

# Recent deglaciation of the upper Wheaton River watershed, Yukon

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Church, A. and Clague, J.J., 2009. Recent deglaciation of the upper Wheaton River watershed, Yukon. *In: Yukon Exploration and Geology 2008*, L.H. Weston, L.R. Blackburn and L.L. Lewis (eds.), Yukon Geological Survey, p. 99-112.

## ABSTRACT

We document rapid loss of glacier ice in the Wheaton River watershed which contains the northeastern-most glaciers within the Coast Mountains. Our research involves the study of the Wheaton glacier, the largest of the glaciers in the Wheaton River watershed. Since the Little Ice Age, the Wheaton glacier has lost 50% of its area and 58 to 63% of its volume. Thinning and retreat have accelerated in the past 40 years and the glacier is now so thin and short that it may disappear during this century. This loss was quantified through the analysis of sequential aerial photography and bivariate scaling analysis. Observations in the climate record from 1907 to 2005 have shown an increase in mean atmospheric temperature, as well as an increase in average winter snowfall. Despite increasing winter snowfall, changes in temperature continue to be the main cause of the persistent negative mass balance of the Wheaton glacier. If air temperatures continue to rise and glaciers disappear from the Wheaton River watershed, discharges and timing of peak flow events of the Wheaton River will be affected.

## RÉSUMÉ

Nous présentons des données sur le recul rapide de la glace de glacier dans le bassin hydrologique de la rivière Wheaton, qui contient le glacier de la chaîne Côtière situé le plus au nord-est. Notre recherche comprend l'étude du glacier Wheaton, le plus grand glacier dans le bassin de la rivière Wheaton. Depuis le Petit Âge glaciaire, le glacier Wheaton a perdu 50 % de sa superficie et entre 58 et 63 % de son volume. Son amincissement et son recul ont accéléré au cours des 40 dernières années, et le glacier est maintenant si mince et petit qu'il pourrait disparaître au cours des 20 prochaines années. Nous avons quantifié la perte de glacier par le biais de l'analyse de photographies aériennes séquentielles et d'une analyse d'échelle à deux variables. Les données climatiques de 1907 à 2005 ont montré une augmentation de la température atmosphérique moyenne ainsi qu'une augmentation de la chute de neige moyenne en hiver. Malgré l'augmentation de la chute de neige en hiver, les changements de température continuent d'être la principale cause du bilan de masse continuellement négatif du glacier Wheaton. Si la température de l'air continue d'augmenter et si les glaciers disparaissent du bassin de la rivière Wheaton, le débit et le moment des débits de pointe dans la rivière Wheaton varieront.

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## INTRODUCTION

The Arctic and sub-Arctic will likely experience greater climate warming in the future than other parts of the world (IPCC, 2007). Over the past several decades, temperatures in these areas have increased at twice the rate of the rest of the planet. One of the manifestations of this warming in Yukon is thinning and retreat of many glaciers (ACIA, 2005; Lemmen *et al.*, 2008). Glacier retreat is intimately linked to changes in geomorphology, hydrology and biotic environments.

The Wheaton River watershed in southern Yukon, supports several small glaciers, which are the northeastern-most glaciers within the Coast Mountains. Glaciers in the Wheaton River watershed are located at the fringe of the region capable of supporting ice, making them highly responsive to climate change. This study thus provides a unique perspective on the impacts of changing climate in southern Yukon. We conducted a study of the largest of the glaciers in the Wheaton River watershed, hereafter referred to informally as Wheaton glacier.

## OBJECTIVES

This project involves a study of the impact of contemporary deglaciation on the upper Wheaton River valley. The research addresses the following questions:

- How has Wheaton glacier changed over the past century?
- What is the relationship between the historic activity of Wheaton glacier and regional climate?

## STUDY AREA

The Wheaton River watershed is in the transition zone between the Coast Mountains and the Yukon Plateau (Bond, 2003). It is located within the Yukon-Stikine Highlands ecoregion, the Boundary Ranges physiographic region, and the Coast morphologic belt (Smith *et al.*, 2004). This part of Yukon is an upland plateau dissected by relatively narrow and deep river valleys (Bond, 2003). The Wheaton River watershed has an area of 875 km<sup>2</sup> and drains to Lake Bennett near Carcross (Fig. 1; Ramage *et al.*, 2006).

Wheaton glacier (Fig. 2) is located in a high cirque in the headwaters of the Wheaton River watershed. A rock ridge and medial moraine divides the glacier into two lobes. The east lobe has a length of 3 km and is the source of the trunk stream that flows 4 km to a debris-flow fan in

the Wheaton River valley. The west lobe has a length of 3 km and terminates in a small proglacial lake, which then drains into the trunk stream. The glacier is bordered by the highest peaks in the watershed that rise up to 2460 m in elevation. The bedrock beneath and around Wheaton glacier is highly fractured and jointed granite, granodiorite and diorite. Scree covers the lower slopes adjacent to the glacier. The glacier forefield is largely un-vegetated, covered by recessional moraine ridges, ground moraine and erratics, and is bordered by an extensive Little Ice Age terminal moraine. The site of a former proglacial, moraine-dammed lake, just inside the terminal moraine, is marked by a shoreline and a flat lake bed. Rock glaciers are common on the east side of the valley downstream from the Little Ice Age terminal moraine.

## GLACIAL HISTORY

The Cordilleran Ice Sheet covered the entire Wheaton River watershed, with the possible exception of the highest peaks, during the Late Wisconsinan McConnell Glaciation (Bond, 2003). During deglaciation, the Cassiar lobe of the Cordilleran Ice Sheet advanced into a zone vacated by the Coast Mountain lobe flowing from the west. A series of proglacial lakes developed throughout southern Yukon at this time. The Wheaton River valley hosted a lake that initially drained via an outlet at the headwaters of Wheaton River, and later through Cowley Creek northward into the Yukon River valley (Bond, 2003).

Wheaton glacier either disappeared or shrank to near its present size during the early Holocene, when climate was warmer than today (Denton and Stuiver, 1966). It reformed or advanced during Neoglaciation and reached its maximum Holocene extent during the Little Ice Age.

## METHODS

### GLACIAL AREA LOSS AND DOWNWASTING

The Canadian Government acquired sequential aerial photographs of Wheaton glacier in 1948, 1964, 1987 and 1995. These photos were scanned using a photogrammetric scanner at the National Air Photo Library in Ottawa. The digital images were imported into a GIS using ArcView software and were geo-referenced using ground-control points collected during the 2007 field season with both differential and hand-held GPS units. The aerial extent of the glacier in 1948, 1964, 1987 and 1995 was determined in ArcView GIS. The Little Ice Age extent of the glacier was measured based on moraine

and trimline geomorphic features. The 2004, 2006 and 2007 glacier extents are based on our field mapping in the 2007 field season and on previous field surveys by the Yukon Geological Survey and Monica Bruckner, a graduate student at Montana State University. Glacier downwasting was determined by differencing ground control points collected with a differential GPS. Points were collected from the top of a rock ridge separating the two lobes of Wheaton glacier that was first exposed in 1964.

### BIVARIATE SCALING ANALYSIS AND VOLUME ESTIMATES

A scaling analysis based on mass and momentum conservation equations shows that glacier volumes can be related by a power law to more easily observed glacier surface areas (Bahr *et al.*, 1997):

$$V \propto S^Y \quad (\text{Equation 1})$$

where  $V$  is glacier volume,  $S$  is glacier surface area, and  $Y$  is an exponent relating volume and surface area.

