Mapping the Retreat of the Asulkan Glacier in Glacier National Park, British Columbia, Canada

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Abstract

To map the retreat of the Asulkan Glacier in Glacier National Park, British Columbia, five dating techniques were applied: lichenometry, dendrochronology, moraine interpretation, dendroclimatology, and airphoto interpretation. Trees on both the distal and proximal sides of lateral moraines were cored and their ages determined. These data sets were used directly as well as in collaboration with climatic history to determine the recent glacial recession within the study area. It was found that after the terminal moraine was deposited, in approximately the 1850's, climatic records show a general warming trend. Winter precipitation decreased and summer temperatures increased during this period which correlates well with ice retreat. Morainal evidence of ice advance and retreat was analyzed as well. The length of exposure time of till in the study area was determined with increasing distance from the current glacier front. This data was used in support of the dendrochronology results for the purposes of mapping retreat. Surveys of the lateral moraines were carried out with the hope of finding ash and/or organic material for dating. No material was found within the till. With the use of five air photos and ground photographs, as well as the previously mentioned methods, retreat of the Asulkan Glacier was outlined between 1850 and 2005.

1. Introduction

The worldwide retreat of glaciers is an essential tool in monitoring climate change. This recession has been of keen interest to researchers and scientists around the world, who attempt to map and better understand how and why it is occurring (Osborn *et al.*, 2006; Savoskul *et al.*, 1997). There are numerous different methods for mapping glacial retreat, including the use of embedded tree sections, dendroclimatology, moraine interpretation and lichenometry. By employing several of these different methodologies, and using all available evidence, a more accurate image of the glacial retreat rate of the Asulkan glacier can be created.

Lichen *(Rhizocarpon spp.)* are slow growing and only establish themselves on stable rock surfaces. Lichen growth generally occurs in three stages, beginning with rapid growth phase in which the lichen grows at a logarithmic rate (approx. 42mm/century for the first 110 yrs), a slower, nearly uniform growth phase (~11.4mm/century) over the next ~140 years and finally and slow decrease until death (Luckman, 1977). Lichenometric work done in the Illecillewaet glacier valley next to the Asulkan valley found a strong correlation between their calculated retreat rate and the known retreat dates (M^{c}Carthy, 2003). The growth curves developed by both M^{c}Carthy (2003) and Luckman (1977) were used to determine the substrate exposure age the lichen were growing on. This, along with the other dating techniques, enabled us to map the Asulkan glacier's gradual recession.

Dendrochronology is the second method employed in this study to map the retreat of the Asulkan glacier. The annual demarcations of light and dark rings, delineating earlywood and latewood respectively, allow the determination of tree age (Walker, 2005). This, in turn, allows an estimate of approximately when conditions began to allow plant growth; conditions that could not have arisen until the glacier had left the immediate area. Both the site location and species of trees sampled affect the tree's annual growth patterns.

Glacial moraines can be a very useful tool for establishing the timeline of glacial recession. They can be used to track the glacier's path from the terminal moraine to the active glacial front as well as the rate of retreat. Methods used for dating the moraine include searching for tephra layers, which can be related to a past volcanic event of known date, and searching for organic material that can be dated using isotopes. The presence of both tephra layers and organic material can provided a minimum date of surface exposure.

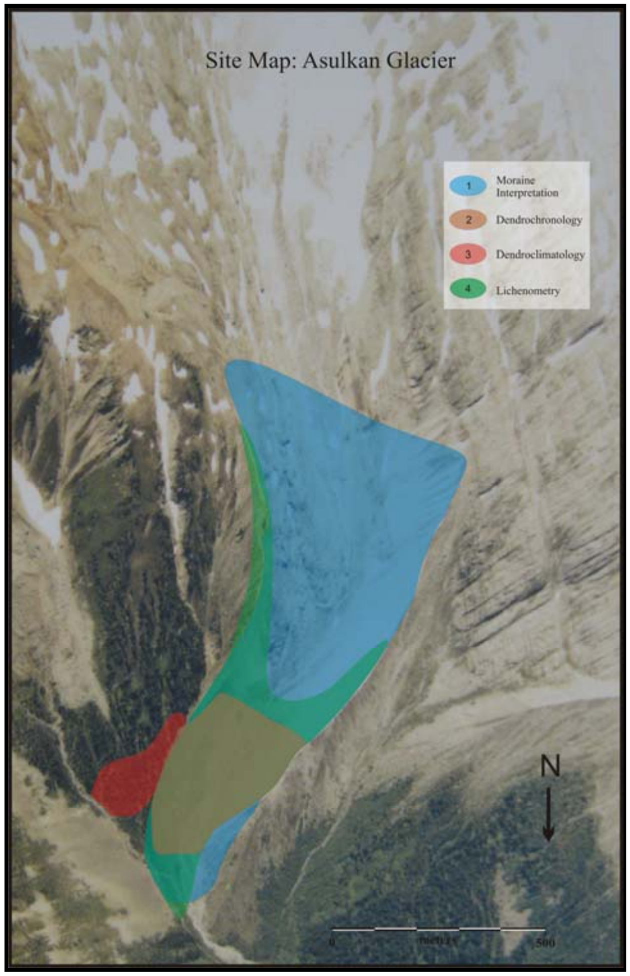
It has been found that in certain sites within temperate regions, ring widths contain significant information on climate (Fritts, 1971). This link between tree growth and climate permits the science of dendroclimatology, a sub-discipline of dendrochronology, to study variations in past and present climates. Air temperature and precipitation are the two limiting factors of tree growth that will be considered in this study; such that dendroclimatology can be linked to the glacial recession. This section of the project will compare tree core widths to historical climatic data and assist in reconstructing the retreat of the Asulkan glacier.

Mapping glacial retreat using air photos has been done since the 1950's in Canada (Sidjak & Wheate, 1999). The spatial arrangement of objects, in particular glacial landforms, vegetation, and bedrock outcrops, are used as reference points to compare aerial photographs. By comparing images taken in different years it is possible to model the rate of retreat of the glacier.

2. Site Description

One of the more prominent glacial complexes in Glacier National Park, British Columbia, is composed of the Illecillewaet Glacier and the Asulkan Glacier to the west. The head of the Asulkan Valley is host to the reminants of the Asulkan Glacier (situated in and around 117˚29'00"W, 51˚14'00"N). Owing largely to size and relatively easy access from Roger's Pass, the Asulkan and Illecillewaet glaciers have been subject to scientific studies since the late 1800's. As such, there is good foundation in the literature for comparison when gauging the Asulkan's retreat in the last century.

The site itself covers a sizable area (approximately 250,000m^2) down slope of the foot of the glacier, with measurements being taken not only along-axis of the glacier's retreat, but across as well. Fed by the glacier is the fast-running Asulkan Creek, which is flanked on each side by about 50m of relatively young avalanche area, dominated by boulder-sized rubble and sparse vegetation. Observations here were entirely lichenometric, as what few trees there were, were too small to obtain an adequate core samples. This area is bordered by two relatively large lateral moraines, whose size (well over 20m in height) is indicative of a relatively constant glacial extent for a long period of time before the retreat. Older, smaller and more densely vegetated lateral moraines may be found further away from the creek, until one reaches the heavily forested area to the east.



Map 1. Study area including various method extents.

3. Methodologies

3.1 Lichenometry

3.1.1 Methods

Lichenometric dating of the glacial forefield involved collecting the diameter of the largest lichens present at each site of interest. Important sites were first determined using old photographs of the glacier from similar vantage points. Two photos taken in 1908 and 1915 were used as known extents of the glacier and the lichen were measured along these transects and various other prominent sites, such as lateral and terminal moraines. Sites chosen were those that could provide data important in interpreting the retreat of the glacier.

