LANDSAT TIME SERIES APPLICATION: THE COLUMBIA GLACIER, CANADA – 1985 TO 2010

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ABSTRACT

Alpine glaciers serve as sensitive indicators of climatic change. They are products of such climatic elements as low mean annual temperatures and high winter snowfalls. As these elements change so do glaciers. Thus, it is important to note and measure changes in alpine glaciers. Historical accounts of these glaciers are frequently written observations that provide little detailed data. The time intervals between these accounts are generally lengthy and irregular, making it hard to obtain a clear, systematic picture of glacial change. In recent years studies based on recessional moraines, dendrochronology, and remote sensing have provided more accurate and regular measurements. This study used Landsat 5 data collected over the last 25 years to provide an annual record of changes in the Columbia Glacier, an alpine, outlet glacier situated on the northwest side of the Columbia Icefield in the Canadian Rocky Mountains. Except for 2005, Landsat 5 data sets were obtained for each year starting with 1985 and concluding with 2010. These data sets were recorded within the period between August 1 and September 19, an ideal time of the year for observing and measuring glacial changes. This paper examines the annual change in the advance/retreat and areal coverage of the Columbia Glacier, and illustrates how satellite imagery can provide a systematic, long-term record of changes in phenomena located on the Earth's surface.

Keywords: Landsat 5, Columbia Glacier, glaciation, proglacial lake, and time series assessment

INTRODUCTION

Approximately sixty-nine percent of the fresh water on the Earth's surface is contained in the frozen form of ice. More than 24 million km^3 (5.7 million cubic miles) of ice covers the Earth's surface (Gleick, 1996). Most of this ice is concentrated in two places – Antarctic and Greenland. The remaining ice is spread across a few mountain ranges as alpine glaciers and ice fields. The fresh water ice that breaks away from Antarctica and Greenland flows directly into salt water oceans, which makes it not readily available for human use. The fresh water coming from alpine glaciers feeds many of the rivers that flow across the land and provides water to farms and cities. It is these fresh water sources that society needs to monitor and protect. Many of the alpine glaciers are melting back and many theories have been put forth as to why these glaciers are retreating. This paper centers on one particular glacier, known as the Columbia Glacier. It is located in the Columbia Icefield, which is one of the major sources of fresh water in North America. Landsat imagery recorded over the last 25 years has been used to observe and measure the changes in this glacier. This paper reports on these changes and shows how Landsat imagery can provide regular chronological records of events occurring on the Earth's surface.

COLUMBIA GLACIER

Straddling the boundary between the Canadian provinces of Alberta and British Columbia, the Columbia Icefield is the largest ice mass in North America, south of the Arctic Circle (Figure 1). Situated in the Canadian Rockies, this ice field covers 365 sq. km. (141 sq. mi.) with a maximum depth of 365 m. (1,197 ft.). It occupies a high, flat-lying plateau in the form of a huge massif with an average elevation of about 3,000 m. (9,842 ft.). Mount Columbia (3,745 m.; 12,187 ft.) and Mount Athabasca (3,491 m.; 11,453 ft.) form the highest points in the ice field. Its average annual snowfall is 7 m. (23 ft.).

