Glacier change, kinematic waves, and outburst floods at Nisqually Glacier, Mountain Rainier, Washington

Data Analysis and Review

By Jonathan Skloven-Gill and Andrew G. Fountain,
Department of Geology, Portland State University, Portland, OR

Introduction

Nisqually Glacier, on the southern flank of Washington's Mount Rainier, has a long history of research and observations dating back to the mid-19th century (Heliker et al 1984). The glacier has produced a number of outburst floods and has exhibited kinematic wave behavior leading to a surge-like advance at the terminus. The termination of a kinematic wave may lead to dead ice because the glacier is in an over-extended position. Nisqually has a well-documented period of dead ice in which the lower part of the glacier became stagnant. The National Park Service proposed that a relationship may exist between the presence of dead ice and the occurrence of outburst floods. Because of it's extensive history of observations Nisqually Glacier was selected for study. If the relationship between kinematic waves, dead ice, and outburst floods can be established, it provides a possible predictive tool for the occurrence of outburst floods and an aid for landscape management in the Park.

Observation History

This report utilizes three different sets of time series data: surveys of glacier elevation, records of glacial floods and debris flows, and positions of the glacial terminus. Variations in glacier elevation provide evidence of kinematic waves. The record of floods and debris flows are used together to infer the occurrence of outburst floods from the glacier. Finally, the position of the glacier terminus is used to mark the effect of kinematic waves and provide the overall advance/retreat history of the glacier.

Most of the data in the three sets came from the Mt. Rainier National Park Service, the United States Geological Survey, Tacoma, WA, and the University of Washington, Seattle. At Portland State University (PSU), the data were initially organized by Justin Ohlschlager in the winter of 2013 and spring of 2014. In addition, glacier area over time was compiled and updated from historic maps and aerial photos, based on Nylen (2005) (Appendix A). All data were rechecked and corrected for consistency in 2015 by Jonathan Skloven-Gill.

Methods and Results

Elevation surveys

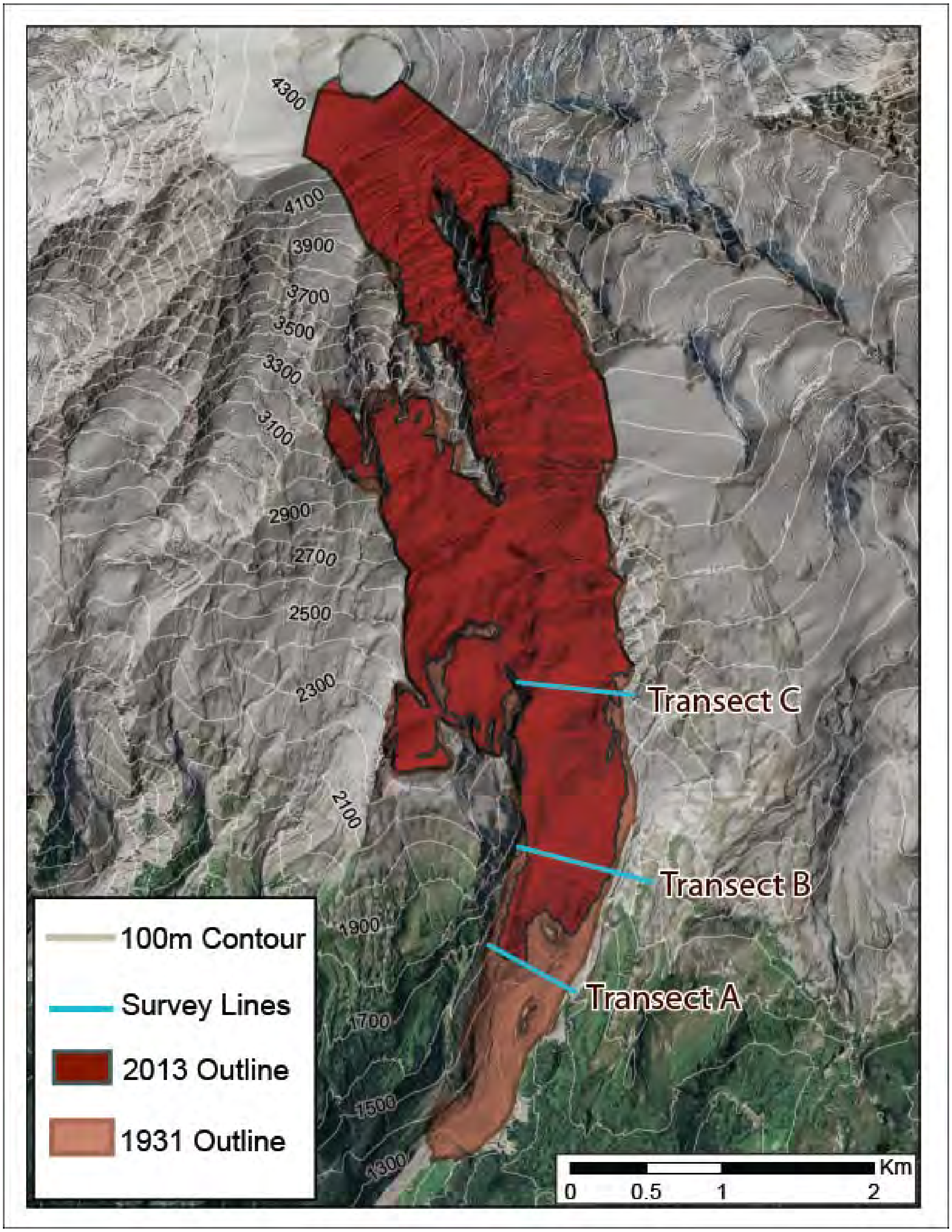

Figure 1: Plan view map of Nisqually Glacier including the 3 survey transect locations. 100m contours derived from 2011 LiDAR data.

Nisqually Glacier has been surveyed regularly since 1931 along three established transects (Figure 1). The lowest profile transect “A” at 1,717 m crosses the glacier perpendicular to its terminus along a north/northwest line. In 1998, the original benchmark, “Burp”, was lost requiring transect A to be moved to a new benchmark at 1,703 m, taking a more northerly direction across the glacier’s surface. As of 2013, this transect is nearly tangential to the active terminus (Figure 2). The middle transect “B” starts at 1,971 m and crosses the glacier at a more westerly line than “A”. The highest transect “C” is at 2,145 m and crosses the glacier at a near due west angle (Heliker et al 1984). The original purpose of the surveys was to monitor glacial “health” by measuring thickness change determined from changes in the average elevation of the ice surface. The observations from the early years, 1931 to 1979, were reported in detail by Heliker et al (1984). Survey data from 1980 to 2012 was provided to us by Dr. Ed Waddington, Department of Earth and Space Sciences, University of Washington. Data from 1980 to 2001 was processed by Carolyn Driedger at the Cascades Volcano Observatory (CVO), 2002 to 2012 from CAD documents created by the surveying company SCA out of Lacey, Washington by Dr. Waddington’s student Max Stevens. These data were compiled by Justin Ohlschlager into one database. The digital files are included in the associated digital folder “ElevationProfiles”. The yearly mean elevations for each transect showed notable variation during the 81 year period of observations (Figure 3).

