sensitive to changes in temperature (UNEP, 1992). Of course, changes in snowfall affect the glaciers. Although glacial surfaces respond immediately to snow accumulation/ice melt, it takes decades to centuries for glacial extents to respond (Bahr, 1998; Jóhannesson et al., 1980). Because of the delay the connection between climate and glaciers is not always clear and is often complicated by non-climatic factors, such as debris cover and aspect.

Glaciers are an important component of regional and global hydrologic systems. At present, Earth's approximate 160,000 glaciers, ice caps and ice sheets contain 75% of its freshwater and cover approximately 10% of its land area (UNEP, 1992). The current volume of water frozen as glaciers and ice caps is equivalent to approximately 50 cm of sea level (Meier and Bahr, 1996). Meier (1984) and Oerlemans (1992) estimated that alpine glaciers contributed a third to one half of the observed 10 to 15 cm rise in sea level between 1884 and 1975. From 1975 to 1990 the rate of glacier contribution to sea level rise has doubled, from 3.5 mm yr^{-1} to 7.3 mm yr^{-1} (Dyurgerov and Meier, 1997b). This increase is attributed to a 2.5°C rise in global air temperatures (Dyurgerov and Meier, 1997b; Oerlemans, 1994).

At a regional scale glacier populated watersheds provide a more stable source of water compared to ice-free watersheds (Braithwaite and Olsen, 1988; Ferguson, 1973; Fountain and Tangborn, 1985). Hydrological basins with 20% or more of their area covered by glaciers have approximately 50% greater summer runoff and significantly lower annual runoff variability than non-glaciated basins (Fountain and Tangborn, 1985). This is especially true during drier than normal summers when the percentage of meltwater from glaciers increases when other water sources are scarce.

Glaciers also pose hazards because of glacial floods, which are initiated by the sudden release of water stored in or damned by glaciers (Bjornsson, 1974). Outburst floods occur in most glaciated regions of the world, although the frequency of floods varies widely (Bjornsson, 1992; Haeberli, 1983; Mottershead and Collin, 1976; Nye, 1976; Russell, 1989; Walder and Costa, 1996). These floods are triggered when significant volumes of water reach the base of glaciers during heavy rainfall events, warmer temperatures, volcanic eruptions (Walder and Driedger, 1994) or when moraine or glacier-dammed lakes fail (Yamada, 2000). Outburst floods often entrain large amounts of debris, which chokes streams and increases the risks of damage to man-made structures and injury to humans (Clarke, 1982; Driedger and Fountain, 1989; Yongjian and Jingshi, 1992). One of the largest recorded glacial floods, nearly 4 km^3 of water, occurred in Iceland in 1996 (Smith et al., 2000). An eruption under the Vatnajokull Glacier, the largest glacier in Iceland, caused significant melting at the base of the glacier. Recent warming of the climate in some areas has increased the frequency of floods. Dams holding back numerous proglacial lakes in the Hialayas have recently formed as the glaciers retreat up mountain valleys. These moraine dams are unstable and often fail, causing floods in Nepal (Yamada, 2000). Other regions with retreating glaciers have similar problems. Failure of 11 Oregon lakes proximal to the Three Sisters and Mt. Jefferson has occurred over the last century (O'Connor et al., 2001). Eight moraine-dammed lakes, ranging up to ~10^6 m^3, still exist in these regions. At Mt. Rainier National Park numerous outburst floods, originating from the Nisqually, Kautz, South Tahoma, and Winthrop glaciers, have occurred during the 20th Century, some of which damaged roads and visitor facilities (Driedger and Fountain, 1989; Walder and Driedger, 1994). These floods are not caused by the failure of moraine dammed lakes or geothermal heating, but by warm temperatures or heavy rainfall events (Hoblitt et al., 1998).

Long-term monitoring is required to gain a better understanding of the relationships between glaciers, climate, hydrology and hazards. Extensive datasets are necessary to track glacier changes over a long time period. Few monitoring programs exist because of limited financial resources. Of the 160,000 estimated glaciers in the world, less than 1% are monitored (Haeberli, 1998). This scarcity of data makes it especially important to use all historic information from maps, aerial photographs and other sources to assess glacier change.

Past research on glacier change and climate has focused on only a few glaciers. Three US glaciers subject to intense, continuous data collection are South Cascade Glacier in the North Cascades, Washington (Krimmel, 1989; Meier, 1965b), and Wolverine and Gulkuna glaciers in Alaska (Trabant et al., 1986). These three are designated as a benchmark glacier for each region (Fountain, 1997). It is not obvious, however, whether these glaciers are representative of the others in the same region. Currently, no rigorous test to the validity of the benchmark concept has been conducted. In fact, the response of glaciers in the same climatic zone may differ in timing and magnitude due to differences in aspect, slope, and distribution of mass with elevation (Oerlemans, 1988; Tangborn et al., 1990). Because of the extensive glacier and climate datasets Mt. Rainier provides an excellent opportunity to examine the response of many glaciers to the same climatic variations, and to test the benchmark concept.

To study the Mt Rainier glaciers I compiled data from maps and aerial photographs into a geographic information system (GIS) database. Using a GIS provides a tool to make quick and accurate measurements and comparisons of maps and aerial photographs with different scales. My research focuses on glacial changes occurring from 1913 to 1994. The starting date is the final year of a three-year effort (1910, 1911 and 1913) to survey the mountain (Matthes, 1915). The ending date represents the last re-mapping of the glacial positions. From the database I measured changes in terminus positions, glacier and debris-covered areas, glacier volumes, glacial aspects, and altitude distributions. The results are correlated with precipitation and temperature data from the Mt. Rainier region to assess their relationship. Additionally, the glacial response times are determined and compared with theoretical calculated values.

My hypothesis is that glaciers in the same climate environment, although with different characteristics such as size, slope, orientation, respond similarly to climatic variations, except when acted upon by non-climatic influences such as debris cover. Besides contributing additional information on the link between glaciers and climate the results of my thesis provide a framework for future research and monitoring in the Mt. Rainier National Park. The spatial dataset is also useful to the National Park Service for park management and educational purposes.

II. Study Site

A. General Description

Mt. Rainier located in Washington State (46° 51' N, 121° 45' W) is the tallest stratovolcano in the Cascade Range, reaching a height of 4392 m (Driedger, 1986). Twenty-six major glaciers and unnamed permanent ice/snow fields occur on Mt. Rainier (Figure 1) with a total area and volume of ice and snow of approximately 92.1 km^2 and 4.4 km^3, respectively (Driedger and Kennard, 1984). The ice on Mt. Rainier

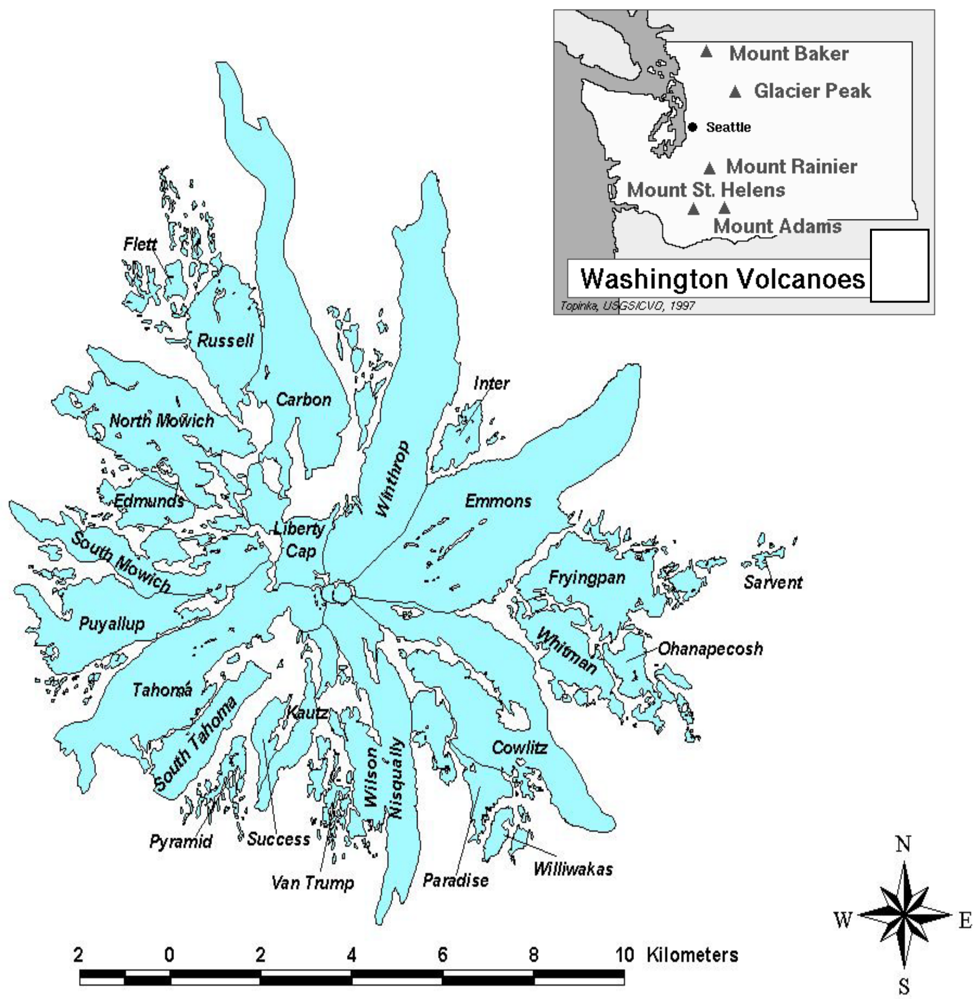

Figure 1: Mt. Rainier glaciers and insert map showing location (Topinka, 1997).

represents 42% and 50% (Table 1) of the total ice area and volume on all of the Cascade volcanoes and about 25% of the total ice area in the lower 48 states (Meier, 1961).

Table 1: Area and volume of glaciers on Washington, Oregon and California Cascade volcanoes in the early 1970s ([1]Driedger and Kennard, 1984; [2]Pinotti, unpublished).

Mountain	Area (km^2)		% Fraction	Volume (km^3)		% Fraction
Mt. Rainier, WA	92.1	1	42%	4.4	1	50%
Mt. Baker, WA	48.5	1	22%	1.8	1	21%
Glacier Peak, WA	27.0	1	12%	0.9	1	11%
Mt. Adams, WA	23.3	2	11%	0.7	1	8%
Mt. Hood, OR	10.3	2	5%	0.4	1	5%
Three Sisters, OR	6.6	2	3%	0.2	1	3%
Mt. Shasta, CA	6.9	1	3%	0.1	1	1%
Mt. Jefferson, OR	4.2	2	2%	0.1	1	1%
Mt. Lassen, CA	0.1	1	0%	0.0	1	0%
Total	219.0			8.6		

The Mt. Rainier glaciers vary considerably in size and extent. The glacier elevations range from the rim of the summit crater at 4,267 m down to 1,097 m. Only five of the 26 glaciers, Winthrop, Emmons, Cowlitz, Nisqually, Tahoma and Liberty Cap begin at the summit crater. At 1,097 m, the Carbon Glacier has the lowest terminus elevation in the contiguous US (Driedger, 1986). Glacial areas of the name glaciers range from 0.2 km^2 (Liberty Cap Glacier) to 11.2 km^2 (Emmons Glacier) and the volumes range from <0.1 km^3 (Liberty Cap Glacier) to 0.8 km^3 (Carbon Glacier). The volume of Carbon Glacier and the area of Emmons Glacier are the largest in the contiguous US. Several glaciers, Cowlitz-Ingraham, Success-Kautz and Nisqually-

Wilson, begin as separate tributaries of ice and flow together to the same terminus. Many glaciers such as Emmons and Winthrop share a common source area, but divide into separate glaciers farther down the mountain. Tahoma Glacier is the only glacier to diverge into two distinct lobes near its terminus.

B. Prior Research

Prehistoric glacier limits for Mt. Rainier have been extensively examined (Burbank, 1979; Crandell, 1965; Davis, 1987; Heine, 1996; Porter and Burbank, 1979; Sigafoos and Hendricks, 1972). Crandell (1965) defined maximum glacial extents during four episodes in the Pleistocene. Holocene-age moraines have been dated using lichenometry, dendrochronology and tephrochronology (Burbank, 1979; Porter and Burbank, 1979; Sigafoos and Hendricks, 1972). Results show that the Mt. Rainier glaciers have receded significantly since the end of the Pleistocene. Several glacial advances occurred during the Holocene but none matched the extent during the Pleistocene. The greatest and most recent Holocene advance occurred around 1750 during the Little Ice Age (Burbank, 1979). Since then all of the glaciers have retreated (Driedger, 1986).

In 1857, Lt. August V. Kautz recorded the first glacier observations at Mt. Rainier, when he noted the position of the Nisqually Glacier terminus (Heliker et al., 1984). The United States Geological Survey (USGS) published the first map of the Mt. Rainier glaciers in 1898 (Russell, 1898). The USGS report recommended further monitoring of the glaciers, especially Nisqually Glacier, to further understand the link between glacier and climate changes. The first complete and accurate topographic map of Mt. Rainier was constructed from regional surveys made by the USGS in 1910, 1911 and 1913 (Matthes, 1912, 1913, 1914a; 1914b; 1915) and finally published in 1955. In 1971, the USGS revised the 1913 map using aerial photogrammetry. In 1996 further revisions were made from aerial photos taken in 1994. The revisions were limited to the larger glaciers.

Because of its accessibility most of the glacier research on Mt. Rainier has focused on Nisqually Glacier. A trail was established to Nisqually Glacier in 1884 and the NPS enlarged it to a road in 1909 (Williams, 1910), which is still in use today. Outburst floods from Nisqually Glacier destroyed several bridges crossing the Nisqually River, forcing the NPS to build increasingly bigger structures (Driedger and Fountain, 1989). The NPS first surveyed Nisqually Glacier in 1908 during road construction (Potts, 1954). In 1918, the NPS started recording annual terminus positions (Johnson, 1973) and continued their measurements until 1979 (Heliker et al., 1984). Between 1931 and 1946, the USGS, the NPS, and the Department of Public Utilities of the City of Tacoma mapped the lower third of the glacier five times to evaluate the hydroelectric potential of the Nisqually River (Bender and Haines, 1955). Starting in 1951 the USGS mapped the entire or most of the glacier every five years. The USGS maps include glacial extent and surface topography. The last Nisqually Glacier map was completed in 1981. Since first observed by Kautz in 1857, Nisqually

Glacier has retreated about 1.5 km with small advances in 1905-1908, 1951-1969 and 1975-1984 (Driedger, 1986). Back in 1857, the terminus was located near the present road. Today, observers cannot see the terminus from the bridge.

In 1931 the USGS started surveying two transverse surface profiles on the lower half of Nisqually Glacier as part of the hydroelectric study. Several more surveys were completed in 1932, 1933, and 1941 (Heliker et al., 1984), before adding a third profile higher up on the glacier in 1942. Presently, the NPS still surveys the three profiles every year. From the survey data kinematic waves have been observed propagating down glacier traveling at two to six times faster than the glacier flow speed (Johnson, 1960; Meier, 1965a; Meier and Johnson, 1962). Kinematic waves are wavelike perturbations of a glacier's surface which travels down the glacier. They result from periods of increased accumulation (Meier and Johnson, 1962). These waves often travel to the terminus and cause glaciers to advance.

Several scientists analyzed terminus changes for the glaciers. Burbank (1981; 1982) measured terminus position changes of the major glaciers and compared them to climate change over a 200-year period. Results show that the equilibrium line altitude (ELA) increased by 160 m since the early 19th Century and that the recession since the Little Ice Age was due to a 1°C increase in annual mean air temperature. Driedger (1986) traced terminus positions of the major glaciers from aerial photographs on to mylar paper and compiled results collected previously by the NPS, Burbank (1982) and Sigafoos and Hendricks (1979). Results indicate an advance of the major glaciers between the 1950s and early 1980s, followed by significant retreat. The exception is Emmons Glacier, which continued to advance after the early 1980s mainly because of a rock avalanche which occurred in 1963 (Driedger, 1986). The rock covered and insolated the lower half of the glacier reducing the ablation.

Area and volume measurements of the Mt. Rainer glaciers have been made by Driedger and Kennard (1984) and Mennis (1997). In response to the 1980 Mt. St. Helens eruption, the USGS estimated the volumes of all the Mt. Rainier glaciers as part of a hazard assessment (Driedger and Kennard, 1984). The volumes for Emmons, Winthrop, Carbon, Tahoma, and Nisqually glaciers were calculated from basal and surface contours. The volumes of the remaining glaciers were calculated using estimation methods. Results of their work are in Table 1. Mennis (1997) digitized several of the USGS maps, as well as developed the database structure used in this study (Mennis and Fountain, 2001). From the 1913 and 1971 maps he calculated area and volume of several glaciers. In his conclusions he noted that the glaciers retreated significantly over the period of record, and the glaciers with southern aspects lost more area and retreated farther than the northern glaciers.

III. Glaciers

A. Sources and Methods

1. Data Source and Description

To determine long-term glacial trends and relationships I examined existing maps, aerial photographs and field data. I digitized glacial features from published and unpublished USGS topographic maps (Table 2) and terminus positions (Table 3) traced on mylar paper from aerial photographs (Driedger, 1986). The maps range in scale from 1:6,000 to 1:62,500, use polyconic or Lambert conformal conic projection and are tied to the North American Datum 1927 (NAD27). Maps before 1950 were derived from field surveys and those after were produced from aerial photogrammetry. All the maps except for the 1994 digital coverage and the 1971 mylar map of Mt. Rainier are on paper. The USGS produced a digital elevation model (DEM) from the 1994 digital coverage, which I used to make various surface measurements.

Driedger and Kennard (1984) conducted radar surveys on five glaciers, Carbon, Emmons, Nisqually, Tahoma and Winthrop to define the basal topography (Table 2). From the depth measurements Driedger and Kennard interpolated basal contour lines using the 1971 map of Mt. Rainier as a base map. Logistic and safety concerns severely limited the number of points collected, particularly on the steep upper sections of the glaciers. Much of the basal topography has to be used with some caution.

Table 2: Maps used in this study

Map Coverage	Type	Year	Notes
All Glaciers	Paper Map	1913	Surveyed in 1910, 1911 and 1913.
Nisqually	Paper Map	1931	Surveyed in cooperation with City of Tacoma and NPS
Nisqually	Paper Map	1936	Surveyed in cooperation with City of Tacoma and NPS
Nisqually	Paper Map	1940	Surveyed in cooperation with City of Tacoma and NPS
Nisqually	Paper Map	1941	Surveyed in cooperation with City of Tacoma and NPS
Nisqually	Paper Map	1951	Aerial photgraphs taken 1951
Nisqually	Paper Map	1956	Aerial photography taken September 4, 1956
Nisqually	Paper Map	1961	Aerial photography taken August 19, 1961
Nisqually	Paper Map	1966	Aerial photography taken August 21, 1966
All Glaciers	Paper Map	1971	Compiled from 1:24,000-scale, 7.5-minute maps from 1962 and 1:62,500-scale, 15-minute maps from 1971.
Carbon, Winthrop, Emmons, Nisqually and Tahoma Glaciers	Mylar Map	1971	Base from USGS Mowich Lake, Wash., 1971; Sunrise, Wash., 1971; Mt Rainier West, Wash., 1971 and Mt Rainier East, Wash., 1971 1:24,000 topographic maps. Basal topography by P. Kennard; glacier boundary update by C. Driedger, USGS
Nisqually	Paper Map	1976	Aerial photographs taken August 31, 1976; Glacier features and vegetation classified by USGS Project Office, Glaciology.
Nisqually	Paper Map	1981	Photograph taken in 1980
All Glaciers	Digital	1994	Revisions to 1971 map using terminus positions determined from aerial photographs

Table 3: Terminus positions traced from mylar overlay (Driedger, 1986)

Glaciers	Year
Carbon	1960, 1964, 1965, 1966, 1967, 1970, 1973, 1974, 1975, 1976, 1979, 1980, 1985, 1990, 1991, 1994
Cowlitz	1958, 1962, 1963, 1964, 1965, 1967, 1969, 1970, 1972, 1973, 1974, 1975, 1976, 1980, 1983, 1990, 1991
Emmons	1928, 1938, 1955, 1958, 1960, 1963. 1964, 1967, 1969, 1973, 1974, 1975, 1979, 1980, 1981, 1982, 1984, 1986, 1991
Kautz	1962, 1963, 1964, 1966, 1970, 1972, 1973, 1974, 1979, 1980, 1982,
Nisqually	1918, 1926, 1936, 1946, 1951, 1956, 1956, 1961, 1968, 1971, 1974,
North Mowich	1958, 1960, 1963, 1967, 1975, 1980, 1982, 1984, 1985
Puyallup	1955, 1959, 1962, 1963, 1964, 1965, 1967, 1968, 1969, 1973, 1974, 1975, 1976, 1979, 1980, 1985
South Mowich	1958, 1960, 1962, 1963, 1965, 1966, 1969, 1975, 1976, 1979, 1980,
South Tahoma	1936, 1958, 1962, 1964, 1965, 1966, 1967, 1969, 1970, 1972, 1974, 1976, 1980, 1983, 1984, 1985
Tahoma	1913, 1958, 1959, 1960, 1963, 1965, 1966, 1967, 1969, 1970, 1974, 1975, 1977, 1980, 1982, 1985, 1990
Winthrop	1912, 1958, 1985

I digitized terminus positions (Table 3), which were traced by Driedger (1986) from aerial photographs on to mylar paper. There is one mylar sheet per glacier. Driedger georeferenced each image by positioning the mylar paper using distinct landmarks near to the glaciers, such as large rocks or bedrock knobs. I also used terminus positions (Table 4) measured by the NPS from fixed points below each glacier to the terminus (Driedger, 1998; Meier, 1963a). Changes in the glacier position measured on the ground represent slope displacement (horizontal and vertical), unlike aerial photographs which consider only horizontal displacement. Unfortunately the fixed-point locations are not known and cannot be re-measured (Driedger, 1998).

Table 4: Terminus data measured by the NPS (Driedger, 1998; Meier, 1963a)

Carbon	1933, 1934, 1935, 1936, 1937, 1938, 1939, 1940, 1941, 1942, 1943, 1944, 1945, 1946, 1947, 1948, 1949, 1951, 1953, 1954, 1956, 1957, 1958, 1959, 1960, 1961, 1962, 1963, 1964, 1965, 1966, 1967, 1971
Emmons	1931, 1932, 1933, 1934, 1935, 1936, 1937, 1938, 1939, 1940, 1941, 1942, 1943, 1944, 1945, 1946, 1947, 1948, 1949, 1951, 1953, 1954, 1956, 1957, 1961, 1967
Nisqually	1918, 1919, 1920, 1921, 1922, 1923, 1924, 1925, 1926, 1927, 1928, 1929, 1930, 1931, 1932, 1933, 1934, 1935, 1936, 1937, 1938, 1939, 1940, 1941, 1942, 1943, 1944, 1945, 1946, 1947, 1948, 1949, 1950, 1951, 1952
South Tahoma	1931, 1932, 1933, 1934, 1935, 1936, 1937, 1938, 1939, 1940, 1941, 1942, 1943, 1944, 1945, 1946, 1947, 1948, 1949, 1950, 1952

2. Data Conversion

I used a CalComp digitizer and ARCINFO 3.4 and ArcView 3.x GIS software to digitize the maps and terminus positions. Digitizing steps and the database structure followed those established by Mennis (1997) and Mennis and Fountain (2001). Below are several cases which need to be highlighted because of their importance to the discussion or the methods differ from those developed by Mennis (1997).

Prior to digitizing, I divided glaciers sharing a common boundary, such as Emmons and Winthrop Glaciers using ice flow directions. I traced lines perpendicular to the surface contour lines from the point the glaciers divide to where they join together or start. It is important to note that the boundaries between glaciers are not constant because they are based on contour lines, which are never the same from one map to the next.

Maps were georeferenced to a universal datum using at least four identifiable control points, usually latitude and longitude marks. I georeferenced maps and photos until the root mean square error (RMSE) of the four or more control points equaled 0.002 or less (Mennis and Fountain, 2001). I used the following equation to calculate the RMSE:

$$\mathrm{RMSE} = \frac{\sqrt{\sum (x_i y_i) - (\hat{x}_i \hat{y}_i)}}{n} \tag{1}$$

where x_i and y_i are the computed latitude and longitude locations, $\hat{x}_i$ and $\hat{y}_i$ are the true locations, and n is the total number of georeferenced points. Inaccurate or insufficient latitude and longitude positions or base map distortions (folding or stretching) caused most of the problems. For example, the 1931, 1936, and 1941 Nisqually Glacier maps provide few or no latitude and longitude marks. To circumvent the problem I used latitude and longitude positions of fixed topographic features found on both orthophotographs taken by the NPS in 1994 and the Nisqually maps. I used the same method to georeference the mylar-overlays traced by Driedger (1986). The latitude and longitude positions of landmarks close to the center of each aerial photograph were measured on the orthophotographs. After digitizing the mylar-overlays, I checked the terminus positions against other digitized maps from the same time period.