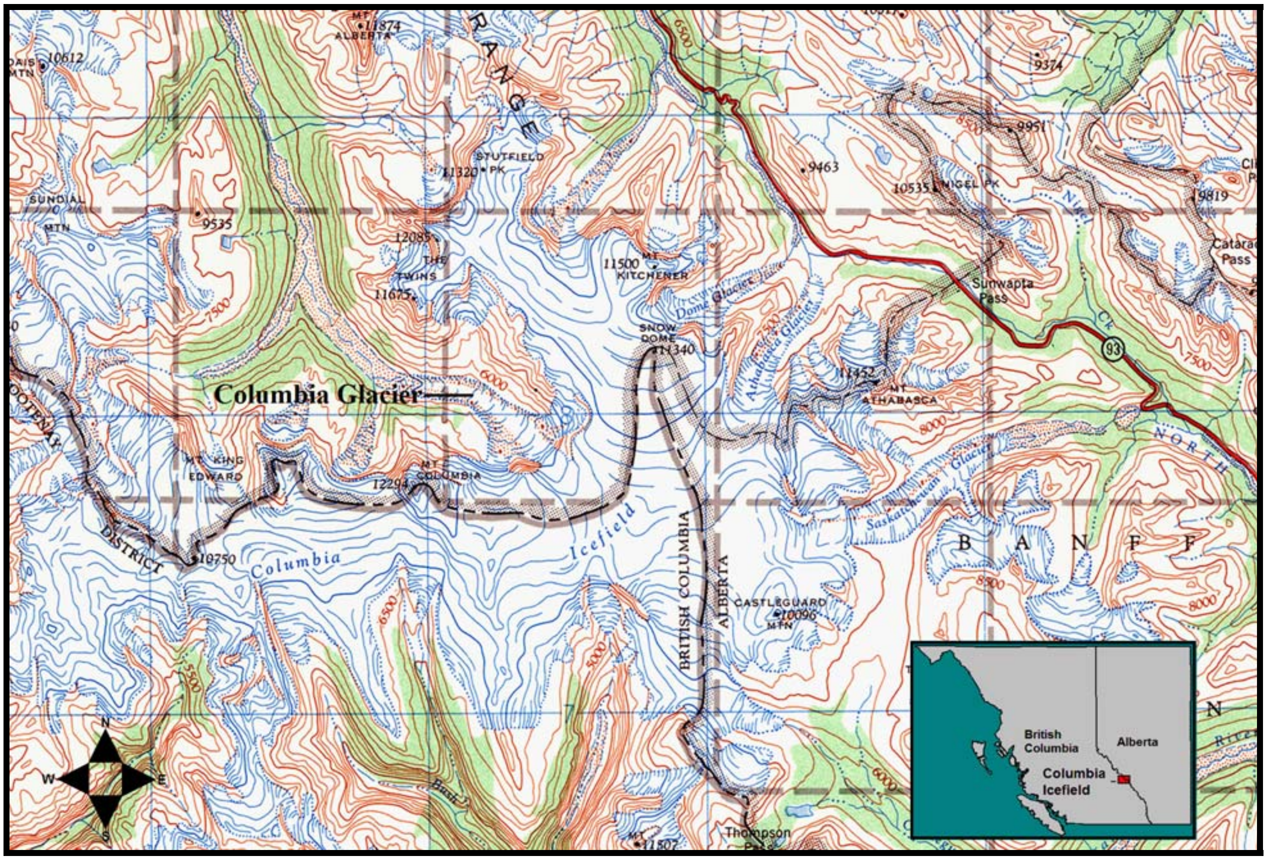

Figure 1. Columbia Icefield Topographic Map, 1960.

Six large outlet glaciers flow from the ice field, one of which is the Columbia Glacier. The others are the Athabasca, Castleguard, Dome, Saskatchewan and Stutfield Glaciers. Through these glaciers fresh water flows from the Columbia Icefield into three different oceans, namely the Atlantic, the Pacific and the Arctic. This situation is referred to as the "hydrographic apex of North America," basically the center of water distribution in North America. The Columbia Glacier is the major outlet glacier flowing from the northwest section of the ice field. Melt water from the glacier enters a large proglacial lake, which feeds the Athabasca River. Water from this river makes its way to the Arctic Ocean by the Mackenzie River system. In comparison to Athabasca, Dome, and Saskatchewan, that are located in close proximity to Highway 93 and the Icefield Centre, the Columbia Glacier is rather isolated and difficult to reach, making it hard to monitor on a regular basis. The Landsat images used in this study have provided an excellent view of the glacier and its development over the past 25 years.

The glacier drops suddenly from the ice field forming a major icefall, which establishes rather evenly spaced ogives across the upper half of the glacier. The icefall divides the accumulation area (the ice field) from the ablation area (the glacier). At one time a large tributary glacier, named Manitoba, merged with the Columbia on its south side but the Manitoba has retreated and is now debris covered, showing little movement.

In 1998 the Columbia Glacier extended about 4 km. (2.48 mi.) from the icefall to the proglacial lake. Robinson (1998) described the tongue as possessing a low gradient of approximately 5 degrees and the central section of the glacier as having relatively clean ice with the northern and southern edges as being debris covered. An oblique aerial photograph taken in 1964 (Figure 2) shows lateral moraines paralleling the glacier as well as a trimline on the south side of the valley, both features indicating that the glacier at one time covered a larger portion of the valley. Below the trimline exists steep, bare slopes; above heavy forest vegetation covers the slopes. A similar line occurs on the north side of the valley but is not easy to detect in the photograph.

Figure 2. Oblique aerial photograph of Columbia Glacier in 1964.

PREVIOUS WORKS: 1901-2002

The first recorded visit to the Columbia Glacier occurred in 1901 (Habel 1902). Based on a photograph taken at the time, the glacier appeared to be near its maximum extent relative to its terminal moraine and the trimline. However, the Manitoba Glacier had receded significantly. The next known visit happened in 1907 (Schaffer, 1908). Photographs from this expedition showed little change in the position of the glacier. It was a few hundred feet back from the terminal moraine. In 1919 the Interprovincial Boundary Commission (1924) came to the area to map the boundary between Alberta and British Columbia and took some photographs of the glacier. Between 1907 and 1919 the glacier apparently had retreated somewhat but still extended across the valley to the forest edges (Field, 1949). Howard Palmer (1924, 1925) visited the glacier in both 1920 and 1924. On his 1924 expedition he took a series of photographs that Field (1949) was able to duplicate partially in his 1948 visit. In examining the 1924 and 1948 photographs Field reported that by 1924 the glacier from its terminus to the terminal moraine had moved back about 396 m. (1,300 ft.) and by 1948 retreated 823 m. (2,700 ft.). Palmer's 1924 photographs also revealed that the glacier had lowered noticeably from its position shown in Habel's and Schaffer's photographs from 1901 and 1908. Additionally, lateral moraines started to appear. Field calculated that the annual recession rate from the terminal moraine, established sometime before 1900, to 1919 was less than 15 m. (50 ft.) per year but increased between 1919 and 1948 to 30.5 m. (100 ft.) per year.