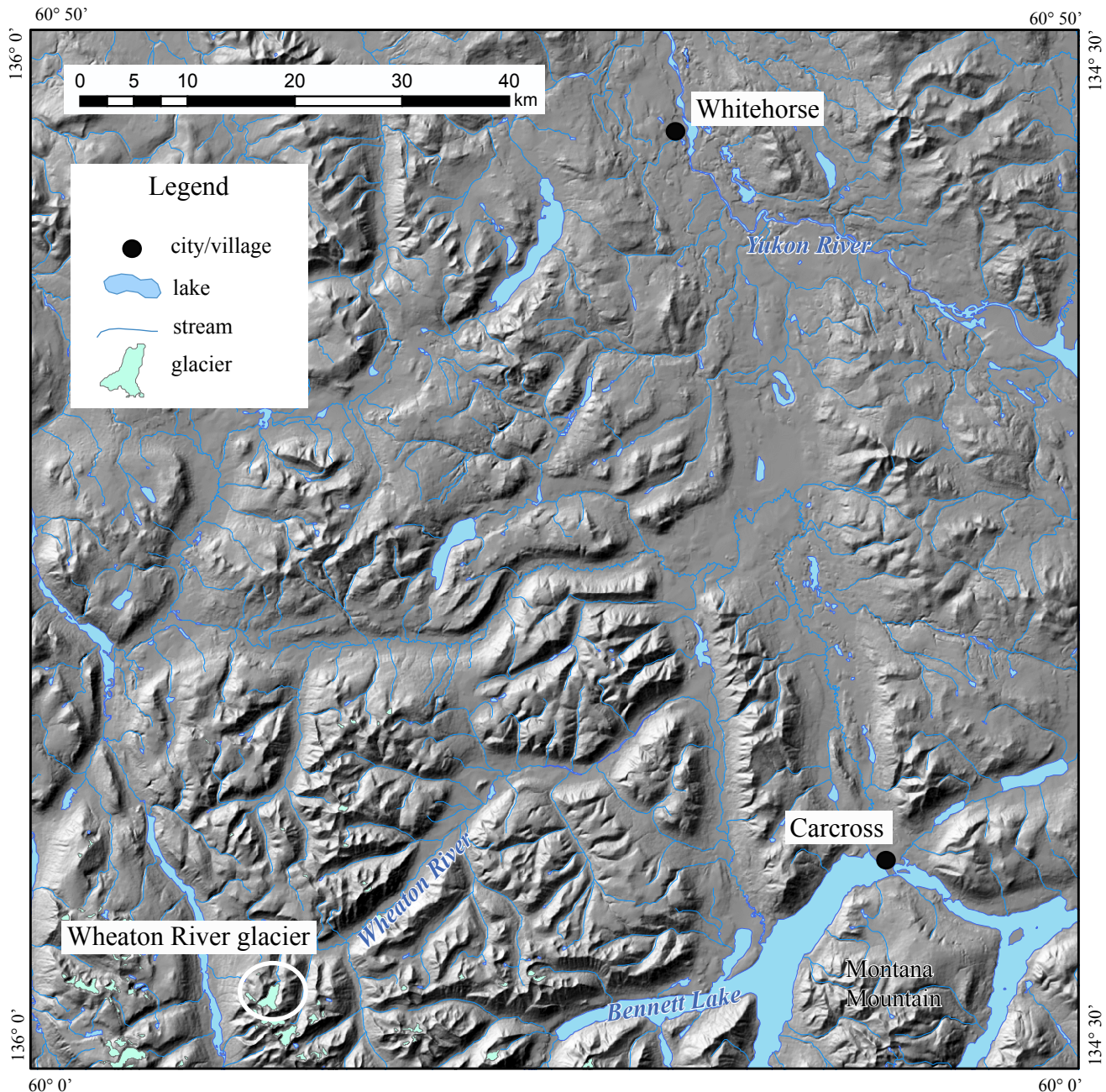
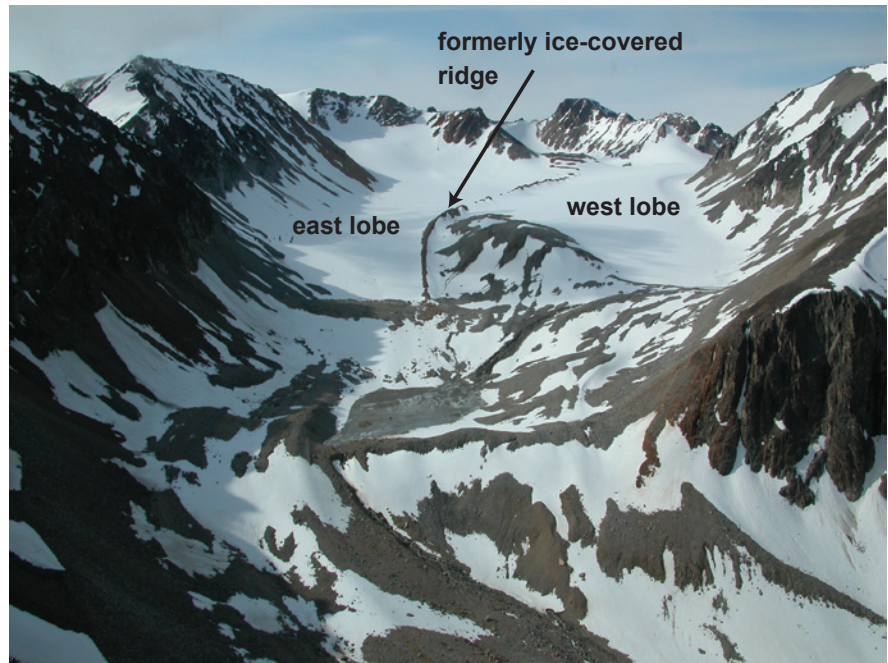


Figure 1. Location of the Wheaton glacier study site.

**Figure 2.** Wheaton glacier; photograph taken in 2007. Note rock ridge that was covered in ice as recently as the early 1960s.



Bahr *et al.* (1997) estimated  $\Upsilon$  to be 1.36 from a dataset comprising 144 glaciers worldwide. Other authors, however, have suggested values in the range of 1.25 (Paterson, 1972) and 1.4 (Macheret *et al.*, 1988). Volume estimates for this study were calculated using three values of  $\Upsilon$  (1.25, 1.36, and 1.4) to capture the potential range of values.

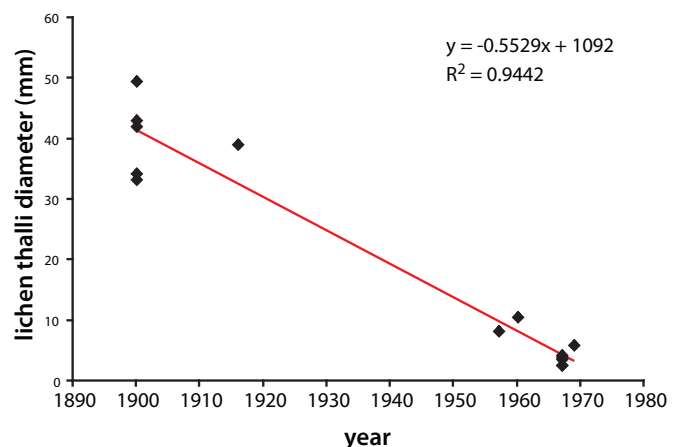
## GEOMORPHOLOGY

Trimlines, moraines and other geomorphic features in the glacier forefield and cirque were mapped and captured in the GIS. Features were identified and mapped through aerial photographic interpretation and field checking in the summer of 2007.