Several maps of Nisqually and Wilson glaciers were incomplete and features from other maps were added. Four maps (1931, 1936, 1940 and 1941) omitted the upper two-thirds of Nisqually Glacier and three maps (1956, 1961 and 1966) omitted the upper third. The 1971 and 1980 maps excluded parts of Wilson Glacier. Appending glacier features from other maps is not ideal, however because most changes occur in the lower elevations of a glacier (Schwitter and Raymond, 1993), this procedure is suitable for glacier area and elevation.

Digitized glacier features include ice extents, glacier boundaries, exposed intra-glacial bedrock (rock islands), surficial debris cover (Figure 2), termini and contour lines (not shown in Figure 2). Stagnant ice, physically separated from the main glaciers, was also digitized, but was omitted from area and volume calculations.

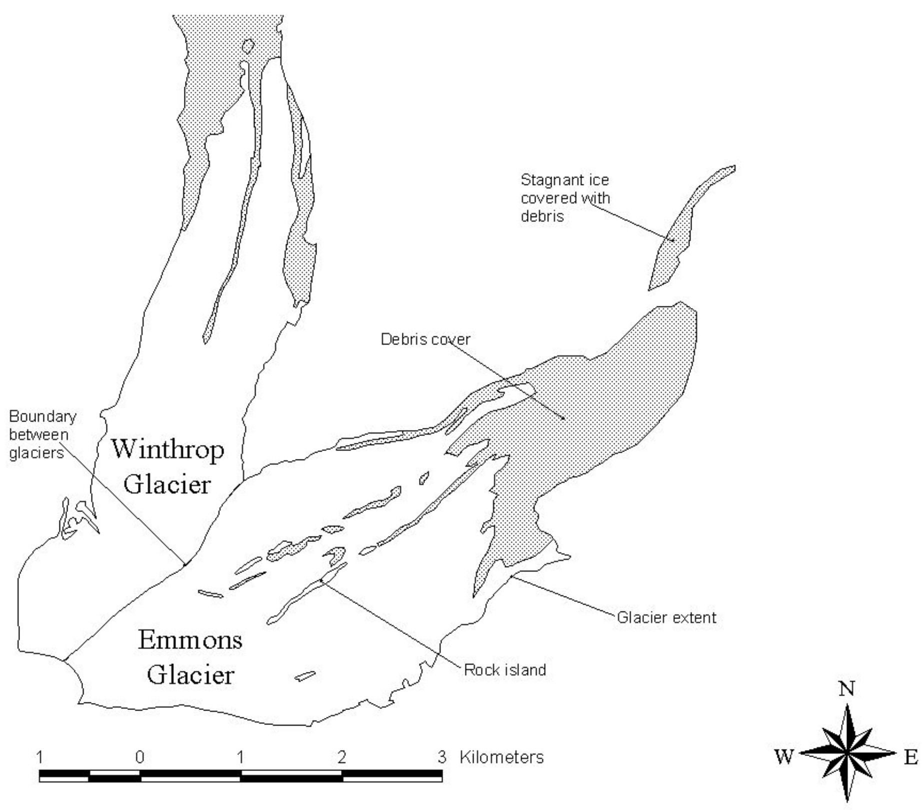

Figure 2: Features digitized on the glaciers

To measure glacial volumes or volume changes I modeled surface and basal topography using Triangulated Irregular Networks (TINs). They are vector representations of surfaces using an irregular or regular spacing of nodes linked together by non-overlapping contiguous triangular faces (Kumler, 1994). TINs provide a better method for modeling complex terrains like Mt. Rainier than grids, i.e. DEM (Pinotti, unpublished). Grids create a stepping effect and underestimate glacial volumes compared to TINs by about 5%.

3. Measurements

Measurements of glacier area, volume and terminus positions were made in ArcView. Changes in terminus position, both horizontally and vertically, were measured along the centerline of 11 glaciers. Figure 3 shows an example of a centerline profile on Emmons Glacier. I extrapolated former terminus positions when they did not cross the centerline.

Glacial volumes were calculated by projecting a horizontal plane from the highest elevation in each TIN to the glacier boundary and measuring the volume from the plane to the glacier and basal surfaces. In both measurements, the glacier boundary is the same. The difference between the volumes measured from the plane to both surfaces equals the glacial volume.

For glaciers without basal topography another method was used to calculate volumes. The following is an empirical relationships used to estimate volume from area (Bahr et al., 1997; Chen and Ohmura, 1990; Erasov, 1968; Macheret et al., 1988; Meier and Bahr, 1996; Zhuravlev, 1988):

$$V = \alpha A^{\beta}, \tag{2}$$

where V is the volume, A is the area and α and β are constants. The volume of all the Mt. Rainier glaciers was calculated using Equation 2 with $\beta = 1.36$ and $\alpha = 0.175$. Meier and Bahr (1996) empirically derived these constants using 144 mountain glaciers around the world, including several from Mt. Rainier.

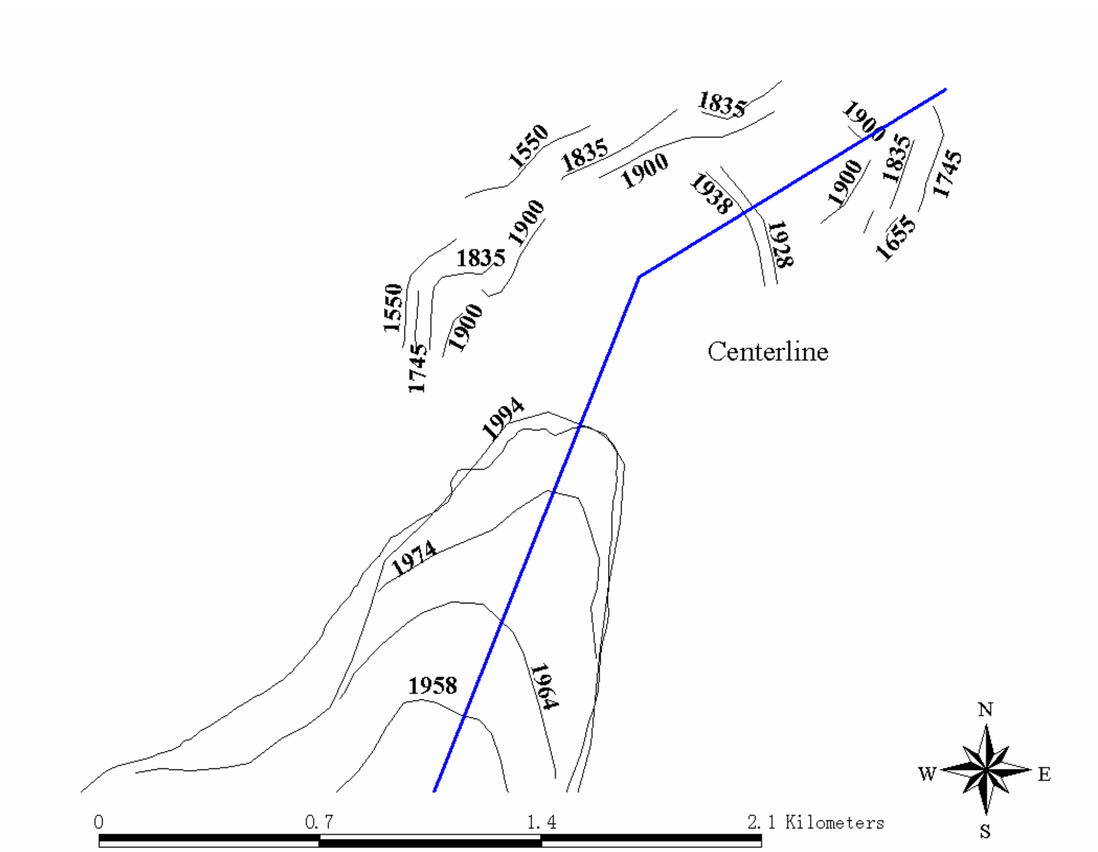

Figure 3: Approximate centerline (thicker line) of Emmons Glacier used to measure length changes between different terminus positions. Former positions are denoted by the thinner lines and years.

4. Errors Estimates

Before the advent of modern map making techniques the process of capturing surficial features was laborious and time consuming. The ability to map large areas accurately was limited and often these maps have significant errors. The 1894 Mt. Rainier map produced by the USGS is fraught with obvious errors in the glacial extents for the whole map. Because the extents are so far off I could not use the map for my thesis. Mennis (1997) discovered significant errors at higher elevations on the 1913 map of Mt. Rainier. Given the steep and dangerous slopes it is unlikely that the surveyors mapped those areas in detail. These maps were completed prior to the time the USGS enacted the National Map Accuracy Standards (NMAS) in 1947 (Schulz, 1998). In 1958, the USGS began implementing the standards. The NMAS require at least 90% of the 20 or more points surveyed in the field to fall within 1/50th of an inch to the same points on the map. For vertical accuracy, 90% of all tested points must fall within half of the specified contour interval. Applied to the 1971 Mt. Rainier map (1:50,000), 90% of the points surveyed must be within 25.4 meters of the horizontal position and 12.2 meters of the map elevation. Currently, the USGS tests only 10 percent of the maps and typically does not check alpine areas. The USGS did not check the 1971 Mt. Rainier map, as well as the 1994 Mt. Rainier map (Landgraf, pers comm.).

Delineating glacial features from aerial photographs and on the ground is difficult, especially in areas with lots of debris and snow cover. Distinguishing debris-covered glaciers from ice-free areas, seasonally snow-covered rock from snow-covered glaciers and stagnant from active ice near the terminus is also problematic. It is important to differentiate the latter because including stagnant ice can cause erroneous conclusions of the glacial terminus activity (Raymond et al., 1986). A glacier may appear to be receding, when in fact a new active terminus above the stagnant ice is advancing. In this thesis I attempted to measure terminus position changes using only the active portion of the termini as identified from the literature, photographs or maps.

There are several errors that can occur when digitizing maps. Positional errors incurred during the digitizing process include tablet precision, weed tolerance, and coordinate precision (ESRI, 1998). The digitizing pen width, typically 0.25 mm, affects resolution. For example, on a 1:50,000 map (e.g. 1971 Mt. Rainier map), a line 0.25 mm wide translates to an effective ground width of 12.5 m. Thus, a glacier or terminus boundary is 12.5 m wide. Digitizer precision controls the accuracy of digitized lines or points. The Calcomp digitizer used has a resolution of 0.25 mm, which, for a 1:50,000-scale map, results in an uncertainty of 12.5 meters. Weed tolerance defines the minimum distance allowed between digitized points. If the distance between two points is less than the tolerance, the last node is deleted, which affects lines with significant curvature, such as glacial termini. ARCINFO default weed tolerance is 1/1000 of the maximum distance between points in the east-west and north-south directions used to georeference the maps. For the 1971 map, 1/1000 of

21,285 m (the distance between two of the georeferenced points) is 2.1 m. The other maps used in this study have smaller weed tolerances because they are less than 1:50,000. The numerical precision of a point depends on the number of significant digits stored by the computer (ESRI, 1998). Single-precision stores seven and double precision stores fifteen significant figures. The decision to use one or the other depends on the GIS program, the map projection, amount of computer storage, and the required level of precision. Double precision was used because using single precision with UTM coordinates deletes the first figure to the right of the decimal place (tenths) in the y direction and the second to the right (hundreds) in the x direction.

Although digitizing errors are important, I assume the largest error source occurred during the construction of the original maps. To estimate the horizontal and vertical errors associate with each map I applied the NMAS. I calculated the area of the error using the buffer function in ArcView. The buffer was extended 1/50th of an inch inward and outward from the glacier extent. This estimation procedure was applied to 9 of the 27 glaciers from both the 1913 and 1971 maps (Figure 4). The resulting uncertainty in area was plotted against the perimeter of each glacier. The slope of the line defined the error factor. I estimated the area uncertainty for the other glaciers by multiplying the perimeter by the error factor. Volume error was calculated for each map by multiplying the area error by the contour interval of the map.

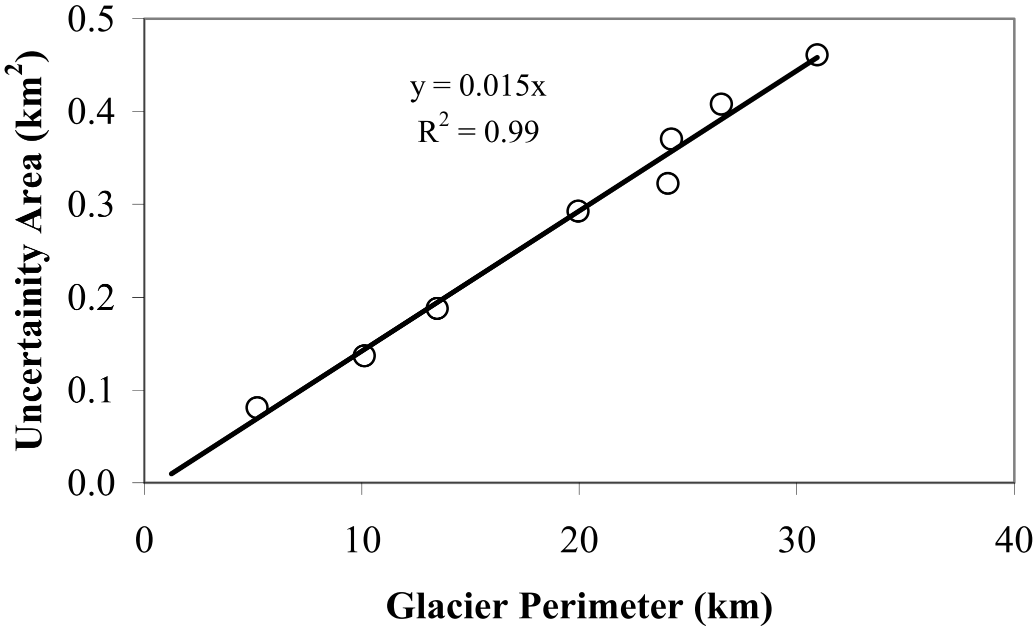

Figure 4: Plot of the uncertainty in glacier area versus the perimeter of nine glaciers from the 1913 map.

I did not attempt to calculate the error for terminus positions measured from aerial photographs. The potential for errors is significant for aerial photographs, but developing a method to quantify the error is difficult. Rather than guess I decided not to include any error estimation.

B. Results

1. Terminus Changes

Abundant terminus data exist for 11 glaciers. Five glaciers, Carbon, Cowlitz, Emmons, Nisqually and S. Tahoma have field measurements (Table 4) from maps (Table 2) and/or aerial photographs (Table 3). Field measurements include horizontal and vertical changes, while those from aerial photographs by the USGS (Driedger, 1998) only assess horizontal changes. These various datasets were combined when possible. Before analyzing the overall changes I will discuss the steps I took to combine the different datasets for each glacier.

Carbon Glacier: Three datasets of terminus positions were compiled from digitized maps in this thesis, ground surveys conducted by the NPS (Table 4) and from aerial photograph measurements made by the USGS (Table 3). The general trends are the same but offsets between different datasets are clearly apparent (Figure 5). The USGS and NPS observations show a relatively constant offset of 183 m and there is a good fit between the two when merged using 1960 as the reference point (Adjusted Version on Figure 5). Because the NPS dataset starts in 1913, the USGS dataset was adjusted down to combine the datasets. My measurements from digitized maps show a different and variable offset and significantly more retreat, 230 m than the USGS-NPS combined dataset. According to Driedger (1998) the terminus is currently near its position in 1913, thus the 230 m retreat I measured is greater than the actual change. The discrepancy in the digitized maps occurs between 1913-1960, 1965-1975 and 1985-1994. I rechecked the terminus positions on the maps and found no obvious errors, though the terminus digitized from the 1913 map is blocky, which is caused by an insufficient number of digitizing points used to define the terminus. Because of the uncertainty of the position of the glacier digitized from the 1913 map, I used the combined measurements made by the NPS and USGS and ignored my measurements. The combined results indicate a total retreat of 13 m, which closely match the terminus changes determined by Driedger (1998).

Cowlitz Glacier: The two different datasets show very similar trends since 1958 with a consistent offset of 1000 m (Figure 6). Because the offset occurs between 1913 and 1958 one of the measured 1913 positions must be incorrect. Based on the results from Carbon Glacier I believe the position I measured from the 1913 map is erroneous. I will use only the changes measured by the USGS and ignore those I

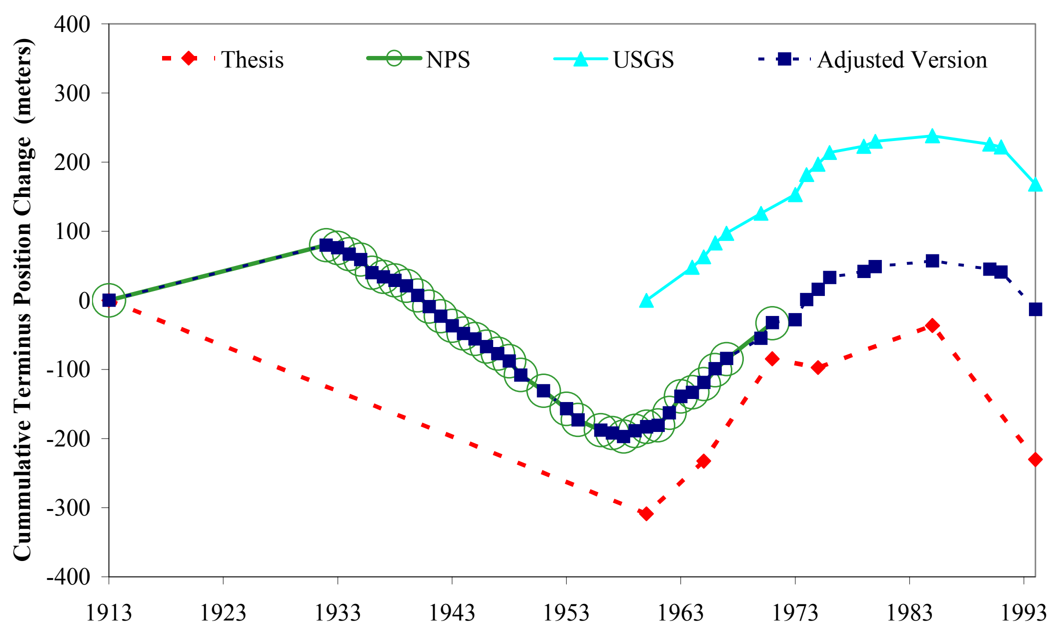

Figure 5: Cumulative terminus changes for Carbon Glacier between 1913 and 1994.

made from digitized maps. The total retreat of Cowlitz Glacier between 1913 and 1994 is 1458 m.

Emmons Glacier: Good correlations exist after 1958 between the NPS and USGS terminus positions and with the positions I digitized from the maps (Figure 7). Curiously, my positions show significant retreat between 1938 and 1958 which is not present in the other datasets. Driedger (1998) attributes this retreat to a datum switch from one active terminus front to another. In the 1930s the terminus region decayed to stagnant ice, and a new active terminus formed farther up valley. NPS measurements of the new active terminus commenced in 1932, the same year Driedger's dataset started. The 1938 terminus position I digitized is probably the stagnant ice front because the trend after 1938 does not follow the NPS and USGS datasets.

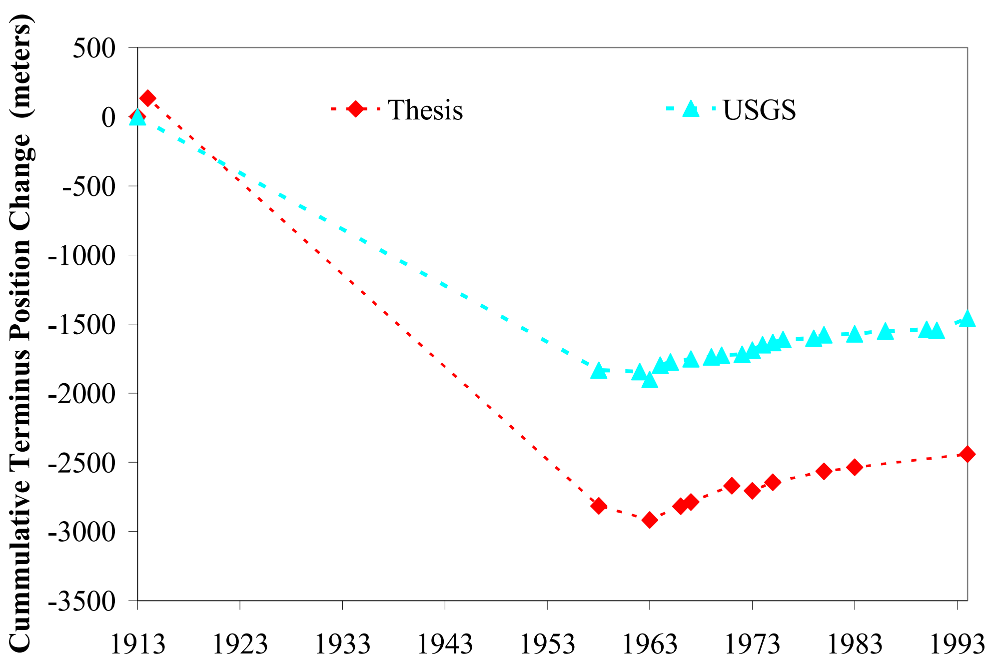

Figure 6: Cumulative terminus changes for Cowlitz Glacier between 1913 and 1994

To reconcile the datasets, I combined the NPS and USGS observations, using 1955 as the common point between data sets (Figure 7). The merger between the USGS/NPS dataset and my measurements posed a bigger problem. By shifting the NPS/USGS dataset down by 1700 m it corresponds fairly well with my results after 1958. Because my dataset includes the datum shift I decided to use it as the baseline for the combined dataset. When I combined the USGS/NPS and my measurements using 1958 as the common point a large jump of 1471 m occurs between the 1928 and the 1932 points. I will use these two points to represent the change in datum between the old to the new terminus. To complete the dataset I added the 1994 digitized

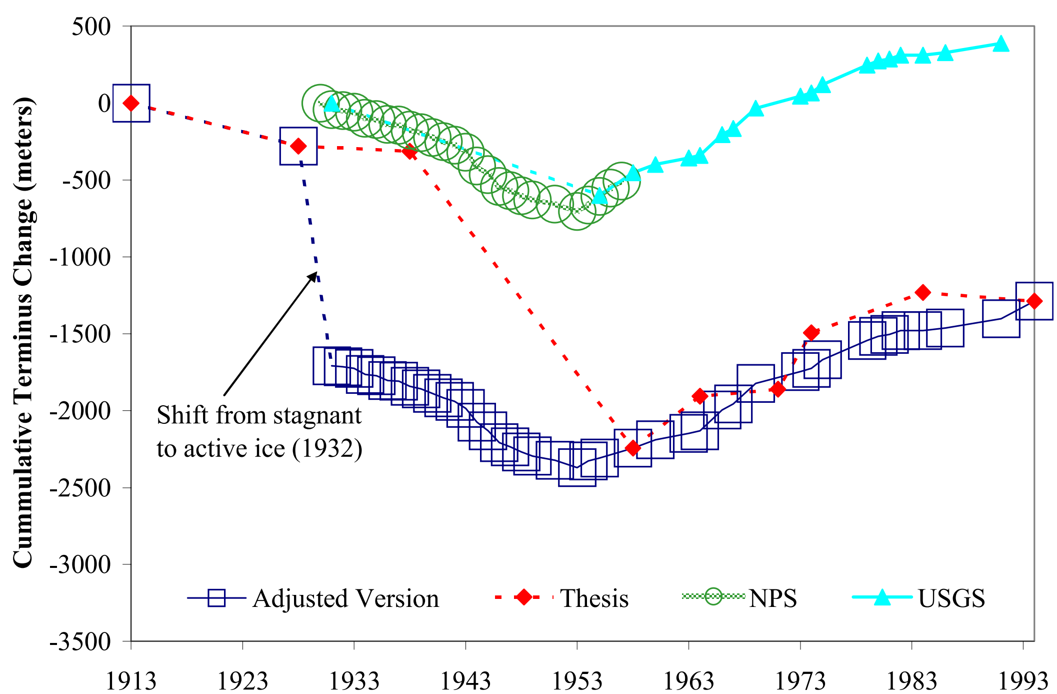

Figure 7: Cumulative terminus changes for Emmons Glacier between 1913 and 1994

position to the combined dataset. Overall, the net retreat of Emmons Glacier between 1913 and 1994 is 1288 m.