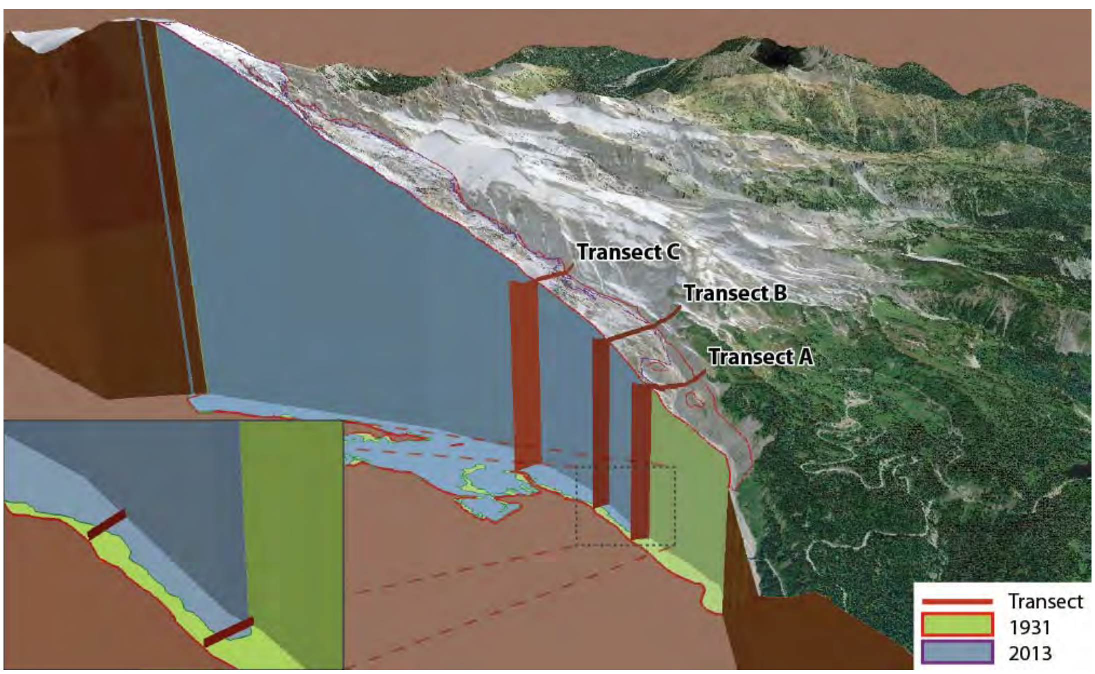

Figure 2: Side cut of Mount Rainier along the centerline of Nisqually Glacier, with survey transects. The zoom in shows detail of the 2013 terminus with respect to transect A.

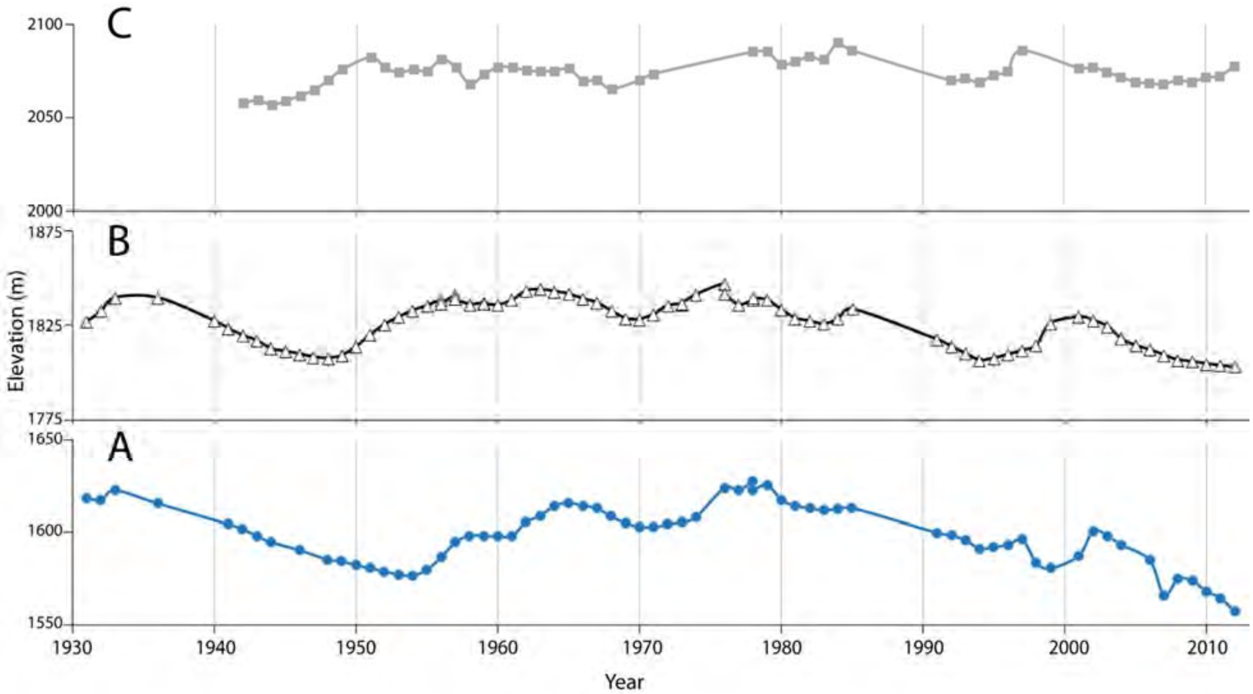

Figure 3: Temporal plot of average annual elevations at each survey transect. Note the deviation in transect A from the trend shown in both B and C beginning in the mid 2000's.

To better compare variations, the period average elevation of each transect was subtracted from the annual values of each (Figure 4). A wave can be seen peaking at transect C in 1952, then at transect B around 1957, and reaching transect A about 1965 with a speed of about 140 m per year. The entire glacier seemed to have thickened in the 1970s and again in the mid-1980s. A second wave may have started around 1998 at transect C.

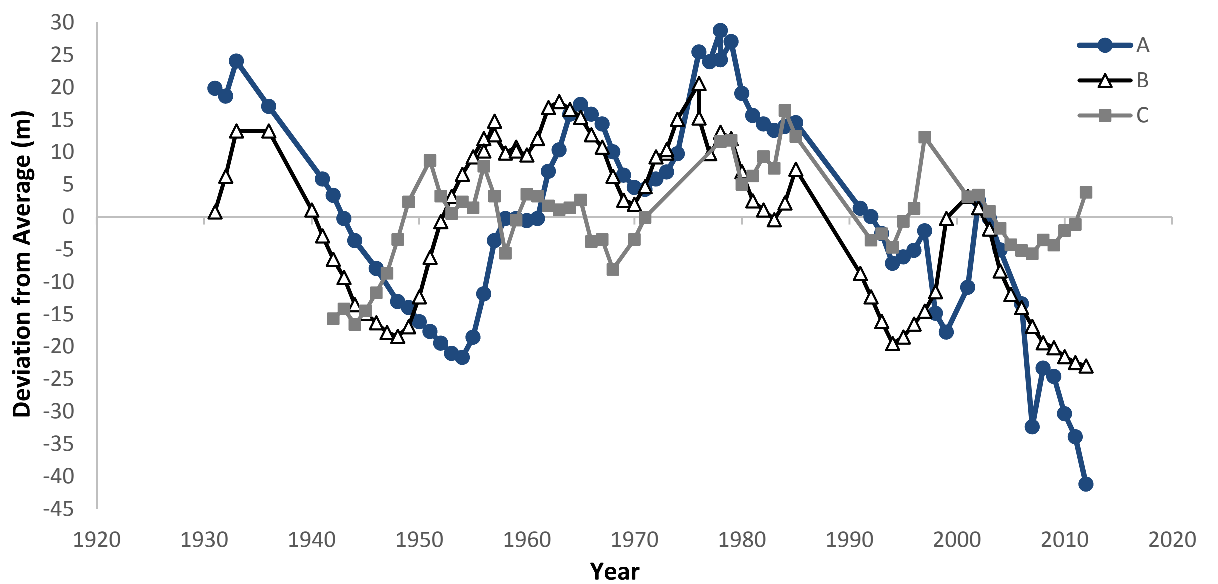

Figure 4: Chart temporally depicting each survey transect as a deviation from its 81 year average.

Glacier Outburst Floods and Debris Flows:

Data summarizing the flood and debris flow history was provided by Mr. Paul Kennard, Mount Rainier National Park in October of 2013. The file includes flood/flow observations in the various glacial basins (File: "MR_Debris Flow Archive"). This table was originally compiled by Nick Legg, then at Oregon State University. Data include the date, glacier, aspect, flood type, estimated peak discharge volume, damage, and preceding precipitation. The data notes suggest that the compilation is probably not comprehensive and likely is missing events if there was little to no geomorphic change or infrastructure damage. This past fall, 2014, Paul Kennard sent data for a 2012 flood on Nisqually River that was added to the compilation. Rain events did precede the majority of the floods depicted in Figure 5, but whether they triggered outburst flooding or were simply rain-induced flooding is unclear. We did not check the meteorological records to verify the notes in the 'MR Debris Flow Archive'. The flood and debris flow data for the Nisqually River below Nisqually Glacier includes 10 events between 1927 and 2012 (Figure 5).