## LICHENOMETRY

Thalli of lichen (*Rhizocarpon geographicum*) on moraines and other features throughout the glacier forefield (Fig. 3) were measured to estimate the time of glacier retreat over the past century. At each site, the maximum diameters of 100 randomly chosen thalli were measured to the nearest millimetre to obtain a sample of the lichen population that included the largest specimens. Measurements for each sample were plotted as histograms for ease of comparison. The value used to estimate the age of each surface is the average of the five largest lichen-thalli diameters (Fig. 4). An average of the five largest thalli was used in order to lessen the influence of anomalous outliers that may have existed within the site lichen population.

A lichen growth curve for subalpine environments in southern Yukon was constructed to estimate the ages of landforms of interest in the Wheaton River watershed. Lichens on surfaces of known age were measured in the same manner as at Wheaton glacier. The surfaces included the Carcross and Tagish First Nations cemetery and several sites on Montana Mountain, including turn-of-the-century stone buildings and national survey points. Each point on the growth curve represents the average of the five largest lichen diameters at a site.



**Figure 4.** Lichen growth curve based on data collected from sites at Montana Mountain and Carcross.

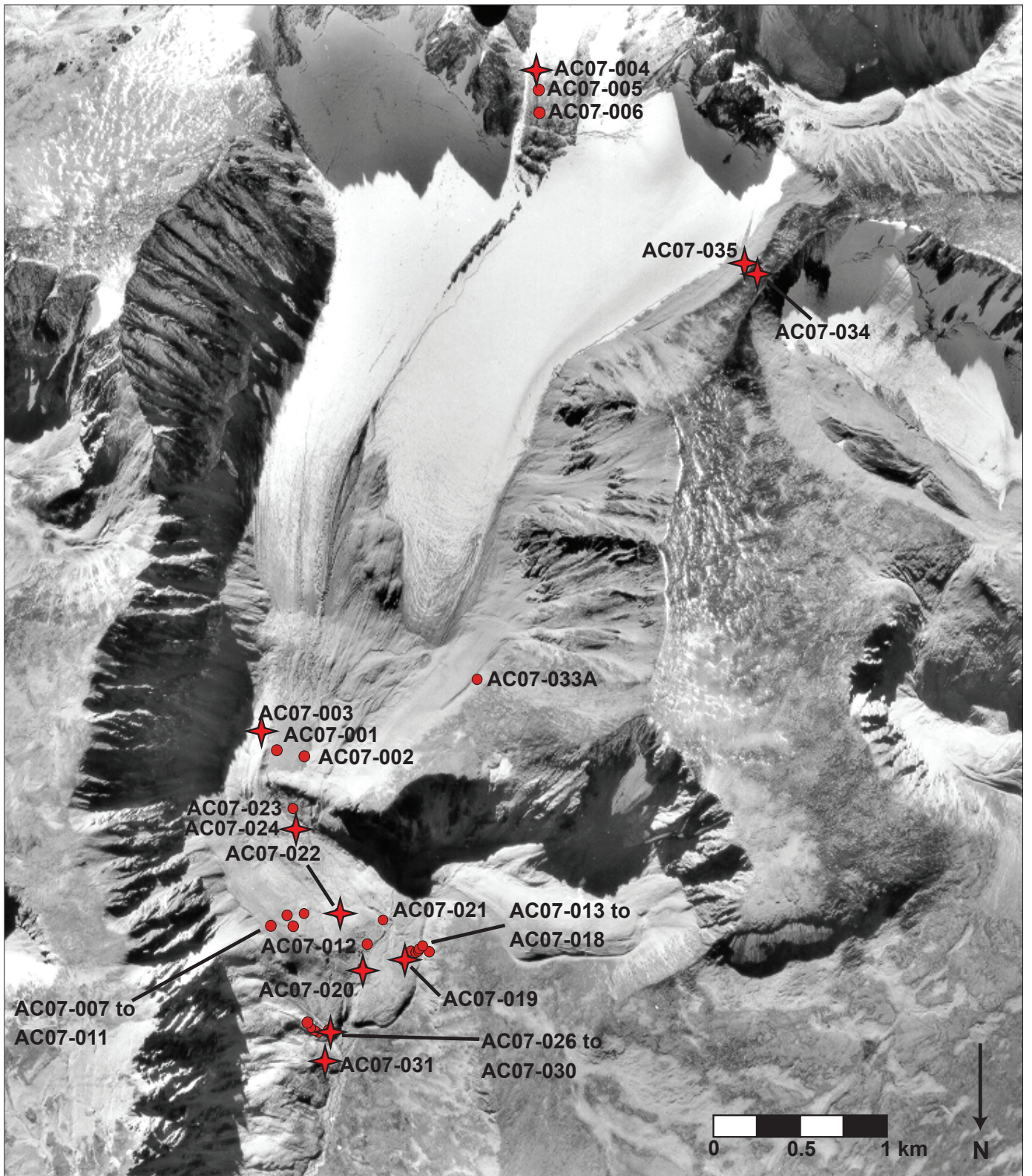


Figure 3. Locations of lichen sample sites. See Figure 5 for histograms showing distribution of lichen size at starred sites.

## CLIMATE ANALYSIS

Temperature and precipitation data for Whitehorse and Carcross, the two closest weather stations to the study area, were obtained from the National Climate Data and Information Archive. Data exist for the period from 1907 to present. Yearly and seasonal temperature and precipitation averages were calculated and plotted to identify dominant trends. Comparison was also made to records of Pacific decadal oscillation (PDO), obtained from the University of Washington, and El Niño-Southern Oscillation (ENSO), obtained from National Oceanic and Atmospheric Administration's (NOAA) National Weather Service Climate Prediction Centre.

**Table 1.** Surface area of Wheaton glacier through time and associated area losses since the Little Ice Age (LIA) and the first aerial photography in 1948.

Date	Area (km <sup>2</sup> )	Area loss (since LIA)	Area loss (since 1948)
Little Ice Age (LIA)	3.55		
1948	3.42	1.05 km <sup>2</sup> /18.5%	
1964	2.72	0.83 km <sup>2</sup> /23.4%	0.70 km <sup>2</sup> /20.5%
1987	2.21	1.33 km <sup>2</sup> /37.6%	1.20 km <sup>2</sup> /35.2%
1995	1.81	1.74 km <sup>2</sup> /49.0%	1.61 km <sup>2</sup> /47.1%
2004	1.78	1.76 km <sup>2</sup> /49.7%	1.63 km <sup>2</sup> /47.8%
2006	1.77	1.77 km <sup>2</sup> /50.0%	1.65 km <sup>2</sup> /48.2%
2007	1.76	1.79 km <sup>2</sup> /50.4%	1.66 km <sup>2</sup> /48.6%

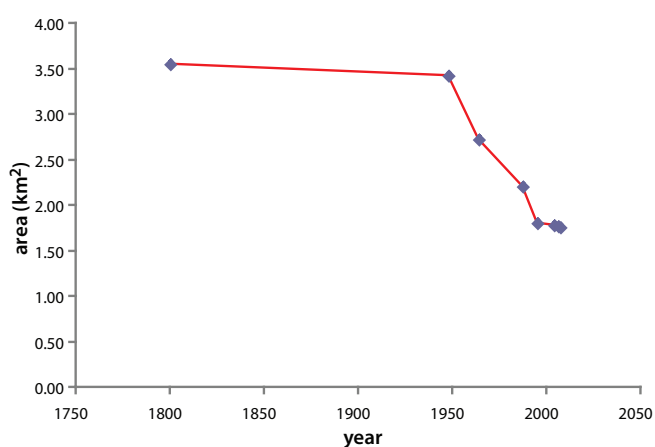
## RESULTS

### GLACIER ICE LOSS

Table 1 and Figure 5 summarize the change in the area of Wheaton glacier through time and Table 2 presents glacier volume changes calculated using the bivariate scaling procedure summarized above.