A chronological series of moraines created by the glacier as it retreated has been identified, with the terminal moraine being dated 1724 (Heusser, 1954). The dates for the recessional moraines are: 1842, 1854, 1864, 1871, 1907, 1909, and 1919. Between 1724 and 1924 the glacier retreated 394 m. (1,292 ft.), nearly one-fourth of a mile. Heusser (1956) visited the glacier in 1953 and found that the north side of the glacier started retreating in 1724; whereas, the south side did not begin to move back until 1763. He concluded the difference in dates might be attributed to Manitoba Glacier, which at the time was still coalescing with the Columbia Glacier.

However, between 1966 and 1977 the glacier had advanced as much as 1 km. (.62 mi.) (Baranowski and Henoch, 1978). During this period the glacier moved forward enough to completely fill the large proglacial lake, a distance of some 800 m. (2,625 ft.) (Ommanney, 2002). Ommanney states that "The glacier is not being surveyed regularly, so it is not known whether this advance is continuing." Between 1992 and 1996 Robinson studied the glacier and developed Table 1, which is based on previous explorations to the glacier. During the early and mid

1900s the glacier's rate of retreat was rather constant at around 25 to 30 meters per year. Between 1966 and 1977 it advanced suddenly and covered a large distance. In1976 it started to retreat again but at a higher rate.

Table 1. Recession of Columbia Glacier

Period	Distance of Retreat (m)	Rate of Retreat (m/yr)	Source
Early 18th century - 1924	400	-	Field & Heusser 1954
1920-1924	75	19	Field 1949
1924-1953	1025	35	Field & Heusser 1954
1948-1955	175	25	Robinson 1998
1955-1966	330	30	Robinson 1998
1966-1974	160	20	Robinson 1998
1974-1976	-71	-36	Robinson 1998
1966-1977	-1000	-91	Baranowski & Henoch 1978
1976-1992	925	52	Robinson 1998
1992-1996	400	100	Robinson 1998

Source: Robinson 1998

CURRENT FINDINGS

The image data sets used in this study came from Landsat 5 Thematic Mapper (TM) sensor. Launched on March 1, 1984, Landsat 5 celebrated its 25th anniversary of operation in 2009, 22 years past its originally planned 3-year mission timetable. Except for 2005, Landsat 5 TM data sets covered the Columbia Icefield and the Columbia Glacier every year starting with 1985 and ending with 2010. These data sets were recorded between August 1 and September 19, the late summer-early fall period of the year. Table 2 provides the date for each data set. By this time of the year most of the winter-spring snow fall has melted away, making it easier to distinguish the glacier from surrounding land surfaces. However, snow conditions can occur over the glacier at any time of year based on its high latitude and high elevation. Finding this remarkable time series of data sets was not easy due to the heavy amount of cloud cover generally associated with the Canadian Rockies. Except for the 1993 and 2000 data sets, the data sets were of high quality. The two exceptions had some haze but were still good enough to use. Finding the data sets was helped by the ice field appearing on two adjacent satellite paths (paths 44 and 45 and row 24). A high degree of overlap between the paths existed due the high latitude location of the ice field. Twenty three of the data sets were freely downloaded from the U.S.G.S. Earth Resources Observation and Science Center, one from the Natural Resources Canada GeoGratis, and one from the Global Land Cover Facility at the University of Maryland.

Distance Measurements

Distance measurements were taken using the glacier's terminus location in 1985 as a base point. A coordinate reading was taken at the mid-point of the terminus' extreme edge in 1985. The edge was determined at the point where the glacier was clearly visible and discernable from the debris and lake water. Coordinate readings were taken at the terminus' extreme edge for each additional year. Straight line distances from the 1985 base point were calculated using the coordinate readings. Included in the calculations was the pixel size for each image, which was 30 m. by 30 m. From this information, annual distance changes were determined (Table 2).

Except for 1987 and 1991, the glacier retreated over the 25 year span. The total retreat was 2.76 km. (1.7 mi.). However, the amount of change per year varied considerably. The average rate of retreat was 111.97 m. (367.26 ft.) but it ranged from -58.44 m. (-191.70 ft.) to 502.25 m. (1647.39 ft.) with a standard deviation of 118.74 m. (389.46 ft.). Figure 3 provides a graphic picture of the glacier's irregular nature with respect to its movement. The red bars indicate retreats and the blue bars advances. The glacier's terminus did not change in the years of 1998, 1999 and 2008. In comparison to previous works this 25 year record of annual changes provides a much more detailed account of how the glacier is functioning. Its change pattern is very irregular. From the perspective of length, the glacier in 1985 was 5.25 km. (3.25 mi.) long. In 2010 it was 2.67 km. (1.65 mi.) long, a change of 2.60 km. (1.60 mi.).