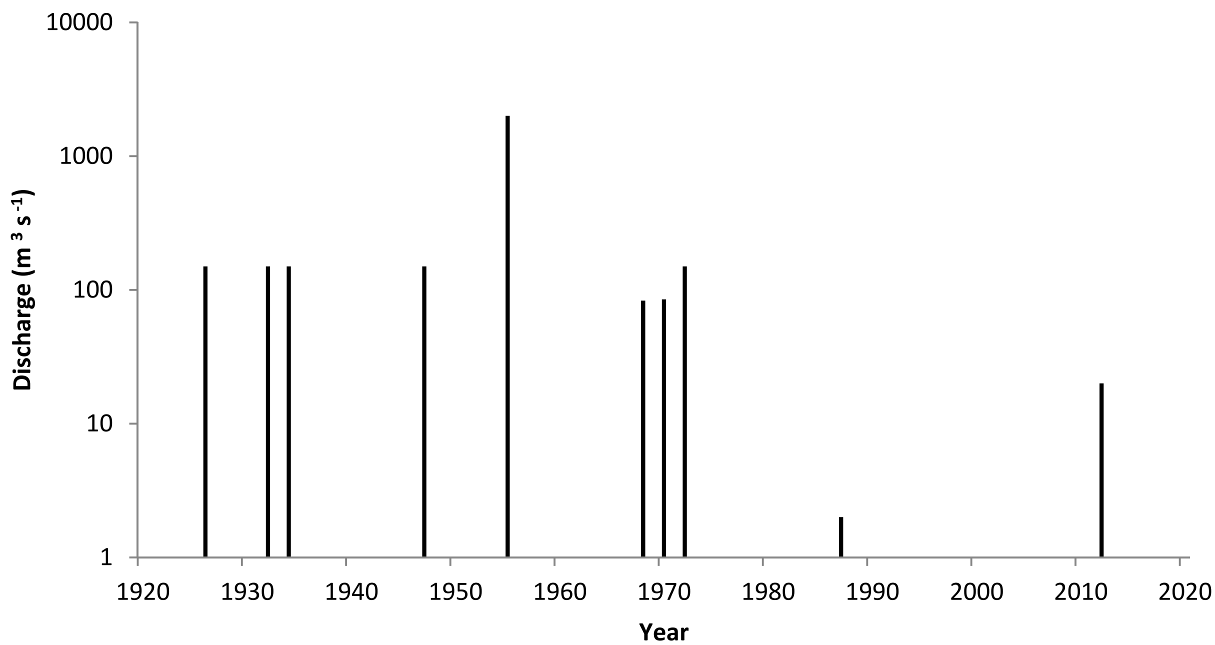

Figure 5: Bar chart of Nisqually River floods. Note that the discharge scale is geometric, not linear.

Terminus Measurement and Recession:

To track the area and length change of Nisqually Glacier we examined three datasets. The collection of measurements can be found within the file “Nisqually Terminus Graph Data”. The baseline dataset is Heliker et al (1984), summarizing terminus changes from 1840 to 1979. This dataset includes only relative change between observations from the previous year’s survey to the new terminus. Each year’s change in terminus position was recorded along the Nisqually River from the former highway bridge. Measurements were taken along the entire glacial front and then averaged to produce a single value. Beginning with the interval 1857-85, Heliker sequentially summed the interval data to produce a cumulative sum of change over time. Heliker noted that despite the recognition of dead ice at the terminus, the 1951 – 1963 surveys continued to be taken along “the stagnant ice front” of Nisqually Glacier.

The second dataset comes from the 1976 USGS Nisqually Glacier map with twenty-two terminus locations from 1840 through 1976. The original 1:10,000 scale map was scanned at high resolution and imported into ESRI ArcGIS. The map depicts the entire length of the glacier from the summit of Mount Rainier to the estimated 1840 terminus location reported by Sigafoos and Hendricks (1961). From this 1840 position, the relative measurements of the Heliker report could be fixed in space. This map also details both dead and active ice fronts during the period between 1951 and 1963 and was the only source to measure active ice terminus locations. To do so, terminus change was measured in a manner similar to the surveys from Heliker et al. (1984). Each year was measured as a change from the previous year’s location, as defined as the furthest downstream point of the terminus. The distance between each location was along a straight line, which was then added or subtracted to the baseline length from 1840.

The third dataset consists of a compilation of glacier outlines originally compiled by Thomas Nylen (2005) and updated by Ohlschlager and Skloven-Gill. This dataset spans one hundred years from 1913 to 2013 and consists of 20 different outlines for the intervening years. The outlines were compiled using high resolution USGS archival map scans and vertical aerial imagery collected from the University of Washington, the National Agriculture Imagery Program of the Department of Agriculture (NAIP), the USGS, the National Forest Service and Mount Rainier National Park. The oldest outlines are derived from USGS maps printed in 1947 and 1960 which were based on surveys from the 1910’s and 1930’s where old terminus positions were identified and the remaining glacial boundary extrapolated. From 1951 onward, outlines were either based on aerial imagery directly, or from the USGS maps derived from them. A detailed account of digitization methods and edit records can be found in the digital files:

“Ohlschlager-Terminus Data” and “Ohlschlager-Rainier Project Overview”. There are no specific outlines for either active or dead ice, only the full glacier extent which may include dead ice. Because dead ice is not replenished with ice emerging from the glacier interior, it adopts a weathered character with a highly porous surface. Dead ice occurs when the flow of ice from up glacier ceases (Schomacker, 2008). However, distinguishing between active and dead ice is not possible, at least on Mt. Rainier, using single frame vertical imagery because of the extensive debris cover over the lower portions of most if not all the glaciers. One would need sequential imagery to determine motion.

With the exception of the NAIP imagery and digital orthorectified quadrangle aerial photos (DOQ), the imagery and map scans did not contain any digital georeferencing data. To georeference the maps the map coordinates were used. For the aerial imagery, a minimum of 12 tie-points were identified between the image and the reference NAIP imagery or DOQ, both of which were acquired georeferenced. These methods not only place the images in the right geographic location, but also attempt to solve for rotational displacement and minor warping errors caused by photographic lens edges. This method is not a true orthorectification process, however, and falls short in the face of extreme topography, creating inconsistent image scale across the photograph (Figure 6). Ideally, each image would be georeferenced on tie-points within the glacier body or its former path instead of the surrounding topography and orthorectified with the aid of detailed elevation data. Unfortunately, there were few instances where this was possible. Many of the older black and white images were not of sufficient quality to find tie points in both NAIP and un-referenced imagery. In other cases, the ephemeral and ever transient nature of a braided river and an alpine glacier failed to produce temporally persistent features. These image flaws remained consistent within the shapefile dataset, and thus create little issue when internally analyzed as a set. Discrepancies can arise when compared to ground measurements or other true-orthorectified imagery.