The area of Wheaton glacier in 2007 was 1.80 km<sup>2</sup> (50.4%) less than at the time of the Little Ice Age maximum in the nineteenth century. Since the first aerial photographs were taken in 1948, 1.66 km<sup>2</sup> or 48.6% of the glacier's area has been lost.

Estimated volume loss of glacier ice between the Little Ice Age and 2007 is 2.8 to 3.7 km<sup>3</sup>, or 58 to 63% of the glacier mass. Since 1948, volume losses on the glacier have ranged from 2.6 to 3.4 km<sup>3</sup>, or 56 to 61%.



**Figure 5.** The area of the Wheaton glacier throughout time.

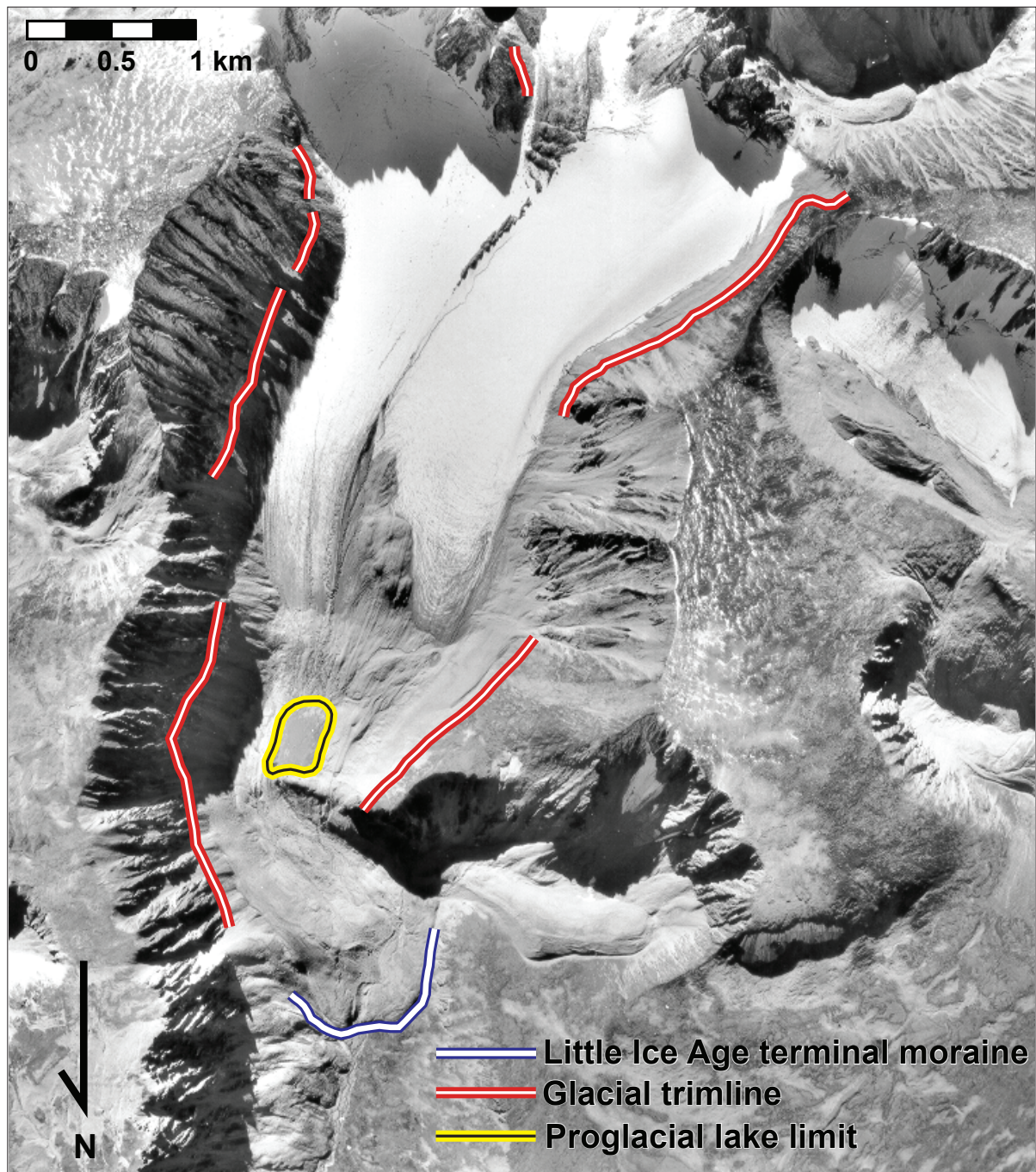
**Table 2.** Volumes of Wheaton glacier through time, estimated using bivariate scaling analysis for three values of  $\Upsilon$  (1.25, 1.36, and 1.4) and associated volume losses since the Little Ice Age (LIA) and the first aerial photography in 1948.

Date	$\Upsilon = 1.25$			$\Upsilon = 1.36$			$\Upsilon = 1.4$		
	Volume (km <sup>3</sup> )	Volume loss since: LIA 1948		Volume (km <sup>3</sup> )	Volume loss since: LIA 1948		Volume (km <sup>3</sup> )	Volume loss since: LIA 1948	
LIA	4.9			5.6			5.9		
1948	4.6	0.2 km <sup>3</sup> /4.5%		5.3	0.3 km <sup>3</sup> /4.9%		5.6	0.3 km <sup>3</sup> /5.0%	
1964	3.5	1.4 km <sup>3</sup> /28.3%	1.2 km <sup>3</sup> /25.0%	3.9	1.7 km <sup>3</sup> /30.4%	1.4 km <sup>3</sup> /26.8%	4.1	1.8 km <sup>3</sup> /31.1%	1.5 km <sup>3</sup> /27.5%
1987	2.7	2.2 km <sup>3</sup> /44.5%	1.9 km <sup>3</sup> /42.0%	2.9	2.6 km <sup>3</sup> /47.3%	2.4 km <sup>3</sup> /44.6%	3.0	2.8 km <sup>3</sup> /48.3%	2.5 km <sup>3</sup> /45.6%
1995	2.1	2.8 km <sup>3</sup> /60.0%	2.6 km <sup>3</sup> /55.0%	2.2	3.4 km <sup>3</sup> /60.0%	3.1 km <sup>3</sup> /58.0%	2.3	3.6 km <sup>3</sup> /61.1%	3.3 km <sup>3</sup> /59.1%
2004	2.1	2.8 km <sup>3</sup> /57.6%	2.6 km <sup>3</sup> /55.6%	2.2	3.4 km <sup>3</sup> /60.7%	3.1 km <sup>3</sup> /58.7%	2.2	3.6 km <sup>3</sup> /61.8%	3.3 km <sup>3</sup> /59.7%
2006	2.0	2.8 km <sup>3</sup> /58.0%	2.6 km <sup>3</sup> /56.0%	2.2	3.4 km <sup>3</sup> /61.1%	3.1 km <sup>3</sup> /59.1%	2.2	3.7 km <sup>3</sup> /62.1%	3.4 km <sup>3</sup> /60.1%
2007	2.0	2.8 km <sup>3</sup> /58.4%	2.6 km <sup>3</sup> /56.4%	2.2	3.4 km <sup>3</sup> /61.5%	3.2 km <sup>3</sup> /59.5%	2.2	3.7 km <sup>3</sup> /62.5%	3.4 km <sup>3</sup> /60.6%

The top of the rock ridge separating the east and west lobes of the glacier was first exposed in 1964. The glacier downwasted 120 m in this area between 1964 and 2007 (from 1873 to 1753 m asl).