Nisqually Glacier: Between 1918 and 1979, except 1977 the terminus position was measured every year by the NPS or USGS (Figure 8). The NPS measurements between 1918 and 1960 used the former highway bridge as a benchmark (Johnson, 1955). In 1960, the USGS Conservation Division assumed responsibility for the measurements and in 1966 it was passed off to the USGS project office in Tacoma (Heliker et al., 1984). In 1975 the USGS started using aerial photographs because of safety concerns near the terminus (Heliker et al., 1984). I digitized maps between 1913 and 1994 (Table 2) and the 1976 USGS map, which includes terminus positions dating to 1840. Positions before 1913 are based on dated glacier moraines.

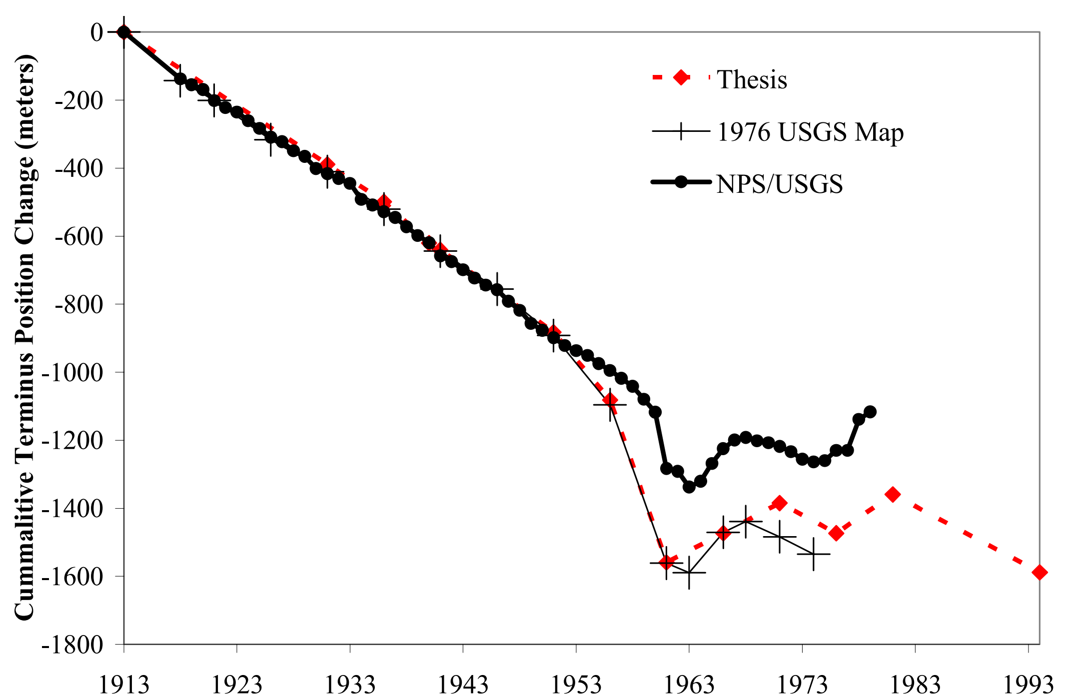

Figure 8: Cumulative terminus changes on Nisqually Glacier between 1913 and 1994

The different data match closely up to 1956, but the NPS/USGS field measurements subsequently diverge from the digitized maps. Stagnant ice developed in 1951 (Heliker et al., 1984; Veatch, 1969) and a new active terminus formed higher up valley which is clearly seen on a 1951 oblique photograph (Veatch, 1969). The field measurements measured the stagnant terminus, not the new active terminus between 1951 and 1963 (Heliker et al., 1984). The development of stagnant ice and the switch in 1960 from the measurements made by NPS to the USGS might be a reason for the discrepancy between the datasets. The trends after 1963 between the three datasets match closely.

The ‘Adjusted Version’ in Figure 9 includes the NPS/USGS field data measured up to 1950. The large decrease in terminus location between 1951 and 1963 represents the switch from the stagnant to the new active terminus. Unfortunately there are no data of the active terminus prior to 1963. Between 1951 and 1961 I used terminus positions (stagnant ice) from the digitized maps. From 1961 to 1979 I resumed using the NPS/USGS field data. Since 1979 the adjusted version was extended using the map positions in 1980 and 1994. The ‘Adjusted Version’ follows the individual digitized maps closely. Based on these adjustments, the glacier retreated 1588 m over the entire period.

<u>South Tahoma Glacier</u>: Terminus positions are derived from digitized maps and aerial photographs, and ground surveys conducted by the NPS. The two datasets are quite different (Figure 10). I did not combine the two because there are no

overlapping points and it was not possible to position the NPS data within the longer dataset with any certainty. Results from the digitized maps show an overall retreat of 2677 m.

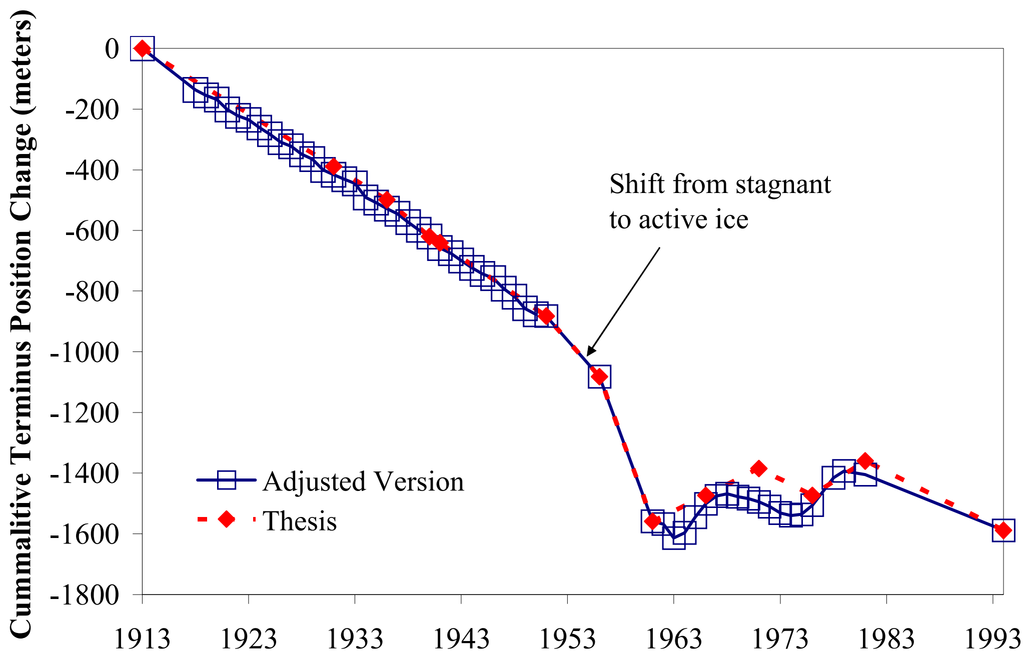

Figure 9: Adjusted version of the cumulative terminus changes on Nisqually Glacier between 1913 and 1994

Different methods of measuring terminus positions yielded much different results. Most of the differences between field measurements and those determined from maps and aerial photographs probably result from errors in digitizing, georeferencing and misidentification of terminus positions. These differences, in some cases, can be corrected. In other cases reconciling the differences is impossible. Inherent differences also exist between ground-based and aerial measurements. The latter only considers changes in the horizontal (map) plane, whereas ground measurements are made on a slope surface. The larger the slope, the more the surface and aerial measurements differ. For example, 1000 m horizontal change in the terminus position on a moderate slope (15^o) and on a steep slope (30^o) equates to 1035 m and 1155 m on the ground, respectively. The average slopes for the Mt Rainier glaciers ranges from 16^o (Williwakas) to 32^o (Sarvent).

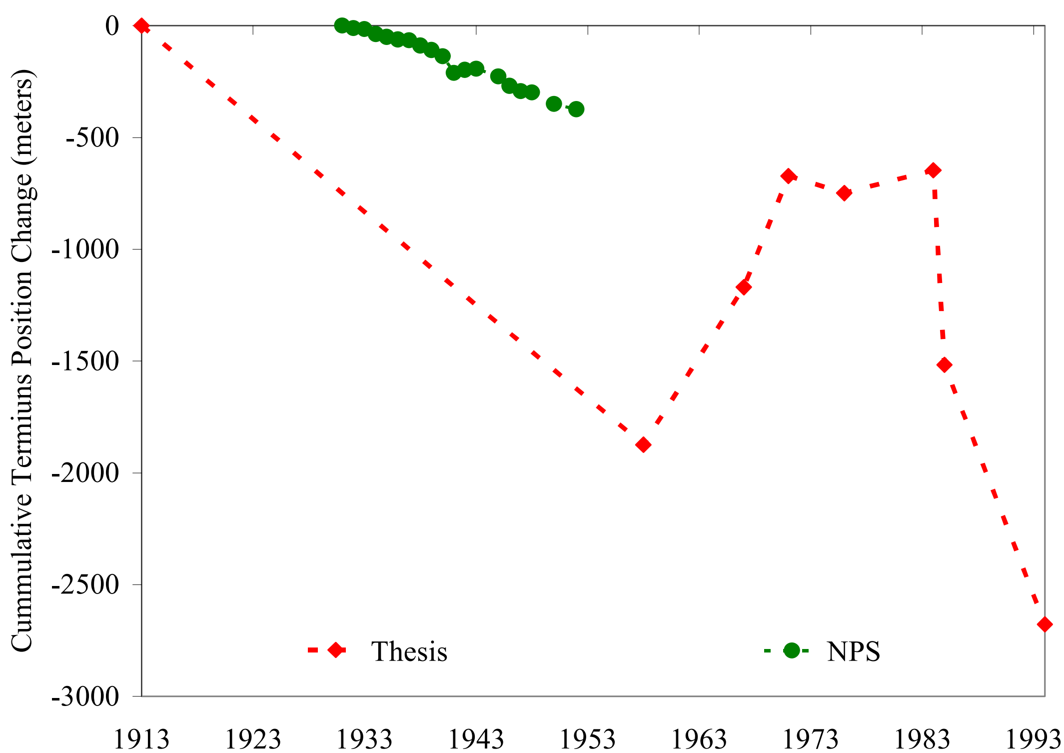

Figure 10: Cumulative terminus changes on South Tahoma Glacier between 1913 and 1994

Stagnant ice presents another problem when determining terminus position changes. No formal procedures for dealing with this issue have been developed by the glaciology community. Some researchers include stagnant ice, while others ignore it. It is a confusing issue because a glacier may have a new active terminus higher up that is advancing, while the stagnant ice is stationary or retreating. Omitting stagnant ice provides a better measure of glacial activity. However, determining stagnant ice either from the air or by ground measurements is not a trivial task.

The changes measured over the 80-year period are similar for the 11 major glaciers examined (Figure 11 and Appendix A). All the glaciers retreated between 1913 and sometime in the early-50s to the late-50s. Specifically Nisqually, Emmons and Carbon Glaciers started advancing in 1951, 1954 and 1959, respectively, and continued until the mid-1980s. Since the 1980s all of the monitored glaciers retreated with the exceptions of the Emmons, Cowlitz and Winthrop glaciers. Over the entire record South Tahoma Glacier retreated the farthest, 2,677 m, followed by Kautz, 2,131 m, and Nisqually, 1,589 m. Carbon, Puyallup and South Mowich Glaciers retreated less than 600 m, and Winthrop Glacier advanced 187 m.

The trends in terminus positions between 1955 and 1994 show strong correlations, either directly or when the time series are lagged (Table 5). This time period was selected because the density of data points is sufficient to compare. Winthrop Glacier was not included because it has only 4 points. Nisqually and Cowlitz glaciers have significant correlations only when the entire dataset is lagged ahead of the other glaciers by 4 to 6 years indicating they may respond earlier than the other glaciers. Other glaciers have slightly better correlations when lagged +/- by one or two years, suggesting there are slight variations in the response times. Besides Nisqually and Cowlitz glaciers no spatial differences between glaciers exist.

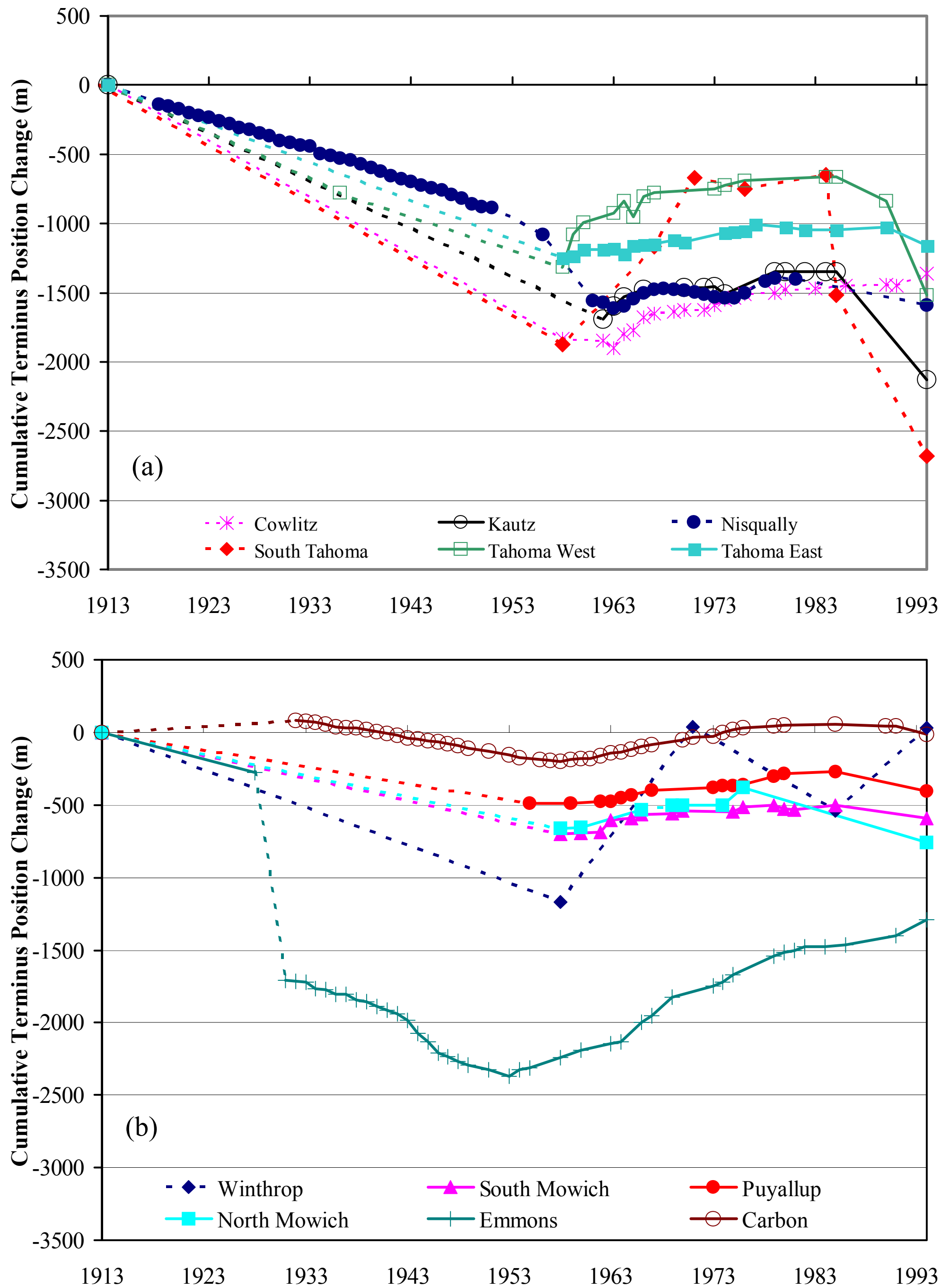

Figure 11: Cumulative terminus change for the glaciers on the southern (top) and northern (bottom) part of Mt. Rainier.

The details of glacier activity during the first 40 years are not as clear because little to no data exists for most of the glaciers except Nisqually, Emmons and Carbon. Between 1932 and 1955 the three glaciers were retreating at about the same rate. Prior to 1932 the glaciers had different trends. Carbon Glacier advanced slightly, while Nisqually Glacier retreated at a consistent rate between 1913 and 1932. It is hard to ascertain exactly the trend of Emmons Glacier because a new active terminus started farther up glacier while the old terminus stagnated.

The changes for the other glaciers between 1913 and 1955 are questionable because of the uncertainty of the terminus positions on the 1913 Mt. Rainier map which I digitized. I did not use the positions for Carbon and Cowlitz glaciers from the 1913 map because of the differences from other positional sources. The only glacier that matched up with the other datasets was the Nisqually Glacier. Without further evidence, it is not possible to determine the accuracy of the other 1913 terminus positions besides Carbon, Cowlitz and Nisqually glaciers.

The results show significant differences in the magnitude of change between the south-facing and north-facing glaciers (Table 6). The east-west facing glaciers were not compared because of the lack of data for the eastern glaciers. Over the entire record, southern glaciers retreated on average 1,755 m while northern glaciers retreated only 503 m. From 1913 to 1959 and 1986 to 1994 the southern glaciers retreated significantly more than the northern glaciers. The largest average difference,

~550 m occurred in 1986-1994. The average advance between 1960 and 1985 was similar for both sides of the mountain.

Table 5: Cross correlations of cumulative terminus change for the major glaciers between 1955 and 1994 using a probability of 0.05. All values are significant. Numbers in the parenthesis represent the lag time in years for the glacier in the columns. For example the entire Carbon time series was lagged +5 years after the Nisqually data. That is the Carbon was shifted by 5 years compared to Nisqually to obtain the best fit.

		North Facing					South Facing				
		Carbon	**North Mowich**	**South Mowich**	**Puyallup**	**Emmons**	**Cowlitz**	**Nisqually**	**Kautz**	**South Tahoma**	**Tahoma West Lobe**
North Facing	**Carbon**										
	North Mowic	**0.95 (-1)**									
	South Mowic	**0.89**	**0.89**								
	Puyallup	**0.90**	**0.88 (+2)**	**0.81 (+1)**							
	Emmons	**0.87 (-1)**	**0.91 (+1)**	**0.80 (+2)**	**0.82 (-2)**						
South Facing	**Cowlitz**	**0.73 (+4)**	**0.71 (+5)**	**0.65 (+4)**	**0.48 (+4)**	**0.62 (+5)**					
	Nisqually	**0.85 (+5)**	**0.80 (+6)**	**0.70 (+5)**	**0.69 (+5)**	**0.78 (+10)**	**0.91 (+1)**				
	Kautz	**0.92 (+1)**	**0.9 (+2)**	**0.83**	**0.99**	**0.82 (+2)**	**0.52 (-3)**	**0.72 (-4)**			
	South Tahom	**0.93 (-1)**	**0.94**	**0.86 (-1)**	**0.89 (-2)**	**0.89**	**0.71 (-5)**	**0.85 (-6)**	**0.90 (-2)**		
	Tahoma - W	**0.86 (-1)**	**0.82**	**0.84 (-1)**	**0.83**	**0.67 (+1)**	**0.79 (-5)**	**0.87 (-6)**	**0.82**	**0.83**	
	Tahoma - E	**0.91**	**0.87 (+2)**	**0.78 (+2)**	**0.80**	**0.78 (+2)**	**0.72 (-4)**	**0.87 (-4)**	**0.81**	**0.83 (+3)**	**0.82 (+1)**

The glaciers show similar responses to climatic changes regardless of aspect, but the magnitude of the response, especially during periods of retreat is not the same. The climatic conditions that prevail during these periods appear to have a bigger impact to those glaciers with southerly aspects. It is also interesting that Nisqually and Cowlitz glaciers, both south facing, have slightly faster response times than all the other glaciers.

Table 6: Cumulative terminus position changes in meters for three periods between 1913 and 1994

Northern Facing	1913-1959	1960-1985	1986-1994	Total
Puyallup (1959, 1985, 1994)	-488	216	-132	-403
South Mowich (1960, 1984, 1994)	-695	196	-91	-590
North Mowich (1960, 1976, 1994)	-655	272	-376	-759
Carbon (1960, 1985, 1994)	-183	240	-70	-13
Winthrop (1958, 1985, 1994)	-1,168	627	574	34
Emmons (1960, 1984, 94)	-2,190	711	191	-1,288
Average	-896	377	16	-503
Southern Facing				
Cowlitz (1958, 1983, 1994)	-1,833	263	112	-1,458
Nisqually (1961, 1981, 1994)	-1,559	154	-184	-1,589
Kautz (1962, 1984, 1994)	-1,694	347	-783	-2,131
South Tahoma (1958, 1985, 1994)	-1,874	358	-1,161	-2,677
Tahoma - West (1958, 1985, 1994)	-1,317	656	-853	-1,514
Tahoma - East (1958, 1985, 1994)	-1,249	203	-116	-1,161
Average	-1,588	330	-497	-1,755

2. Glacial Area

The planimetric area of each glacier was calculated by ArcView from the digitized maps. Area calculations do not include stagnant ice and snowfields. In some cases the boundary between adjoining glaciers had to be interpolated to create distinct glacier polygons. As explained earlier the glaciers were divided using ice flow divides inferred from surface contour lines, which are not the same from one map to the next. Because the contour lines vary from one map to the next, the boundary locations will not remain fixed. For example, the boundary between Winthrop and Emmons glaciers shifted east between 1971 and 1994, decreasing and increasing the area of Emmons and Winthrop glaciers, respectively by 0.35 km^2.

Differences exist in calculated areas for the same glacier and the same time. For example, the 1971 area I calculated for Liberty Cap is 2.1 km^2 (Table 7), which is much higher than the 0.2 km^2 measured by Driedger and Kennard (1984). In contrast, the area for Tahoma and Winthrop, which border Liberty Cap are 1.0 and 0.2 km^2 smaller according to my calculations. Some of the differences between Puyallup, South Mowich and Kautz might also be explained by the placement of the boundary. Overall, the difference between the 1971 total area determined in this thesis and by Driedger and Kennard (1984) is 1.7 km^2, which is greater than error. The cause is unclear. Variations in the interpolated boundary may explain some of the differences between the measurements I made and those made by Driedger and Kennard (1984) and Post (1963). Furthermore, the 1913 glacier areas determined by Post (1963) are consistently smaller from mine.

The area of all Mt. Rainier glaciers decreased by 21.6% between 1913 and 1994, at an overall average rate of –0.30 $km^2\ yr^{-1}$ (Table 7; Table 9). Only maps digitized in this thesis were used for area and volume calculation. Most of the decrease occurred between 1913 and 1971 when area decreased by 20.9% at an average rate of -0.40 $km^2\ yr^{-1}$. Between 1971 and 1994 the average rate significantly slowed to –0.03 $km^2\ yr^{-1}$ and only 0.7% was lost. All glaciers decreased over the 81-year period.

Area changes for Nisqually Glacier, including the tributary, Wilson Glacier, provide a more complete picture of the changes over the entire time period (Table 8 and Figure 12). Between 1913 and 1994 area decreased by 0.6 km^2 (9%), which is slightly greater than the estimated uncertainty of 0.4 km^2. The average rate of area loss is 0.01 $km^2\ yr^{-1}$, but varied over time with expansions at about 1931, 1967 and 1980.

Changes in glacier area also vary according to glacier size and location. The greatest decrease in area occurs for glaciers smaller than 5 km^2 with an average fractional loss of 32% over the entire time period. For glaciers larger than 5 km^2 the average loss is 14%, and the greatest decrease is 23% (Cowlitz/Ingraham) and the smallest is 6% (Carbon Glacier). Losses of over 50% occurred for Ohanapecosh, Paradise, Pyramid and Wiliwakas glaciers.

Table 7: Area (km^2) of the Mt. Rainier glaciers in km^2. The error was determined by creating a buffer1/50th of an inch inward and outward from the glacier extent for 9 glaciers and the relationship between the error area and the perimeter was applied to the other glaciers.