Digital callipers were used to measure the lichen diameters precisely, with the black thalli surrounding them being considered the outermost extent. The ecesis rate for *Rhizocarpon* *geographicum*, the species of interest, is known to be relatively short when compared to subalpine fir, but due to limitations in sites of known age no local ecesis rate was calculated. The ecesis of the Mount Rainier was used; ca.-10 years (O'Neal and Schoenenberger, 2003). At least 30 samples were taken at each site and along each transect to ensure a representative sample size. Two perpendicular axes were measured for each lichen, which represented the longest (Axis 1) and the shortest (Axis 2) diameter.

Once the raw data was compiled, outliers were removed, data was graphed to create a curve, and some basic statistics were applied. The use of statistics is helpful in determining the change in the size of lichen diameters. Statistics can be used to investigate whether there is a significant decrease in diameter size with elevation. Firstly, by applying the Two Independent Samples Difference of Means Test using the measurements from two prominent transects (the terminal moraine and the 1918 transect) it can be determined whether there is indeed a difference in lichen size between samples. This test is used to compare two sample means to determine if a significant difference exists between two independent samples. It calculates the difference between two sample means, which is then divided by an estimate of the standard error.

After finding a significant size difference, the mean was calculated for the 1918 and 1905 transects and applied to the Illecillewaet curve (McCarthy, 2003). Despite their physical proximity, the data did not fit successfully on the curve. Due to the limited known extents of the glacier, it was not possible to create a lichen curve. Next the 1918 and 1905 data was applied to the Mount Edith Cavell curve developed by Luckman (1977). The study site at Mount Edith Cavell is on a similar substrate and was used for similar purposes by McCarthy (2003).

3.1.2 Results

The results proved significant. It can be inferred from the test that the mean of Sample 1 (lichen measurements taken from the terminal moraine) is significantly greater than the mean of Sample 2 (measurements taken from the 1918 transect) (Figure 3.1).

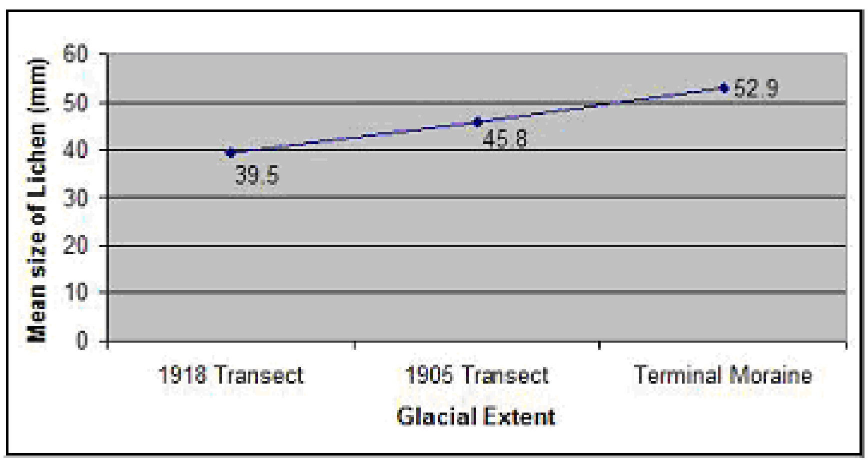


Figure 3.1 General trends of lichen growth in the Asulkan Valley.

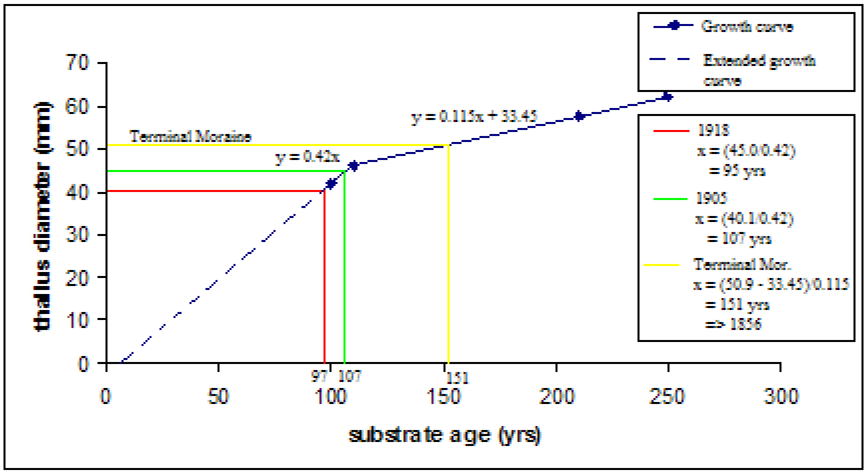


Figure 3.2 Mount Edith Cavell curve with 1905, 1918 and terminal moraine transect data in place.

Graphing the data was another extremely helpful tool in mapping the retreat of the Asulkan glacier. Although the data did not fit onto the Illecillewaet Glacier lichen growth curve, the Mount Edith Cavell curve proved supportive (Luckman, 1977) (Figure 3.2). After checking the fit of the curve, it was possible to apply unknown data to the curve to calculate their approximate ages (Figure 3.3).

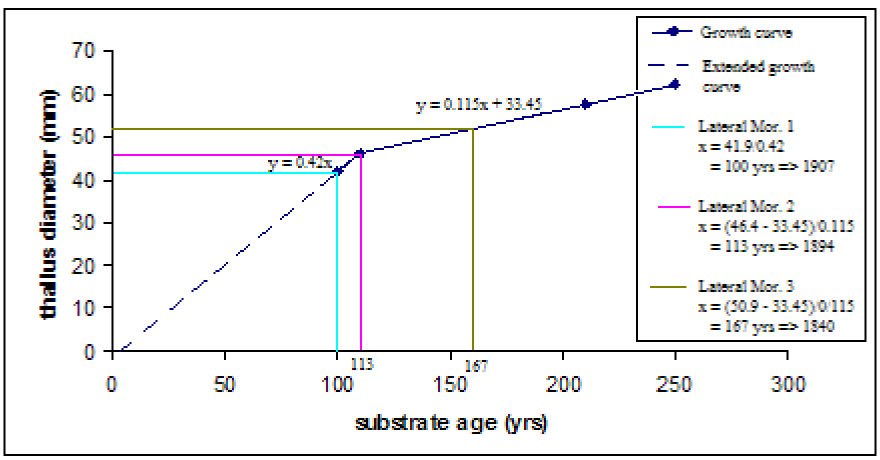


Figure 3.3 Three lateral moraines found on distil side of east moraine.

The terminal moraine found along the Asulkan Ridge Trail was dated to be 151 years old, originating in 1856 (Figure 3.3). The three small, lateral moraines found on the distal side of the large, western lateral moraine were dated at 1907, 1894 and 1840 respectively (Figure 3.3)

3.1.3 Discussion

The steady increase in lichen radius (Figure 3.1) observed moving down from the glacier to the terminal moraine provided the basis for using lichen growth to help date glacial retreat in the Asulkan Valley. Previous research has shown that the number of control points, as well as their accuracy and distribution in time affect the reliability of growth curves (Solomina and Calkin, 2003). Having only three dates of known glacial extents, it was not possible to create a lichen curve for the Asulkan Valley. Nonetheless, despite Mount Edith Cavell being located in Jasper, Alberta, the climate of the site was similar to that of the Asulkan Valley, and the lichen curve (Luckman, 1977) fit the Asulkan Glacier's known extents within 2 to 4 years.

Lichen in the study area could have been misrepresented due to the following potential recording errors: the consistency of lichen measuring may have been compromised by having more than one person measuring the lichen; the largest diametre lichen may not have been sampled in a given area. Lichenometric dating may also have been influenced by the sites selected for taking lichen measurements varying in light exposure. An example of this would be lichen sampled on the proximal versus the distal side of the lateral moraines. Another factor affecting lichen growth is competition (O'Neal and Schoenenberger, 2003). Still, given that the lichen sizes measured for a given study location did not vary largely supports the fact that the lichen which were sampled were not being limited by competition.