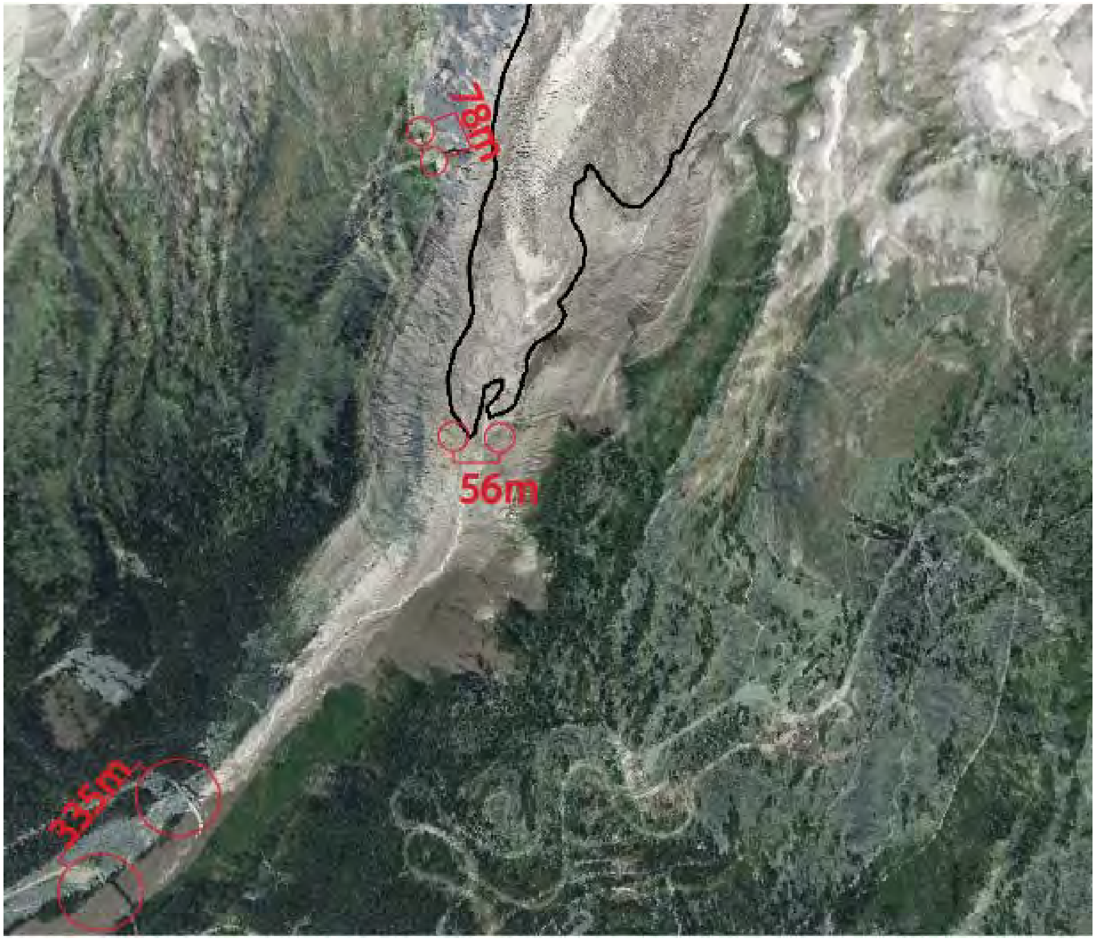

Figure 6: 2013 NAIP and 1951 aerial imagery overlay highlighting georeferencing concerns with regard to image scale inconsistency. These inconsistencies can lead to increased error when using these images to digitize glacier extent and length.

To determine Nisqually Glacier's length from the glacier outlines we need to define the terminus. Different methods yield different results and while not an issue for a single data set where methods were consistent, using different data sets that applied different methods can yield important discrepancies. We used three different methods. The first two methods start with the upper most point on the Nisqually head wall which is the same from map to map and follows the center line of the glacier towards the terminus. The first method measures to the furthest point away from the head wall down the centerline of the glacier (Red line in Figure 7A and B). The second method also starts at the headwall, but follows the topographic center of the glacier and terminates where the glacial stream exits the glacier. For the terminus region, this second method was an attempt to replicate the average terminus measurements reported by Heliker et al (1984), in that the stream exit was rarely at the furthest extent of the glacier (Figure 7A, B). The third method measured the distance up/down-valley from the previous terminus position as depicted by the outlines using the 1840 terminus position on the 1976

USGS map as the starting point. For example, distance measured from the 1913 terminus position to the 1931 position, then from the 1931 to the 1936 position, and so on. Like in method 2, we defined the terminus point where the glacial stream exits the glacier. The path between points was a straight line.

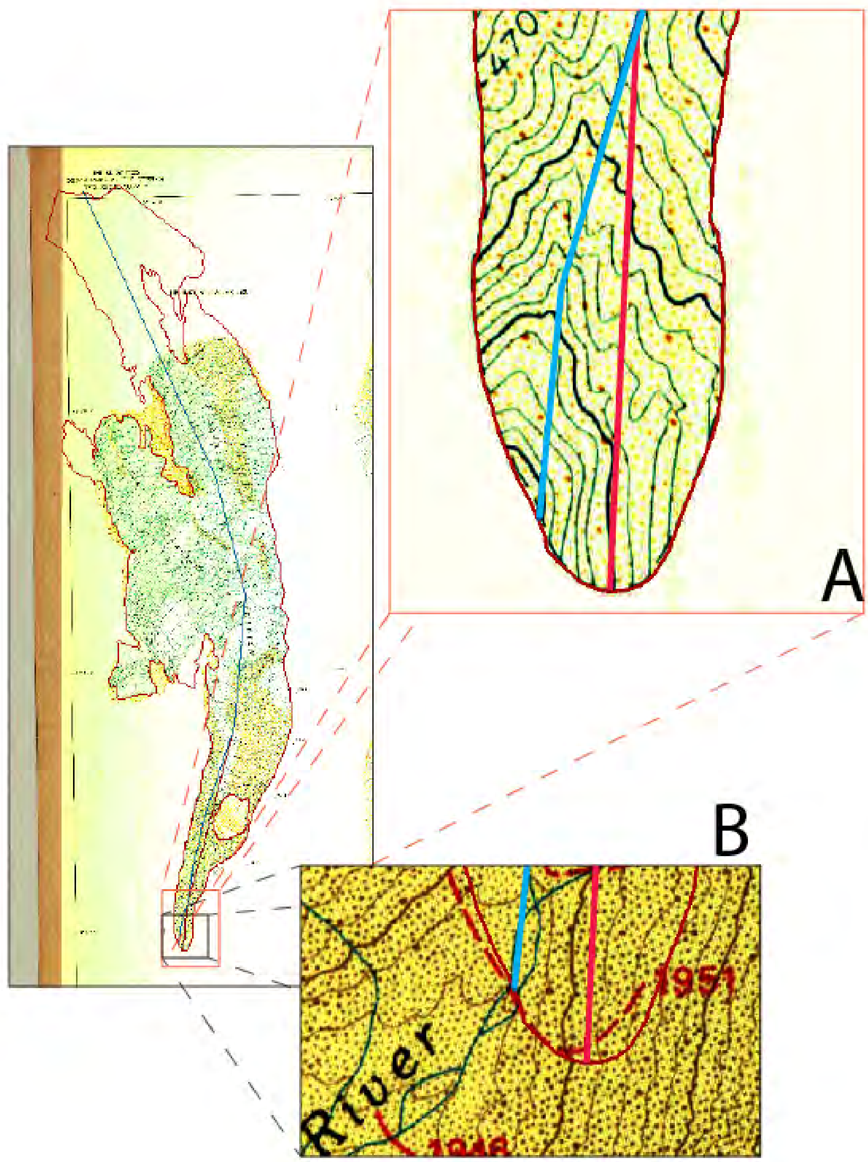

Figure 7: Example of variations in glacier outline measurements. Source: 1951 USGS map. A) Zoom of terminus shape on digitizated source map. B) Zoom of terminus shape on 1976 USGS map depicting Nisqually River intersection with the glacier outline. The red line indicates the measurement taken from the furthest down-glacier point on Nisqually Glacier from the headwall. The blue line indicates the measurement taken where the Nisqually River appears from under the glacier.

Glacier Length

The results of the three methods including matching data from Heliker et al. (1984) report are summarized in Figure 8. Each method of tracking terminus change from glacier outlines exhibited the same temporal pattern as the terminus measurements from Heliker et al. (1984). However, differences between datasets as large as 80 m for any given year, and when compared to Heliker et al. (1984) differed as much as 200 m. The source of these differences can be traced back to two issues in the digitization and surveying methods. First, the subjectivity in defining the terminus as described earlier. It can be defined as the outflow point of the glacial stream, the furthest plan-view point from the glacier's headwall, the point of lowest elevation along contiguous ice, or as in the case of Heliker et al. (1948), an average across the terminus. In this last case, years where the sides of the glacier receded significantly more than the center, Heliker's average recession would be greater than glacier outline measurements, and vice versa. The other issue, georeferenced vs. orthorectifified aerial photography, can create scalar inconsistancies in mountainous geography.