Based on Heusser's 1954 work the glacier's terminal moraine dates to 1724, which relates to the Little Ice Age. The location of the terminal moraine can be detected on the images. The distance between the farthest advance of the terminal moraine and the 1985 terminus is 1502.70 m. (4930.11 ft.) or 1.50 km. (.93 mi). By adding this distance to the other distances the amount of change since the Little Ice Age can be ascertained. Within the 25 year period from 1985 to 2010 the glacier has retreated nearly double the distance that it receded in the 261 years from 1724 to 1985.

Table 2. Distance and area measurements per year

Year	Month/Day	Distance: M/1985	Distance: Ft/1985	Distance: M/YR	Distance: Ft/YR	Area: Sq. Km.	Area: Sq. Mi.
1985	Sept. 10	0.0	0.0	-	-	2.45	.946
1986	Aug. 3	94.87	311.25	94.89	311.25	2.48	.959
1987	Aug. 6	67.08	220.09	-27.79	-91.16	2.43	.939
1988	Sept. 2	569.21	1867.48	502.25	1647.39	2.33	.898
1989	Aug. 11	778.85	2555.26	209.68	687.78	2.08	.802
1990	Sept. 15	953.42	3128.00	174.61	572.74	2.08	.802
1991	Aug. 1	894.99	2936.30	-58.44	-191.7	2.08	.803
1992	Aug. 2	924.18	3032.07	29.19	95.77	2.05	.793
1993	Sept. 7	982.70	3224.08	58.53	192.01	2.05	.791
1994	Sept. 19	1247.81	4093.82	265.16	869.74	1.97	.760
1995	Sept. 13	1336.60	4385.16	88.82	291.34	1.90	.735
1996	Aug. 7	1425.55	4677.00	88.97	291.84	1.87	.721
1997	Aug. 10	1574.07	5164.27	148.55	487.27	1.79	.690
1998	Sept. 5	1574.07	5164.27	0.00	0.00	1.79	.680
1999	Sept. 8	1574.07	5164.27	0.00	0.00	1.78	.688
2000	Aug. 18	1693.07	5554.69	119.03	390.42	1.76	.678
2001	Aug. 12	1752.63	5750.08	59.57	195.39	1.67	.646
2002	Aug. 8	1879.49	6166.31	126.89	416.23	1.68	.650
2003	Aug. 2	2155.41	7071.55	275.98	905.24	1.67	.645
2004	Aug. 13	2318.36	7606.16	162.99	534.61	1.60	.617
2005	No Data	-	-	-	-	-	-
2006	Aug. 26	2476.95	8126.47	79.31	260.15	1.59	.616
2007	Aug. 6	2606.55	8551.65	129.62	425.18	1.55	.599
2008	Aug. 8	2606.55	8551.65	0.00	0.00	1.55	.599
2009	Sept. 12	2671.52	8764.80	64.98	213.15	1.53	.592
2010	Aug. 14	2765.86	9074.34	94.37	309.54	1.52	.588

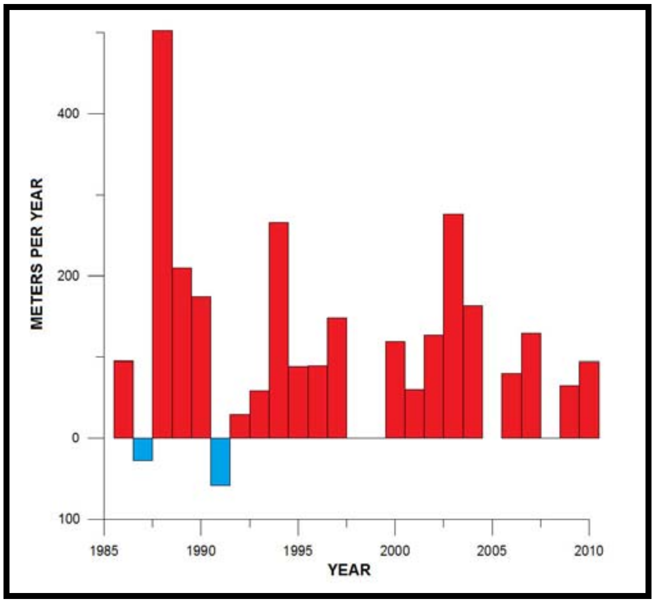

Figure 3. Advances and retreats of the Columbia Glacier between 1985 and 2010.

Area Measurements

The area measurements were obtained by digitizing the discernable portion of the glacier from the debris and lake water. The glacier was separated from the ice field at the bottom of the ice falls. Table 2 shows that the glacier decreased in area from 2.45 square kilometers (.95 sq. mi.) to 1.52 square kilometers (.59 sq. mi.) in the 25 year period. At this rate of shrinkage the glacier might not be detectable within the next 25 to 35 years. The light blue in Figure 4 illustrates the shrinkage of the glacier between 1985 and 2010. The red identifies the glacier's areal coverage in 2010.