3.2 Dendrochronology

3.2.1 Methods

The gathered tree core samples were all sub alpine fur (*Abies lasiocarpa*). The use of a single species of tree ensures less growth variation, reducing uncertainty in the data. A minimum of five trees were sampled from each site to ensure reliable averages were obtained.

An increment borer was used to remove tree cores. As tree wedges are not necessary for accurate dating, tree cores can provide a growth record without permanently damaging a tree. Images were taken using a 6.0 mega pixel digital camera for reference purposes. A Magellan 315 G.P.S. was used to gather UTM coordinates for all the sample locations. This data was later entered into a computer in order to map the extent of the sampled terrain.

Two increment cores were taken at 90º on the lower portion of selected tree trunks along transects aligned with the toe of the glacier during 1918 and 1905. By cross-dating the age of the trees with the recession of the glacier, an ecisis interval can be estimated and used on trees elsewhere in the study area.

Five samples were taken on a lateral moraine for dating purposes, and the mean ages of these trees was added to the time rendered from the transects. The addition of the ages will give an approximation of when the glacier last retreated from that particular moraine.

In the lab, the core samples were air dried and mounted on grooved blocks of wood and sanded flat with 400 and then 600 grit sandpaper. This was to ensure that the samples were smooth enough to make the annual growth rings easier to distinguish. Subsequent tree-ring counting was done using a microscope.

3.2.2 Results

Trees along the 1918 transect were found to have a mean age of 33 years while the trees along the 1905 transect had a mean age of 46.5 years. Together, this puts the ecesis interval at roughly 56 years after glacial recession. If this number is correct, then it can be applied to the third set of five cores taken along the Eastern lateral moraine, from 467.073 East, 5.674.747 North to 467.005 East, 5.674.619 North, with these trees having a mean age of 98.4 years (Table 3.1). Adding the ecesis interval to the mean tree age results in the approximate year of morainal deposition. This older lateral moraine is dated at approximately 155 years B.P.

Table 3.1. Calculations for ageing the far terminal moraine. The bottom row denotes the mean age of the trees.

1918 transect	1905 tansect	Eastern Lateral Moraine
33	44	82.5
36	34	140.5
24	39.5	91
39.5	54	96.5
34	58.5	81.5
33.3	**46**	**98.5**

3.2.3. Discussion

With an appropriate ecisis interval and sufficient specimens it is possible to interpolate the period between a disturbance and when the tree was cored. The samples that were taken directly on the site of the 1905 and 1918 glacial toes, were used to create a reliable ecisis interval. The 1850 lateral moraine seems to follow the pattern of retreat that was determined through photo analysis and tree dating. The numbers should only be regarded as approximate due to the small amount of acceptable specimens located along the transects; more samples would have provided a more accurate mean. Miscounting rings due to broken core samples or the potential presence of false rings, and frost lines could have biased the mean values as well (Fritts 1971).

3.3. Moraine Interpretation

3.3.1. Methods

Tephrochronology is used to establish age equivalence between ash layers in a moraine. During volcanic eruptions, ash is ejected into the atmosphere and dispersed over a large area downwind. Tephra can accumulate on moraines and on glacial ice and be subsequently overlain by further deposition. These materials are characteristic of each particular eruption because they have their own unique geochemical fingerprint (Walker, 2005). Tephra deposits are normally radiocarbon dated, although lacking the facilities to chemically analyze a volcanic ash sample, noting properties such as colour and texture would aid in identifying the ash layer. Coupled with knowledge of ash layers mapped in the area, a suitable estimate of relative age could be established.

In the current study of glacial retreat in the Asulkan Valley, dating of tephra would have involved identifying isochronous marker horizons. In this area, evidence of two volcanic eruptions are expected to be found. The eruption of Mt. St. Helen's, in 1980, and the eruption of Mt. Mazama, in 5000 B.C., were close enough to Glacier National Park that ash could have been deposited.

Pedogenesis uses the presence of soil horizons to date when that layer was deposited. Based on soil development and weathering of clasts, moraines can be resolved into distinct relative-age groups (Walker, 2005). Pollen assemblages indicate climatic conditions. In this area of B.C. the dispersal of Western Hemlock pollen is easily identified (Rosenberg, *et al.* 2003).

The lateral moraines at the Asulkan Glacier were examined for any traces of organic material or volcanic ash that may have assisted in determining the relative ages of the moraines.

While lichen and tree whorl measurements were collected on both lateral moraines, the south moraine proved easier to access; thus, most observations of physical characteristics of the moraine itself were gathered from the south side. If trees had been found within the moraines, dendrochronology would have been used to date glacial retreat. Tree ages would have shown how long the moraine crest was exposed between the last advance and retreat.

3.3.2. Results

Moraine dating using the aforementioned methods failed during the field portion of this study. No ash or organic layers were found during examination of the lateral moraines in the Asulkan Valley. Some layering, particularly in the top half of the North moraine could be seen supporting the suggestion that the South moraine has been significantly eroded.

3.3.3. Discussion

Glacial retreat was too quick to allow soil profile development thus no organic layers were found. Trees, especially, did not have enough time to develop on moraine ridges before the next glacial advance deposited more till. Increased erosion on the southern moraine in the study area may be attributed to frequent use of the trail along the crest of the moraine. This erosion may have obscured any marker horizons that were present.

Layers of tephra may not have been found because deposition of ash is aerially specific. It depends on the strength and direction of prevailing winds during and after eruption, as well as the magnitude and type of volcanic eruption (Walker, 2005). Especially in coarser grained deposits, tephra can also fall between boulder sized clasts making location and correlation even more difficult (Savoskul and Zech, 1997).

3.4. Dendroclimatology

3.4.1 Methods

Core samples were collected in the Asulkan Valley on 09/12/07 and 09/13/07. Subalpine fir (*Abies lasiocarpa*), located in the high elevation regions of the Asulkan Valley, is one of the preferred genera for dendroclimatic interpretation (Fritts, 1971). Eighteen sub-alpine firs were selected, each having two cores taken 90° apart, for a total of 36 core samples. Characteristics considered in tree selection were a healthy crown, no evident stress or burns and similar slopes (Map 1).

In the lab, methods used to prepare the core samples were the same as for dendrochronology (see section 3.2.1). The samples were then scanned into a computer and WinDENDRO (ver.2006b) image analysis system was used to help measure the tree cores.

In WinDENDRO, lines were drawn perpendicular to ring direction to ensure accurate measurement of ring-width. Annual rings were measured to the nearest 0.01 mm. COFECHA (ver.2.04p, 1997), a computer program that cross-dates samples, was used to verify the accuracy of tree-rings identified using WinDENDRO (Holmes, 1983) with 50 year segments and 25 year lags. This was done to ensure that a minimum series intercorrelation of 0.30 was attained (Penrose, 2007). ARSTAN (ver.6.05p, 2007) was used to standardize the chronologies by removing non-climatic age-related growth trends (Penrose, 2007). The following two de-trending methods were performed: a negative-exponential curve to remove age growth trends, and a cubic smoothing spline to diminish the affects of abiotic factors on radial growth (Fritts, 1976). The spline was a 50% wavelength cut-off.