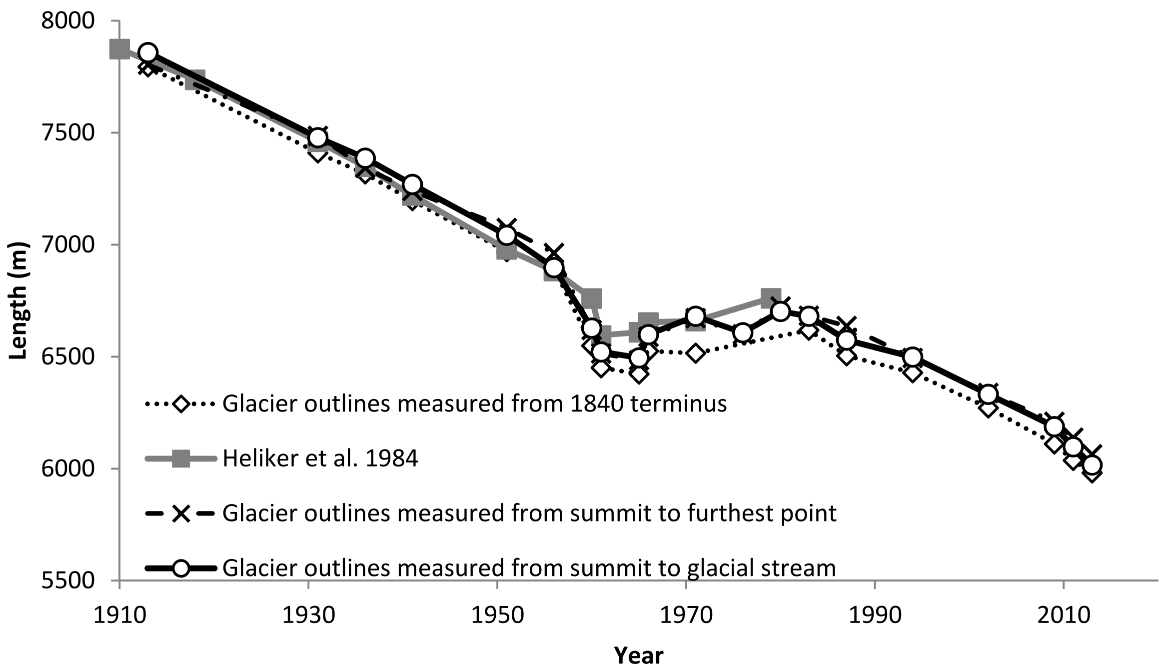

Figure 8: Chart depicting the three methods used to measure Nisqually Glacier's outlines along with the field measurements from Heliker et al. (1984) as reference.

To reconcile the data into a single terminus record that spans the entire period of observation, we included the Heliker et al. (1984) record for the early years with the record of length based on where the glacier outline intersects the stream (method 2). The method was chosen because it follows the topographic center line of Nisqually Glacier thus the flow direction of the ice; and uses the middle location of the terminus front better mimicking Heliker et al. (1984)'s field survey averages compared to the other measurements. The two datasets were merged by using the unchanged data from Heliker et al. (1984) that predate the glacier outline data and the outline data where it extended beyond the Heliker data (from 1980 onward). For the overlapping period, the data for years that matched were averaged, while the remaining data points were discarded (Figure 9).

The merged data show a steady recession of Nisqually Glacier from its 1840 position to the early 1950's with accelerated recession in the mid to late 1950's. From the mid 1960's to early the 1980's a period of equilibrium was achieved, followed by a small advance. Since then, the recession rate was similar to that prior to 1950. Beginning in 2010, the rate of recession increased similarly to that of the mid 1950's. In total, since 1840 Nisqually Glacier has receded nearly 1/3rd of its length, slightly over 2.6 km.

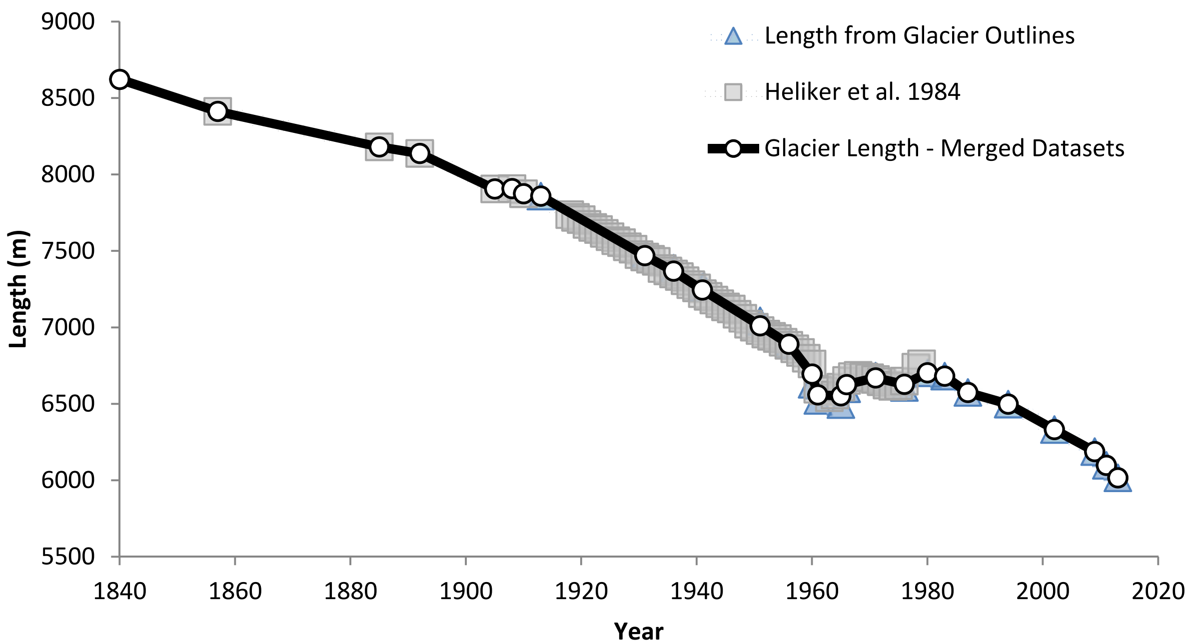

Figure 9: Chart of merged data for Nisqually Glacier's total length (1840 to 2013)

A question persists regarding the length of the glacier: is the dead ice to be included? Up until now the time series of terminus position (Figure 9) is inclusive of all ice whether the its active or dead. A 1953 'Glacier Studies: Mt Rainier National Park' report (NPS, 1953), a question was posed as to what defines the terminus of the glacier. Is it at the end of the dead ice or active ice? Which one is more valuable to track? The report notes that since 1952, there had been no change in the conditions of the terminus ice, and that it had simply receded by melt with no signs of ice flow from above. The report makes a comment regarding a new survey location, "D and D^1", at what was believed to be the active terminus, but no measurements were included locating its position, nor were there measurements to estimate the distance from the dead terminus to the active ice. That being said, the only source cataloging the surveyed location of the active and dead ice fronts is the 1976 USGS map and it includes them for only 1951 and 1956. The NPS reports of 1952 – 1960 discuss dead ice as unchanged material conditions at the terminus, but include no measurements for the active front. Beginning in 1961, NPS reports no longer made measurements from the dead ice as it had "practically disappeared". If we presume all ice afterwards is active, and all notations of the 1976 USGS map reflect that, then resulting length measurements produce a much different impression of glacier change with time (Figure 10). During the period in which active ice was identified, the difference between the limit of the active ice and the full extent of the glacier including the dead ice reaches a maximum of about 1,416 m. This is 39 m more than the total recession from the preceding century (1,377 m; 1840 – 1941). Although the existence of the dead ice in 1951 is first documented in a 1953 report (NPS, 1953), Veatch (1969) pointed out the dead ice in a 1951 ground-based photograph (Figure 11). We are unclear on the timing when the ice was no longer active and how much of the lower glacier was dead ice. The 1953 report conjectures that the terminus may have become dead following the severe storm and floods of 1947.

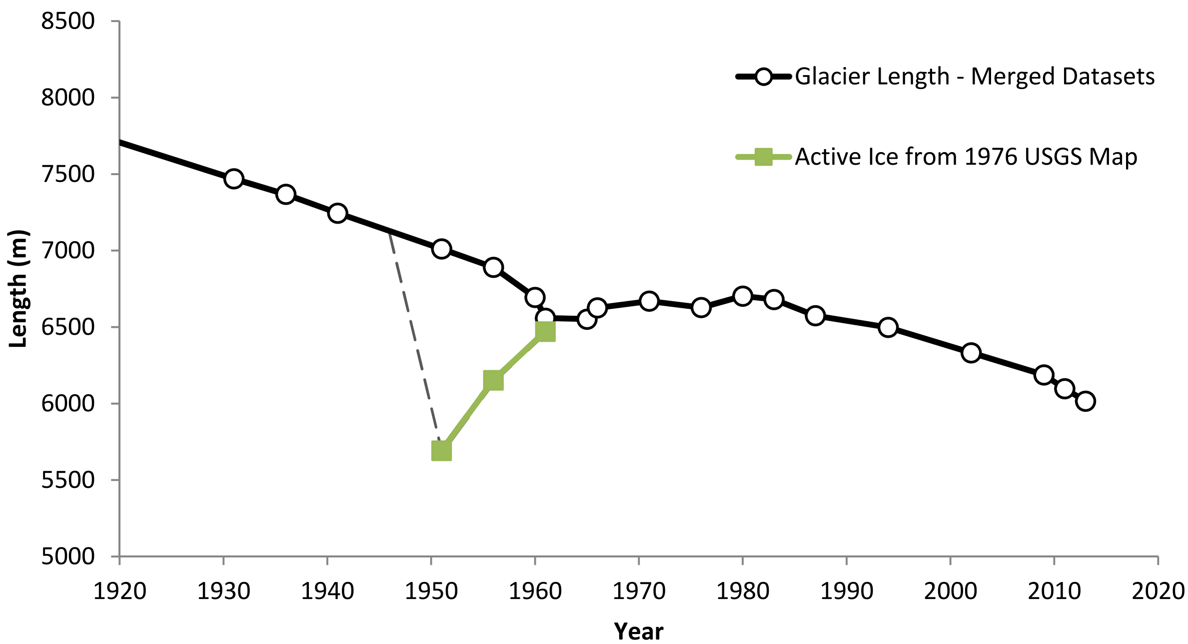

Figure 10: Chart of Nisqually Glacier's length change (1920 to 2013). Data indicating active ice from the 1976 USGS map are highlighted in green.