	1913 USGS Map		Post (Meier, 1963a)	Post (Meier, 1963a)	1971 USGS Map		Driedger and Kennard (1984)	1994 USGS Data	
	Area	Error	1913 Area	1963 Area	Area	Error	1971 Area	Area	Error
Carbon	13.23	0.37	7.73	7.09	11.01	0.30	11.21	11.01	0.08
Columbia Crest	0.11	0.02			0.25	0.03		0.20	0.01
Cowlitz/Ingraham	9.84	0.46	6.60	4.99	7.44	0.34	7.38	7.61	0.10
Edmunds	1.52	0.09			1.39	0.08	1.39	1.32	0.02
Emmons	12.62	0.32	8.21	7.09	10.94	0.22	11.17	11.21	0.08
Flett	0.74	0.07			0.58	0.09	0.30	0.58	0.03
Frying Pan	6.11	0.26	4.19	2.25	3.62	0.17	3.27	3.72	0.06
Inter	1.14	0.08			0.81	0.06	0.78	0.79	0.02
Kautz	2.37	0.23	2.09	1.77	2.03	0.18	1.15	1.53	0.04
Liberty Cap	2.40	0.15			2.08	0.11	0.16	2.10	0.03
Muir Snowfield	1.22	0.13			0.97	0.08	0.94	0.98	0.02
Nisqually/Wilson	6.59	0.41	4.83	4.35	6.07	0.15	6.06	6.01	0.08
North Mowich	8.03	0.36	4.99	4.03	6.04	0.37	6.17	6.29	0.10
Ohanapecosh	2.97	0.24			1.30	0.15	1.61	1.31	0.05
Paradise	3.19	0.17	1.77	0.81	1.24	0.12	1.01	1.20	0.03
Puyallup	4.57	0.24	2.90	2.74	4.02	0.19	5.09	4.01	0.05
Pyramid	1.39	0.10			0.57	0.10	0.54	0.52	0.03
Sarvent	1.15	0.16			0.69	0.13	0.58	0.69	0.03
South Mowich	4.70	0.29	4.35	3.22	4.01	0.25	3.57	3.97	0.07
South Tahoma	3.43	0.23		1.77	2.91	0.16	2.82	2.22	0.03
Success	0.66	0.05			0.68	0.05	0.69	0.63	0.02
Tahoma	9.07	0.39	8.05	4.67	7.59	0.28	8.63	7.24	0.08
Van Trump	1.37	0.19			0.68	0.17	0.62	0.72	0.06
Whitman	2.35	0.14	1.61	1.21	2.14	0.14	2.21	2.21	0.04
Wiliwakas	0.42	0.06			0.12	0.02		0.14	0.01
Winthrop	10.07	0.30	6.60	6.44	8.93	0.25	9.11	9.21	0.07
Total Area	111.25	1.27			88.11	0.95	86.45	87.41	0.28

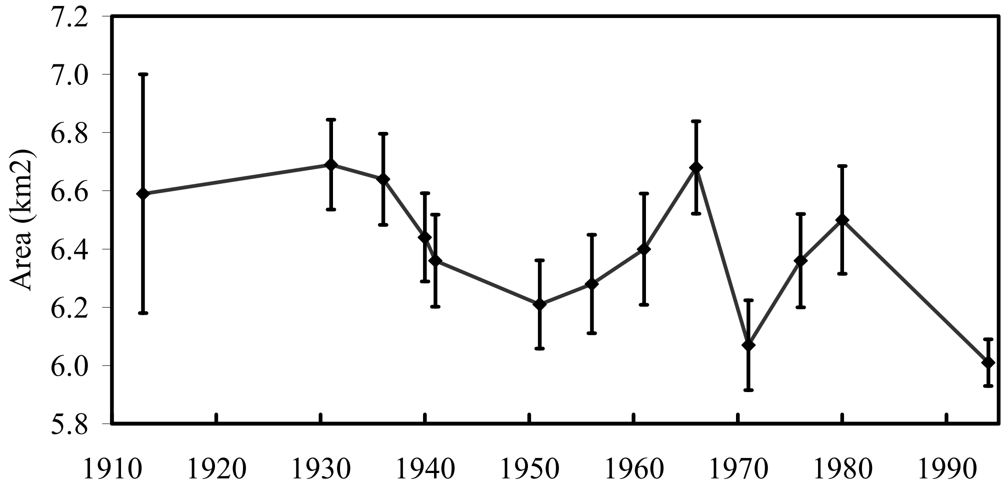

Figure 12: Change in area of Nisqually. Bars represent the calculated error

Table 8: Area of Nisqually and Wilson glaciers determined from digitized maps between 1913 and 1994 ([1]1951 map extent appended to unmapped parts of the glacier and [2]1976 map extent append to unmapped parts of the maps).

Year	Area (km^2)	+/- (km^2)
1913	6.59	0.41
1931[1]	6.69	0.15
1936[1]	6.64	0.16
1940[1]	6.44	0.15
1941[1]	6.36	0.16
1951	6.21	0.15
1956[2]	6.28	0.17
1961[2]	6.40	0.19
1966[2]	6.68	0.16
1971[2]	6.07	0.15
1976	6.36	0.16
1980[2]	6.50	0.19
1994	6.01	0.08

The southern glaciers lost considerable more area, 2.3 km^2 (1913-1994) than the northern glaciers (Table 9). Between 1913 and 1971 both halves of the mountain lost about the same glacier area, but because the glacier area on the south side was smaller initially, the percentage decreased was greater in the south. Between 1971 and 1994, the northern glaciers increased in area by +1.6% while the southern glaciers continued to shrink by -3.8%.

The changes in area have distinct differences relative to size and location. The

Table 9: Total glacier area change in the northern and southern sides of Mt. Rainier.

	1913-1971				**1971-1994**			
	Area Change km^2	+/- km^2	% Change	Rate km^2/yr	Area Change km^2	+/- km^2	% Change	Rate km^2/yr
N. facing glaciers	-11.6	1.1	-18.8%	-0.2	0.8	0.7	1.6%	0.0
S. facing glaciers	-11.7	1.1	-23.6%	-0.2	-1.4	0.6	-3.8%	-0.1
<5 km^2	-13.7	1.0	-29.6%	-0.2	-1.2	1.1	-3.7%	-0.1
>5 km^2	-9.6	1.3	-14.9%	-0.2	0.5	1.5	0.9%	0.0
Total	-23.3	1.6	-20.9%	-0.4	-0.7	1.0	-0.7%	0.0

	1913-1994			
	Area Change km^2	+/- km^2	% Change	Rate km^2/yr
N. facing glaciers	-10.8	0.9	-17.5%	-0.1
S. facing glaciers	-13.1	0.9	-26.5%	-0.2
<5 km^2	-14.8	0.8	-32.2%	-0.2
>5 km^2	-9.1	1.0	-14.1%	-0.1
Total	-23.9	1.3	-21.5%	-0.3

greatest decrease in area occurred for glaciers smaller than 5 km^2. The average fractional loss for glaciers smaller than 5 km^2 is 32% while those larger than 5 km^2 is 14%. Losses of over 50% occurred for Ohanapecosh, Paradise, Pyramid and Wiliwakas glaciers. For the larger glaciers (> 5 km^2), the greatest decrease, 23%, occurred for the Cowlitz/Ingraham glaciers and the smallest, 6%, for Carbon Glacier.

3. Debris Area

Defining the debris cover area is important because a thick cover insulates ice and reduces ablation (Bozhinskiy et al., 1986) and might result in glacier extension beyond that expected for clean glaciers (Pelto, 2000). For example, shortly after the 1963 rockfall the Emmons Glacier started advancing rapidly and continued up to at least 1994 (Driedger, 1986). Though it is an important glacial attribute, debris cover is often overlooked or missed when maps are made. Estimation of debris cover extents are prone to sizeable errors because a summer snowfall blankets a glacier particularly at higher elevations reducing the apparent debris covered area.

Table 10: Debris expressed as total area and fraction of glacier area. Only glaciers with mapped debris cover are included.

	1913			1971			1994		
	km^2	Error	Fractional Area	km^2	Error	Fractional Area	km^2	Error	Fractional Area
Carbon	5.6	0.4	66%	3.4	0.2	42%	3.6	0.1	45%
Cowlitz	1.0	0.1	10%	1.1	0.1	15%	1.9	0.0	24%
Emmons	1.3	0.1	10%	3.1	0.2	28%	3.4	0.0	30%
Flett	0.1	0.0	7%	0.0	0.0	0%	Not Measured		
Fryingpan	0.1	0.0	2%	0.0	0.0	0%	Not Measured		
Inter	0.0	0.0	0%	0.0	0.0	5%	Not Measured		
Kautz	0.2	0.0	9%	0.2	0.0	10%	Not Measured		
Nisqually	0.7	0.0	10%	1.2	0.1	18%	1.4	0.0	23%
North Mowich	1.5	0.1	18%	0.6	0.0	9%	Not Measured		
Ohanapecosh	0.0	0.0	0%	0.0	0.0	0%	Not Measured		
Puyallup	0.4	0.0	9%	0.3	0.0	7%	Not Measured		
Pyramid	0.0	0.0	0%	0.0	0.0	26%	Not Measured		
South Mowich	0.4	0.0	9%	0.8	0.0	19%	Not Measured		
South Tahoma	0.4	0.0	13%	0.7	0.0	23%	0.5	0.0	21%
Success	0.0	0.0	0%	0.0	0.0	1%	Not Measured		
Tahoma	1.5	0.1	16%	1.1	0.1	15%	1.2	0.0	17%
Winthrop	2.1	0.1	21%	2.3	0.1	24%	Not Measured		
Total	15.3	1.0	14%	14.9	0.8	17%			

Carbon Glacier has the largest fractional coverage of debris compared to the other glaciers (Figure 13). The area of debris in 1994 was 3.6 km^2 or 45% of the total area of Carbon Glacier, a decrease of 22% from 1913 (Table 10). A large rockfall on Emmons Glacier in 1963 covered the lower half of the glacier (Driedger, 1986). The rockfall increased the debris cover threefold, from 10% to 28%. Other significant increases in debris cover (8-11%) occurred between 1913 and 1994 on Nisqually, South Mowich, Cowlitz and South Tahoma glaciers. North Mowich Glacier decreased by 8.7% during the same period. The only glacier to experience little change in debris cover was Tahoma Glacier.

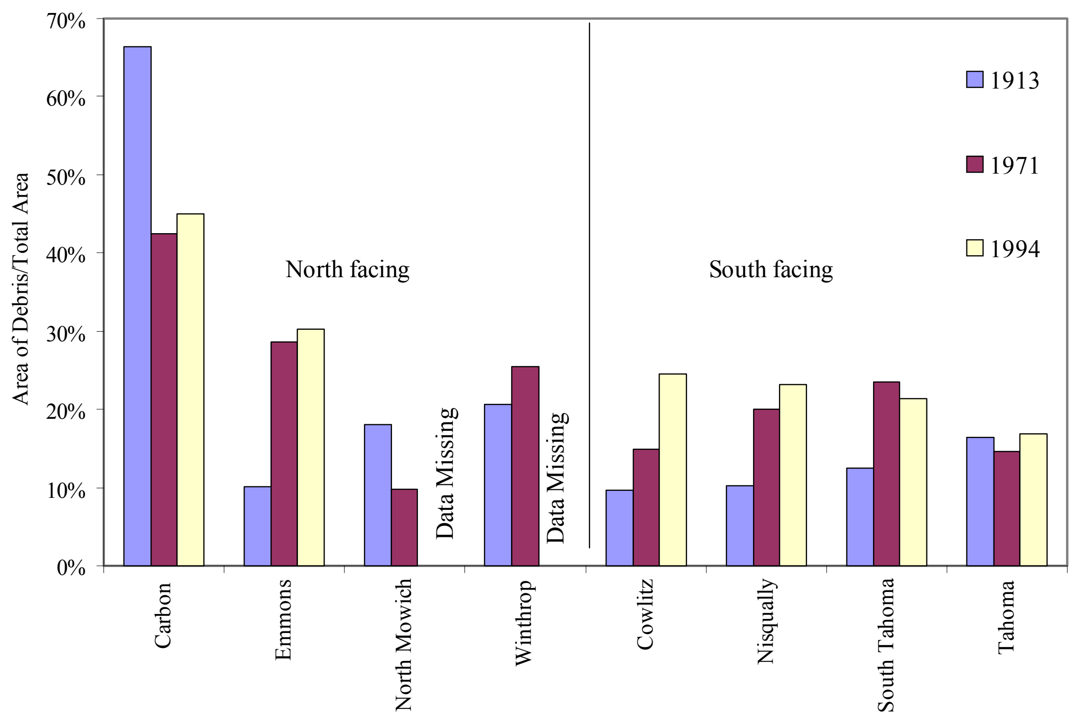

Figure 13: Debris cover area to total area for eight glaciers

4. Volume Changes

The volumes of Carbon, Emmons, Nisqually, Tahoma and Winthrop were determined using surface and basal TINs. Of the five glaciers, all but Nisqually Glacier lost volume between 1913 and 1994 (Table 11 and Table 12). The volume of Carbon Glacier decreased by 15%, while Emmons, Tahoma and Winthrop glaciers decreased by 22-23%. The slight increase in the volume of Nisqually Glacier is within the error range I calculated. The volume change is different than the change in the area, which decreased by 9%. Errors at higher elevations of the 1913 map (Mennis

Table 11: Calculated ice volumes in km^3.

	1913 Vol	Error	1971 Vol	Error	1994 Vol	Error
Carbon/Russell						
Thesis	0.86	0.10	0.76	0.05	0.73	0.05
Mennis, 1997	0.96		0.81			
Driedger and Kennard, 1984			0.80			
Emmons						
Thesis	0.81	0.15	0.64	0.07	0.63	0.07
Mennis, 1997	0.86		0.63			
Driedger and Kennard, 1984			0.67			
Nisqually						
Thesis	0.25	0.08	0.25	0.08	0.26	0.04
Mennis, 1997	0.16		0.27			
Driedger and Kennard, 1984			0.27			
Tahoma						
Thesis	0.49	0.11	0.40	0.05	0.38	0.04
Mennis, 1997	0.52		0.41			
Driedger and Kennard, 1984			0.33			
Winthrop						
Thesis	0.58	0.12	0.48	0.05	0.45	0.06
Mennis, 1997	0.65		0.52			
Driedger and Kennard, 1984			0.52			

and Fountain, 2001) might account for some of the differences and the volume of Nisqually and the other glaciers are probably higher in 1913 than estimated.

Volumes measured from the 1931, 1936, 1940 and 1941 Nisqually Glacier maps are also questionable, because the upper two-thirds of the glacier during these periods are pasted from the 1951 and 1976 maps. The surface elevation of Nisqually Glacier may have changed considerably since the 30s and 40s. Nisqually Glacier during this period was probably thicker than it was in the 50s because the glacier started advancing at the end of the 1940s. For this reason the volumes calculated from the 30s and 40s maps probably underestimate the actual volume of the glacier.

The results are within the error limits I calculate to the volumes calculated by

Table 12: Calculated ice volumes for Nisqually Glacier in km^3

Year	Thesis	Error	Mennis, 1997	Driedger and Kennard, 1984
1913	0.25	0.08	0.16	
1931	0.27	0.04		
1936	0.27	0.04		
1940	0.25	0.04		
1941	0.24	0.04		
1951	0.23	0.02		
1956	0.24	0.02	0.25	
1961	0.27	0.02		
1966	0.25	0.02	0.25	
1971	0.26	0.04	0.25	
1976	0.28	0.02	0.27	0.27
1980	0.24	0.02		
1994	0.26	0.04		

Driedger and Kennard (1984) and Mennis (1997), except for the 1913 Nisqually and 1971 Tahoma glaciers. I used the same digitized basal and surface contours as Mennis (1997), however I converted the contour lines into TINs instead of grids. Grids tend to underestimate the volume (Pinotti, unpublished), though the volumes I measured are in most cases smaller than Mennis (1997). The difference between the 1971 Tahoma volume calculated in this thesis and by Driedger and Kennard (1984) is caused by differences in the interpolated boundary of the glacier. For the 1913 volume of Nisqually Glacier I included the basal topography from a DEM created by the USGS from the 1994 map of Mt. Rainier to fill in the area missing from the 1971 basal area. Mennis (1997) only calculated the volume to the terminus of Nisqually Glacier in 1971, which was farther up valley than it was it 1913.Volumes for all the glaciers were calculated using Equation 2 and show a significant decrease over the 81 year record (Table 13). From 1913 to 1971 the total volume decreased 22.7%, from 5.62 km^3 to 4.35 km^3, and from 1971 to 1994 it decreased 3.1% to 4.21 km^3. As expected, over the entire record southern glaciers shrank more than northern glaciers, 29% and 22.4%, respectively.

The differences between the volumes calculated using the TIN method and those from Equation 2 were generally within the error (Table 13). The only exceptions are Carbon and Winthrop glaciers in 1971 and Winthrop Glacier in 1994. Equation 2 generally overestimated glacier volume relative to the TIN method.

Overall the terminus, area and volume results provide good information on the activity of the glaciers between 1913 and 1994. There were problems in comparing and combining terminus changes between different datasets and there are differences in calculated areas between others. The area change follows terminus change as expected. Overall the small glacier (< 5km^2) shrank more than the large

Table 13: Measured (bolded) and estimated volume of all Mt. Rainier glaciers.

	1913		1971			1994	
	Thesis km^3	Error	Thesis km^3	Error	Driedger and Kennard, 1984 Km^3	Thesis km^3	Error
Carbon/Russell	0.86	0.10	0.76	0.05	0.80	0.74	0.05
Columbia Crest	0.00	0.00	0.00	0.00		0.00	0.00
Cowlitz/Ingraham	0.57	0.12	0.40	0.04	0.37	0.41	0.05
Edmunds	0.05	0.02	0.04	0.01	0.03	0.04	0.01
Emmons	0.81	0.15	0.64	0.07	0.67	0.63	0.07
Flett	0.02	0.01	0.01	0.00	0.01	0.01	0.00
Frying Pan	0.30	0.07	0.19	0.02	0.08	0.18	0.02
Inter	0.03	0.01	0.02	0.00	0.02	0.02	0.00
Kautz	0.08	0.03	0.07	0.01	0.04	0.05	0.01
Liberty Cap	0.08	0.03	0.07	0.01	0.00	0.07	0.01
Muir Snowfield	0.03	0.01	0.02	0.01	0.02	0.02	0.01
Nisqually/Wilson	0.25	0.08	0.26	0.04	0.27	0.26	0.04
North Mowich	0.43	0.10	0.31	0.04	0.27	0.31	0.04
Ohanapecosh	0.11	0.04	0.04	0.01	0.04	0.04	0.01
Paradise	0.12	0.04	0.03	0.01	0.02	0.03	0.01
Puyallup	0.24	0.06	0.18	0.02	0.29	0.19	0.02
Pyramid	0.04	0.02	0.01	0.00	0.01	0.01	0.00
Sarvent	0.03	0.01	0.02	0.00	0.01	0.02	0.00
South Mowich	0.21	0.06	0.17	0.02	0.13	0.17	0.02
South Tahoma	0.14	0.04	0.11	0.02	0.13	0.08	0.01
Success	0.01	0.01	0.02	0.00	0.01	0.01	0.00
Tahoma	0.49	0.11	0.40	0.05	0.46	0.38	0.04
Van Trump	0.04	0.02	0.02	0.00	0.01	0.02	0.00
Whitman	0.08	0.03	0.08	0.01	0.12	0.08	0.01
Wiliwakas	0.01	0.01	0.00	0.00		0.00	0.00
Winthrop	0.58	0.12	0.48	0.05	0.52	0.45	0.06
Total	5.62	1.28	4.35	0.51	4.34	4.21	0.51

ones (32.1%, 14.1%). The south facing shrank more than (-26.5%) the north facing (-17.5%). The total volume loss (1913-1994) is estimated to be 1.41 km^3.

Table 14: Measured and calculated areas and volumes for 5 glaciers on Mt. Rainier.

	1913			1971			1994		
Method	TIN		Equation 2	TIN		Equation 2	TIN		Equation 2
Glacier	km^3	Error	km^3	km^3	Error	km^3	km^3	Error	km^3
Carbon	0.86	0.10	0.86	0.76	0.05	0.66	0.74	0.05	0.71
Emmons	0.81	0.15	0.80	0.64	0.07	0.66	0.63	0.07	0.68
Nisqually	0.25	0.08	0.33	0.26	0.04	0.30	0.26	0.04	0.29
Tahoma	0.49	0.11	0.52	0.40	0.05	0.40	0.38	0.04	0.38
Winthrop	0.58	0.12	0.59	0.48	0.05	0.55	0.45	0.06	0.58
Total	3.00	0.26	3.09	2.54	0.12	2.56	2.45	0.12	2.63

IV. Climate

A. Introduction

Understanding the connection between glaciers and climate on an annual timescale requires seasonal meteorological values. Because detailed meteorological measurements are not available I use temperature and precipitation data, which are available from meteorological stations in the park. Winter precipitation and summer temperatures correlate well with glacier behavior over long time periods (Bitz and Battisti, 1999; Tangborn, 1980; Walters and Meier, 1989). Because of the dynamic response time of the glaciers to changes in mass balance long meteorological datasets (>decade) are necessary to determine the relationship. Mt. Rainer has both sufficiently long glacier and climate datasets.

B. Regional Climate

Topography and location next to the Pacific Ocean influence temperature and precipitation patterns in the Pacific Northwest. The State of Washington is divided into five distinct climatic zones (Figure 14). The zone incorporating the Cascade Mountains is characterized by dry, warm summers and wet, cool winters. Westerly winds laden with moisture from the Pacific Ocean result in high precipitation and moderate temperatures in the winter (Untersteiner, 2001). Mt. Rainier, which rises 3,050 m across a distance of approximately 16 km, creates a local orographic effect on precipitation patterns. Some of the largest seasonal snowfalls in the world have been recorded at Mt. Rainier. During the 1971/72 winter season 28.5 m of snow fell at the Paradise Station, a world record until Mt. Baker, also in the Cascade Mountains recorded a higher winter total in 1998-99 (NPS, 2001).

Figure 14: Climate regions of Washington State (Untersteiner, 2001)

The North Pacific subtropical high-pressure system influences seasonal precipitation patterns along the west coast (Trewartha, 1980). The position of the high-pressure system controls the location of the jet stream and therefore the track of moisture-laden cyclonic storms along the west coast. There is a southern migration of the high pressure system during the late fall and winter. Precipitation peaks occur in the Alaska Panhandle in September, southern British Columbia in November, northern Oregon in December, northern California in January, and southern California in February (Trewartha, 1980).

Changes in atmospheric circulation patterns control decadal variations in temperature and precipitation in the Pacific Northwest (Cayan and Peterson, 1989; Redmond and Koch, 1991). The strength and position of winter storms along the Pacific coast are controlled by the Aleutian Low (Cayan and Peterson, 1989). One method to determine the variability in the North Pacific atmospheric circulation pattern is to quantify the sea surface temperature (SST) anomalies. The leading principal component of North Pacific monthly SST variability defines the Pacific Decadal Oscillation (PDO) Index and indicates circulation pattern shifts (Mantua et al., 1997). The PDO is similar to the El Nino/Southern Oscillation (ENSO) index, but the PDO signal persists on a longer time-scale in the North Pacific. ENSO phases last about 6 to 18 months while the PDO phases operate on a 20 to 30 years cycle (Mantua et al., 1997). During positive PDO phases, cooler than average SST occurs in the north Pacific Ocean (Figure 15), and warmer than average SST persists near the west coast of North America. During this phase, winter precipitation in the Pacific Northwest is above average. Below average winter precipitation occurs during negative phases. These variations have been documented in the glacial mass balance records. The winter 700-mb height anomalies associated with the Aleutian Low are inversely correlated with the mass balance of South Cascade Glacier in the North Cascade Range of Washington and directly correlated with Wolverine Glacier in Alaska (Bitz and Battisti, 1999; McCabe and Fountain, 1995).