Multiple station data sets were used to construct a complete historical climate data record. There are no climate records for Glacier National Park, so the nearest station used was Revelstoke (45 km east of the park). While the elevation of this site is much lower (450 m asl) compared to the Asulkan Glacier (1,800m asl), it is the best near-complete set available for use. Mean monthly air temperature and precipitation from the stations Revelstoke (51°0' N, 118°12' W; 456 m asl; 1902-1969), Revelstoke Airport (50°57' N, 118°10' W; 450 m asl; 1969-1999), and Revelstoke A (50°58' N, 118°11 W; 445 m asl 1994-2004) were obtained (Environment Canada, 2005). These monthly climatic sets had significant gaps in varying years throughout; therefore, it was necessary to infill the missing records with climate data from a similar site. The weather station in closest proximity to Revelstoke was Golden (51°18'N, 116°59' W; 784 m asl; 1902 -2005), which is 100 km to the east and is 334 m higher in elevation.

In order to use these sites, a comparison file was made that matched the monthly data of both sites. Next, the averages and standard deviations were calculated based on the average monthly differences between the two. Since the standard deviation was lower than the average difference for each month, the Golden data set was deemed acceptable to use to infill the missing data. Thus, the long standing value difference between Golden and Revelstoke was added to the Golden values where Revelstoke data was missing. When climate data was missing for both Revelstoke and Golden, the corresponding long standing monthly average from Revelstoke was used.

PRECON (ver.5.17b, 1999) was used to determine the amount of variance explained by the set of monthly climate variables (Larocque, 2003). This program requires a 100-year interval, and 1905-2004 was selected so that the most recent year of data could be included. The preformatted tree-ring width, temperature, and precipitation data were input and a 16-month, May until August, climatic analysis was run.

Winter precipitation and summer temperature were examined as there are good proxies for glacial mass balance (Watson and Luckman, 2003). Winter precipitation (October – February) and summer temperature (June – August) were chosen based on the largest longstanding mean values due to their effects on glacier accumulation (precipitation) and ablation (temperature).

3.4.4. Results

Out of the 36 cores collected, 21 dated series were used to compare to climatic data. These series, spanning from 74 years to 180 years were calculated with COFECHA to have a series intercorrelation of 0.422 (Table 3.2). The critical statistical outputs from the ARTSAN standardization computations are displayed in Table 3.3 The residual values that resulted from the ARTSAN computation were then used to create a Tree-ring Growth Index (Figure 3.4).

Table 3.2 COFECHA output using a 99% confidence level, producing a critical correlation of 0.3281.

Master series 1827 - 2007 (yrs)	181
Portion with two or more series is 1833 - 2007 (yrs)	175
Series intercorrelation	0.422
Average mean sensitivity	0.211

Table 3.3 Summary of ARTSAN chronology statistics.

First-order Autocorrelation	ARSTAN = 0.8872 Residual = -0.0131
Signal-to-noise ratio	2.522
Variance in first eigenvector	42.00%
Standard deviation	0.3126

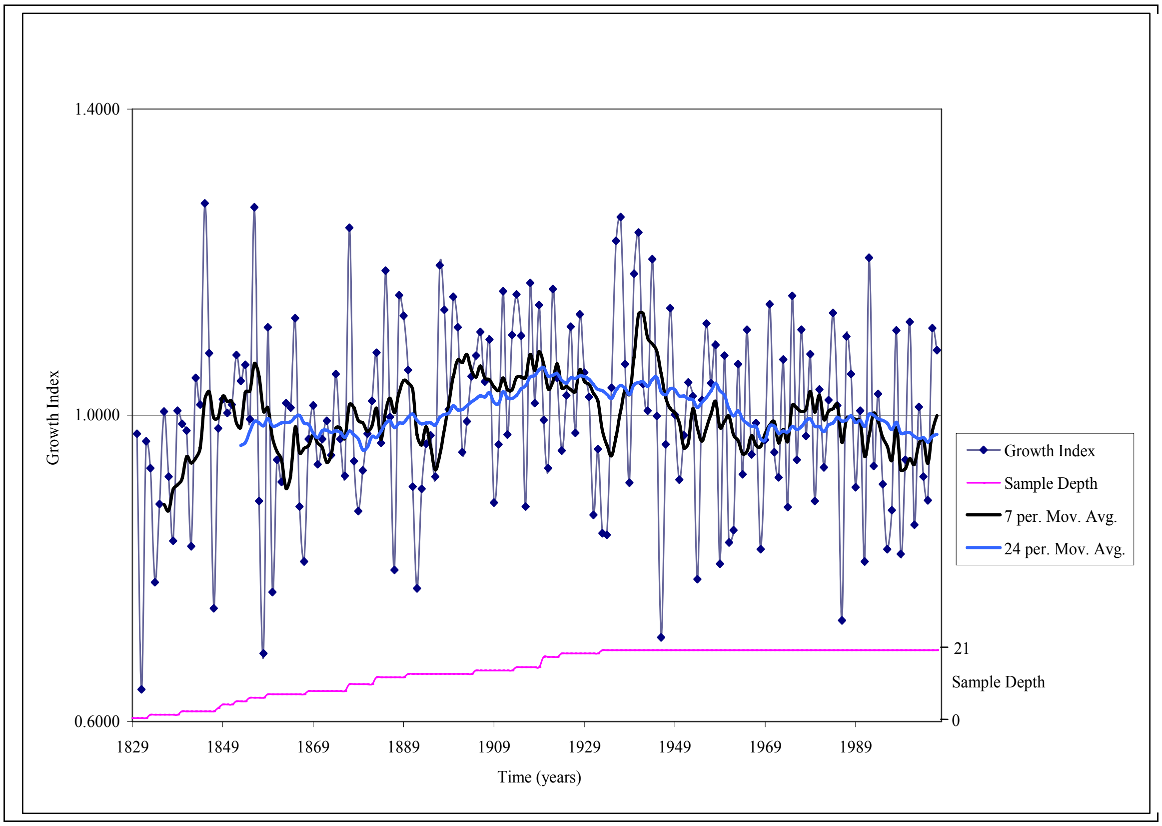


Figure 3.4 Tree-ring Growth Index from 1830-2007 using the Residual values output by ARSTAN. A value of 1.0000 on the Growth Index axis indicates average radial growth.

Output results from PRECON are displayed graphically in Figure 3.5. Significant correlations are marked by asterisks for both precipitation and air temperature over the 16 months (May – August).

Simple statistical methods, mean and standard deviation (Table 3.4), attempt to show variances in the winter and summer climatic elements. The input data was from the reconstructed climate data for Revelstoke, BC.

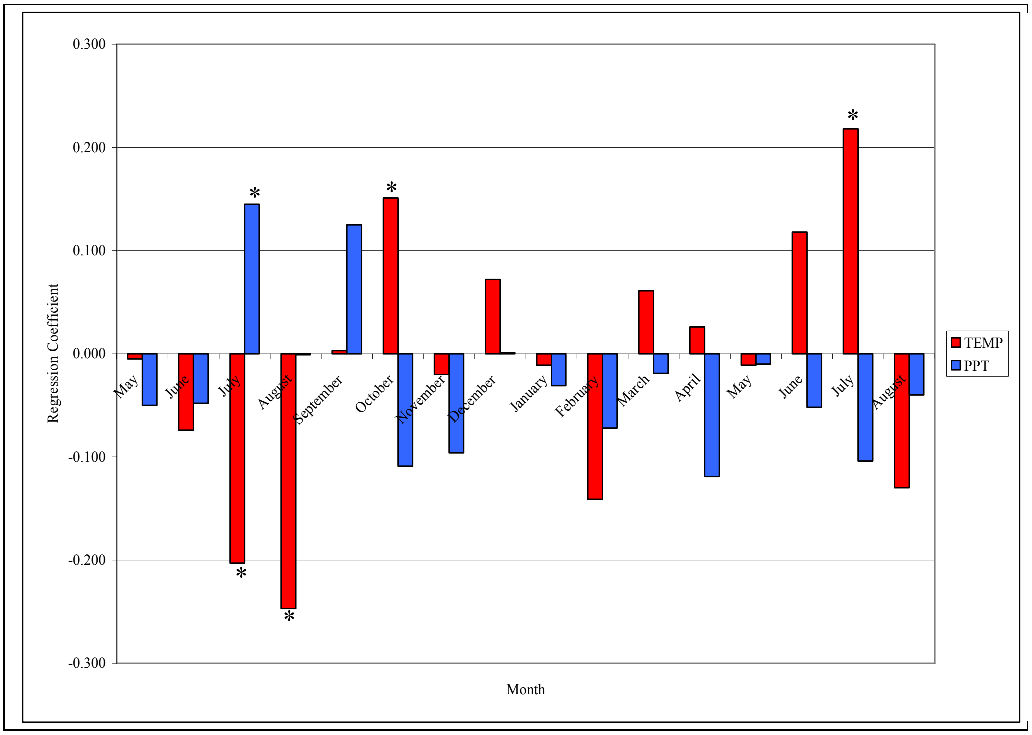


Figure 3.5 Correlations between growth chronologies and mean monthly temperature and precipitation values. Regression coefficient on the y-axis was calculated using PRECON. The asterisks mark the months that were calculated to have significant correlations.

