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GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8503

Mass balance results from the Cordillera Glacier-Climate Observing Network, British Columbia, Northwest Territories, and Alberta, for 2015 and 2016 balance years

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ABSTRACT

Geological Survey of Canada Open File 8503 presents mass balance data from glaciers in the Cordillera Glacier-Climate Observing network for the 2015 and 2016 balance years. Glacier-wide net annual balances at all observing sites were negative for both years. Results from the surveys indicate warmer summer conditions with less winter accumulation occurred throughout western and northern Cordillera in 2015 compared to 2016. Where historical mass balance data exists, annual glacier-wide mass balances during both balance years were more negative than long-term averages. Historically significant melt rates were observed at Peyto Glacier where annual balance was 2nd most negative on record.

TERMINUS OF HELM GLACIER, SEPTEMBER 29, 2016, GARIBALDI PROVINCIAL PARK, BRITISH COLUMBIA.

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1. Introduction

Since the start of the International Hydrological Decade in 1965 (Nace, 1965), the Government of Canada has been observing and assessing information describing the distribution, mass and surface area of numerous glaciers across the western Cordillera – in particular along an east-west transect through the southern Canadian Rocky Mountain, Interior Ranges and Coast Mountains (Østrem, 1966; Østrem 2006; Demuth and Keller, 2006; Demuth and Ednie, 2016). The main goal of the work was to examine the spatio-temporal variations of glacier health – in particular glacier mass balance – and relate these changes to their causality (f.ex., climate variability and climate change: Moore and McKendry, 1996; Bitz and Batisti, 1999; Hodge et al., 1998; Demuth and Keller, 2006; Demuth et al., 2008) and their impacts (f.ex., changes in regional hydrology and eco-system services: Young, 1982; Hopkinson and Young, 1998; Moore and Demuth, 2001; Demuth and Pietroniro, 2002; Hopkinson and Demuth, 2006; Demuth et al., 2008; Moore et al., 2009; Stahl and Moore, 2006; Comeau et al., 2009; Marshall et al., 2013). The work also provides contemporary information with which to calibrate and contextualize geo-botanical data describing neo-glacial variations of several of the observing glaciers (f.ex., Demuth and Horne, 2017; Wood et al., 2011; Luckman, 1996). Notably, the information is also regularly submitted to the World Glacier Monitoring Service (WGMS, formerly the "Permanent Service on the Fluctuation of Glaciers"; UNEP/WGMS, 2010; Demuth, 2010; WGMS, 2017) as part of a co-ordinated effort whereby reference monitoring glaciers are utilized in the study of global changes (f.ex., Zemp et al., 2015). In addition, results from this work are disseminated to the local communities, federal and provincial government departments (e.g. Parks Canada Agency for use in the State of Parks reporting (e.g. Haggarty and Tate, 2009), and Statistics Canada – Environmental Accounts Division.

Significant changes in the mass balance of the reference study glaciers have been linked to decadal and sub-decadal variability in atmospheric circulation regimes (i.e., climatic variability: Bitz and Battisti, 1999). Some of the most negative mass balance values since the initiation of measurement

(Demuth and Ednie 2016; Zemp et al., 2015;) have been recorded in the last 20 years which has largely been influenced by secular warming (Vaughan et al., 2013).

This GSC Open File presents the findings of in-situ glacier mass balance studies conducted in 2015 and 2016 for observing sites in Canada's western and northern Cordillera (see Appendix A). Results include seasonal, ie. winter (b_w) and summer (b_s) balance, and annual surface glacier mass balances (b_n), specific (see Cogley et al, 2011 for terminology) net glacier balance, Equilibrium Line Elevation (ELA), and the Accumulation Area Ratio (AAR).

2. Study Sites

Geological Survey of Canada (GSC) maintains five glacier mass balance observing sites in the western and northern Cordillera (details in Appendix A) which includes Helm and Place Glaciers in the southern Coast Mountains of British Columbia, Wapta and Columbia Icefields in Banff and Jasper National Parks, and Bologna Glacier in National Park and Reserve in the Selwyn Mountains of the Northwest Territories (Figure 1). Three of the five glacier observing sites (Place, Helm and Peyto Glaciers) maintained by GSC are considered reference glaciers by the World Glacier Monitoring Service which are defined as having more than 30 years of continuous glaciological mass-balance measurements.