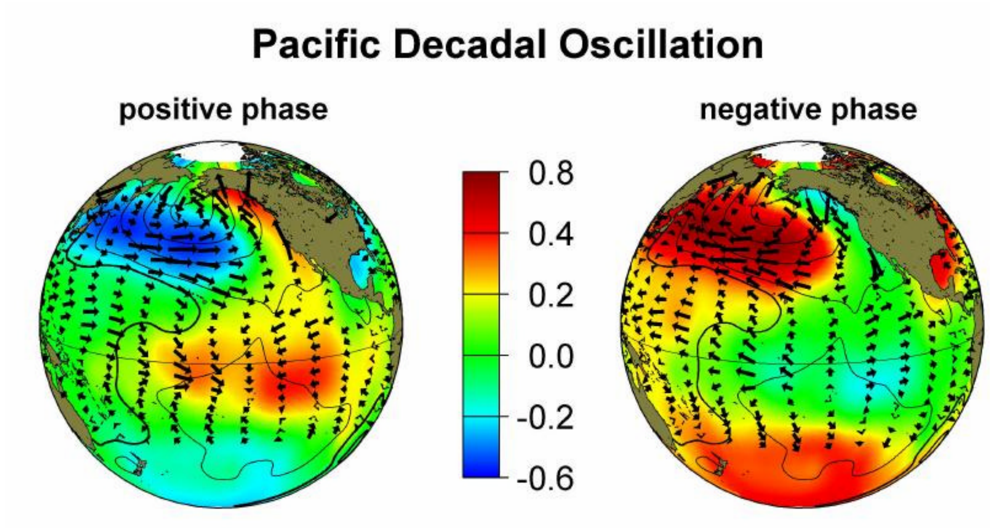

Figure 15: Color comparison of deviations in average SST (in ^{o}C) of positive versus negative phase PDO with surface wind (arrows) stress anomaly patterns (Mantua, 2000)

C. Source and Methods

1. Meteorological Data

To assess the effect of regional climatic patterns on the Mt. Rainier glaciers I analyzed summer temperature and winter precipitation/snowfall data from three stations, Longmire, Paradise and Ohanapecosh. These stations have operated in the Mt. Rainier National Park since the early 1900's (Figure 16). Two other stations, White River and Carbon, operated for less than 10 years.

Station records include all or some of the following variables: daily maximum and minimum temperature, precipitation, snowfall and snow depth (Table 15). Ohanapecosh has the longest precipitation record, starting in 1909, while Longmire

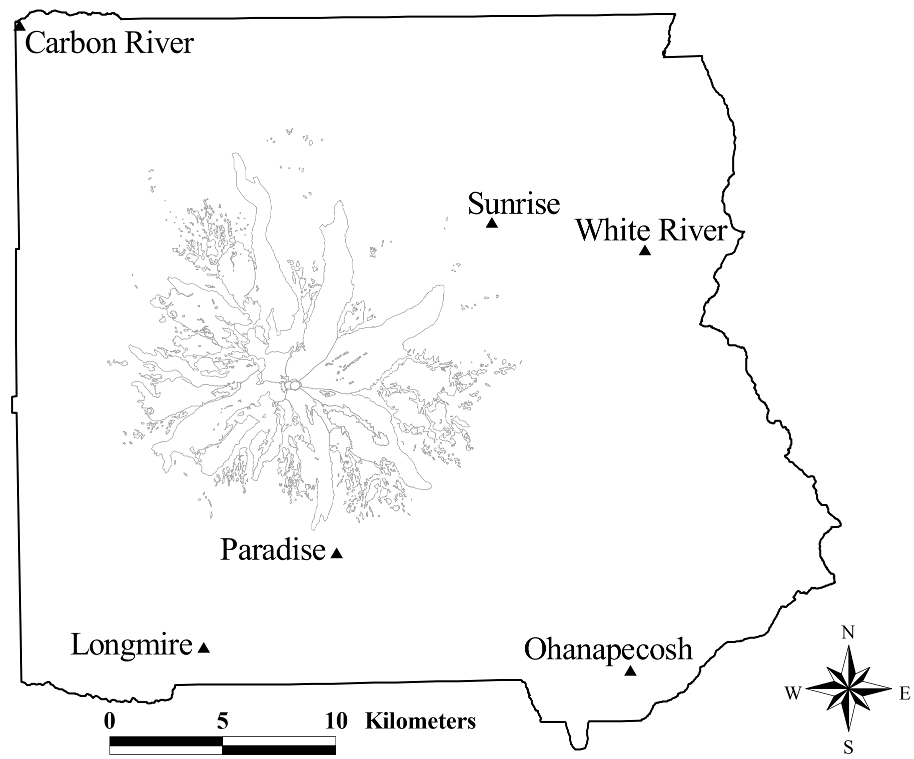

Figure 16: Location of meteorological stations in the Mt. Rainier National Park.

has the longest snowfall record, starting in 1932. Precipitation records for Longmire and Paradise start in 1932 and 1955, respectively. Only seven years of precipitation and temperature data are available for Carbon and White River stations. Longmire temperature records, the longest in the park, start in 1909.

Table 15: Mt. Rainier Climate Records.

	Longmire	Paradise	Ohanacopesh	Whie River	Carbon
Latitude	46° 45'	46°47'	46°43'	46°54'	46°59'
Longitude	121°49'	121°44'	121°34'	121°39'	121°50'
Elevation (m)	841	1692 (1948-70) 1655 (1970-98)	579	1341	1419
Max/ Min Temperature	1909-1998	1948-1998	Not Recorded	1967-1976	1948-1956
Precipitation	1932-1998	1948-1998	1909-1998	1967-1976	1948-1956
Snowfall	1932-1998	1948-1998	1949-1970	1967-1976	1948-1956

I summed precipitation and snowfall over the winter (October to April), and averaged temperature over the summer (May to September) for each station. This seasonal division is based on long-term accumulation and ablation studies on South Cascade Glacier, in the North Cascades, Washington (Tangborn, 1980). Data were smoothed using five-year running averages, using the current year and the four previous years. This smoothing scheme is useful when comparing climate with glaciers because glaciers respond to current and previous climatic conditions.

2. Solar Radiation Modeling

Limited solar radiation records exist for the Mt. Rainier National Park. The park collected data at Camp Muir, but not enough to characterize either the temporal or spatial variations around the mountain. To determine the spatial distribution of potential incoming radiation I used the model, SOLARFLUX (Rich et al., 1995). The model, which operates within the GRID module of ArcInfo, calculates surface orientation (slope and aspect) from an elevation grid, temporal shifts in solar angle (azimuth and zenith), and topographic shadowing (Rich et al., 1995). It uses these parameters to estimate incoming solar radiation (MJ m^{-2}) for each grid cell during the specified time interval. The program requires an elevation grid model, Julian day, start and end times, time increment, geographic position, and atmospheric transmittivity. Transmittivity is the proportion of radiation that passes through the atmosphere to the earth's surface and ranges from zero (opaque) to one (clear sky). I specified a constant transmissivity of 1.0 because I wanted to determine the spatial variation of solar radiation without clouds and atmospheric turbidity. Spatial variations in cloud cover will be considered later. The 1994 DEM was used for the elevation grid and a 0.5 hr time increment between sunrise and sunset. Because of the computational time required, I only ran the model once every two weeks during the ablation period (May to October 4).

3. Cloud Cover

One of the factors not addressed by the solar radiation model is the distribution of clouds around Mt. Rainier. Spatial differences in cloud affect the intensity and duration of shortwave radiation reaching the surface and the balance of longwave radiation. On cloudy days, the net radiation (longwave and shortwave) can decrease from 70% to 45% (Holmgren, 1971). These two variables are important components of the surface energy balance of glaciers (Holmgren, 1971). Consequentially spatial variations in the cloud cover will cause variations in the energy balance of the glaciers.

To evaluate the spatial distribution of cloud cover around Mt. Rainier I used Advanced Very High Resolution Radiometer (AVHRR) satellite images (Figure 17). The images are relatively easy to process and are free. The AVHRR sensors measure five spectral bands: Band 1: 0.58 – 0.68 μm, Band 2: 0.75-1.10 μm, Band 3: 3.55-3.93 μm, Band 4: 10.50-11.50 μm, and Band 5: 11.50-12.50 μm (NOAA, 1999). One limiting factor of AVHRR is its spatial resolution, 1.1 km. The images were georeferenced using embedded ground control points that are included with the data. I spot checked the georeferenced images by comparing specific points to visible features on other AVHRR images, such as the peak of Mt. Rainier. For cloudy images where Mt. Rainier could not be discerned, other visible features were compared, such as the Columbia River or other Cascade volcanic peaks.

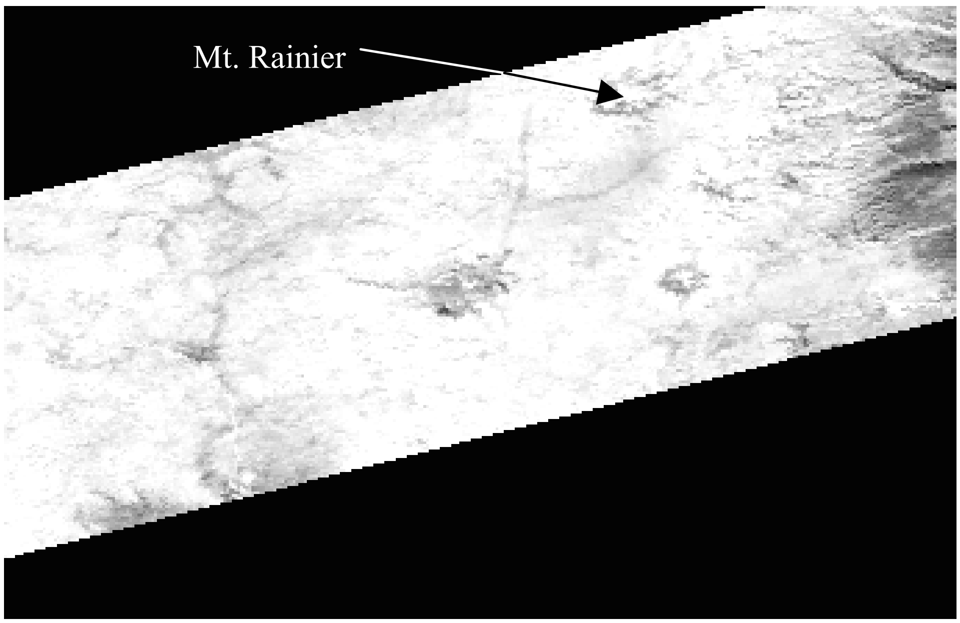

Figure 17: AVHRR Image (spectral band: 3.55-3.93 μm) of Southern Washington taken on Oct 26, 1998.

The images were filtered for clouds. I used the Normalized Cloud Ratio (NCR) to discern clouds from other spectral features (Scambos, 1998):

$$NCR = \frac{(\text{Band3} - \text{Band4})}{(\text{Band3} + \text{Band4})} \tag{3}$$

A positive NCR indicates greater reflection of band 3 than band 4 and more clouds. However, the NCR does not always discriminate between high cirrus cover and snow at temperatures well below freezing because they have very similar reflectance values.

Fortunately the snow on Mt. Rainier is at or near the freezing temperature in the summer.

The NCR was calculated from images using a 24 by 24 pixel sampling grid centered on Mt. Rainier. This grid, approximately 26 x 26 km, was selected to ensure complete coverage of the mountain. Spatial variation in cloud cover was determined by dividing the grid into two halves, north and south and averaging the NCR for each quadrant.

D. Results

1. Meteorological Measurements

No significant long-term trends exist in the winter precipitation records (Figure 18 and Appendix B), but a decreasing trend in snowfall exists at Longmire and Ohanapecosh (Figure 19 and Appendix C). Total snowfall at the Longmire station decreased 2.6 cm yr^{-1} ($P = 0.08$) between 1932 and 1996 and at Ohanapecosh station decreased by 3.1

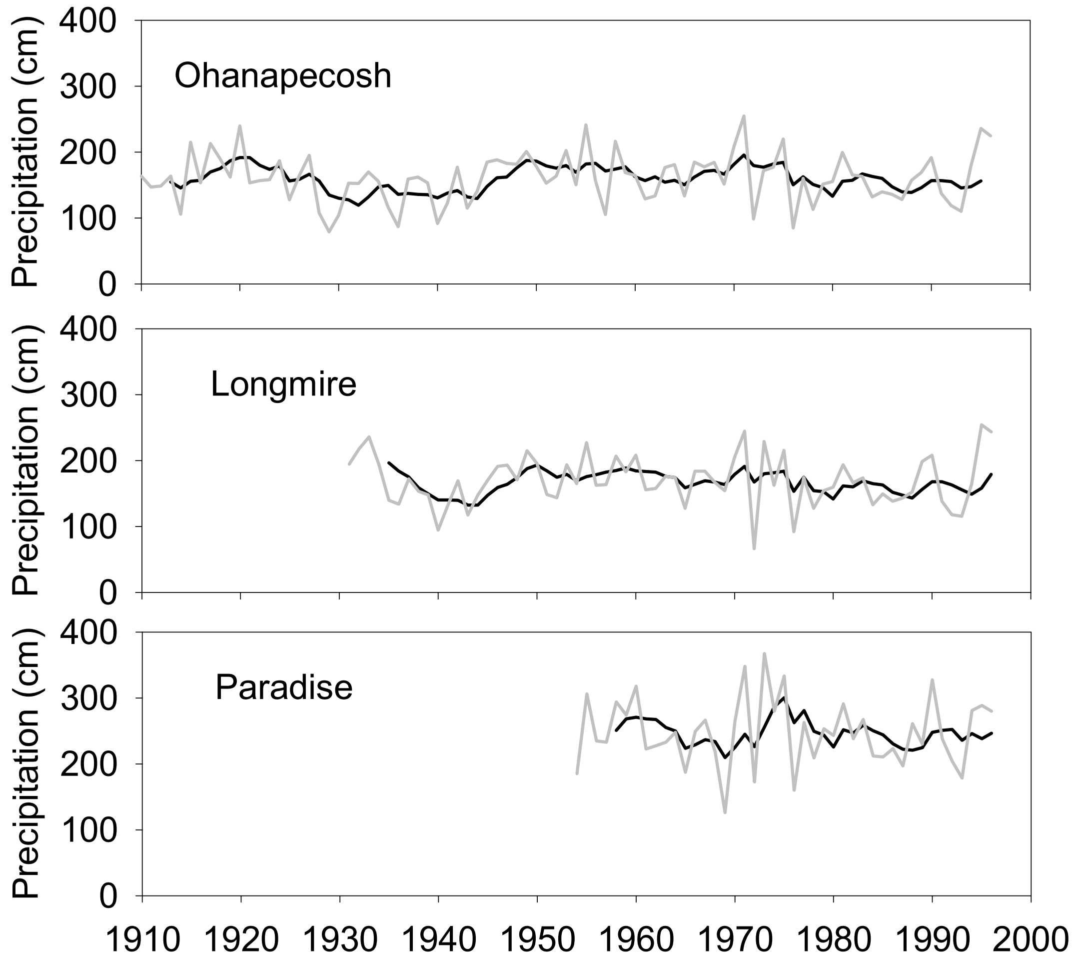

Figure 18: Yearly totals (gray lines) and five year running averages (black lines) of winter precipitation (October to April) for Ohanapecosh, Paradise and Longmire stations.

cm yr^{-1} (P = 0.17) between 1949 and 1996. There are no significant trends in snowfall at the Paradise station.

The orographic effects of the mountain are clearly evident from the results. The average winter precipitation (1954-1996) at Paradise (1655 m amsl) , the highest elevation of all the stations was 248 cm, while Ohanapecosh (579 m amsl) and Longmire (841 m amsl) averaged 164 cm and 170 cm respectively. During the same period Paradise averaged about three times more winter snowfall (1145 cm) than

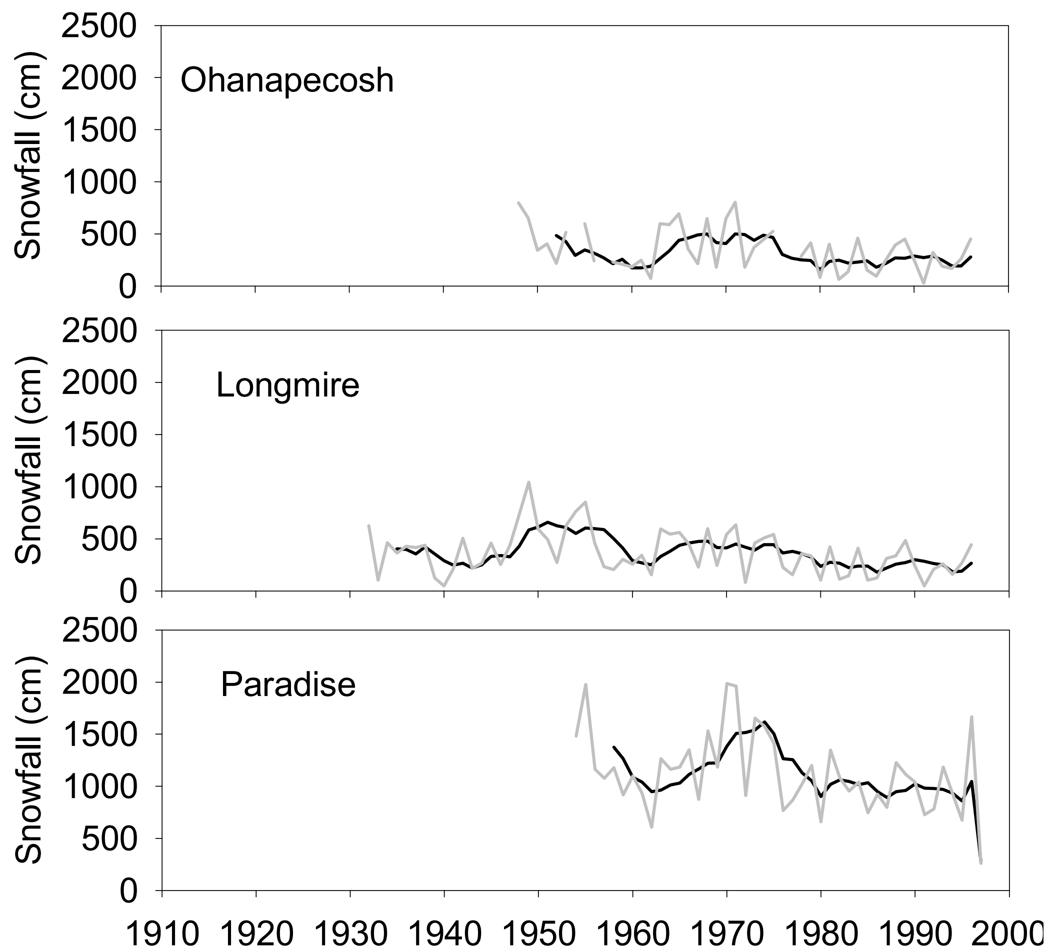

Figure 19: Yearly and five-year running average of total winter snowfall for Ohanapecosh, Paradise and Longmire stations.

Longmire (344 cm) and Ohanapecosh (330).

Annual changes in winter precipitation are well correlated between the three stations over the 1958 and 1995 period (Table 16). Snowfall is not as well correlated because of the elevation differences. Precipitation is more likely to fall as snow rather than rain at higher elevations.

Table 16: Correlations of winter (October to April) precipitation (prec) and winter snowfall (snow) between 1958 and 1995. All correlations have P values ≤ 0.05. Carbon and White River data are not included because of their short record duration.

	Longmire Prec (841 m)	Ohanacopesh Prec (579 m)	Paradise Prec (1655 m)	Longmire Snow (841 m)	Ohanacopesh Snow (579 m)
Ohanacopesh - Prec	0.91				
Paradise - Prec	0.82	0.75			
Ohanacopesh - Snow				0.71	
Paradise - Snow				0.52	0.60

Ohanapecosh has the longest precipitation record (Table 15) and therefore was used to examine long term variations. Standardized residuals were calculated and distinct dry and wet periods were documented throughout the record (Figure 20). Wetter periods occurred in 1917-1926, 1948-1958, and 1966-1983 and drier periods occurred 1909-1916, 1925-1947, 1959-1965 and 1984-1993. Snowfall deviations, which closely matched the precipitation, showed (since 1931) snowier periods: 1931-1938, 1947-56 and 1963-75; and the drier periods were 1939-1946, 1957-1962 and 1975-1995.

It is not clear if spatial variations in precipitation and snowfall patterns occur around the mountain. Winter precipitation and snowfall measured at the Carbon station were less than Longmire and Ohanapecosh, even though Carbon is at a higher elevation (Table 17). In contrast, White River, which has a similar elevation to Carbon station, has a higher winter precipitation average between 1966 and 1972 than Longmire and Ohanapecosh. The average winter snowfall at the White River station during the same period was 678 cm, and is higher than at Longmire (397 cm) and Ohanapecosh (433 cm).

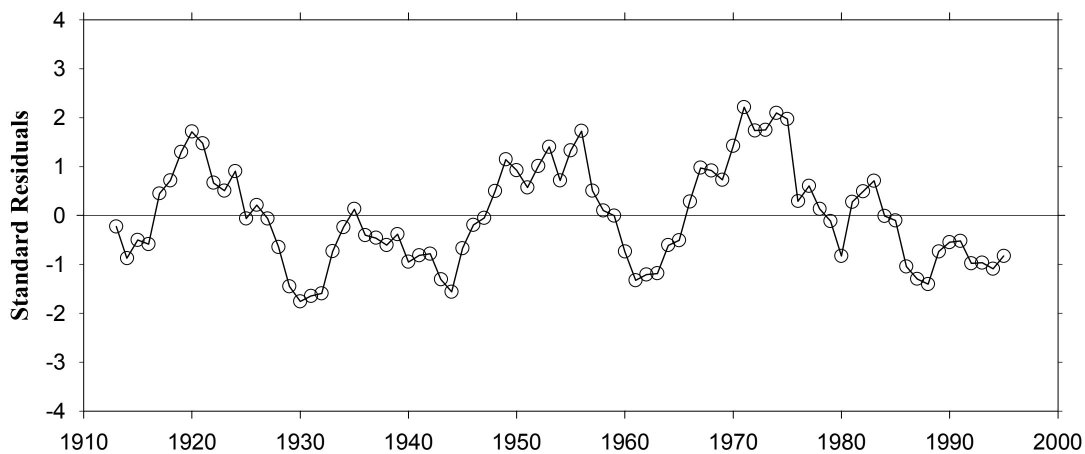

Figure 20: Standard residuals of the 5-year running averages of winter (October to April) total precipitation for the Ohanapecosh station.

No significant trends ($P \leq 0.1$) exist for Longmire and Paradise summer temperature (May to September) records (Figure 21 and Appendix D). Average summer temperature for Longmire between 1914 and 1996 was 13.0°C (Table 18). Between 1950 and 1996 overlapping records exist for Longmire and Paradise and the average summer temperature at Paradise was 8.1°C and at Longmire was 13.0°C. The lapse rate between the two stations is 5.3°C km^{-1}, which is a typical value for a mountainous region (Barry and Chorley, 1992). Correlation of average summer temperature between 1950 and 1996 for Longmire and Paradise stations is 0.63 ($P < 0.001$). The average summer temperature for White River between 1966 and 1972 was 12.3°C, similar to Longmire during the same period. Carbon station has an average summer temperature between 1966 and 1972 of 9.2°C. The lapse rate between Carbon and Longmire is 6.9°C km^{-1} and between Carbon and Paradise is 3.4°C km^{-1}.

Table 17: Total winter precipitation and snowfall (October to April) in cm for all climate stations in Mt. Rainier National Park.

Precipitation	Longmire Elev: 841 m	Paradise Elev: 1655 m	Ohanapecosh Elev: 579m	White River Elev: 1341m	Carbon Elev: 1419m
1909 to 1996	Partial data	Partial data	160.5	Partial data	Partial data
1931 to 1996	169.9	Partial data	161.1	Partial data	Partial data
1954 to 1996	170.3	247.7	164.0	Partial data	Partial data
1948 to 1952	174.7	No data	175.4	No data	144.5
1966 to 1972	172.3	235.0	180.2	186.4	Partial data
Snowfall					
1931 to 1996	369.3	Partial Data	Partial Data	Partial Data	Partial Data
1948 to 1996	377.4	Partial Data	351.8	Partial Data	Partial Data
1948 to 1951	714.5	No data	550.0	No data	181.3
1954 to 1996	344.0	1145.6	330.7	Partial Data	No data
1966 to 1972	396.6	1400.4	433.2	677.9	No data

Table 18: Average summer (May to September) temperatures in °C for all climate stations in Mt. Rainier National Park.

	Longmire	Paradise	Ohanopecosh	White River	Carbon
1914 to 1996	13.0	Partial Data	No data	Partial Data	Partial Data
1950 to 1996	13.0	8.1	No data	Partial Data	Partial Data
1948 to 1955	12.8	Partial Data	No data	No data	11.0
1967 to 1972	13.2	8.4	No data	12.3	9.2

Deviations from average temperatures at Longmire show cooler periods in 1913-1933 and 1969-1985 (Figure 22), with warmer than normal in between. The highest +2.9°C and lowest, -2.0°C, deviations occurred only five years apart (1966 and 1971).