Table 3.4 Mean monthly temperatures (°C) and precipitations (mm) from 1902 to 2004, with standard deviations.

	Mean	Standard Deviation
January	-5.6º	4.0
February	-2.9º	3.0
March	1.7º	1.9
April	7.0º	1.6
May	12.3º	1.6
June	15.9º	1.5
July	18.6º	1.4
August	17.7º	1.4
September	13.0º	1.9
October	6.9º	1.5
November	0.9º	2.4
December	-3.7º	2.8

Temperature

	Mean	Standard Deviation
January	136.2	56.3
February	95.3	44.0
March	72.1	30.5
April	51.9	23.7
May	55.1	24.0
June	70.3	30.4
July	56.4	36.2
August	55.5	35.3
September	69.6	41.3
October	90.6	45.5
November	117.4	45.6
December	136.3	47.7

Precipitation

The mean annual temperature (Figure 3.6) and precipitation (Figure 3.7) have been graphed to show relationships with PDO and ENSO cycles, as well as trend patterns. A seven-year ENSO and 24-year moving average trendline attempt to show correlations between these Pacific phenomena and the reconstructed climate data. Assumptions were made that even though the Asulkan Glacier is located inland, there would still be a significant relationship.

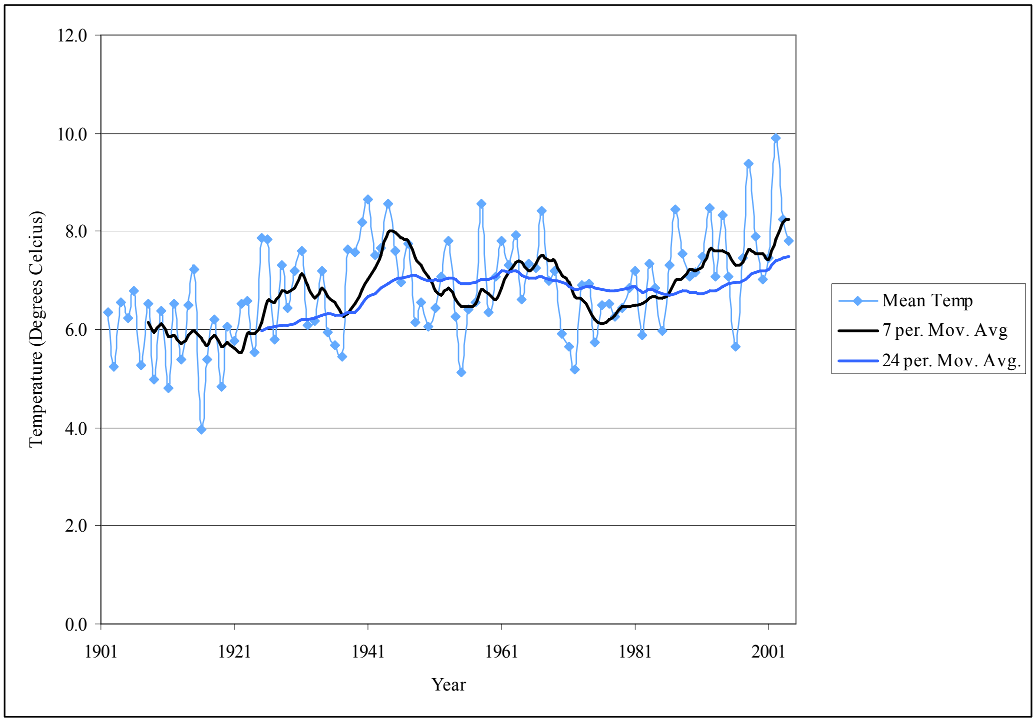


Figure 3.6 Mean annual temperatures from 1902-2004. 7-year and 24-year moving average trendlines have been fitted to the data to show a correlation to possible ENSO and PDO effects, respectively.

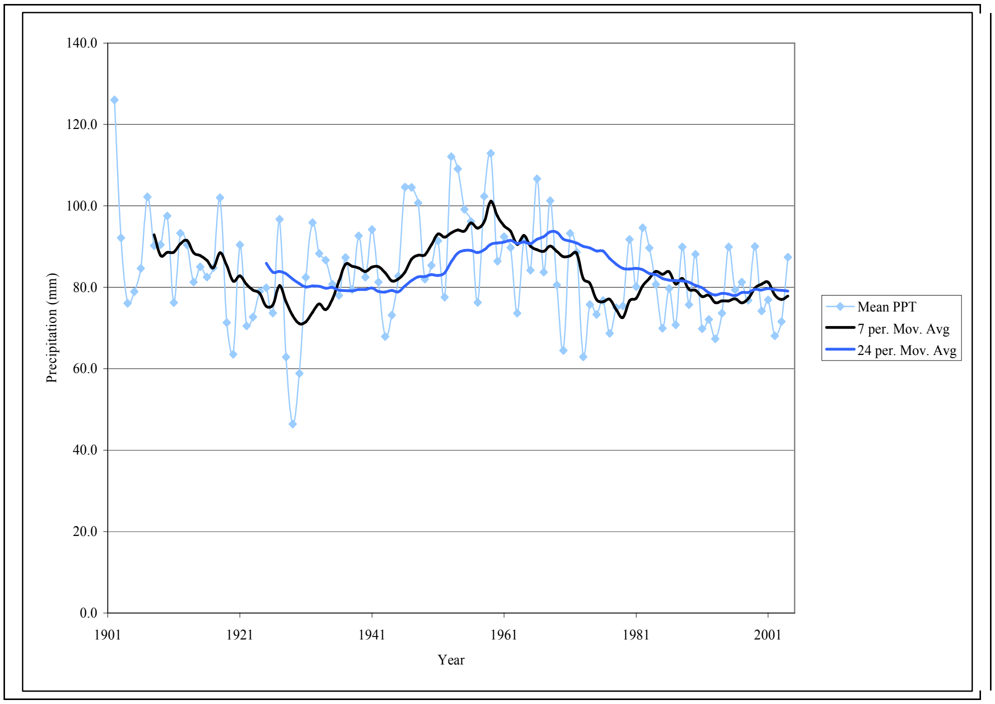


Figure 3.7 Mean annual precipitation from 1902-2004. 7-year and 24-year moving average trendlines have been fitted to the data to show a correlation to possible ENSO and PDO effects, respectively.

To study the accumulation and ablation seasons of the glacier, a comparison between winter precipitation (accumulation) and summer air temperature (ablation) is shown in Figure 3.8. Linear trendlines are presented to show positive relationships between these climatic parameters and glacial equilibrium characteristics.