The issue of including or excluding dead ice can be an important issue in understanding glacier behavior as Figure 10 shows. The 'active' Nisqually Glacier receded nearly 1.4 km due to the development of dead ice at the terminus. This represents the largest and fastest retreat during the period of record. The glacier re-advanced even more rapidly as the active terminus overrode the dead ice by 1964 (Heliker et al., 1984; Nylen, 2005; Veatch, 1969) (Figure 11). It then advanced from the early 1960's through to about 1980. It is not clear from the information we have whether the presence/absence of dead ice was recognized in earlier years. Therefore, the length changes of active ice on Nisqually may be incomplete. Given the spotty record of observing active and dead ice, and given our inability to detect dead ice in our imagery, we consider only the full (active and dead ice) glacier change as representing the glacier change (Figure 9). This is consistent with studies of glacier change elsewhere that do not differentiate between active and dead ice.

Figure 11: 1950 ground photograph of Nisqually Glacier's lower region (left) and 1965 ground photograph of Nisqually Glacier's lower region (right) depicting the active ice front overriding the dead ice of the 1950's period. Photography from USGS records (Veatch, 1969)

Analysis

Kinematic Waves and Glacier Length

To examine whether a relationship exists between kinematic wave activity, glacier length, and the presence of dead ice, the relevant data sets are plotted together (Figure 12). Here, the changes in surface elevation of transect A is plotted alone for clarity recognizing that the most obvious kinematic wave arrived in the mid 1960's (Figures 4, 12B). The time period of known dead ice, roughly 1945-1960, corresponds to a period of decreasing elevation at transect A as the ice melted away without replenishment from above (mid to late period A in Figure 12).

During this period, transect A was about 900 m from the terminus. The dead ice appears to develop prior to the arrival of the kinematic wave, as the wave peak does not arrive until the mid-1960's. Alternatively, the dead ice formed after the arrival of a prior wave, before measurements began. The increasing elevation at transect A may be associated with the dead ice being overridden by the active ice, which peaks in 1964 (Heliker et al, 1984; Nylen, 2004; Veatch, 1969). This is consistent with the notion of a glacier advance as the wave reaches the terminus of active ice (Nye, 1963; Palmer, 1972).

Unfortunately, there is insufficient detail to understand the evolution of the slowing of ice near the terminus and its relationship to dead ice. The well-described kinematic wave of the 1960's (Johnson, 1968; Veatch, 1969) may be associated with or obscured by a general thickening and advance of the whole glacier from the middle 1960s to the mid-1980s (Figures 4, 12).

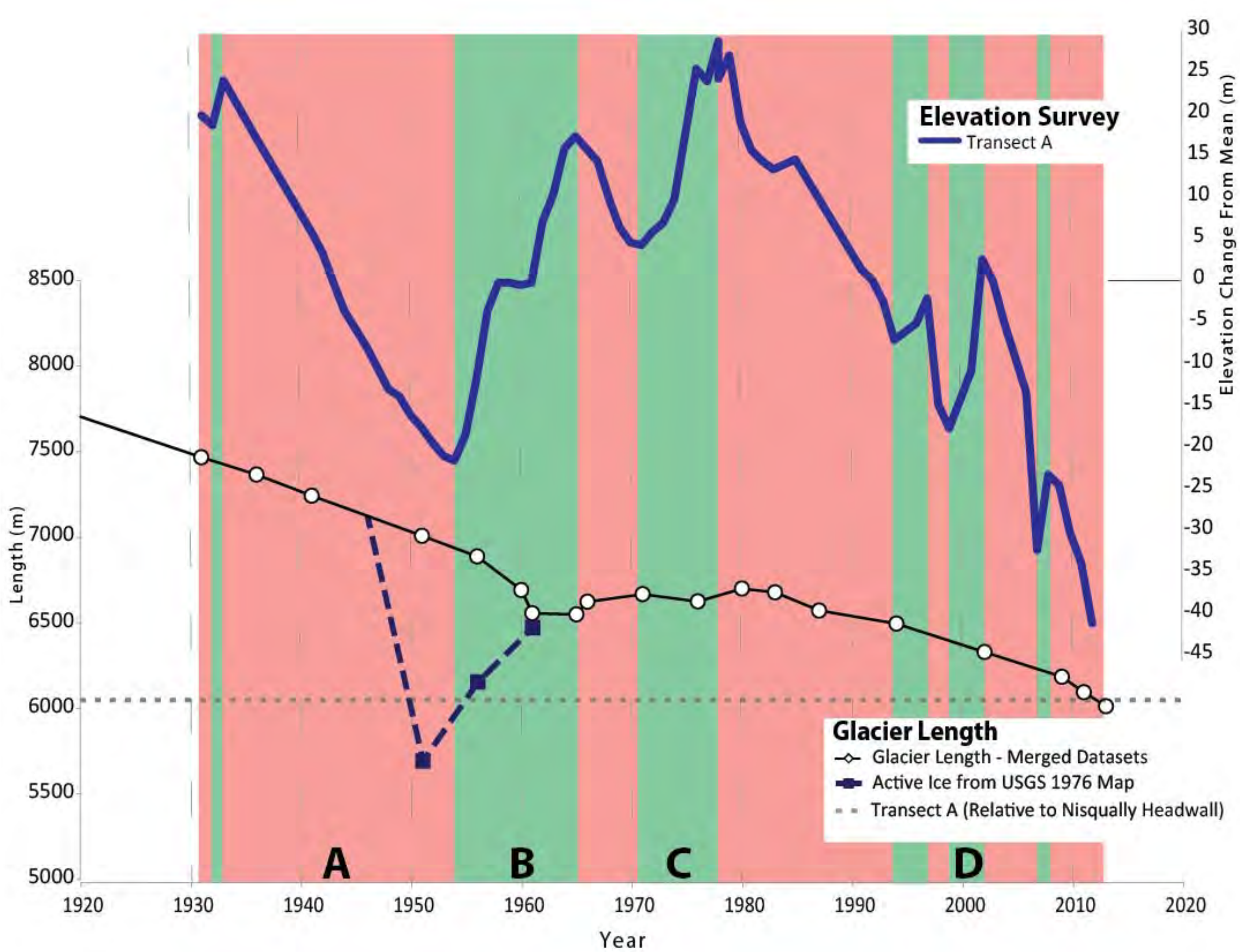

Figure 12: Glacier elevations of Transect A and Nisqually Glacier length. Red indicates periods of thinning (green; thickening) at transect A. Dotted line near 6000 m is the distance down valley to Transect A.

The 1960s-1970s is a difficult period of time to interpret kinematic wave behavior because the glacier is far from equilibrium. The glacier has been in overall recession in the first half of the 20th Century. The 1960s and 1970s is a period of overall glacier stasis or growth in the Pacific and can be seen by the elevation increases on all transects in the late 1970s (Figure 4 and 12C). Effects of the kinematic wave are superimposed on these climatic variations both with similar time scales. No further kinematic waves are observed except for one perhaps in the early 2000's (Figure 4 and 12D). It is important to note that the elevation of transect A has precipitously decreased since the early 2000s, reflecting the thinning and retreat of the glacier (Figure 13). By the mid 1990's the glacier had narrowed severely at transect A leaving only a small tongue of ice intersecting the transect. By 2013, nearly the entire glacier has retreated above transect A (Figure 14). The proximity of the terminus, as well as its narrowing width, clearly indicate that transect A will lose its utility in the near future if it hasn't already.