## GEOMORPHOLOGY AND CHRONOLOGY

The Little Ice Age terminal moraine is a distinct ridge bordering the glacier forefield. A conspicuous trimline above the current glacier surface is continuous with the terminal moraine and delineates the glacier margin at the Little Ice Age maximum (Fig. 6).



**Figure 6.** Locations of Little Ice Age trimline, moraines in the glacier forefield, and a former proglacial lake visible on 1995 aerial photographs.

Figure 7 presents lichen data from the glacier forefield, and Figure 4 shows the lichen growth curve used to estimate the ages of surfaces in the Wheaton glacier forefield. Table 3 summarizes the age of each lichen site predicted from the lichen growth curve, and Figure 8

shows locations of the glacier terminus at several different times since the Little Ice Age. The lichen ages suggest a steady rate of retreat between the Little Ice Age and 1940s, a period during which no photographs are available.

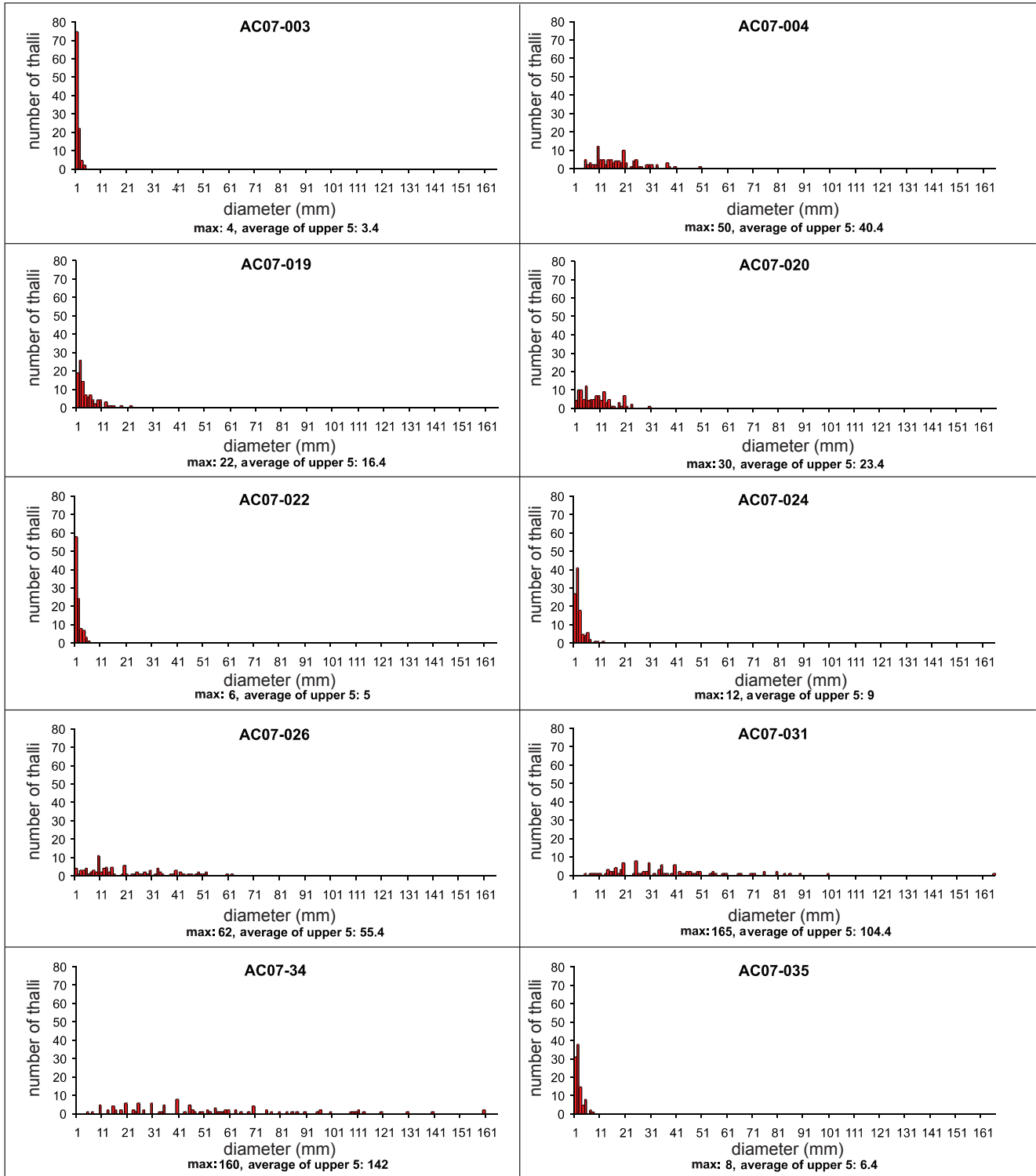
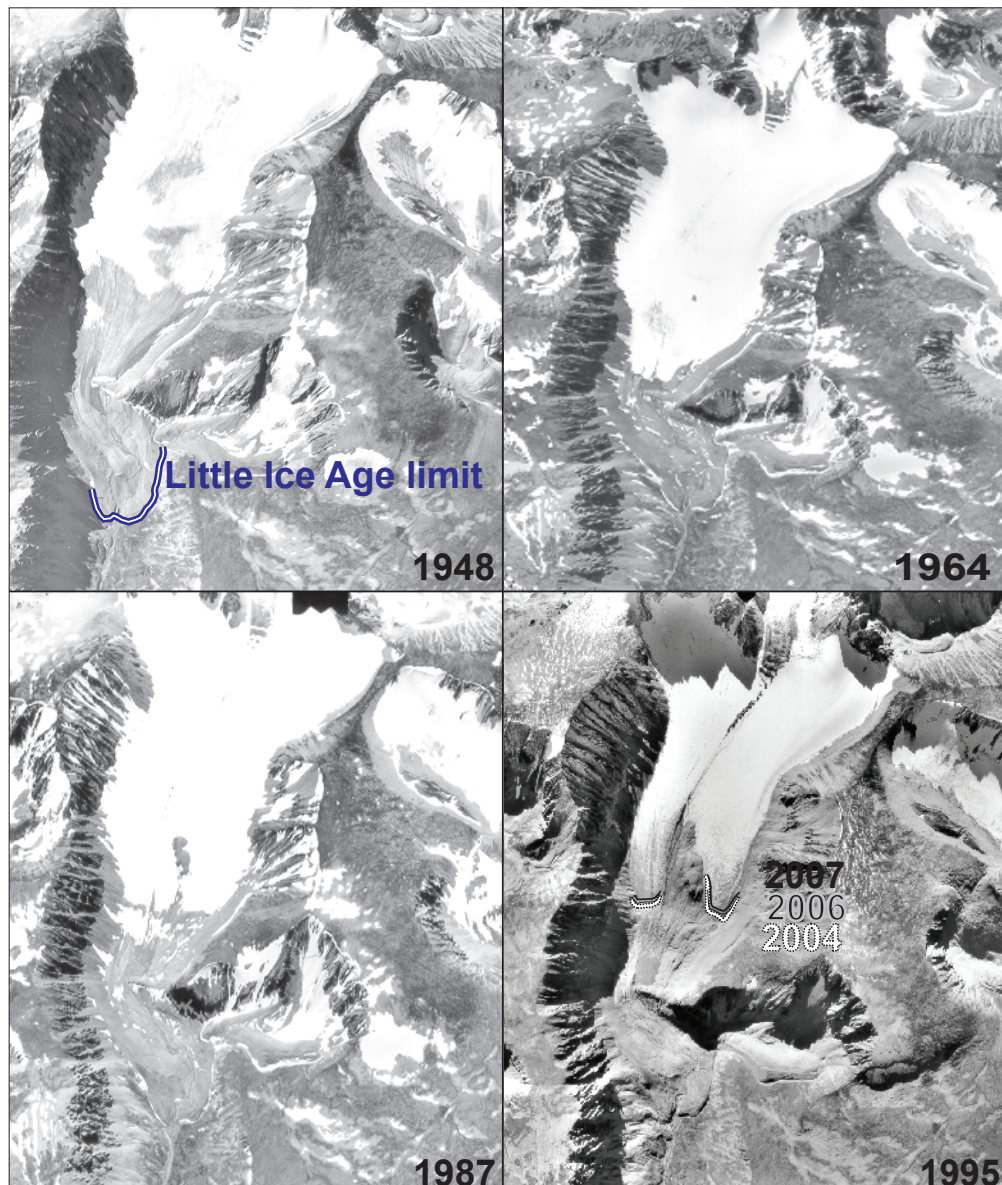