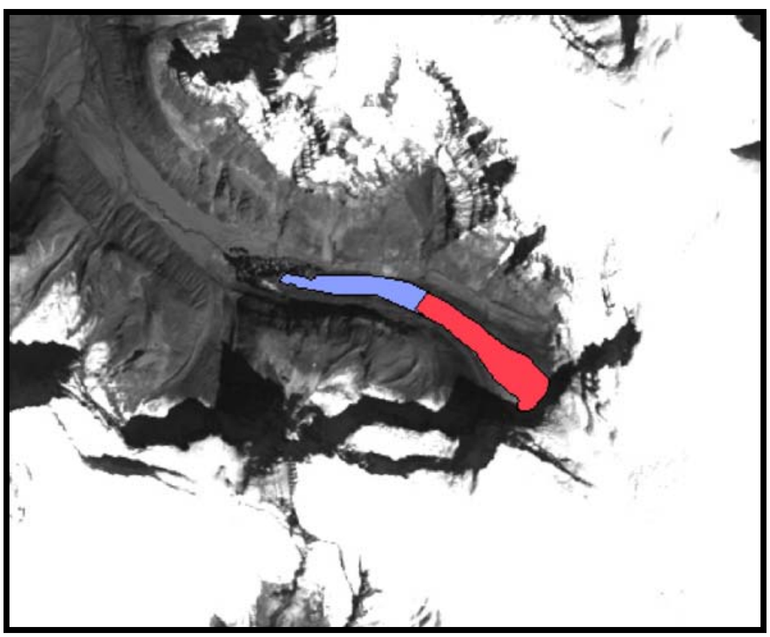

Figure 4. Glacier shrinkage1985-2010 (blue); glacier in 2010 (red).

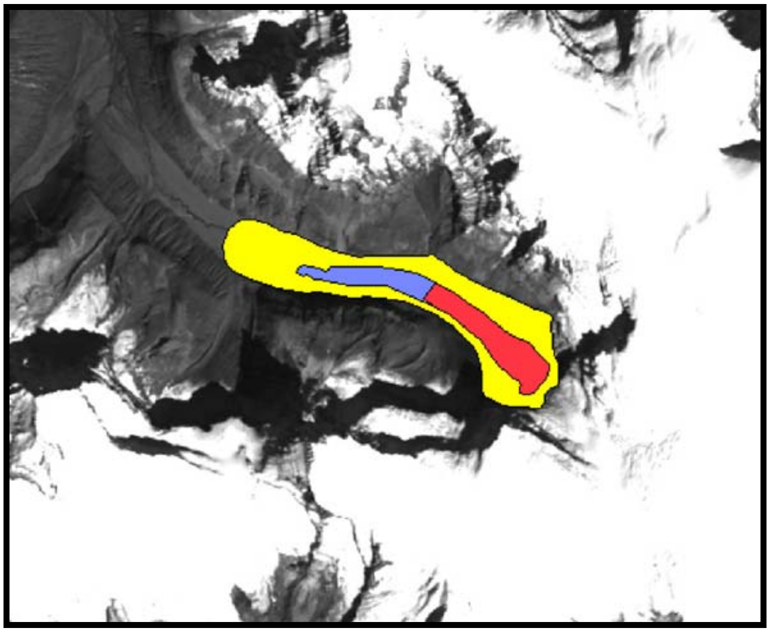

Figure 5. Glacier in 1724 (yellow).

The trimlines on the north and south valley walls define the maximum width of the glacier at its fullest extent. These lines can be easily identified in the Landsat images. As the trimline extents down the valley its top edge gradually slopes toward the valley floor identifying the maximum growth of the glacier. This pattern can be clearly seen on the north side of the valley. Where the top edge of the trimline intersects the valley floor the terminal moraine can be detected. Using the trimlines and the terminal moraine the maximum size of the glacier was ascertained (5.45 sq. km.; 2.10 sq. mi.). Figure 5 compares an aerial coverage of the 1724 glacier to the 1985 and 2010 glacier and provides a clear picture of the glacier's meltdown over the 286 year period. Not knowing the terrain under the glacier makes it impossible to determine volume measurements. Such measurements would provide the best information on the amount of meltdown.