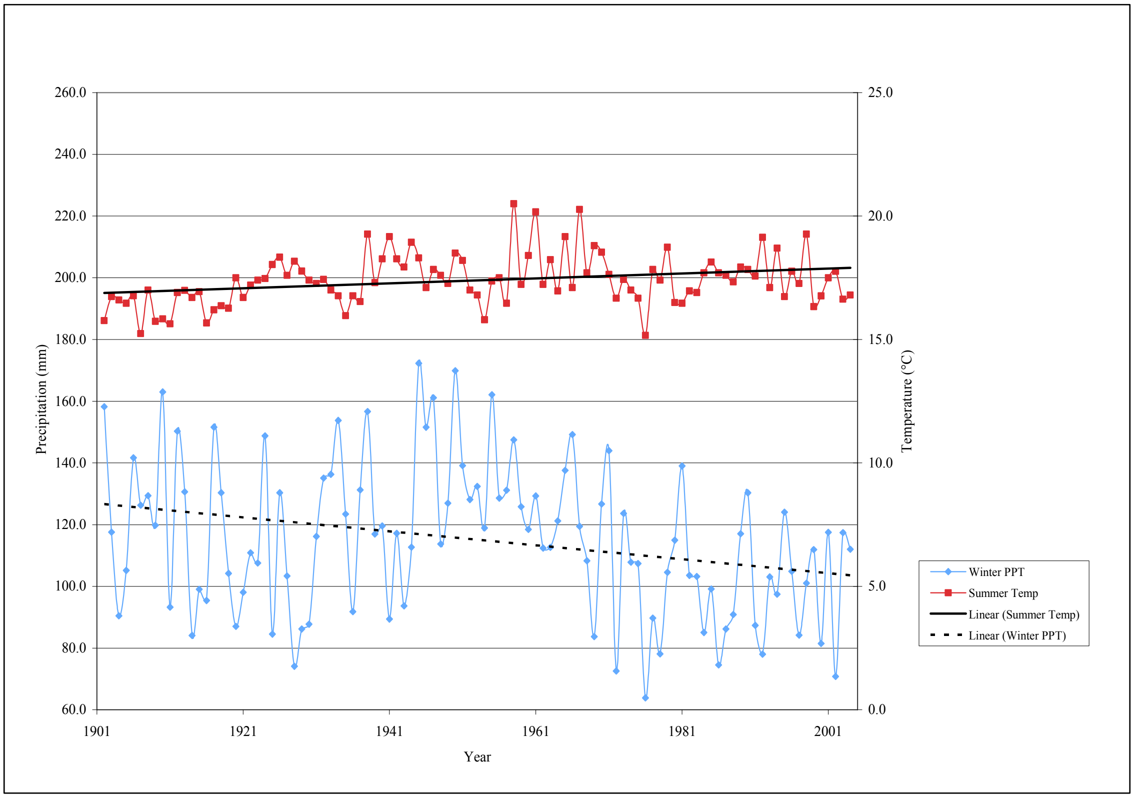


Figure 3.8 Mean summer temperature and winter precipitation from 1902 to 2004. Summer is defined by the months of June through August, while winter is defined by the months of October through February. These season boundaries were chosen based on the longstanding mean values shown in Table 3.3.

3.4.5 Discussion

The chronology is a representative average sample of all the trees from site 3 (Map 1). All of the cores had the general pattern of smaller growth closest to the pith, followed by a series of wider growth rings and ending with smaller growth rings near the bark (Figure 3.4). This trend is shown well by the 24-year moving average.

COFECHA cross-dating outputs (Table 3.2) show a master series range of 181 years with the oldest tree dating back to 1827. However, the portion of the chronology with two or more series dates back 175 years. Only 5 of the 21 tree cores used for analysis were over 158 years old, therefore the earlier portion of the Growth Index (Figure 3.4) is less statistically robust. The series intercorrelation was 0.422 (Table 3.2) which is acceptable (Larocque, 2003) due to the fact that multiple variables affect tree growth.

High mean sensitivity values indicate high year-to-year ring width differences within a chronology (Hughes *et. al.*,1982). The resulting mean sensitivity value of 0.211 (Table 3.2) is classified as being an intermediate value, whereas a sensitive value would be greater than 0.30

(Grissino-Mayer, 2001). This indicates that the year-to-year ring width differences were not as sensitive as desired for use in climatic analysis. Generally, high year-to-year ring width variability is desired as this alludes to growth being driven by a limiting factor. A high percent variance for the first-order eigenvector is indicative of a common forcing variable for the tree-growth. Despite being at the lower end, the first-order eigenvector value of 42% does allude to a forcing variable, which was found to be temperature.

The statistical significance of the high autocorrelation value (Table 3.3) of 0.887 suggests that the growth in any year is strongly influenced by growth in the preceding year (Parish *et al.,* 1999). Thus, it was important to detrend these growth rings so that the residual growth ring values, having an autocorrelation of 0.0131, could be used for further analysis procedures.

The colder winter months, November to January inclusive, had the highest longstanding mean monthly precipitation values (Table 3.4). January held the highest standard deviation values for both precipitation and mean air temperature.

Precipitation was only found to have a significant correlation with tree-ring growth for the July proceeding the growth year (Figure 3.5). This was a positive correlation, indicating this to be the only month where precipitation was potentially a limiting factor to tree growth. For the remaining months of the year, precipitation was not a limiting factor for the growth of the subalpine firs in the study area, sampled from a downsloping location. This location was subject to ground water saturation from glacial run-off. In September, during field work, the ground was observed to be saturated and many trees were difficult to core, perhaps due to the small diameter of the borers.

Air temperature has a negative correlation to tree ring width in July and August of the previous year. Warmer temperatures would increase rates of evapotranspiration, thus depleting the water supply necessary for tree growth. Ultimately, this lack of water availability in July will have a direct negative impact on radial growth (Woodward *et al*., 1994). However, there has been research that has demonstrated that the warmer summer air temperatures allow for increased rates of snowpack melt, thus contributing to and lengthening the growing season (Peterson and Peterson, 1994). This could explain the oversaturation observed in September, as well as precipitation not being a limiting factor in growth during August. In recent years, tree growth has been suppressed potentially as a result of increased rates of glacial run-off due to warmer summer temperatures. In contrast, the positively correlated fall temperature of the previous year (Figure 3.5) will have a significant positive effect on the radial growth. This may lead to an extended period of nutrient storage, and will augment growth in the following season (Peterson and Peterson, 1994). Positively correlated July temperature during the growth year could be attributed to favourable photosynthetic conditions, which increase growth rates of the cambial tissue and stimulate stem growth (Ettl and Peterson, 1995).

Consecutive years (≥ 3) where the tree ring growth index showed above average values, and summer temperature showed above longstanding average values were: 1928-1930 and 1940-1944. Yet a consistent relationship between summer temperature and tree growth was not found. Temperature had opposing correlations to the growth depending on the year; July and August temperatures from the year preceeding tree growth had a negative correlation to tree growth, while July temperatures of the growth year were positively correlated to growth. It is difficult to use tree growth as a proxy for glacial mass balance as multiple variable can affect tree growth. In light of the opposing relations with summer temperatures, this sample set is particularly difficult to relate to glacial recession.

Seven and twenty-four year moving average trendlines were run on Figures 3.4, 3.6, and 3.7 to determine potential correlations with the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) climatic anomalies, respectively. ENSO, is a phenomenon that is a result of atmospheric and oceanic coupling (Battisti and Sarachik, 1995). While these interactions occur in the tropical Pacific, this decadal variability has been found to be related to mid-latitude variability, suggesting a link between the tropics and mid-latitudes (Kleeman *et al.*, 1999). The seven-year moving trendline shows the predictive pattern of ENSO cycles (Figures 3.6 and 3.7). However, correlations to specific historical ENSO events did not occur throughout the entire climatic dataset. One explanation could be the fact that ENSO predominately affects the Pacific Coast of British Columbia, while the study site was in the interior near the border with Alberta.