Figure 7. Histograms of the maximum diameter of lichen thalli in the Wheaton glacier forefield and surrounding area.

**Table 3.** For each site, average long-axis diameter of the five largest lichen thalli and ages predicted using the lichen growth curve.

Lichen site number	Average diameter of five maximum lichen thalli (mm)	Estimated age from lichen growth curve	Lichen site number	Average diameter of five maximum lichen thalli (mm)	Estimated age from lichen growth curve	Lichen site number	Average diameter of five maximum lichen thalli (mm)	Estimated age from lichen growth curve
AC07-001	4	1968	AC07-012	25	1930	AC07-023	13	1952
AC07-002	4	1967	AC07-013	33	1915	AC07-024	9	1959
AC07-003	3	1969	AC07-014	21	1936	AC07-026	55	1875
AC07-004	40	1902	AC07-015	13	1952	AC07-027	97	1799
AC07-005	17	1944	AC07-016	19	1941	AC07-028	93	1808
AC07-006	49	1886	AC07-017	17	1944	AC07-029	68	1853
AC07-007	11	1954	AC07-018	18	1942	AC07-030	54	1877
AC07-008	10	1957	AC07-019	16	1945	AC07-031	104	1786
AC07-009	8	1960	AC07-020	23	1933	AC07-033A	11	1954
AC07-010	27	1925	AC07-021	8	1960	AC07-034	142	1718
AC07-011	126	1748	AC07-022	5	1966	AC07-035	6	1963



**Figure 8.** Glacier margins at the peak of the Little Ice Age and in 1948, 1964, 1987, 1995, 2004, 2006 and 2007.

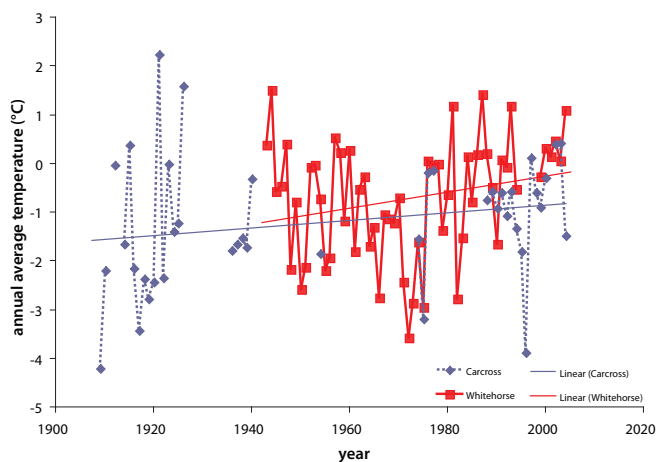
## CLIMATE

Annual average temperature at Whitehorse and Carcross increased for the period 1907 to 2005 (Fig. 9). Annual average precipitation increased in Carcross but has been relatively constant at Whitehorse for the period 1907 to 2005 (Fig. 10).

At both stations, average winter (November to February) temperature increased; average spring (March to May) and summer (June to August) temperatures also increased; and average fall (September to October) temperature decreased (Fig. 11). Average summer and fall precipitation increased over the period of record; winter precipitation increased at Carcross, but decreased at Whitehorse (Fig. 12). Spring precipitation has not changed significantly at Carcross and has decreased at Whitehorse.

ENSO events have been associated with warming and increased precipitation in some areas of northwest North America (Cayan *et al.*, 1998). Figure 13 shows the relationship between ENSO events and the temperature and precipitation records for Carcross and Whitehorse.

Negative PDO events appear to amplify warm ENSO events, further increasing warming and precipitation in northwest North America (Mantua *et al.*, 1997). Figure 14 illustrates a negative correlation between PDO and temperature and precipitation at Carcross and Whitehorse suggesting that ENSO and PDO do not have a major effect on climate of southern Yukon, and therefore, on the mass balance of Wheaton glacier.



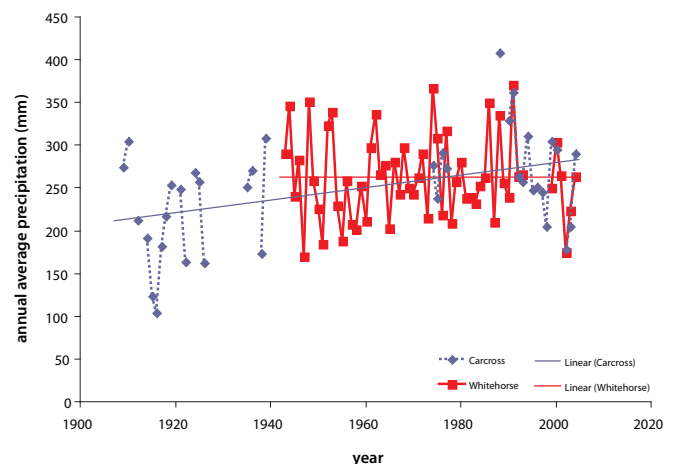
**Figure 9.** Annual average temperature at Whitehorse and Carcross for the period 1907 to 2005.

## DISCUSSION

Wheaton glacier has lost 50% of its area and 58 to 63% of its mass since the maximum of the Little Ice Age in the nineteenth century. Most of the loss since the Little Ice Age (92%) has occurred since the 1940s suggesting that thinning and retreat have accelerated post-1948. In the past 60 years, Wheaton glacier has undergone a steady rate of retreat until the 1990s when its rate of retreat decreased slightly. The glacier is now so thin and short that it may disappear during this century.