Empirical Observations

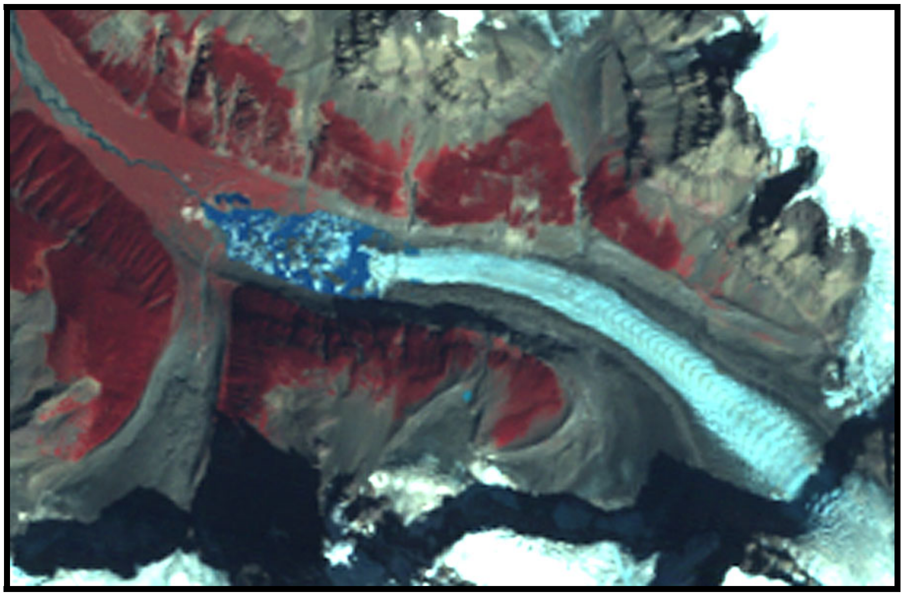

Figure 6. 1988 -- High density of bergs and irregular shaped tongue.

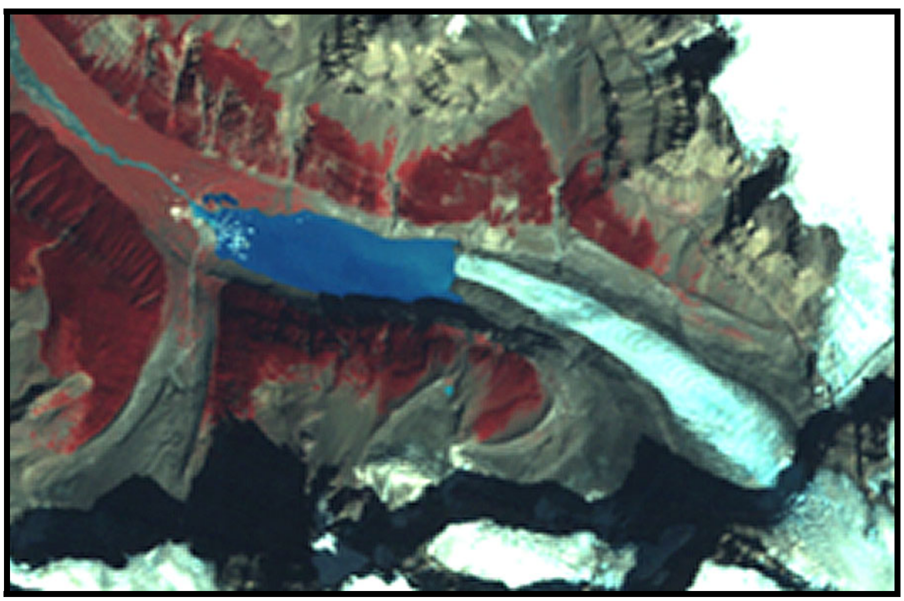

Figure 7. 1998 – Bergs concentrated at far end of lake and the glacier's terminus is straight lined.

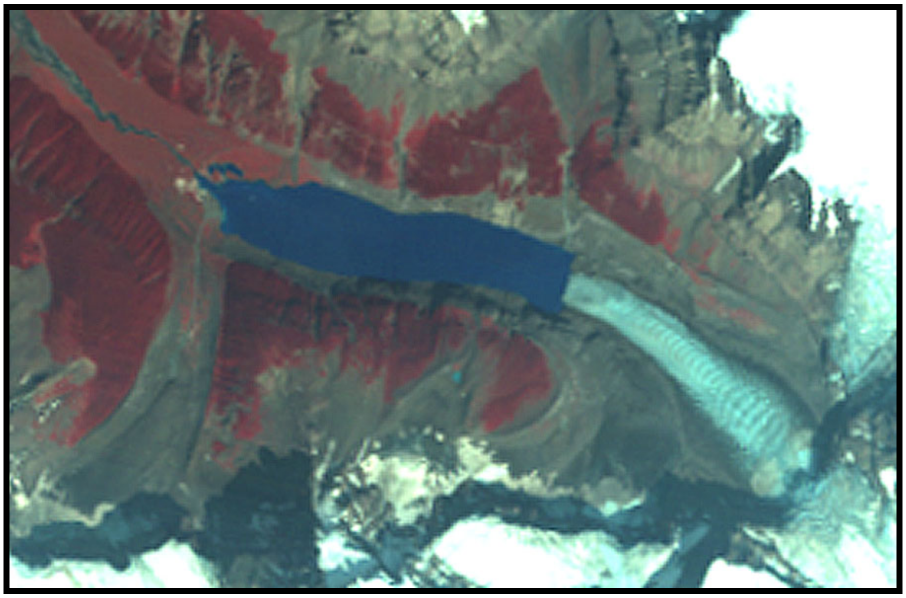

Figure 8. 2008 – No bergs and lake is longer than the glacier.

Since it would not be feasible to display all 25 images, three images were selected to illustrate some of the patterns observed. The three images cover the years 1988, 1998, and 2008, providing a ten year interval between the images. The images are false color composites using the near infrared (Band 4), red visible (Band 3), and green visible (Band 2). The near infrared helps to delineate the water features from the land surfaces. It also assists in separating the evergreen forests (dark red) on the valley sides from the vegetation (light red) on the valley floor and the non vegetated areas.