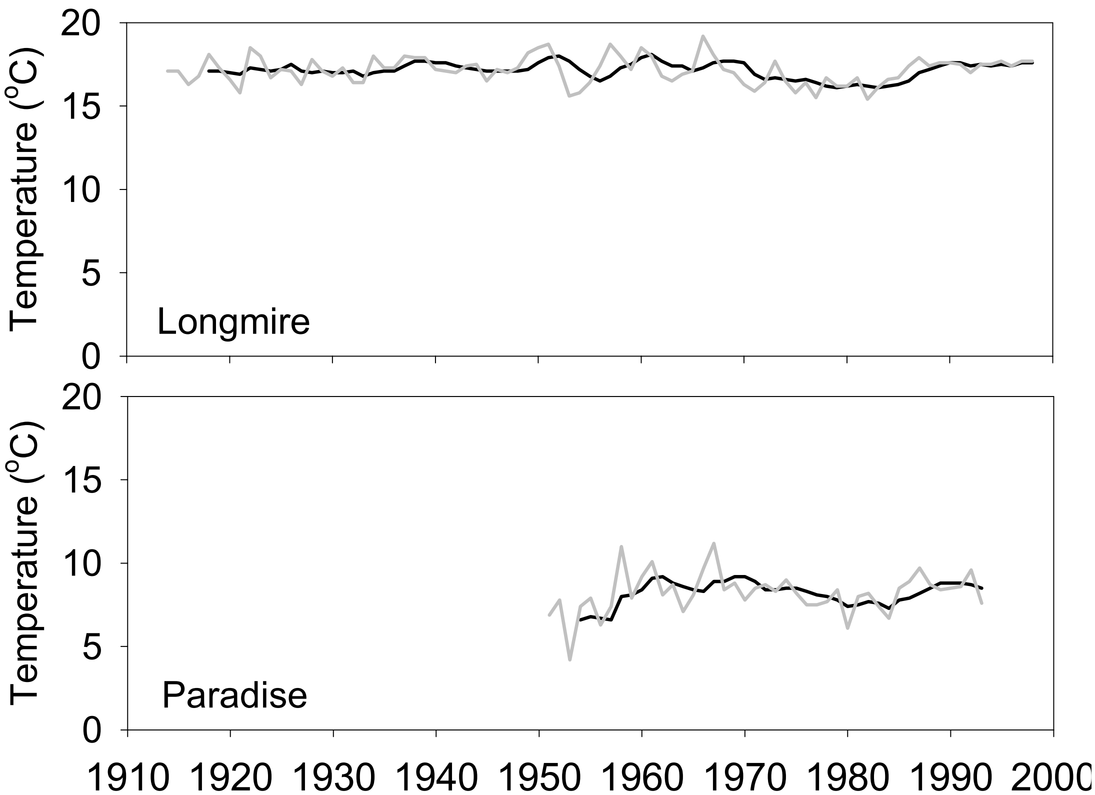

Figure 21: May to September average temperatures (gray line) and five-year moving averages (black line) for Longmire and Paradise climate stations in Mt. Rainier National Park.

Comparison of summer temperatures and winter precipitation show they are not strongly correlated (Figure 23). Comparison with the PDO shows a significant negative correlation, -0.64 ($P < 0.001$) for winter precipitation also consistent with other studies (Mantua et al., 1997). Temperature correlates poorly with PDO.

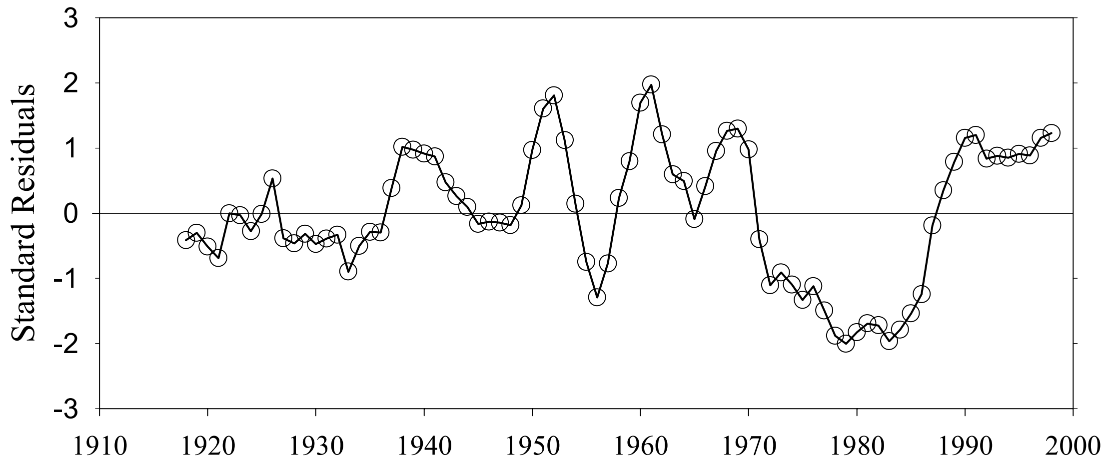

Figure 22: Standard residuals of the 5-year running averages for Longmire average May to September temperatures.

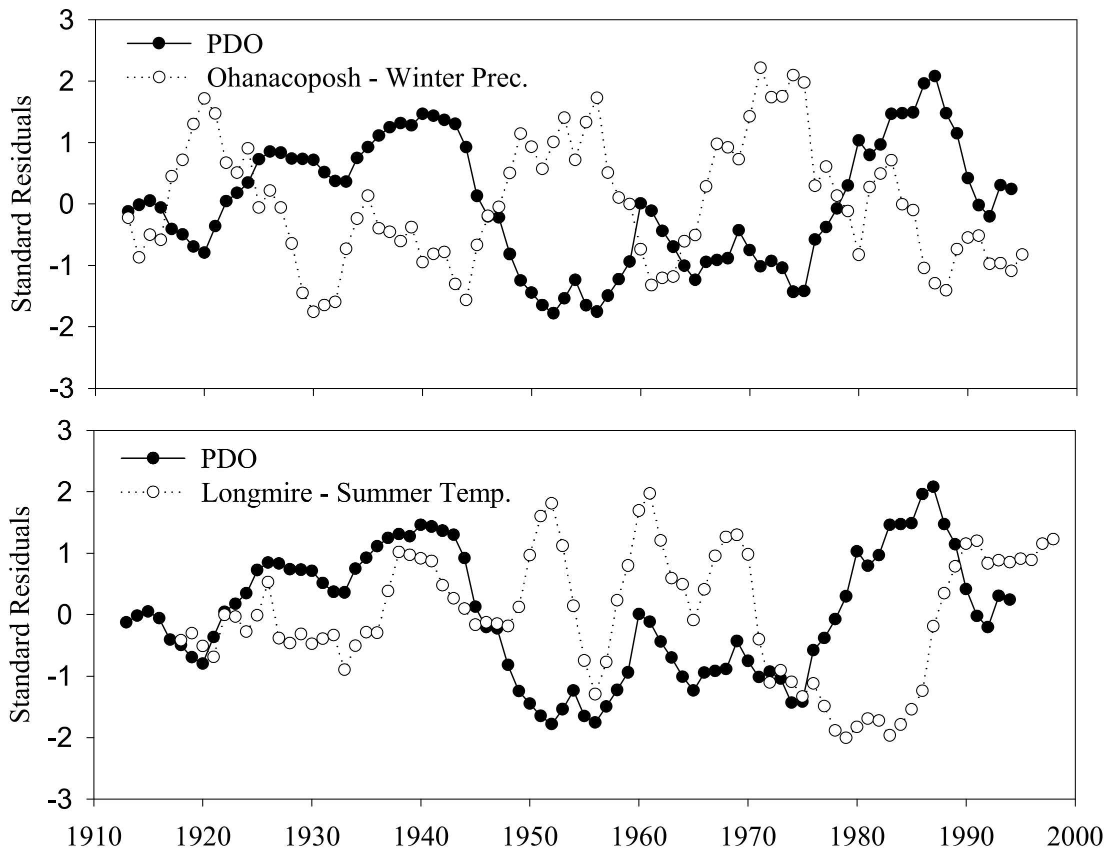

Figure 23: Standard residuals values of winter precipitation at Ohanapecosh, summer temperatures at Longmire and the PDO (Mantua, 1997). All data are averaged using a 5-year running average.

Other findings in the region show similar climatic trends since the early 1900s. Harper and Johnston (1992) reported dry periods at Mt. Baker between 1935-1943 and 1975-1990, with a wetter period in between. In Oregon the 100-year record between 1896 and 1996 is can be divided into distinct 20-25 years segments (Taylor, 1999). The periods 1920-1945 and 1975-1994 were drier and warmer, while the periods before and after were wetter and cooler (Taylor, 1999). Snow pack thickness also show strong correlations with PDO (Cayan and Peterson, 1989).

The significant trends documented in Washington State since 1920 are not apparent at the Mt. Rainier. Precipitation west of the Cascade Mountains in Washington State increased by at least 25% (Figure 24) over the last century (Mote, 2003.). Division 5, which encompasses Mt Rainier and the Cascade Mountains (see Cascade Mts. on Figure 14), shows a significant increase between 1910 and 1997 in winter precipitation, 0.3 cm a^{-1} ($P = 0.01$; Figure 25) or 19%. This trend is not

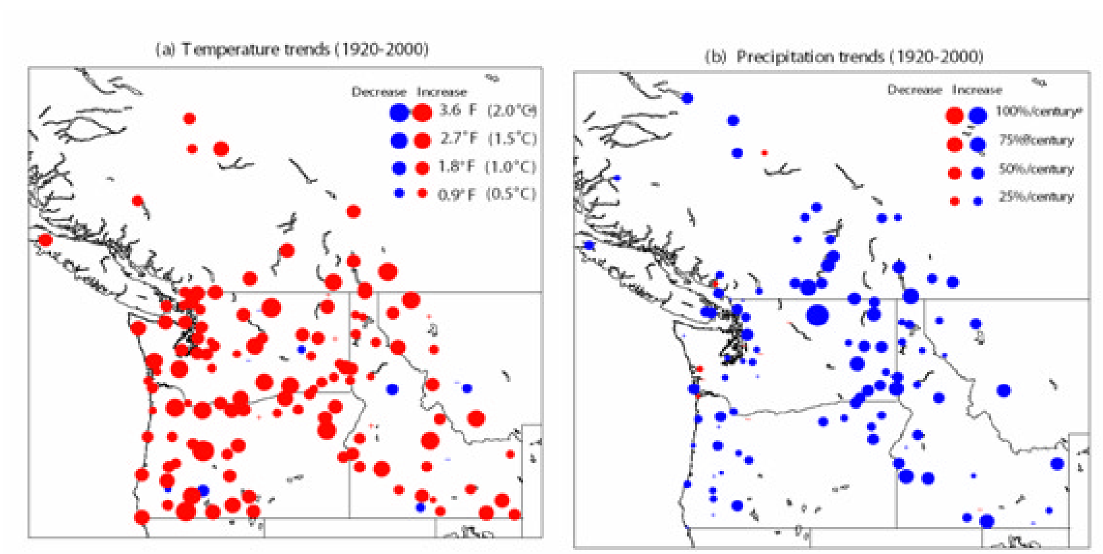

Figure 24: 20th century trends (1920-2000) in (a, b) average annual Pacific Northwest temperature and precipitation (Mote, 2003.).

apparent at Mt. Rainier (Ohanapecosh Station). There is no significant correlation between total winter precipitation measured at Ohanapecosh and Washington Division 5. The only significant precipitation trend at Mt. Rainier is a decrease in winter snowfall (2.7 cm a^{-1}).

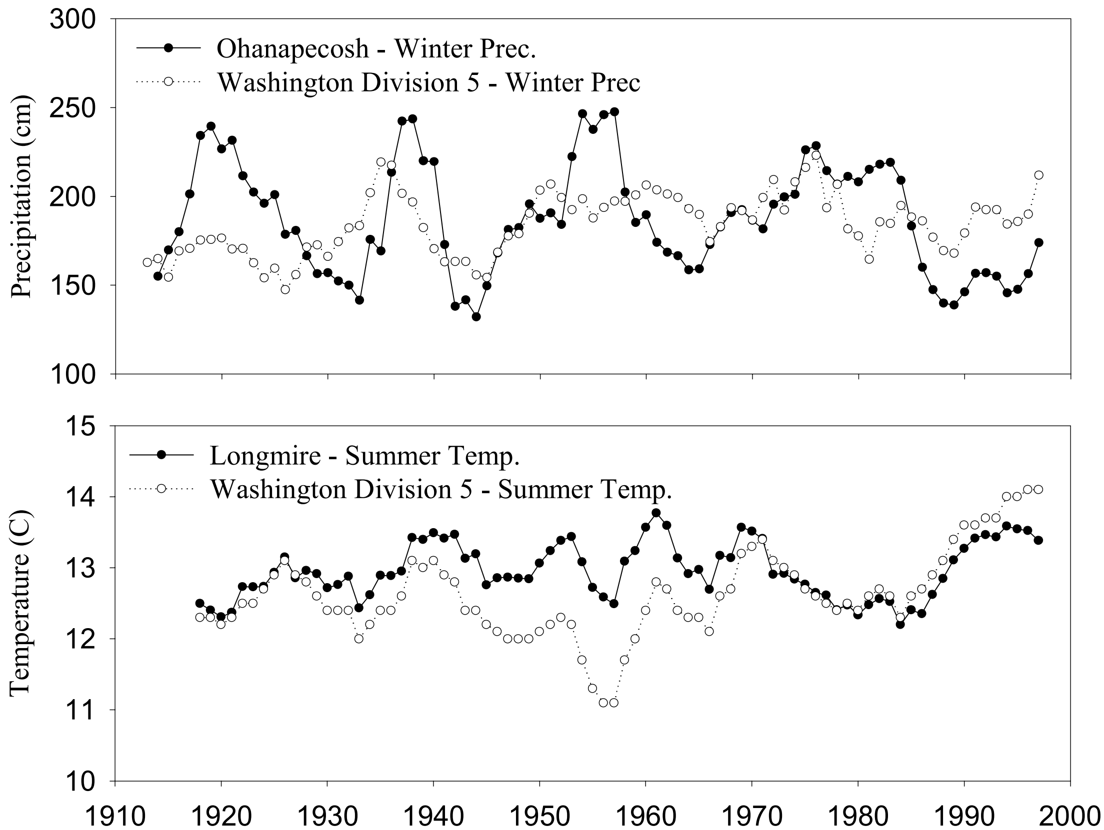

Figure 25: Washington State Division 5 average summer temperature (May to September) and total winter precipitation (October to April) plotted with Longmire average summer temperature and Ohanapecosh total winter precipitation. Data have been smoothed using a 5-year running average.

Since 1920, temperatures across the State of Washington, including Division 5 increased by at least 0.9^{o}C (Figure 24), while no significant trends in temperature have been observed at Mt. Rainier during the same time period. Unlike precipitation, there is significant correlation ($R^2 = 0.56$, $p < 0.01$) between average summer temperature measured at Longmire and Washington Division 5.

2. Incoming solar radiation modeling

The solar modeling shows distinct spatial differences in incoming solar radiation, especially in late summer (Figure 26). As expected between north-facing and south-facing glaciers, the south-facing receive greater total daily incoming solar

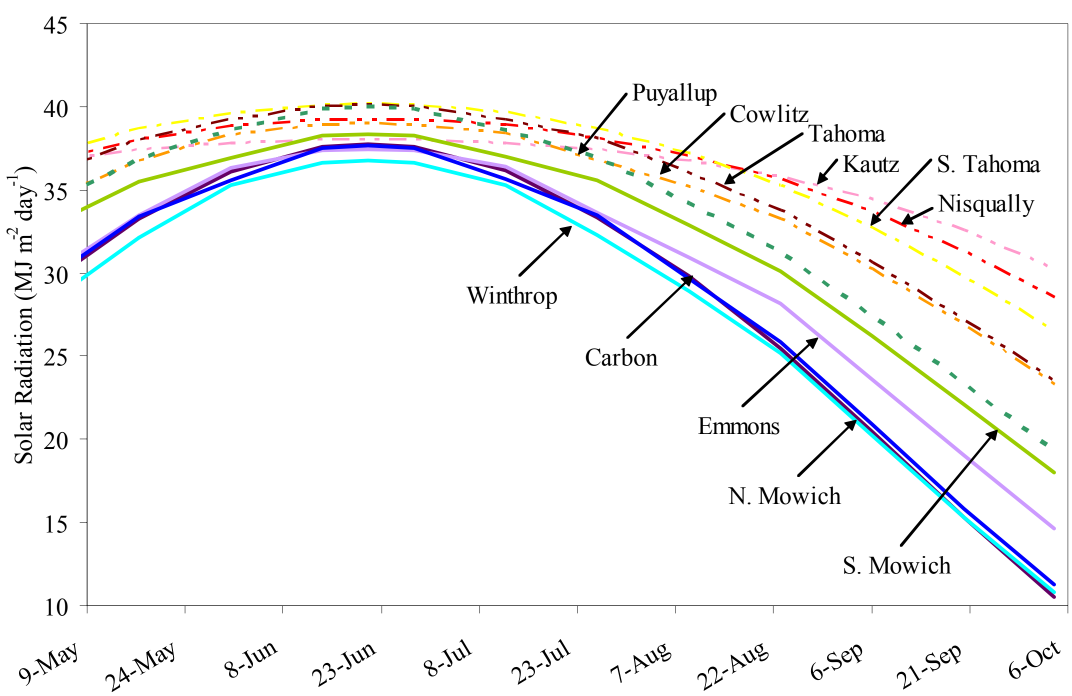

Figure 26: Solar radiation modeling results. Southern glaciers are dashed and northern are solid lines.

radiation. Differences in the incident solar radiation between the glaciers on June 21, when the sun is at its highest solar zenith angle are relatively small, differing by only

8%. Late in the season, the differences between glaciers with northern and southern aspects increase. By September 21, the maximum difference is 53%. The greatest difference of 18 MJ m^{-2} day^{-1} occurs between the Winthrop and Kautz glaciers.

3. Cloud Cover

No significant differences in cloud cover (P = 0.37) exist between the southern and northern sides of the mountain (Figure 27). This conclusion is based on the analysis of 40 AVHRR images taken over three summers. Further work needs to be completed to understand the spatial variations in cloud cover.

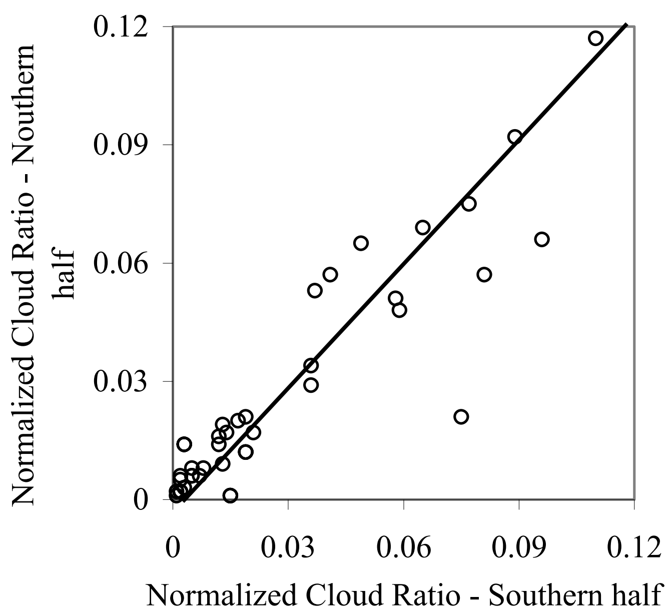

Figure 27: Plot of average NCR measured from AVHRR images between 1995 and 1998. The solid line is a 1:1 line.

V. Comparison of Glacier Response to Climate Variations

Mass gain causes glaciers to lengthen and mass loss causes glaciers to retreat. However, a time lag exists between mass change and size change due to dynamic processes in a glacier (Bahr et al., 1998; Jóhannesson et al., 1989). A glacier may respond decades after a change in climate. Also a glacier may be responding to the cumulative effect of several past climate changes. For example, a glacier might be thickening in its upper reaches, while its lower part is thinning and retreating. The time required for glaciers to equilibrate to a shift in mass balance is called the "response time". Jóhannesson et al.(1980) developed a simple method to determine the order of magnitude response time (T_m) by dividing the average glacier thickness (h) by the annual ablation rate at the terminus (b):

$$T_m = \frac{h}{-b} \tag{4}$$

Estimated response times for temperate alpine glaciers are on the order of 10^1 to 10^2 years, which are close to field observations.

Using Equation (4) I calculated response times for five glaciers. I used a range of 5 to 10 m a^{-1} for b, which was based on a measurements of 8.7 m a^{-1} made on Nisqually Glacier (Hodge, 1973). The range was created to account for spatial variations in the ablation rate. The average glacier thickness (h) was calculated by subtracting the top from the bottom surface using grids in ArcView. The calculated response times range from 7 to 14 years for Winthrop Glacier to 18 to 36 years for Carbon Glacier (Table 19), which match well with observations.

Table 19: Calculated response times determined by dividing measured thickness from the center of each glacier and suggested response time determined from cross-correlations.

Glacier	Thickness (m)	Measured Lag Time (yr)	Annual Balance Range (m a-1)	Response Time Range (yr)
Emmons	94	10	5 - 10	9 - 19
Winthrop	70	8	5 - 10	7 - 14
Carbon	181	9	5 - 10	18 - 36
Tahoma	77	9	5 - 10	8 - 15
Nisqually	81	8	5 - 10	6 - 18

The calculated respond times using Equation 4 were compared with empirical response times determined from glacier and climate data. To measure the response time of the glaciers, I linearly interpolated each glacier area over time using the mapped dates as the observed data. To improve the accuracy of comparison with precipitation and temperature data, all data were transformed into standardized residuals. A cross correlation was calculated between the glacier and climate data and the cross correlation was recalculated, up to a 12 year lag. There was no reason to think that the glacier change would precede a climate change so those forward lags were not calculated.

The changes in Nisqually Glacier follow winter snowfall at Longmire by about 10 years (Figure 28). Comparing the changes in Nisqually Glacier to the other stations, winter precipitation and snowfall measured at Ohanapecosh, Longmire and Paradise, the lag in glacier response is 7-9 years (Table 20). The highest correlation, 0.58, occurs between winter snowfall measured at Paradise and a nine year lag of Nisqually Glacier.

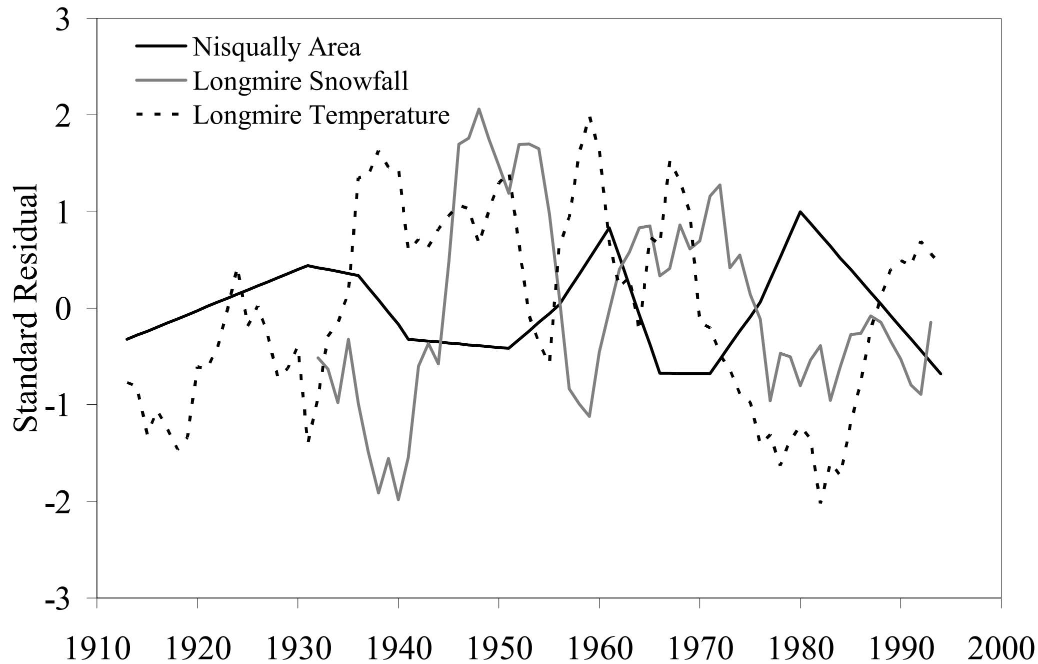

Figure 28: Comparison of standardized residual values for Nisqually Glacier area, and winter snowfall and summer temperature from the Longmire meteorological station.