The majority of the lichen ages determined using the constructed lichen growth curve appear to agree with the aerial photographs of the area. One notable exception is sites AC07-007, AC07-008 and AC07-009. The lichen populations measured at these three sites suggest ages of 1954, 1957 and 1960, respectively. These ages appear to be anomalous. Sites AC07-001, AC07-002 and AC07-003 all record ages within the 1960s and coincide closely with the ice margin captured in the 1964 aerial photograph. Other sites nearby the three anomalous sites record significantly older ages. The three anomalous sites lie within the boundaries of a rock fall track that is suspected of triggering a debris flow that affected the valley below; we will explore this in a subsequent paper.

The climate record shows that mean temperature in southern Yukon has increased since 1907. Average winter snowfall in Carcross has increased over this period and although winter precipitation has decreased at Whitehorse, annual average precipitation has increased. The lower elevation, drier climate and greater distance of Whitehorse from Wheaton glacier, make that weather



**Figure 10.** Annual average precipitation at Whitehorse and Carcross for the period 1907 to 2005.

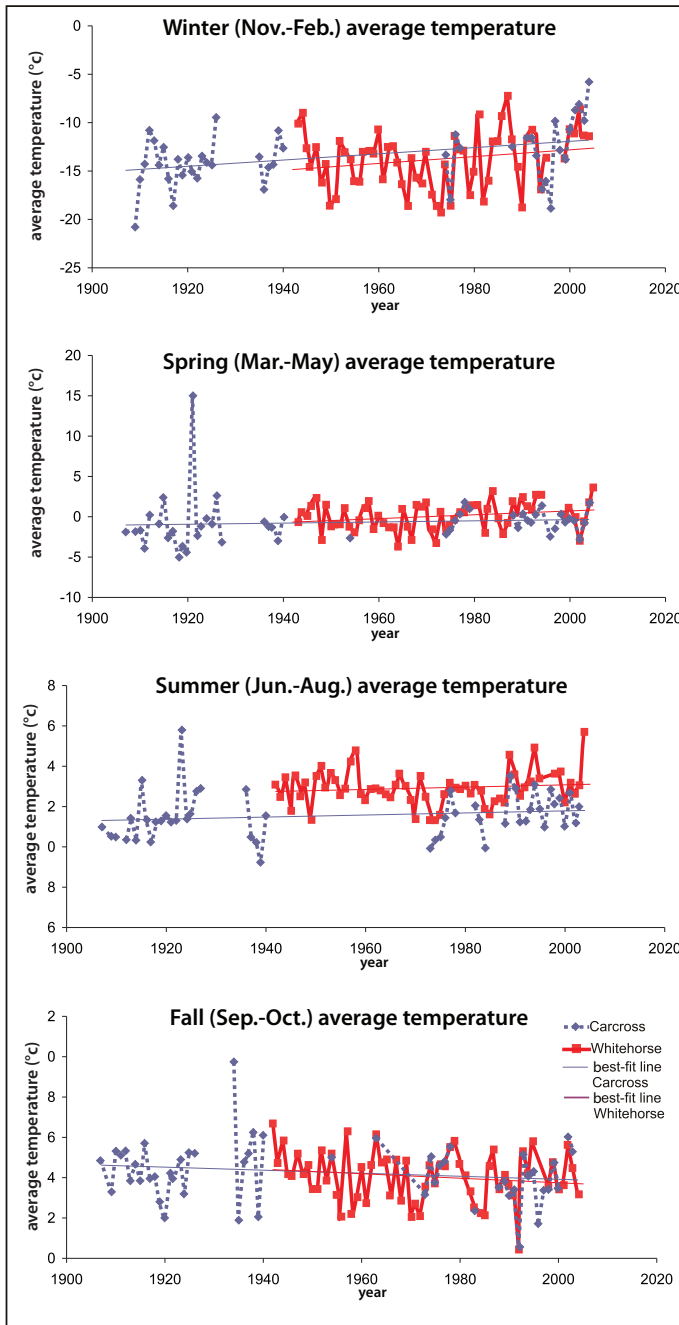


Figure 11. Average seasonal temperatures at Whitehorse and Carcross for the period 1907 to 2005.