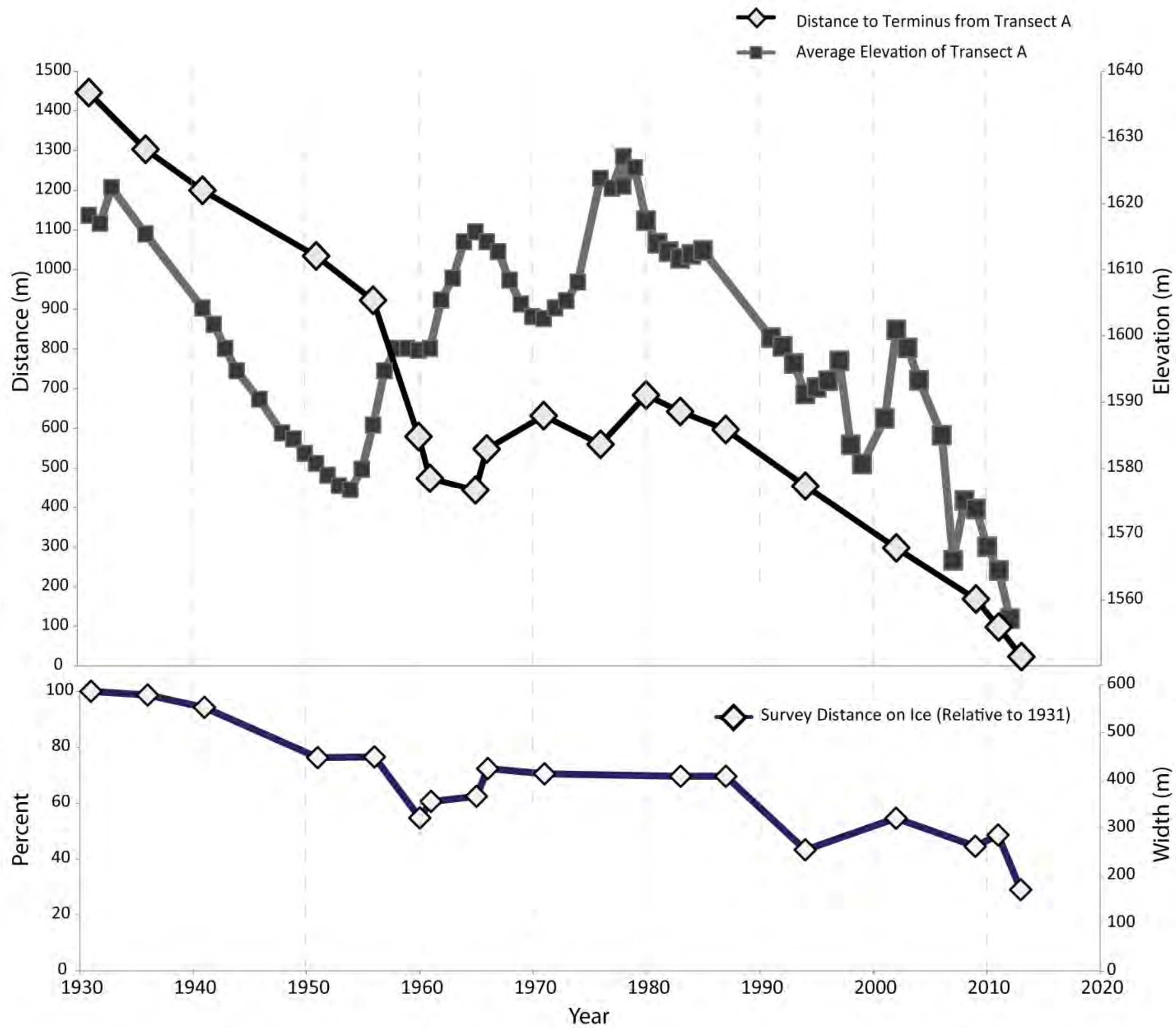

Figure 13: The terminus region of Nisqually Glacier relative to survey transect A. Top panel distance is the distance to the terminus from Transect A. The bottom panel is the width of the glacier at Transect A also with percentage fraction based on the 1931 width.

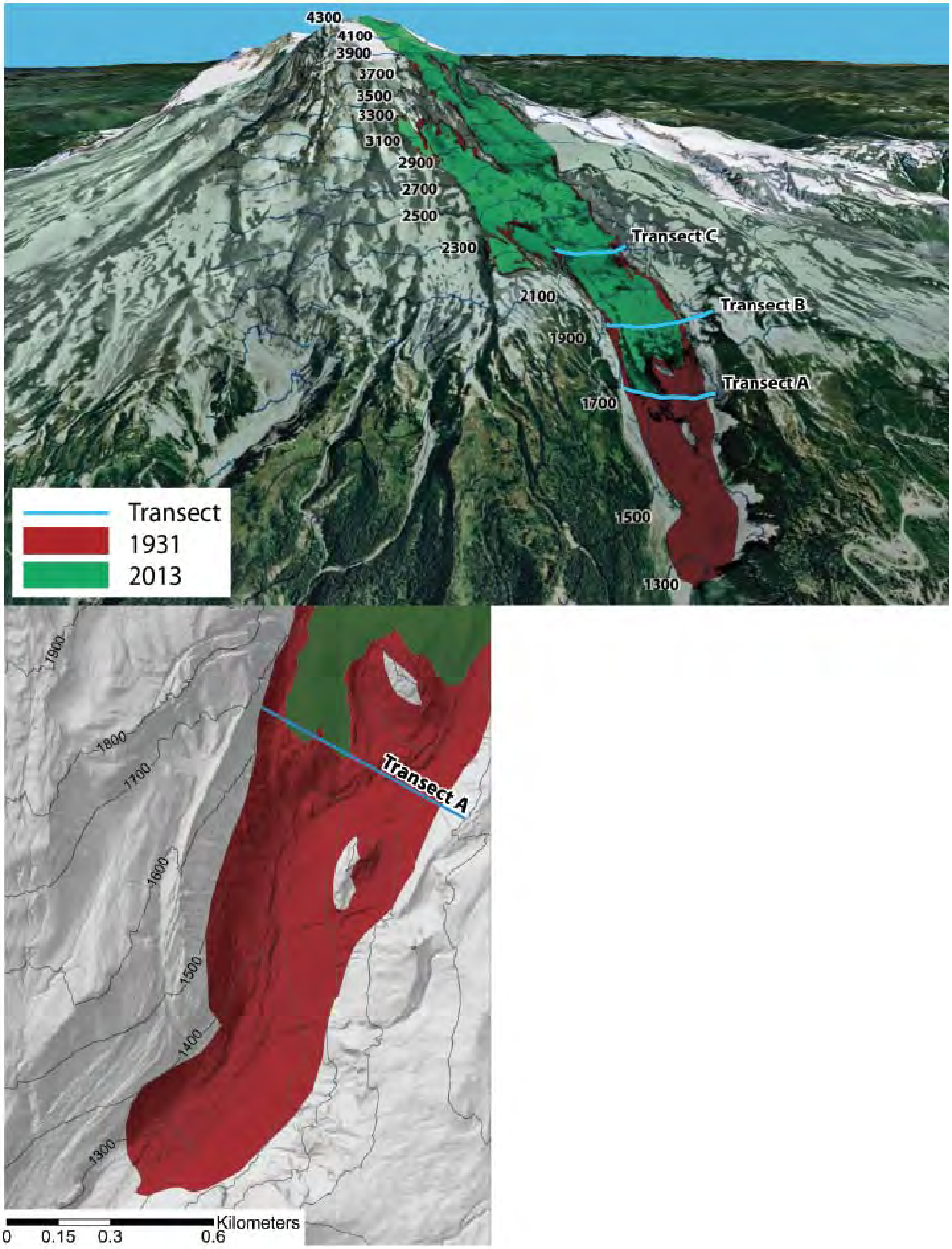

Figure 14: Aerial 3D and plan view of 1931 and 2013 glacier outlines with survey transect locations. Contours derived from 2011 LiDAR

Floods vs. Glacier Activity

To test the hypothesis that outburst floods occur during periods of dead ice at the terminus, we should find more frequent flooding during such a period. Comparing the time series of glacial length, elevation of transect A, and outburst floods we see no obvious correlations (Figure 15). The only documented period of dead ice is ~1950-1960 and during this period two flood events, one in 1947 and the other in 1955. The latter flood had an extraordinarily high volume (2000 $m^3 s^{-1}$), but was also preceded by a 32 hour storm that dropped 96 mm of rain. Floods do seem to correlate with thin periods of the glacier. Six of the ten floods are associated with times where the glacier was thinner. Perhaps with less overburden pressure, flood frequency increases. This is certainly an over simplification of a series of linked processes that would allow a glacier to impound and rapidly release water. The empirical relationship between dead ice formation and kinematic waves is not clear at Nisqually. The dead ice period precedes the kinematic wave of the 1960s when the ice overrode the dead ice. One may expect intuitively that dead ice forms after the passage of a kinematic wave when the glacier is in an abnormally extended position, compared to its equilibrium state (Schomacker, 2008). At Nisqually, however, there is no documented evidence of dead ice after the passage of the wave, and there is no evidence that the dead ice observed formed after a prior kinematic wave. Could the dead ice have formed prior to the arrival of the kinematic wave? The records are not clear on this issue.