Between 1985 and 1995 the proglacial lake contained a large number of icebergs. These bergs might have been due to calving or the melt back of the glacier as it retreated from its earlier advancement over the lake. Its only two advancements within the 25 year period occurred in this 10 year span. They were in 1987 and 1991. However, the glacier's greatest annual retreat took place in 1988. Figure 6 provides an example of the number and density of bergs in the lake. From 1996 to 2000 the number of icebergs per year decreased considerably. They were concentrated more at the far end of the lake (Figure 7). By the mid-2000 decade the lake was free of bergs (Figure 8).

From 1985 to 1989 the glacier's terminus was irregular in shape, lacking the typical tongue pattern. The lake raps around the terminus on three sides (Figure 6). By 1990 the terminus started to have a straight line pattern (Figures 7 and 8). This pattern continued through 2010. The glacier's tongue might be under the lake's water, which would account for the straight line pattern. As previously indicated Robinson (1998) recorded the glacier's tongue in 1996 as having a low gradient. The lake colorization in Figure 7 suggests a tongue pattern extending from the glacier into the lake. This pattern was detected on the 1997 and 1999 images but not after 1999.

Figures 6 and 7 provide excellent views of the lateral moraines on both sides of the glacier and the sections of the valley cut earlier by the glacier when it advanced during the Little Ice Age. As the glacier retreats in size and the lake grows, the lateral moraines are being submerged under the water. Figure 2 provides some idea of the height and width of these moraines. Figures 7 and 8 show how the glacial end of the lake extends in width well beyond the width of the glacier's terminus, covering the lateral moraines. Based on the size of the moraines being covered and the before mentioned sharp, straight line pattern between the glacier and lake, the lake water might be extending over the front of the glacier and its sections of the lateral moraines.

Figures 6-8 show the flow path of the Manitoba Glacier. Its valley enters into the lake from the south side. A small stream appears to originate from it and to run into the lake. At one point in time the Manitoba had coalesced with the Columbia Glacier. The glacier is heavily saturated with debris and can be distinguished by its darker color from the other valley floor surfaces. It has been reported to have had no movement in many decades. However, a close examination of Figures 6-8 indicates a change in the glacier's terminus and a slight retreat in the glacier.

Proglacial Lake

Since the proglacial lake represents such a prominent feature in the glacier's overall system, some comments about it are required. It was first recorded in aerial photographs taken in 1948 (Field, 1949). Morphologically the lake with its long, narrow shape and morainic build-up at the outlet end appears to have the same structure as a finger lake. It is large when compared to similar lakes associated with other outlet glaciers originating from the ice field. In 2010 its length exceeded the full length of the glacier. The Saskatchewan and Athabasca, the two largest outlet glaciers flowing from the ice field, have established proglacial lakes but these lakes are small relative to the Columbia's proglacial lake. Large deposits of morainic material exist between the Saskatchewan and Athabasca glaciers and their respective proglacial lakes, something that does not occur with the Columbia Glacier and its proglacial lake. The Columbia Glacier appears to flow directly into its proglacial lake. All three lakes have similar morphologies with respect to their wide V-shaped termini from which streams originate carrying fresh water into large river systems. Figure 9 compares the proglacial lakes for the Columbia and Saskatchewan glaciers. The Saskatchewan Glacier is considerably larger than the Columbia Glacier but its proglacial lake is dwarfed by the Columbia proglacial lake. At its present rate of decrease the Columbia Glacier might disappear over the next 25 to 35 years leaving behind a huge lake. It might be necessary to monitor the buildup of water against the morainic dam holding it in place. A sudden rupture of this barrier could result in an outburst flood, something that has happened with other proglacial lakes.