Lag times measured against changes in annual terminus positions for 11 glaciers are similar to the results for Nisqually Glacier (Figure 29). The lag times determined from the terminus and climate data match well with the theoretical response times (Table 19) except for Carbon Glacier, which has maximum cross-correlation value at 9 years, well below the theoretical range of 18-36 years. Perhaps, the mass balance at the terminus is higher than 10 m a^{-1}. A mass balance of 20 m a^{-1} yields a response time of 9 years. The higher rate is reasonable because the elevation of the Carbon Glacier terminus is the lowest of all the glaciers.

Table 20: Cross-correlation of the area of Nisqually and various meteorological variables from the Longmire, Ohanapecosh and Paradise stations. All bolded values are significant correlations.

Lag Time (yr)	Ohanac. Winter Prec 1913-1994	Longmire Winter Snowfall 1931-1994	Paradise Winter Snowfall 1954-1996	Paradise Winter Prec 1954-1995	Paradise Summer Temp 1950-1995	Longmire Max Temp 1915-1994	Longmire Average Temp 1918-1994
0	-0.26	-0.25	-0.42	-0.10	-0.05	-0.12	-0.04
1	-0.21	-0.24	-0.36	0.02	-0.06	-0.15	-0.07
2	-0.16	-0.19	-0.24	0.09	-0.12	-0.19	-0.12
3	-0.11	-0.12	-0.12	0.13	-0.24	-0.27	-0.21
4	-0.03	-0.02	0.02	0.19	-0.29	-0.29	-0.26
5	0.09	0.11	0.19	0.30	-0.38	**-0.34**	-0.34
6	0.20	0.25	0.36	0.36	**-0.41**	**-0.34**	-0.37
7	0.26	0.33	0.49	**0.41**	-0.38	-0.32	**-0.39**
8	0.33	**0.37**	0.53	0.39	-0.34	-0.27	**-0.39**
9	**0.39**	**0.37**	**0.58**	0.37	-0.25	-0.18	-0.34
10	0.37	0.35	0.52	0.28	-0.09	-0.09	-0.28
11	0.33	0.35	0.41	0.14	0.07	0.02	-0.20
12	0.31	0.31	0.33	0.10	0.16	0.09	-0.12

The relation between temperature and glacier changes is not as clear. The best correlations (r^2 = -0.34 and –0.39, P < 0.01) occur for a 5 year lag of Nisqually Glacier relative to average maximum temperature (Longmire) and 7-8 year lag to average summer temperatures (Longmire), respectively.

The lag times of five to nine years for temperature, similar to those for precipitation. Thus, winter precipitation and summer temperatures appear to be working together to affect the glacier behavior, and are not mutually exclusive of each other. Performing multiple regressions with the above variables slightly improves the correlation values.

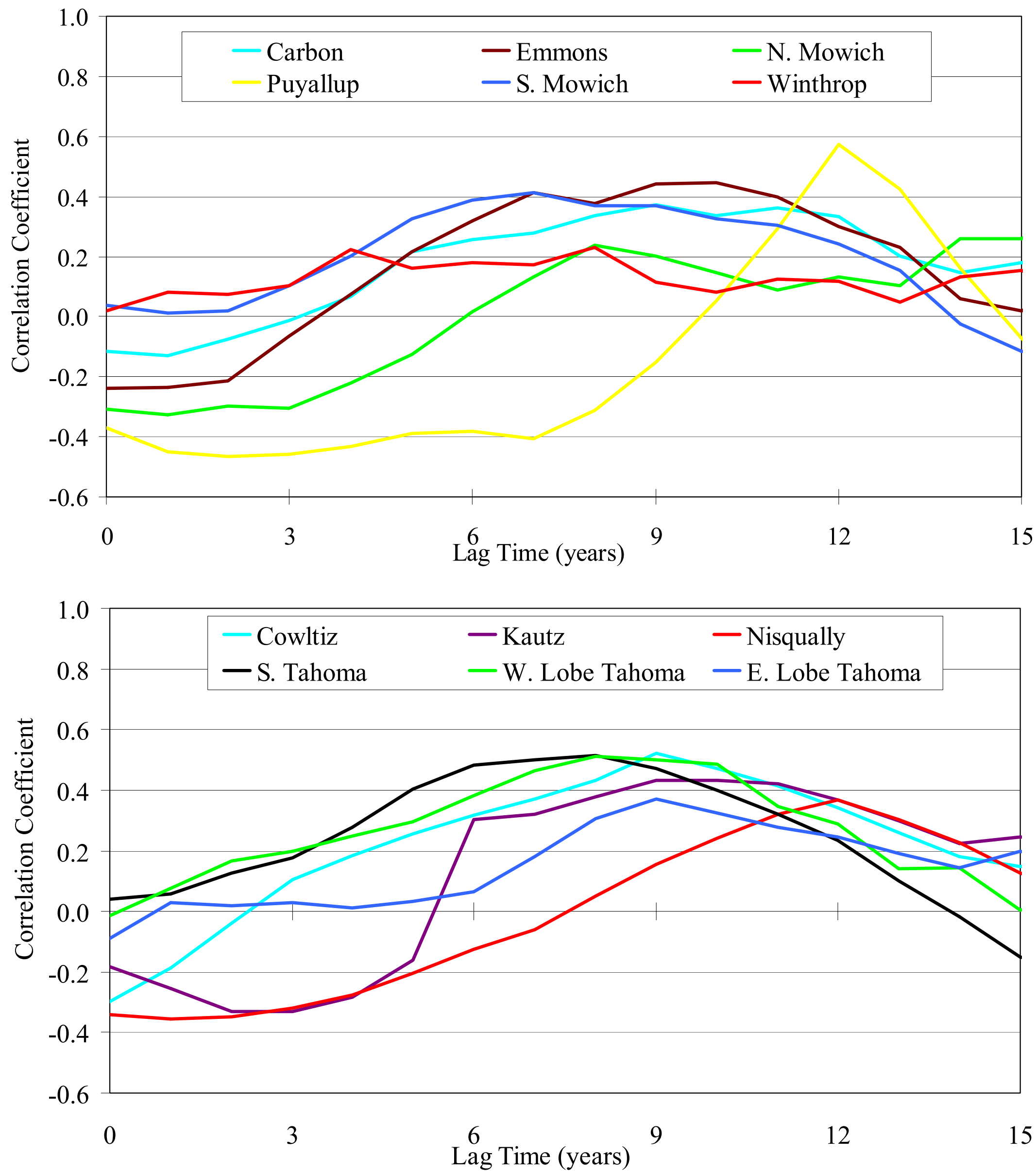

Figure 29: Cross-correlation of snowfall (fixed) at the Longmire weather station and annual changes in terminus positions (lagged) for the northern (top chart) and southern (bottom chart) glaciers

The response time of the glaciers might be modified because of kinematic waves. The propagation of these waves down glacier has been observed on Nisqually Glacier (Johnson, 1960; Meier, 1963b). The waves, which travel two to six faster than glacier ice, can cause glaciers to advance. Because of higher speeds, kinematic waves might cause glaciers to respond sooner than in their absence.

VI. Discussion

Since the Little Ice Age the glaciers of Mt. Rainier have significantly retreated, as have other alpine glaciers in temperate regions around the globe (Haeberli et al., 1998; UNEP, 1992). The glaciers in the European Alps and Caucasus have lost about a third of their area since the 1850s (Meier et al., 2003). In more recent times, the glaciers of Mt. Rainier have followed global trends of short term advances and overall retreat and ice loss (Haeberli et al., 1998).

Between 1935 and 1950 almost all of the glaciers in the contiguous United States retreated (Meier and Post, 1962), matching the trend at Mt. Rainier. The period of growth at Mt. Rainier between the 1950s and the 1980s was more or less consistent for most of the glaciers in Washington and Oregon (Wood, 1988). The first sign of a climatic shift in this region was at Nisqually Glacier, which started to thicken in the late 1940s (Johnson, 1960). In 1955, 48 of the 68 glaciers investigated in the Olympic and North Cascade mountains were advancing, and the others were stable (Hubley, 1956). This period of growth in the Pacific Northwest preceded glaciers growth in other temperate regions by 10 to 20 years. During the late 50s, only 6.3% of the monitored glaciers in other parts of the world were advancing, but by the beginning of the 1970s, 77% of the glaciers were advancing (Wood, 1988).

From the mid-1970s to 1994 most of the glaciers throughout Washington and Oregon were retreating, including all but three of the Mt. Rainier glaciers. Of 107 glaciers monitored in the Cascades in 1988, only three were advancing and 22% were retreating rapidly (Pelto, 1993). By 1992, all the glaciers were retreating. In the European Alps, 75% of the monitored glaciers were advancing at the end of the 1970s (Wood, 1988), but in the early 1980s this trend reversed. Since the early 1990s, most glaciers in the European Alps have retreated, thus joining the global trend of alpine glaciers (Dyurgerov and Meier, 1997a).

The glaciers on Mt. Rainier are primarily controlled by changes in large-scale atmospheric circulation, similar to other glaciers around the world (Meier et al., 2003). Variations in atmospheric circulation patterns are the primary reason for the differences in trends around the globe (Braithwaite and Raper, 2002; McCabe and Fountain, 1995; Wood, 1988) The recent differences in regional glacial trends have led to some observers to conclude that there is no recent global glacial recession trend (Pinotti, unpublished) and highlights the difficulties in assessing global changes on a small number of glaciers worldwide.

Using a glacier or glaciers as a benchmark is useful for assessing the current behavior of the glaciers in a particular region, but does not apply to assessing the magnitude of the change. For example, at Mt. Rainier the area of the southern glaciers decreased by 27%, while the northern only decreased by 18% since 1913. Of the 11 glaciers that decreased by more than 30% four are located on the northern half of the mountain. The other remaining seven glaciers are located on the southern side. Average terminus retreat for the southern and northern glaciers was 1685 m and 593 m, respectively. Therefore any of the glaciers around Mt. Rainier accurately reflects the trend but not the magnitude of change for each glacier. Similarly five of the glaciated Cascade volcanic peaks examined by Pinotti (Pinotti, unpublished) have larger losses on the southern side (Table 21). In the Austrian Alps between 1973 and 1992 36% of the area for the glaciers with southern exposure was lost, compared with a loss of 5.8% for those with a northern exposure (Paul, 2002).

Table 21: Changes in area and volume for glaciers on Cascade Mountain peaks in southern Washington and Oregon (Kääb et al., 2001; Paul, 2002; Pinotti, unpublished).

		% Area Change	
		Southern	Northern
Mountain	Period	Glaciers	Glaciers
Mt. Rainier	1913-1994	-27%	-18%
Mt. Adams	1907-1983	-49%	-33%
Mt. St. Helens	1919-1975	-35%	10%
Mt. Hood	1907-1989	-45%	-32%
Mt. Jefferson	1936-1990	-55%	-30%
S. Sister	1936-1990	-24%	-46%
Broken Top	1936-1990	-18%	-37%

Based on the data shown, it appears that south facing glaciers are receding more rapidly than north-facing. However, the size of the glacier appears to be the controlling factor affecting their response. Several authors (Granshaw, 2002; Kääb et al., 2001; Paul, 2002) have pointed out that despite aspect the most important correlation with the magnitude of glacier recession was the size of the glacier. Generally, smaller glacier retreated more than larger. To help analyze this trend, I divided the glaciers into four size classes. Based on this division the smaller glaciers decreased by more than the larger glaciers (Table 22, Figure 30). The average percentage decrease for glaciers less than 1 km^2 is the highest (39%), while glaciers greater than 5 km^2 the decrease is only 15%. My results match those found by Granshaw (2002), Kääb et al. (2001) and Paul (2002). In the Swiss Alps, glaciers smaller than < 1 km^2 represented 55% of the total area loss between 1973 and 1998 (1980).

Table 22: Average area and percentage decrease between 1913 and 1994 for Mt. Rainier glaciers grouped by size and orientation.

Glacier Size (km^2)	Northern Number of Glaciers	Northern Average Area (km^2)	Northern % Area Decrease	Southern Number of Glaciers	Southern Average Area (km^2)	Southern % Area Decrease	All Glaciers Number of Glaciers	All Glaciers % Area Decrease
<1	3	0.7	-31%	4	0.5	-45%	7	-39%
1 to 2.5	2	1.7	-9%	7	1.6	-36%	9	-30%
2.5 to 5	3	3.6	-30%	1	4.0	-12%	4	-26%
>5	3	8.9	-14%	3	7.0	-17%	6	-15%
Total/average	11	4.2	-18%	15	2.6	-26%	26	-22%

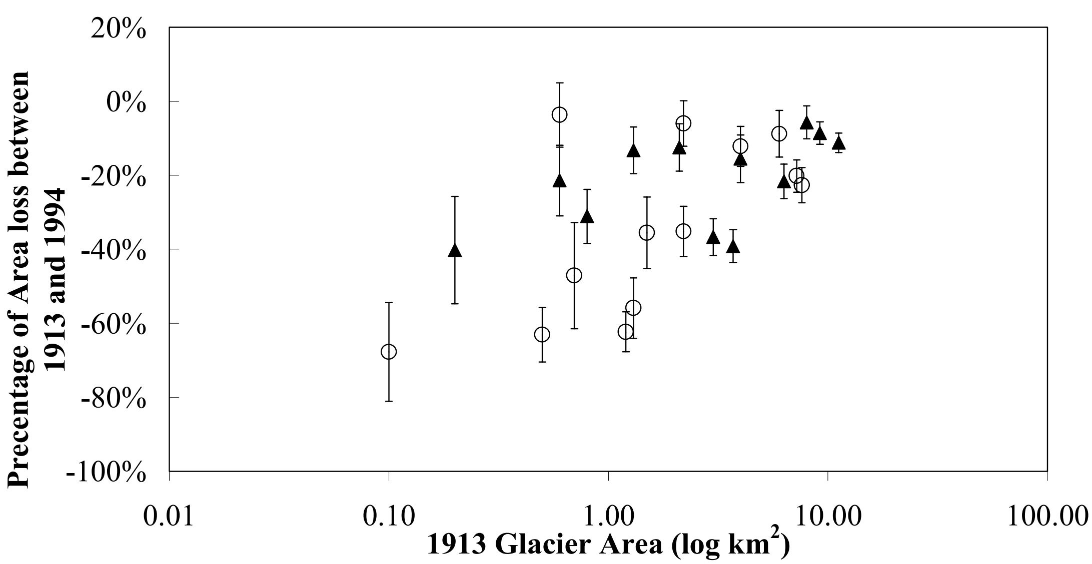

Figure 30: Comparison of glacier size of northern glaciers (triangles) and southern glaciers (circles) to percentage of area loss between 1913 and 1994 for all glaciers

Most of the glaciers greater than 6 km^2 extend up to or near the top of the mountain. These glaciers have a much larger area distributed across a wide elevation range (dashed lines in Figure 31). Changes in the ELA have smaller affect on the mass balance of these glaciers in comparison to others with smaller elevation ranges (solid lines in Figure 31). In some instances an increase in the ELA of only 200 m would shift the line above the altitudinal extent of a glacier. For the larger glaciers, a 200 m increase has a much smaller impact on the overall mass balance.

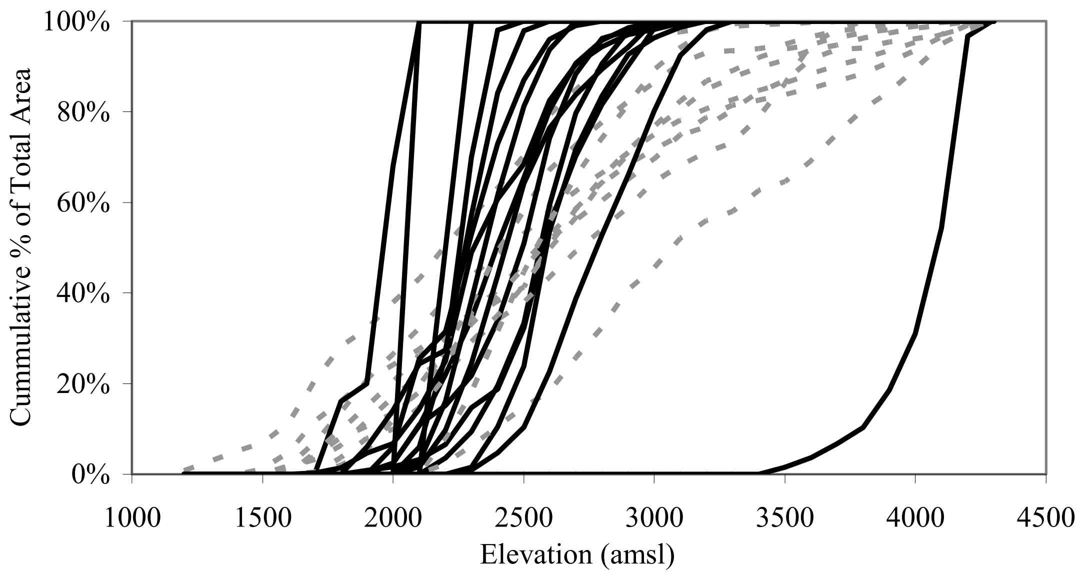

Figure 31: Cumulative area change between 1913 and 1994 and the approximate average location of ELA. Solid lines are glaciers with a small elevation range and dashed are glaciers with a large range (see Appendix E for data).

Comparison of the area change and glacial elevation range also highlights the sensitivity of the smaller glaciers to changes in the ELA (Figure 32). Most of the glaciers with greater than a 30% decrease in area have an elevation range of 1000 m or less. The only exception is Kautz Glacier, which is split by a rock headwall into two parts.

Not all the small glaciers decreased more than 30% of their total area between 1913 and 1994. Five glaciers, Edmunds, Flett, Liberty Cap, Success and Whitman, with elevation ranges of 1000 m or less decreased by less than 25% of their area. Four of these glaciers have the highest average elevations of the small glaciers in Figure 31. The exception is Flett Glacier, which is a small glacier on the north side of the mountain. Because of shading from local topography Flett Glacier receives less radiation than most of the other glaciers.

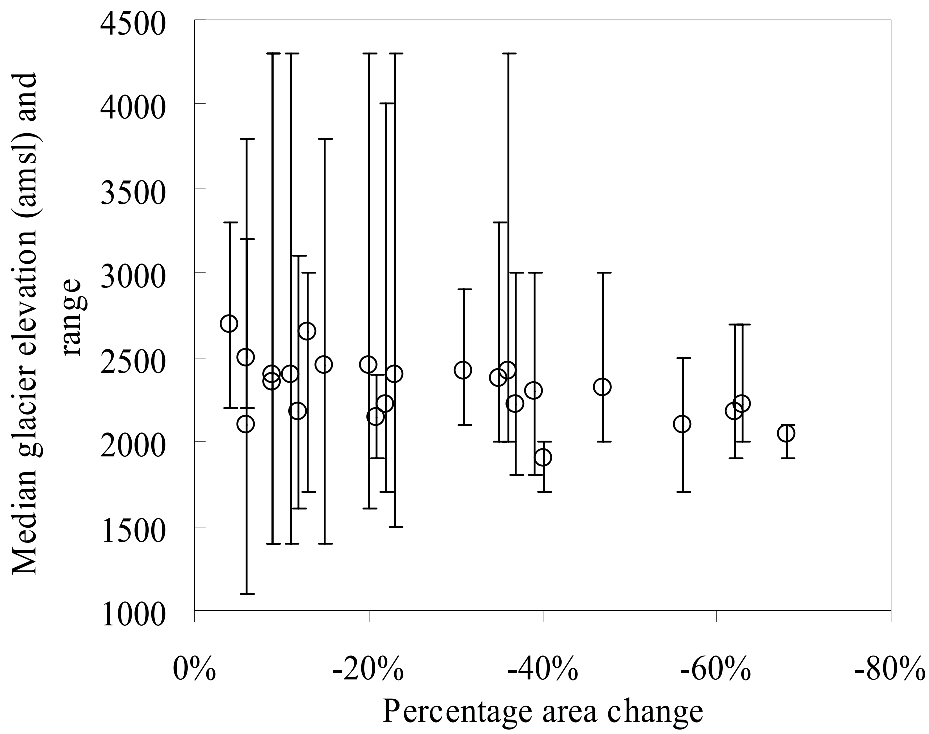

Figure 32: Medium elevation (circle) and range (bars) of the Mt. Rainier glaciers measured in 1994 versus percentage area change between 1913 and 1994.

It appears that smaller glaciers, especially those located at lower elevations are more sensitive to climate changes than larger glaciers. To note the errors associated with the smaller glaciers are larger because the uncertainty in the extent of the glaciers is large relative to the overall glacier area. The uncertainty was determined by creating a buffer 1/50th of an inch inward and outward from the glacier extent. The resulting uncertainty in area was plotted against the perimeter of each measured glacier, and the resulting factor was applied to the remaining glaciers. Even with the larger uncertainty, the smaller glaciers decreased by a higher percentage.

Spatial variations in snowfall might cause some of the observe differences between the different sides of the mountain. At Mount Rainier, the direction of storm tracks ranges from the south to the west (Ferber and Kramer, 1995). I would expect the southern and western glaciers to have more snow accumulation and positive mass balances in the winter. The lack of spatial variations in cloud cover, as determined from the AVHRR imagery suggests that the west and south aspects of the mountain receive more solar radiation increasing the ablation and compensating for the extra snowfall.

Variations in cloud cover also affect the energy balance at the surface. Clouds block incoming shortwave radiation, but also cause outgoing longwave radiation to be reflected back to the surface. The analysis of AVHRR images over a short time period does not show any significant spatial differences in cloud cover distribution around the mountain. The other aspect to consider is temporal variations in cloud cover.

Differences in cloud cover affect the diurnal temperature range because clouds block incoming radiation during the day and outgoing radiation at night (Tangborn, 1980). Without clouds, more insolation reaches the surface, thus increasing the daily maximum temperature. Conversely, at night more radiation is emitted back to space lowering minimum temperatures.

Differences in total incoming radiation exist between glaciers with southern and northern aspects. During the summer solstice period, the total incoming solar radiation does not vary spatially by much. Later in the summer, the differences in incident solar radiation increase significantly. For example, solar radiation averaged over the Winthrop and Kautz glaciers differs by 17.3 MJ/m^2 on September 21, as compared to 1.2 MJ/m^2 on June 21. During cloudier days absolute differences between the two sides are less. Thus during periods of decreased cloudiness there is much more energy available for melt on the southern than the northern glaciers during cloudy days.

To examine temporal variations in cloud cover I use a proxy, the differences between maximum and minimum temperatures. Tangborn (1980), using data from Stampede Pass, Washington (≈ 50 km northeast of Mt. Rainier), found a strong correlation (0.87) between the temperature difference of maximum and minimum temperature, and cloud cover. The linear relation between temperature difference and cloudiness at Mt. Rainier was determined from Tangborn's Figure 4. Average September temperature differences measured at the Paradise station decreased by

3.7˚C, from 18.4 to 14.7˚C, between 1963 and 1983 (Figure 33), suggesting a 45% increase in monthly mean cloud cover. Between 1983 and 1995 the September temperature range at Paradise increased to 5.0^{o}C, equivalent to a 69% decrease in the summer average cloud cover. Variations over these two periods coincide with growth of the glaciers during the first period and retreat during the second. The average growth for the largest 12 glaciers from the 50s to early 80s was similar on both sides of the mountain. Terminus changes are used here instead of area because there is more data coverage. From the early 80s on the southern glaciers retreated on average (-497m), which is considerable more than the northern glaciers (+16 m). This big difference during the final 10 years suggests that a decrease in cloudiness, especially late in the season might be a contributing factor to the observed spatial variations.

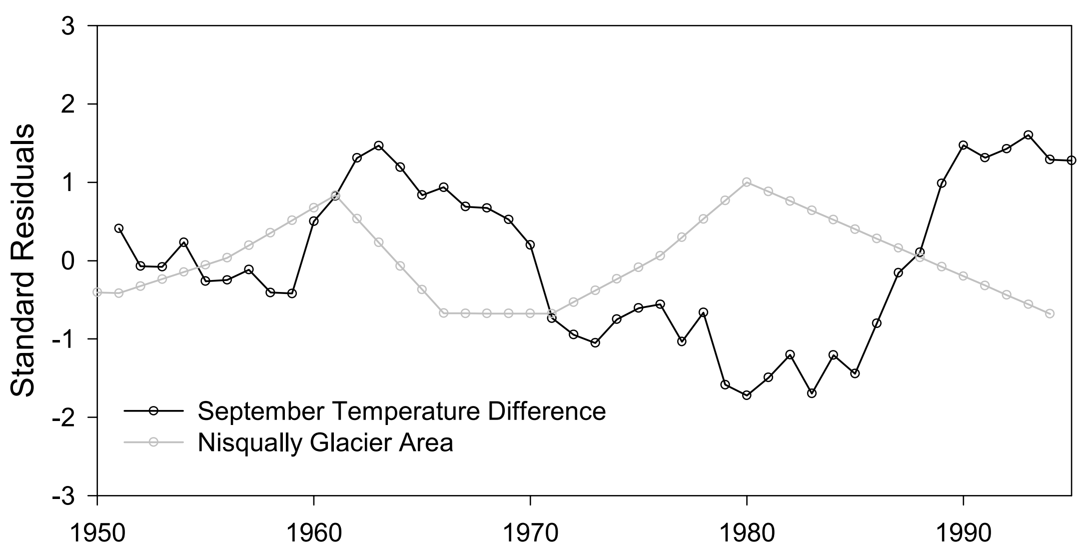

Figure 33: Comparison of standardized residual values for average September differences between maximum and minimum temperatures measured at the Paradise station and the area changes on Nisqually Glacier between 1954 and 1995.