The PDO is a 20-30 year pattern in Pacific climate variability. Along the West Coast of Canada, the cold phase is characterised by anomalously low sea surface temperatures, dominant wind stress coming from the North and lower than average sea-level pressure, whereas the warm phase of the PDO is characterised by anomalously high sea surface temperatures, dominant wind stress coming from the South, and higher than average sea-level pressure. Cold phases of the PDO were from 1890-1924 and 1947-1976, while the warm phases were from 1925-1946 and 1977-1999 (Mantua and Hare, 2002). A positive correlation between one warm-phase PDO (1925-1926) and the 24-year moving average air temperature (Figure 3.6) is observed. The cold phase from 1947-1976 appears to show a positive relationship to precipitation (Figure 3.7), while the warm phase from 1977-1998 shows a decreasing trend in precipitation.

Climate data shows that mean summer temperatures are increasing while mean winter precipitations are decreasing (Figure 3.8). This supports the fact that the glacier is receding and mass balance studies for the Asulkan glacier could provide insight into rates of recession. Without mass balance values for the Asulkan Glacier, it is difficult to link the results of the dendroclimatology study to the glacial retreat. As the topography varies, so to does the width to length to depth ratio of the glacier, and therefore, the rate of glacial recession cannot be accurately calculated without mass balance studies. Nonetheless, Watson and Luckman (2004) show that winter precipitation and summer temperatures provide a good proxy for mass balance of the Peyto Glacier in the neighbouring Canadian Rockies. Based on these findings, it is assumed that the climate data from Revelstoke can be used to approximate glacial retreat of the Asulkan Glacier. Consecutive years (≥ 3) where winter precipitation was below and summer temperatures were above the longstanding average allude to increased rates of glacial recession. These years were: 1927-1930, 1977-1979, 1984-1988, and 1996-1998. Consecutive years (≥ 3) where winter precipitation was above and summer temperatures were below the longstanding average allude to decrease rates of glacial recession or even glacial advance. These years were: 1906-1910, 1933-1935, and 1952-1957. Revelstoke climate data also shows that beginning in the early 1980's until present, growing trends in warmer yearly temperatures and decreasing yearly precipitation suggest a phase of increasing ablation (Figure 3.8).

3.5 Airphoto Interpretation

Mapping the extent of glacial retreat in the Asulkan Valley was largely done using aerial photographs. Three air photos: 1984, 1996, 2005 (BC Air Photo Warehouse, Victoria) and two ground-based photographs: 1905 and 1918 (Cavell, 1983) were used for mapping purposes. The glacier fronts at different dates were mapped onto the most recent air photo.

The 1984 aerial photograph had a scale of 1:60,000 and was taken on July 17th. In this photo there is still seasonal snow cover on the top of the glacier as well as on the surrounding glacial till. The aerial photograph from 1996 has a scale of 1:15 000. It was taken on September 10 when the least amount of late lying snow was present. The third and most recent airphoto was taken on August 3, 2005. It has a scale of 1:30 000 and the image shows very little late lying snow.

Only two ground-based photographs of the Asulkan Glacier could be found. Both were referenced by the air photos to determine ground positions of the glacier fronts. The Asulkan Glacier has formed lateral moraines with unique characteristics. These were used in determining the extent of glacial retreat. Boulders found in the 1905 image were also seen during the field work portion of this study in the fall of 2007. The persistence of this boulder alignment for the past century has provided a ground reference point for the 1905 photograph. The 1918 photograph was taken such that it is difficult to find a reference point within the image. The two photographs were taken from different perspectives making comparisons difficult. Neither image has a seasonal date, but based on the crevasse exposures it is assumed that there is minimal late lying snow in both.

Limitations for mapping using these 5 images include differences in resolution, seasonal differences with respect to snow coverage, and migration of river channels. As well, there is a large gap in the data. No images of the Asulkan Glacier were found between 1918 and 1984.

By combining aerial photography, oblique photos, dendrochrononlogy and lichenometry, a rough glacial retreat pattern was extrapolated (Figure 3.9). This glacial retreat was based on the known and calculated extents of the glacier and a straight line distance between two extents. The resulting information shows regression rates ranging from 2.7 meters to 44.5 meters annually. Due to the lack of available information between 1918 and 1984, the rate of retreat can only be hypothesised. The climate data from Revelstoke (presentated in section 3.4 of this paper) shows that more years between 1918 and 1984 supported positive glacial mass balance than negative glacial mass balance, thereby negatively impacting the recession rate for this time frame. Documented occurances of nearby glacial advances in the mid to late 1970's (Watson and Luckman, 2004) present the possibility that perhaps the Asulkan Glacier was advancing during this time frame as well; and this could also account for the overall declining recession trend between 1918 and 1984. The rate of retreat between 1996 and 2005 shows a dramatic increase, having a maximum value of 44.5 metres per year. If this ablation trend continues, the Asulkan Glacier (approximately 3,250,000 m^2 surface area remaining) will have completely disappeared within 75 years, and will have disappeared visually from the Asulkan Valley within 33 years.