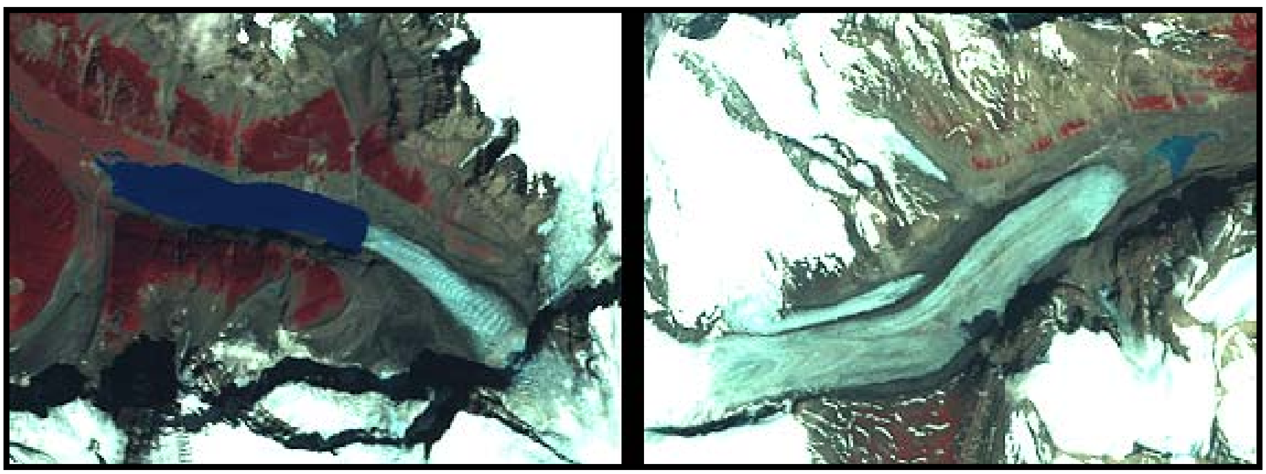

Figure 9. Landsat 5 images of Columbia Glacier (left) taken in 2010 and Saskatchewan Glacier in 2008. The images show the proglacial lakes for both glaciers. The images are at the same scale.

SUMMARY

In comparison to previous works on the Columbia Glacier, this study was able to provide information on the annual change of the glacier over a 25 year period. The measuring and observing of the annual changes in the glacier was made possible by remotely sensed data obtained from the same sensor system and the long service of Landsat 5. Although previous works were able to measure changes farther back in time, long and irregular time spans occurred between these studies; consequently, measurements were rather generalized as shown in Table 1. In addition, different methods were used to measure changes. This study showed that conditions changed dramatically from year to year. The reasons for such irregularity need to be studied.

In addition to determining the 1724 date for the terminal moraine Heusser (1954) calculated the dates for a series of recessional moraines, which were: 1842, 1854, 1864, 1871, 1907, 1909, and 1919. If these dates could be linked to specific moraines shown on remotely sensed imagery, additional distance measurements could be ascertained. He does provide a distance measurement between 1724 and 1924. Imagery used in such a study might be Landsat 7's Band 8 that has a higher resolution than TM images or other high resolution imagery.

The next step in the use of this 25 year data record is to use the Thermal Infrared (IR) band to study temperature conditions on both the glacier and the ice field. It might be possible to distinguish between the zones of accumulation and ablation and determine if the boundary between these zones is changing.

Finally, the importance of having a long imagery record for studying remotely located phenomena cannot be overemphasized. Without the Landsat 5 imagery record on the Columbia Glacier, the annual changes in the development and dynamics of the glacier could not have been observed and measured. Hopefully this record can be continued.

The Columbia Glacier is receding at what appears to be a rapid rate. The images show this recession. The reasons for the recession might not be clearly known, but the consequences can be predicted. The flow of fresh water to the Mackenzie River system will decrease. This could the fate of the other outlet glaciers originating from the Columbia Icefield.

REFERENCES

Baranowski, S., and W.E.S. Henoch, 1978. *Glacier and landform features in the Columbia Icefield area, Banff and Jasper National Parks, Alberta, Canada*. Ottawa, Ontario: Environment Canada, Inland Waters Directorate, Glaciology Division, (Supplementary report on a study carried out for Parks Canada), 175 p. (with maps)

Field, W.O., 1949. Glacier Observations in the Canadian Rockies, 1948, *Canadian Alpine Journal 32*: 99-114.

Gleick, P. H., 1996. Water resources, *In Encyclopedia of Climate and Weather*. ed. by S. H. Schneider, Oxford University Press, New York, Vol. 2, pp.817-823.

Habel, J., 1902. At the Western Source of the Athabaska River, *Appalachia, 10*: 23-43.

Heusser, C.J., 1954. Glacier fluctuations in the Canadian Rockies: General Assembly of Rome, International Association of Hydrological Sciences, International Union of Geodesy and Geophysics, *IASH 39*: 493–497.

Heusser, C.J., 1956. Postglacial Environments in the Canadian Rocky Mountains, *Ecological Monographs 26*(4): 263–302.

Interprovincial Boundary Commission, 1924. *Report of the Commission appointed to delimit the boundary between the Provinces of Alberta and British Columbia, Part II*. Ottawa, Ontario: Office of the Surveyor General, 155 p. (with maps)

Ommanney, C. S. L., 2002. Glaciers of North America—Glacier of Canada: Glaciers of the Canadian Rockies, *Satellite Image Atlas of Glaciers of the World.* ed. by Williams, R. S. and J. G. Ferrigno, U.S. Geological Survey Professional Paper 1386(J-1). 289p.

Palmer, H., 1924. Travels and Ascents Among the Highest Canadian Rockies, *Appalachia 16*: 257-277.

Palmer, H., 1925. The First Ascent of Mt. King Edward, Canadian Rockies, with a note on Mt. Alberta, *The Alpine Journal 37*:306-315.

Robinson, B.J., 1998**.** *Reconstruction of the glacial history of the Columbia Icefield, Alberta* (Master's thesis). London, Ontario: Faculty of Graduate Studies, University of Western Ontario.

Schaffer, M.T.S., 1908. Untrodden Ways, *Canadian Alpine Journal 1*: 288-294.