The final factor to consider in assessing the cause of the spatial differences is debris cover. Debris over 2.5 cm thick causes a measurable reduction in ablation compared to clean ice and ice with debris cover less than 2.5 cm thick . The debris cover on Carbon Glacier is one of the reasons why it has the lowest terminus elevation in the US except Alaska. Most of the other Mt. Rainier glaciers have an extensive debris cover.

The debris cover on several glaciers has changed significantly since 1913 (Figure 13). Between 1913 and 1994, the debris cover doubled on Cowlitz and Nisqually glaciers. The ~15% debris cover increase on Cowlitz Glacier might explain its advance between 1971 and 1994, which occurred when most of the other glaciers were retreating. Additionally, the 13% increase in debris cover for the Nisqually Glacier between 1913 and 1994 might explain why it decreased less than the other southern glaciers. The only significant decrease in debris cover area occurred on N. Mowich Glacier. The debris cover decreased between 1913 and 1971 by over a half, from 1.5 to 0.6 km^2. Over that time period the glacier retreated 2000 m, the farthest of any of the northern glaciers. The best evidence of the effects of debris cover change is Emmons Glacier. The glacier debris cover increased threefold due to a rockfall that occurred in December 1963. The debris, which covered the lower half of the glacier, effectively reduced ablation. It caused the glacier to start rapidly advancing several years later and the glacier continued to advance up to the end of the study period.

Comparison of glacial area changes and debris cover suggests a negative relationship between the two (Figure 34), though the relationship is not statistically significant. Further analysis of aerial photographs is warranted to determine temporal and spatial variations in debris cover and if they are impacting the response of the glaciers.

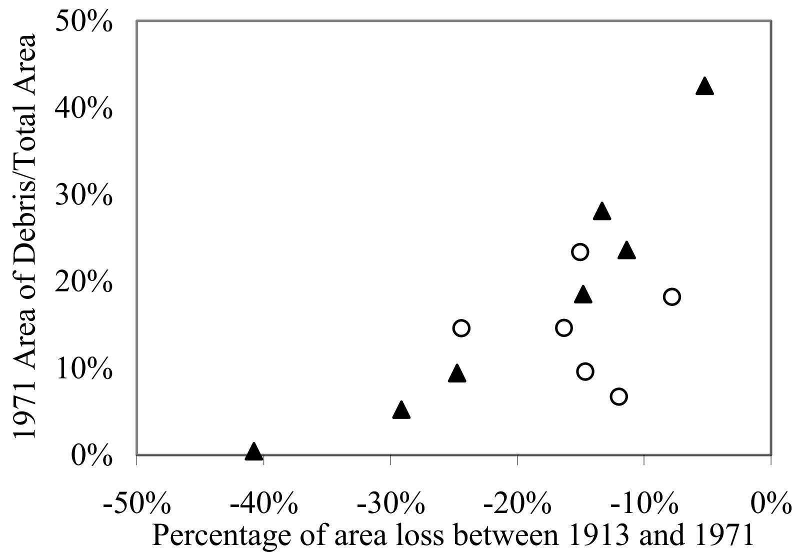

Figure 34: Debris area of northern glaciers (triangles) and southern glaciers (circles) as a percentage of total area in 1971 versus percentage area change between 1913 and 1994.

VII. Conclusions

The glaciers on Mt. Rainier have a fairly consistent response to changes in climate between 1913 and 1994. Since 1913, the glaciers on Mt. Rainier have decreased in area, volume and length. From 1913 to 1994 the total area and volume shrank by 21% and 25%, respectively at an average rate of 0.30 km^2 yr^{-1} and 0.02km^3 yr^{-1}. The average retreat of the 11 largest glaciers was 1,139 m, or on average 14 m yr^{-1}. South Tahoma Glacier incurred the largest retreat of 2,540 m, while Winthrop Glacier was the only glacier monitored to have advanced 187 m.

The retreat over this period was not continuous. Three distinct periods of changes on the mountain are observed between 1913 and 1994. Between the mid-50s and the mid-80s all of the 11 monitored glaciers were advancing. On average during this period the glaciers advanced 390 m. After the mid-80s most of the glaciers were retreating, except Emmons and Cowlitz glaciers, which might be caused by an increase in debris cover. The change from advance to retreat did not occur simultaneously, but over a period of about 10 years, and is probably due to differences in response time and in some cases paucity of data collected.

The temporal changes in area, volume and terminus position are driven mainly by variations in climate. The most important indexes for glacial mass balances are winter snowfall (accumulation) and summer temperatures (melt). Winter snowfall at the Paradise Station decreased by 5.1 cm yr^{-1} between 1954 and 1994. There are no significant trends in summer temperatures between 1954 and 1994 or 1913 and 1994.

Significant correlations exist between changes in snowfall (or precipitation) and terminus positions, when terminus data are shifted by 6 to 13 years after snowfall. The relationship between terminus and temperature changes is not as clear, which suggest summer temperature has a less direct effect on the response of the glaciers.

Most of the glaciers responded similarly to climate variation however significant spatial differences existed in the magnitude of the response. Southern glaciers decreased in area, volume and length more than the northern glaciers. The northern glaciers decreased in area by 17.5%, while the southern glaciers decreased by 26.5%. Glaciers larger than 5 km^2, regardless of location, decreased in area by 15% and glaciers smaller than 1 km^2 decreased by 29%. Since the southern glaciers are generally smaller (2.6 km^2) than the northern glaciers (4.2 km^2) it appears that the controlling factor on area decrease is glacier size and not aspect. Aspect is probably the reason the glaciers on the southern side of the mountain are on average smaller. This finding supports studies elsewhere. Smaller glaciers appear to be more sensitive to climate changes than larger glaciers because they have smaller elevation ranges.

Variations in cloud cover may also be an important factor in spatial variations. Changes in cloud cover over time cause differences in the energy balance between northern and southern glaciers. The difference in total daily solar radiation increases during periods with less cloud cover, and towards the end of the summer, when the solar incidence angle is lower. Cloud cover based on the diurnal temperature range in September, increased by 45% between 1963 and 1983 and decreased by 69% between

1983 and 1992. These time periods correlated with periods of glacier advance and retreat, respectively. With fewer clouds, there is relatively more energy available for melt on the southern glaciers. Debris cover is a non-climatic factor affecting glacial response to changes in climate. It appears that glaciers with more debris cover have had smaller area changes than those with less. Also though glacier that experienced a sudden increase in debris cover, due to a rockfall, experienced a reduction in ablation and consequentially advanced.

Overall, the results show that the glaciers on Mt. Rainier have a similar response time to climatic variations even though they have different characteristics such as size, slope, and orientation. Debris cover changes modified the response of some of the glaciers such as Emmons and Cowlitz glaciers. What is different is the magnitude of the response of the glaciers. Smaller glaciers have decreased by a greater percentage than the larger glaciers. Thus, using one glacier as a benchmark for an entire region might not give a good representation of the changes occurring across a spectrum of glacier sizes. Monitoring several glaciers of different sizes provides a better gauge of changes occurring in a region than just one glacier.

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Appendix A: Measured terminus position changes

Winthrop		South Mowich		Puyallup		North Mowich		Emmons		Carbon	
year	(m)	year	(m)	year	(m)	year	(m)	year	(m)	year	(m)
1913	0	1913	0	1913	0	1913	0	1913	0	1913	0
1958	-1009	1958	-543	1955	-411	1958	-2800	1928	-237	1932	80
1971	187	1960	-539	1959	-414	1960	-2709	1931	-1708	1933	76
1985	-388	1962	-534	1962	-405	1963	-2483	1932	-1714	1934	67
1994	187	1963	-454	1963	-400	1982	-1713	1933	-1724	1935	59
		1965	-437	1964	-376	1984	-1705	1934	-1764	1936	40
		1966	-419	1965	-365	1985	-1705	1935	-1773	1937	34
		1969	-415	1967	-340	1994	-1760	1936	-1803	1938	29
		1970	-412	1973	-318			1937	-1808	1939	21
		1975	-416	1974	-311			1938	-1841	1940	7
		1976	-394	1975	-304			1939	-1858	1941	-9
		1979	-382	1976	-298			1940	-1888	1942	-23
		1980	-402	1979	-244			1941	-1916	1943	-37
		1981	-407	1980	-228			1942	-1938	1944	-48
		1985	-376	1985	-211			1943	-1984	1945	-56
		1994	-461	1994	-338			1944	-2074	1946	-67
								1945	-2130	1947	-77
								1946	-2208	1948	-88
								1947	-2235	1949	-108
								1948	-2268	1951	-131
								1949	-2295	1953	-157
								1951	-2322	1954	-173
								1953	-2371	1956	-188
								1954	-2327	1957	-192
								1955	-2309	1958	-197
								1958	-2161	1959	-189
								1960	-2108	1960	-183
								1963	-2066	1961	-181
								1964	-2048	1962	-163
								1966	-1913	1963	-139
								1967	-1873	1964	-133
								1969	-1741	1965	-119
								1973	-1664	1966	-99
								1974	-1642	1967	-84
								1975	-1587	1970	-55
								1979	-1462	1971	-32
								1980	-1434	1973	-28
								1981	-1422	1974	1
								1982	-1397	1975	16
								1984	-1397	1976	33
								1986	-1380	1979	42
								1991	-1320	1980	49
								1994	-1173	1985	57
										1990	45
										1991	41
										1994	-13

Appendix A: cont.

Cowlitz		Kautz		Nisqually		South Tahome		Tahoma - W. Lobe		Tahoma - East Lobe	
year	(m)	year	(m)	year	(m)	year	(m)	year	(m)	year	(m)
1913	0	1913	0	1913	0	1913	0	1913	0	1913	0
1958	-1833	1962	-1500	1918	-137	1931	-750	1936	-158	1958	-1240
1962	-1844	1963	-1427	1919	-155	1932	-761	1958	-833	1959	-1226
1963	-1901	1964	-1382	1920	-169	1933	-765	1959	-599	1960	-1181
1964	-1797	1966	-1348	1921	-201	1934	-787	1960	-513	1962	-1175
1965	-1774	1970	-1337	1922	-222	1935	-800	1963	-429	1963	-1175
1966	-1676	1972	-1332	1923	-235	1936	-812	1964	-344	1964	-1208
1967	-1654	1973	-1328	1924	-260	1937	-816	1965	-462	1965	-1153
1969	-1639	1974	-1363	1925	-283	1938	-839	1966	-306	1966	-1146
1970	-1627	1979	-1251	1926	-309	1939	-859	1967	-287	1967	-1137
1972	-1622	1982	-1248	1927	-322	1940	-887	1973	-260	1969	-1109
1973	-1591	1984	-1248	1928	-349	1941	-961	1974	-231	1970	-1094
1974	-1551	1985	-1248	1929	-365	1942	-948	1976	-202	1974	-1048
1975	-1536	1994	-1927	1930	-401	1943	-942	1984	-156	1975	-1042
1976	-1513			1931	-416	1945	-977	1985	-156	1976	-1034
1979	-1504			1932	-431	1946	-1020	1990	-333	1977	-988
1980	-1479			1933	-445	1947	-1043	1994	-987	1980	-1006
1983	-1472			1934	-492	1948	-1049			1982	-1025
1986	-1452			1935	-508	1950	-1100			1985	-1025
1990	-1441			1936	-528	1952	-1124			1990	-999
1991	-1448			1937	-545	1958	-1824			1994	-1135
1994	-1360			1938	-572	1967	-1124				
				1939	-598	1976	-716				
				1940	-619	1984	-622				
				1941	-658	1985	-1453				
				1942	-675	1994	-2540				
				1943	-699						
				1944	-723						
				1945	-744						
				1946	-757						
				1947	-791						
				1948	-818						
				1949	-857						
				1950	-876						
				1951	-2036						
				1956	-1903						
				1961	-1752						
				1964	-1499						
				1965	-1447						
				1966	-1403						
				1967	-1378						
				1968	-1370						
				1969	-1380						
				1970	-1386						
				1971	-1397						
				1972	-1412						
				1973	-1434						
				1974	-1442						
				1975	-1438						
				1976	-1408						
				1978	-1317						
				1979	-1295						
				1981	-1307						
				1994	-1538						

Appendix B: Winter (October to April) Precipitation Totals

Year	Ohanapecosh cm	Longmire cm	Paradise cm	Carbon cm	White River cm
1908					
1909	94.7				
1910	103.7				
1911	100.5				
1912	99.8				
1913	99.3				
1914	43.2				
1915	132.8				
1916	93.9				
1917	181.9				
1918	120.1				
1919	89.5				
1920	165.6				
1921	74.7				
1922	118.1				
1923	107.3				
1924	120.7				
1925	89.0				
1926	96.5				
1927	96.2				
1928	61.0				
1929	56.8				
1930	64.8				
1931	105.2	123.4			
1932	100.3	130.1			
1933	129.1	176.0			
1934	95.7	107.5			
1935	94.1	108.9			
1936	63.1	95.7			
1937	95.7	90.9			
1938	117.3	105.4			
1939	113.4	103.2			
1940	49.0	44.8			
1941	73.7	74.1			
1942	98.2	97.3			
1943	75.7	74.3			
1944	93.0	99.2			
1945	119.8	116.7			
1946	111.1	111.1			
1947	109.7	99.4			
1948	119.2	102.6		77.4	
1949	143.8	144.3		115.4	
1950	102.6	124.4		98.7	
1951	82.8	74.1		57.3	
1952	144.2	122.8		94.8	
1953	150.2	139.1			

Appendix B: cont.

Year	Ohanapecosh cm	Longmire cm	Paradise cm	Carbon cm	White River cm
1954	89.4	104.2	111.2		
1955	151.0	131.9	192.8		
1956	114.3	109.8	160.6		
1957	47.7	99.5	143.2		
1958	117.8	112.9	157.8		
1959	81.0	85.9	136.2		
1960	92.8	120.2	192.7		
1961	68.0	89.3	132.7		
1962	56.8	78.6	120.0	51.8	
1963	119.4	113.3	151.2		
1964	126.6	126.0	171.6		
1965	100.5	84.9	130.2		
1966	130.7	128.9	177.3		118.4
1967	111.6	106.2	164.0		129.3
1968	114.9	93.2	123.5		97.1
1969	111.3	111.7	86.2		106.1
1970	155.6	153.8	198.2		141.7
1971	193.3	183.2	244.8	104.5	142.4
1972	73.4	35.5	124.6		74.2
1973	115.8	150.4	240.7		
1974	138.8	131.6	221.1		
1975	145.9	141.8	213.2		
1976	60.1	59.0	115.4		
1977	98.3	102.6	149.0		
1978	78.1	83.4	139.5		
1979	118.9	112.7	189.8		
1980	89.6	91.8	139.0		
1981	147.2	136.7	205.4		
1982	115.6	116.0	161.3		
1983	95.1	100.2	156.1		
1984	62.2	61.4	107.7		
1985	82.1	80.5	120.8		
1986	72.5	72.0	118.8		
1987	95.5	106.2	105.3		
1988	86.2	77.9	148.3		
1989	115.0	129.0	134.0		
1990	97.1	92.4	162.8		
1991	74.8	69.3	125.0		
1992	59.2	56.3	106.9		
1993	87.0	82.4	150.5		
1994	105.0	83.5	168.9		
1995	118.0	122.7	128.4		
1996	149.5	159.0	231.0		
Average	103.0	105.4	154.8	85.7	115.6

Appendix C: Winter (October to April) Snowfall Totals

Year	Ohanapecosh cm	Longmire cm	Paradise cm	Carbon cm	White River cm
1931		462			
1932		625			
1933		104			
1934		462			
1935		364			
1936		429			
1937		415			
1938		437			
1939		126			
1940		48			
1941		209			
1942		504			
1943		217			
1944		264			
1945		459			
1946		253			
1947		438			
1948	798	731		220	
1949	653	1041		184	
1950	344	594	1173	163	
1951	405	492		158	
1952	217	273			
1953	516	634			
1954		762	1483		
1955	599	852	1979		
1956	244	458	1163		
1957		231	1078		
1958	231	203	1180		
1959	209	302	918		
1960	183	255	1100		
1961	247	342	932		
1962	74	154	610		
1963	597	593	1266		
1964	588	545	1165		
1965	695	559	1185		

Appendix C: cont.

Year	Ohanapecosh cm	Longmire cm	Paradise cm	Carbon cm	White River cm
1966	356	450	1350		725
1967	215	229	875		535
1968	646	597	1530		908
1969	182	244	1186		385
1970	647	544	1986		1041
1971	804	634	1962	117	894
1972	182	82	913		258
1973	371	458	1656		
1974	445	508	1575		
1975	525	544	1412		
1976		225	768		
1977		154	868		
1978	285	357	1021		
1979	415	336	1199		
1980	83	104	659		
1981	401	422	1349		
1982	63	110	1080		
1983	139	146	954		
1984	459	410	1041		
1985	152	101	747		
1986	94	124	924		
1987	251	313	799		
1988	392	337	1229		
1989	452	482	1115		
1990	250	245	1041		
1991	28	48	727		
1992	324	208	784		
1993	189	259	1186		
1994	170	157	925		
1995	260	264	675		
1996	451	442	1666		
Average	352	369	1146	168	678

Appendix D: Summer (May to September) Temperature Totals

Year	Ohanapecosh (°C)	Longmire (°C)	Paradise (°C)	Carbon (°C)	White River (°C)
1914		13.6			
1915		14.0			
1916		13.2			
1917		13.6			
1918		15.0			
1919		13.8			
1920		13.8			
1921		12.9			
1922		15.2			
1923		14.8			
1924		13.9			
1925		14.0			
1926		13.8			
1927		13.8			
1928		14.4			
1929		13.8			
1930		14.1			
1931		14.0			
1932		12.9			
1933		14.1			
1934		15.0			
1935		14.2			
1936		14.3			
1937		15.5			
1938		14.4			
1939		15.2			
1940		14.0			
1941		14.7			
1942		13.7			
1943		15.0			
1944		15.3			
1945		14.3			
1946		14.0			
1947		13.8	9.6	11.3	
1948		14.6		11.3	
1949		14.8		10.9	
1950		15.5	10.5	14.0	
1951		15.4	9.1	12.2	
1952		14.1	7.2	11.1	
1953		12.8	7.5	12.4	
1954		13.3	9.2	12.7	
1955		14.4	7.2	7.3	
1956		14.6	8.5	14.0	

Appendix D: cont.

Year	Ohanapecosh cm	Longmire cm	Paradise cm	Carbon cm	White River cm
1957		16.5	11.5		
1958		14.0	9.2		
1959		14.7	10.7		
1960		16.1	11.6		
1961		14.5	9.8		
1962		14.5	9.8	13.6	
1963		12.9	8.3	12.5	
1964		15.0	9.8	13.7	
1965		14.2	9.7	13.5	
1966		17.1	12.9	9.0	15.9
1967		14.3	9.5	8.6	13.2
1968		14.5	9.3	10.7	13.9
1969		12.4	9.2	12.7	13.8
1970		12.3	9.3	12.3	12.7
1971		12.2	9.4	10.8	12.2
1972		13.1	9.1	11.4	12.4
1973		14.6	10.9		
1974		13.3	9.3		12.5
1975		12.3	8.5		
1976		14.1	9.1		
1977		12.6	9.1		
1978		14.4	9.8		
1979		12.8	6.9		
1980		13.9	9.3		
1981		14.1	9.5		
1982		12.5	7.8		
1983		13.2	8.1		
1984		14.1	9.6		
1985		13.4	10.2		
1986		15.1	10.8		
1987		14.2	9.8		
1988		14.3	9.7		
1989		15.2	9.9		
1990		14.6	10.0		
1991		14.9	10.2		
1992		13.4	7.8		
1993		14.7	8.6		
1994		14.3	9.9		
1995		14.4	10.4		
1996		14.4			
Average		14.1	9.4	11.7	13.3

Appendix E: Percentage area-altitude distribution per 100 meters of elevation on the 1994 Map of Mt. Rainier.

CONTOUR	Carbon	Russell	Winthrop	Flett	North Mowich	Emmons	Inter	Edmunds	Liberty Cap	South Mowich	Frying Pan	Sarvent
1200	2%											
1300	2%											
1400	2%											
1500	3%		2%			1%				0%		
1600	4%		2%			3%				2%		
1700	4%		3%		1%	3%				3%		
1800	3%		3%		2%	3%		2%		4%		7%
1900	4%	2%	4%		4%	3%		1%		3%	0%	27%
2000	5%	3%	4%	2%	8%	3%		1%		5%	7%	67%
2100	4%	12%	4%	14%	7%	3%		2%		6%	9%	
2200	6%	13%	5%	30%	8%	4%	7%	6%		4%	6%	
2300	8%	15%	5%	44%	9%	5%	12%	6%		3%	10%	
2400	8%	16%	5%	10%	9%	5%	13%	12%		2%	13%	
2500	10%	16%	4%		7%	5%	19%	13%		4%	16%	
2600	9%	10%	5%		6%	5%	21%	15%		5%	15%	
2700	7%	6%	4%		5%	6%	15%	18%		5%	11%	
2800	6%	6%	4%		6%	6%	11%	11%		5%	5%	
2900	4%	2%	5%		6%	6%	3%	9%		5%	4%	
3000	3%	0%	4%		5%	6%		5%		4%	2%	
3100	3%		4%		3%	5%				5%		
3200	2%		3%		2%	4%				5%		
3300	1%		3%		1%	4%				6%		
3400	1%		3%		1%	3%			2%	6%		
3500	1%		3%		2%	3%			3%	6%		
3600	0%		3%		2%	3%			2%	6%		
3700	0%		3%		2%	2%			6%	5%		
3800	0%		3%		1%	2%			9%	2%		
3900			3%		1%	2%			14%			
4000			3%		1%	2%			17%			
4100			3%			1%			27%			
4200			2%			1%			17%			
4300			1%						2%			
4400												

Appendix E: cont.

Elevation (m)	Tahoma	Puyallup	Cowlitz	Whitman	Nisqually	Kautz	Ohanapecosh	Cowlitz	S. Mowich	Success	Van Trump	Pyramid	Paradise	Williwakas
1200														
1300														
1400														
1500					1%									
1600			2%		1%									
1700	1%	1%	2%		1%									
1800	3%	3%	2%		2%		3%							
1900	2%	4%	3%		3%		4%							
2000	2%	6%	4%		3%		18%						12%	57%
2100	5%	8%	6%		2%	1%	9%		5%		4%	9%	7%	43%
2200	6%	15%	5%		4%	2%	10%		8%		16%	16%	18%	
2300	6%	15%	5%	5%	7%	4%	26%		13%	3%	10%	22%	26%	
2400	6%	13%	5%	12%	7%	3%	25%		12%	4%	18%	14%	19%	
2500	6%	9%	7%	17%	6%	2%	5%		10%	6%	12%	18%	10%	
2600	7%	8%	9%	18%	5%	6%			9%	8%	16%	14%	6%	
2700	6%	6%	8%	16%	5%	5%			7%	12%	7%	7%	1%	
2800	5%	4%	7%	11%	5%	6%			9%	14%	7%			
2900	4%	3%	6%	9%	5%	5%			7%	15%	7%			
3000	2%	2%	5%	6%	4%	6%			7%	18%	4%			
3100	3%	2%	5%	4%	5%	4%			6%	13%				
3200	4%		3%	2%	3%	3%			6%	5%				
3300	4%		4%		3%	3%			1%	2%				
3400	5%		3%		2%	4%		33%						
3500	5%		2%		2%	3%		67%						
3600	4%		1%		2%	6%								
3700	2%		2%		2%	6%								
3800	2%		2%		3%	5%								
3900	2%		1%		4%	3%								
4000	1%		1%		3%	6%								
4100	2%		1%		3%	5%								
4200	3%		1%		2%	6%								
4300	3%				2%	3%								
4400														