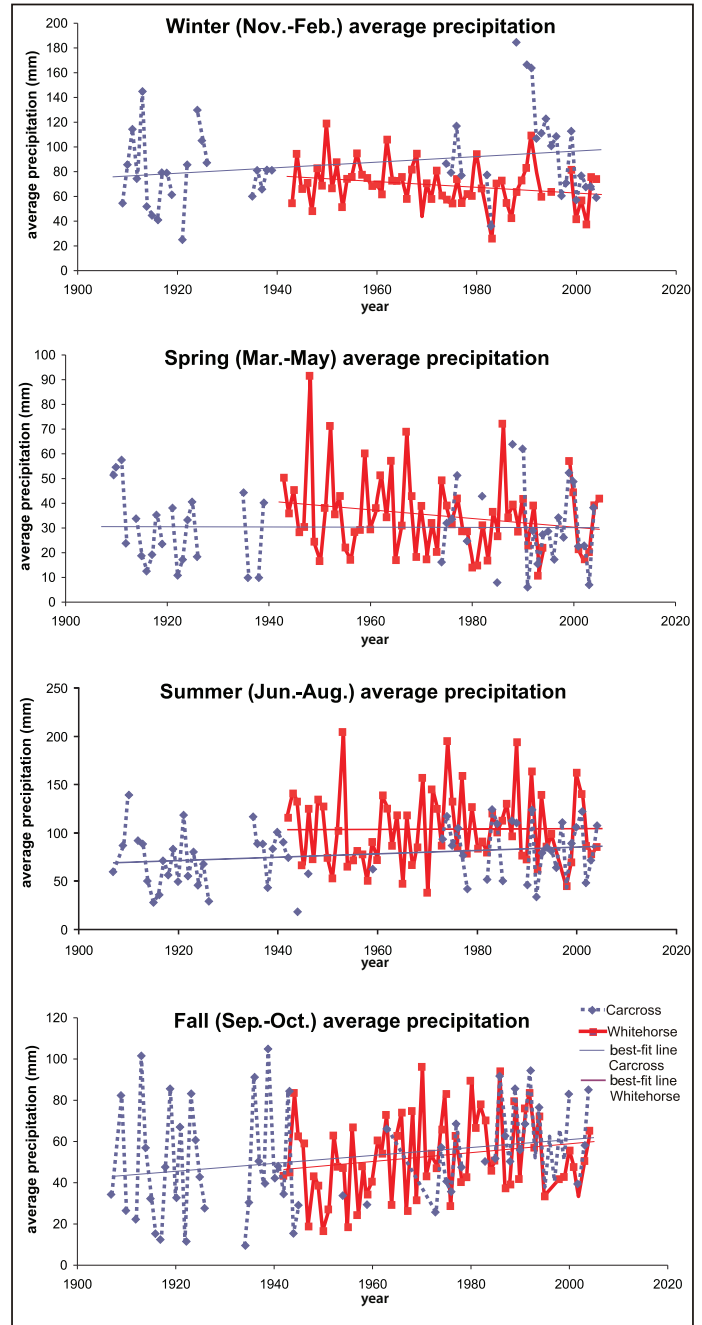
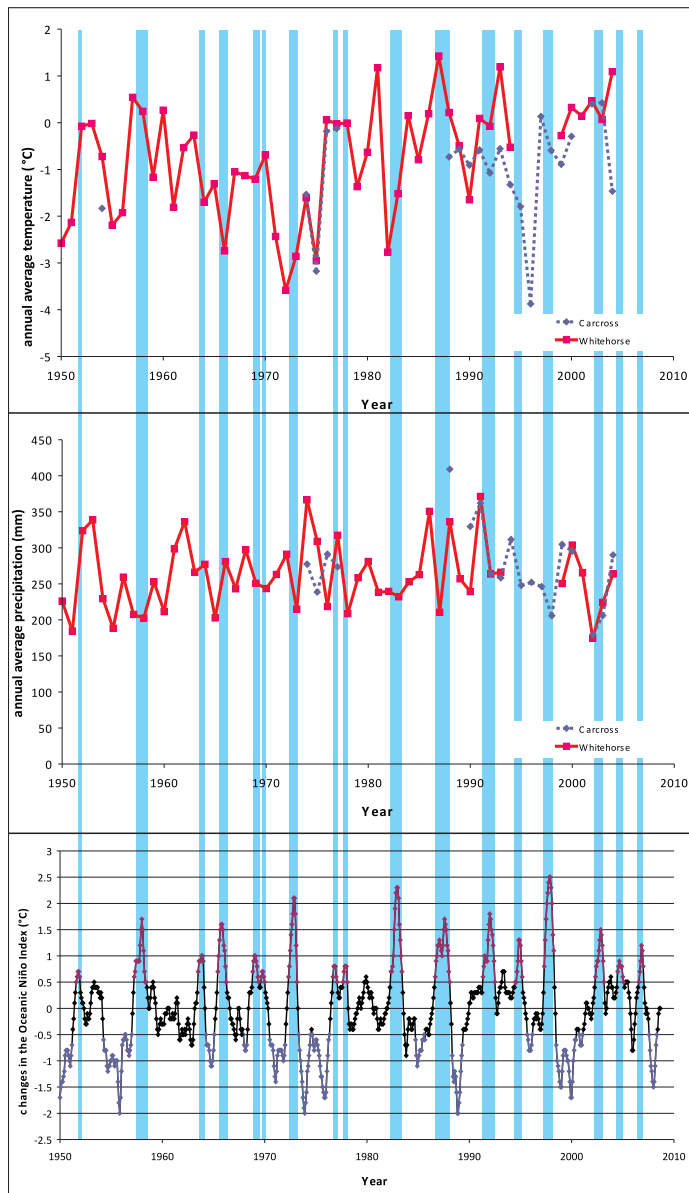
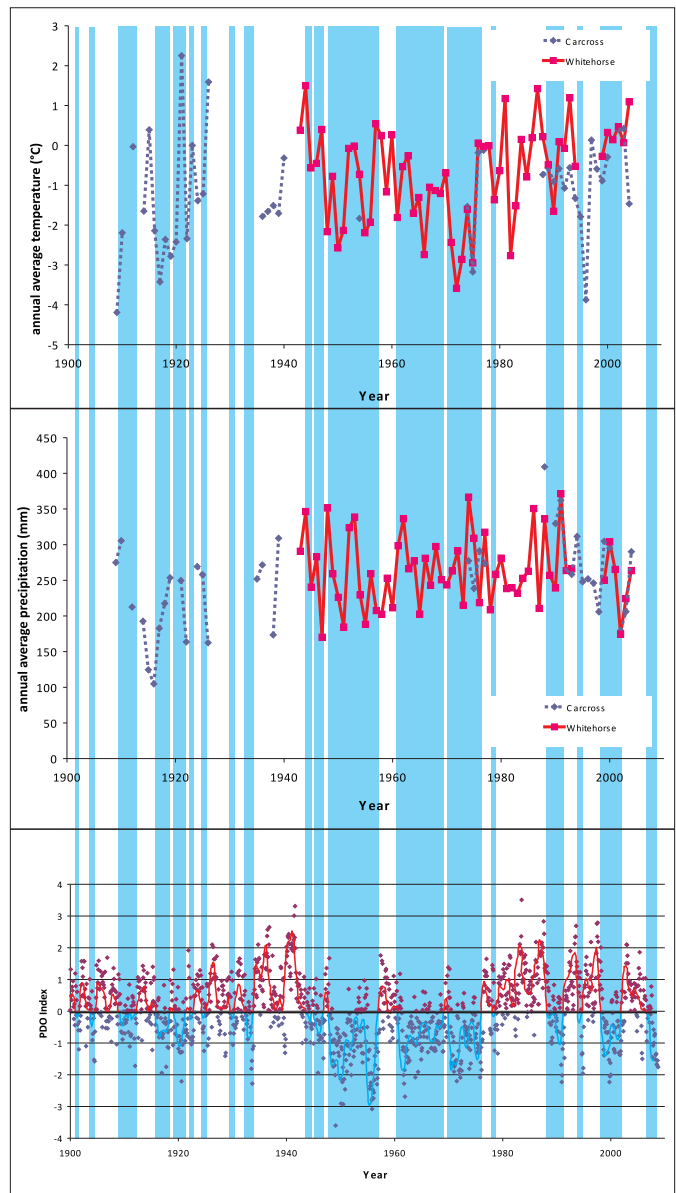


Figure 12. Average seasonal precipitation at Whitehorse and Carcross for the period 1907 to 2005.



**Figure 13.** ENSO record for the period 1950 to 2008 compared to precipitation and temperature at Whitehorse and Carcross. Shaded bars are warm ENSO events.



**Figure 14.** PDO record for the period 1900 to 2008 compared to precipitation and temperature at Whitehorse and Carcross. Shaded bars are negative PDO events.

station less representative than the Carcross station with regards to conditions at Wheaton glacier. On a larger scale, increases in precipitation and temperature during the historic period are consistent with trends throughout most of Yukon territory (Furgal and Prowse, 2008).

Although PDO and ENSO have a significant impact on climate in many areas of northwest North America, they do not appear to significantly affect the climate of the Wheaton River watershed. The increase in temperature during the twentieth and early twenty-first centuries is the main cause of the persistent negative mass balance of Wheaton glacier. Neither PDO phase changes nor increased winter snowfall have affected the activity of the glacier.

## CONCLUSION

Wheaton glacier has significantly thinned and retreated over the past century. Since the Little Ice Age in the 1800s, the glacier has lost 50% of its area and 58 to 63% of its mass. Most of this loss has occurred since the first aerial photographs of the glacier were taken in 1948. Climate data from Whitehorse and Carcross show that temperature in southern Yukon has increased since 1907; winter snowfall has increased at Carcross, but not at Whitehorse. Warming appears to be the main cause of the persistent negative mass balance of Wheaton glacier. If temperatures continue to rise, the glacier will disappear, probably in this century.

## ACKNOWLEDGEMENTS

We wish to thank the Yukon Geological Survey, the National Science and Engineering Research Council, the Yukon Mining and Petroleum Environmental Research Group, the Association for Canadian Universities for Northern Studies, the Northern Scientific Training Program and the Northern Research Institute for their financial, logistical and moral support. In particular we would like to thank Jeff Bond for his support of this project and careful review of this manuscript. Tyler Kuhn, Kayla Vickers and Denny Capps made the whole project possible through their excellent field assistance and positive attitudes in often challenging conditions.

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