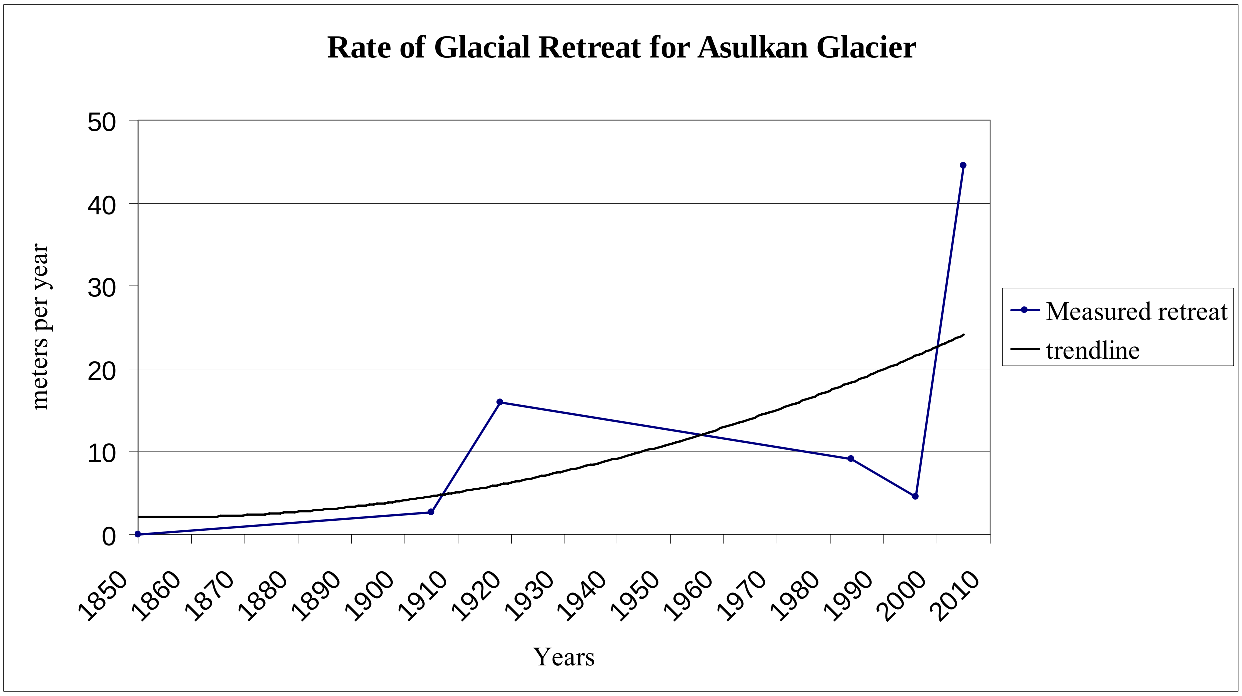
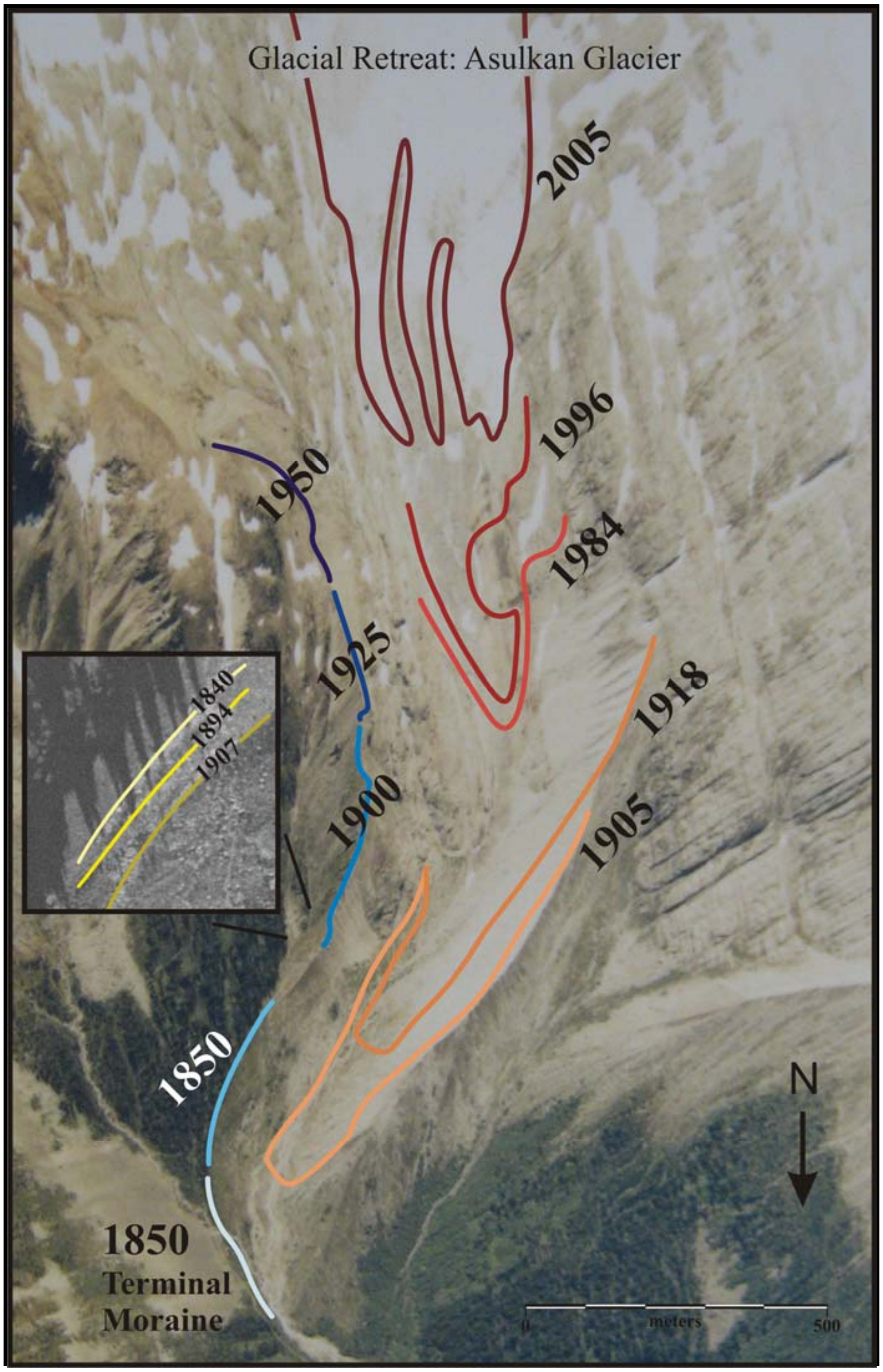


Figure 3.9 Yearly recession rate of the Asulkan Glacier from 1850 to 2005.



Map 2. Final map created using data from lichenometry, dendrochronology, and airphoto interpretation.

4. Conclusion

Past glacier recession can be reconstructed through the use of various quaternary dating methods, such as lichenometry, dendrochronology and dendroclimatology. These methods can be complemented and enhanced through the application of more qualitative dating methods such as photographic interpretation. By combining several different methods a more accurate narrative of glacial history can be drawn.

There was a large difference between the ecesis intervals for lichen colonies and subalpine fir in the Asulkan Valley. Lichen ecesis intervals were much shorter because they are smaller organisms and require less specific growing conditions than trees. The ecesis interval for the subalpine fir was approximately 56 years and according to McCarthy and Luckman (1993) this falls within the range of values (5-60 yrs) for conifer trees in the Canadian Cordillera. In their study they do, however, indicate that overestimates may have resulted from sampling techniques such as using small sample sizes. The subalpine fir ecesis estimate in the Asulkan Valley study site may be too large due the number of trees cored. The ecesis interval could be more accurately determined by sampling trees along an increased number of transects. For example, given more time, trees along the terminal moraine could have been cored. In the Asulkan Glacier retreat path there were a limited number of locations with known exposure age, and trees large enough to be cored for ecesis interval determination. If there had been more locations with known age then a lichen ecesis interval could have been created for the area.

The general retreat of the Asulkan Glacier corresponds to climate data found from the dendroclimatology study within this project. It was found that, over the past century, an overall warming trend of summer temperatures has occurred as well as a decreasing trend in winter precipitation. This provides reasoning for glacial retreat within the Asulkan Valley. On a more detailed scale, it is sometimes hard to correlate Revelstoke climatic data with recession rates predicted by lichenometry, dendrochronology and airphoto interpretation. One reason for this could be the fact that the rate of glacial recession could only be roughly estimated without mass balance studies as the width, to length, to depth ratio of the glacier varied due to varying topography in the study area. Another reason is that due to the Asulkan Glacier having a higher elevation than Revelstoke and a slight variation in geographic location, the climate data might not always be accurate. Also, Revelstoke data was not always available and adjusted Golden data had to be used in its place, which could have led to further inaccuracies. It would be helpful to have details of retreat between 1918 and 1984 to be able to better define the relationship between Revelstoke climate data and the retreat of the Asulkan Glacier. This time period has no data regarding where the glacial front was located and how it was changing. Information could be obtained via lichenometric data or dendrochronologic data (possibly tree whorls). Further studies could include a more statistically robust dendrochronology, perhaps sampled in the summer when sample collection might be more favourable to create a historical climate model based on tree ring data. If possible, samples from mountain hemlock would be prefered over subalpine fir as the former species has an established relationship with climate that affects glacial mass balance (Lewis and Smith, 2004). It should be remembered that none of the dating techniques used in this study are absolute, but rather tools that aid in explaining the past and predicting the future. Further studies should include a more detailed sampling design covering a larger area within the path of glacial retreat. It should be noted that dating accuracy is limited by the relatively short time restraint imposed on the study. And as such, future work in the area would benefit from a more structured and thorough approach.

Impacts from the retreat of the Asulkan Glacier affect the future of Parks Canada in this area. Depending on climatic factors, the rate of ice melt may affect the Asulkan Valley trail. Fluctuations in outwash stream volumes can cause channel migration threatening trail stability. The aesthetic appearance of valleys within Glacier National Park is reliant on the presence of glaciers. If ice retreat continues at its present rate, by the year 2040 the Asulkan Valley will not have a glacier to attract visitors and Parks Canada will no longer be able to boast about "glacier views" in their hike descriptions. The attraction to mountaineers in Glacier National Park will likely also be diminished.

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