At best this association is speculative. The best time series available are total glacier length and elevation, only sketchy information describing dead ice and its duration, and probably a very incomplete history of outburst floods. We cannot distinguish between rain floods and outburst floods, and most likely numerous floods were missed. Detection of floods is random and depends on accidental observers who take the time to recognize and report the observation. To provide definitive empirical information on the hypothetical association between the presence of dead ice and outburst floods, a dedicated program of measurements is required. One interesting outcome was the development of dead ice prior to a kinematic wave rather than after the wave, which is counter intuitive.

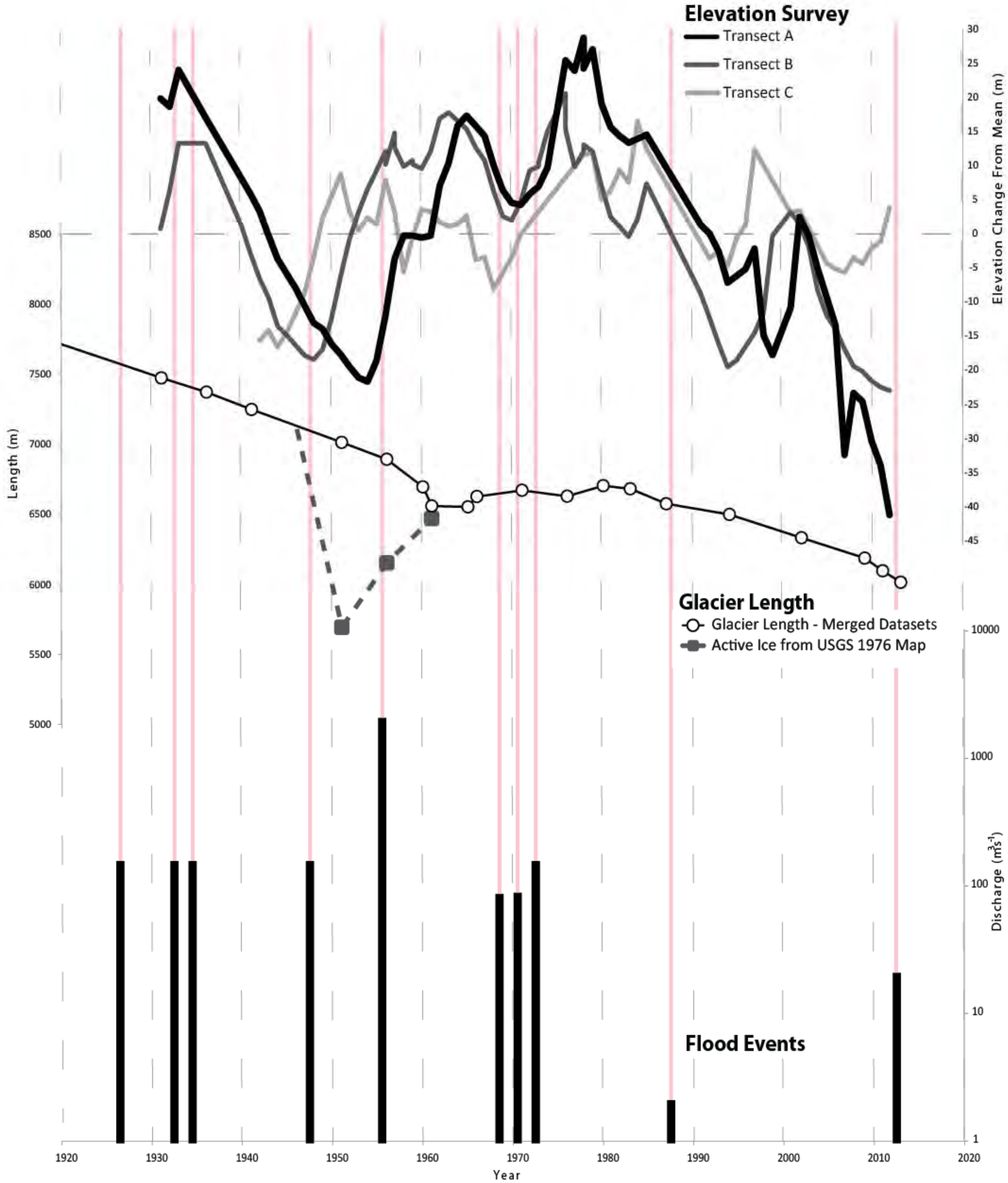

Figure 15: Combined graphs of surveyed elevations, measured lengths and flood events for Nisqually Glacier

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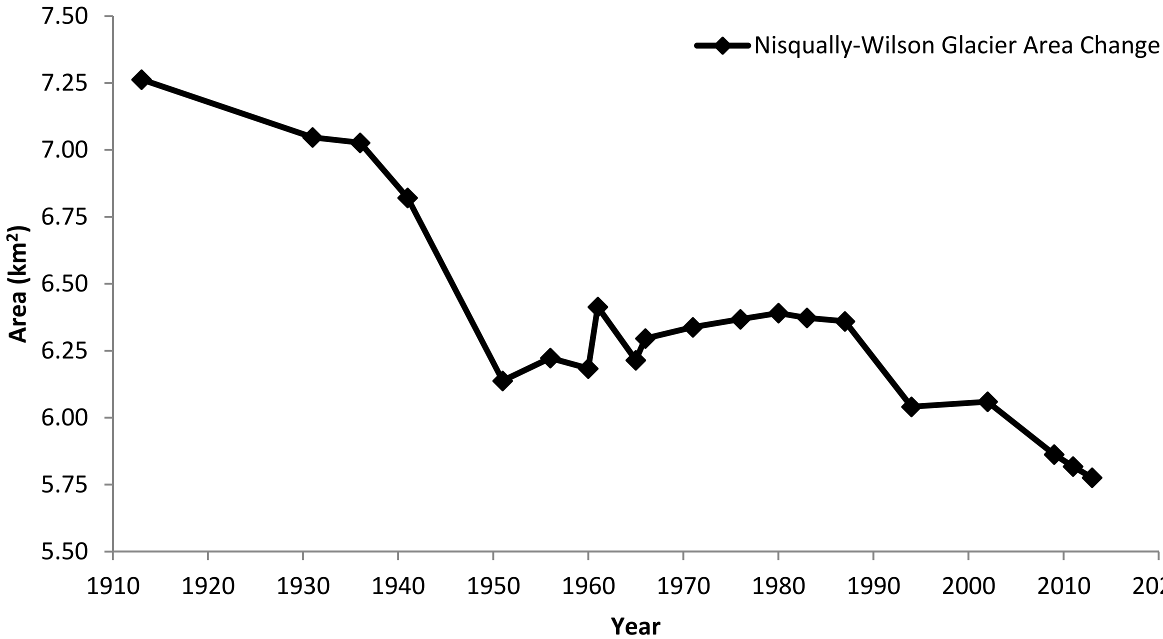
Appendix

A) Nisqually-Wilson Glacier Area Data



Year	Area (km2)	Change (km2)
1913	7.263	0
1931	7.047	-0.216
1936	7.027	-0.02
1941	6.821	-0.206
1951	6.138	-0.683
1956	6.223	0.085
1960	6.184	-0.039
1961	6.414	0.23
1965	6.215	-0.199
1966	6.296	0.081
1971	6.338	0.042
1976	6.368	0.03
1980	6.391	0.023
1983	6.373	-0.018
1987	6.36	-0.013
1994	6.041	-0.319
2002	6.06	0.019
2009	5.863	-0.197
2011	5.818	-0.045
2013	5.776	-0.042