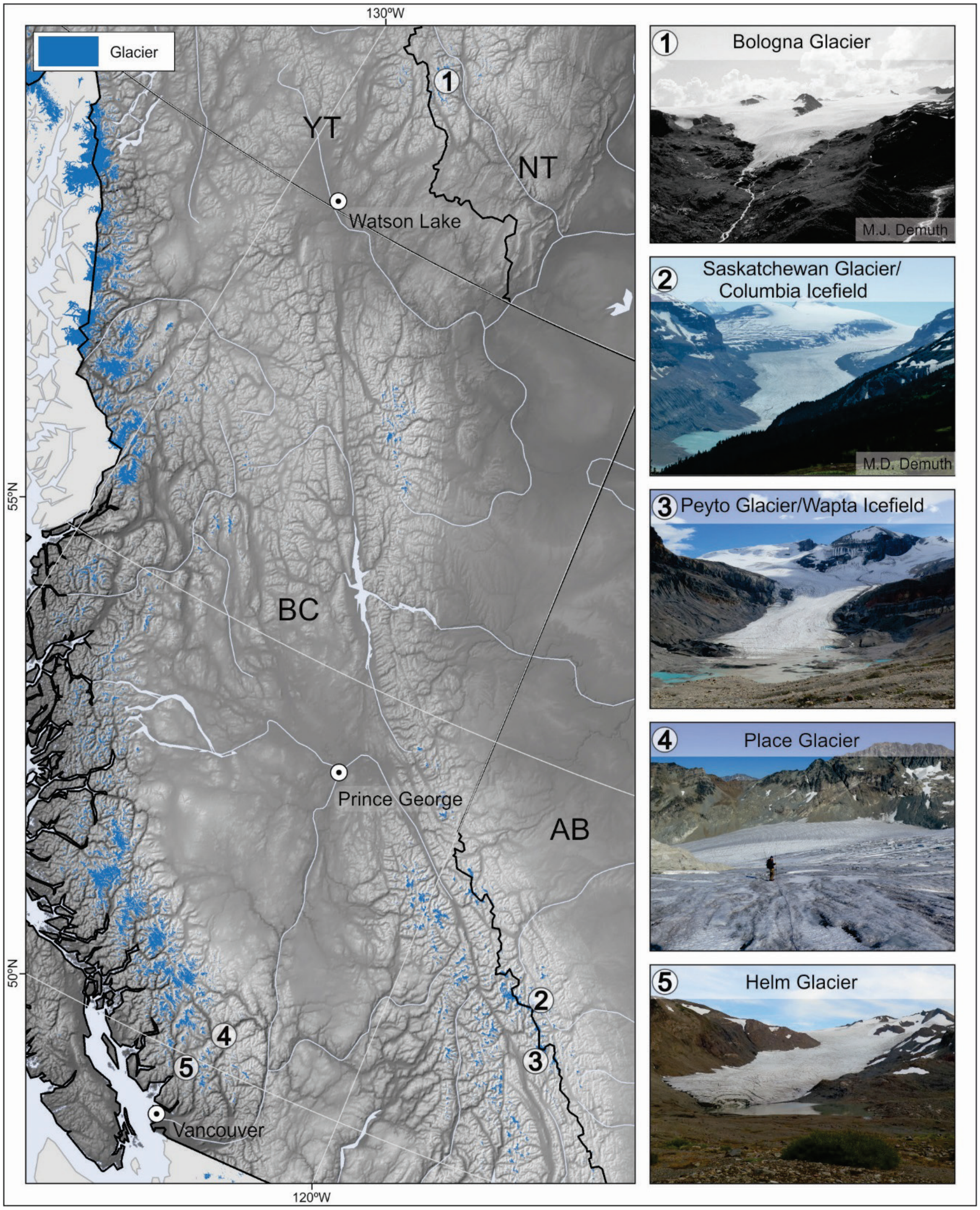

FIGURE 1. LOCATION AND IMAGE OF GLACIERS/ICEFIELDS IN THE CORDILLERA GLACIER-CLIMATE OBSERVING NETWORK MAINTAINED BY GEOLOGICAL SURVEY OF CANADA.

2.1 Helm Glacier

Helm Glacier is located 70 km north of Vancouver B.C. in Garibaldi Provincial Park in the southern Coastal Mountain range (Figure 1). Currently there are 5 mass balance stakes on Helm glacier ranging in elevation from 1831 m a.s.l. to 2004 m a.s.l. (Figure 2). Snow pits and snow coring sites are established each spring at stake 40 (~1858 m) and at stake 70 (~1994 m). Helm Glacier ranges in elevation from 1781 m a.s.l. to 2142 m a.s.l. and in 2015 had an area of 0.74 km^2 (personal communication Brian Menounos). Glacier surface area and mass balance have been measured at Helm glacier since 1977 and is designated a reference glacier by the World Glacier Monitoring Service (WGMS). There have been numerous advances and retreats since the last glacial maximum but most glaciers in the Coastal Mountains range reached a

FIGURE 2. MASS BALANCE STAKE LOCATIONS AND GLACIER OUTLINE, HELM GLACIER.

maximum Holocene extent during the Little Ice Age (LIA) (Ryder and Thomson, 1986). As of 2005, Helm glacier has lost more than 80% of its surface area since the LIA with the majority of ice loss since 1928 (Koch et al., 2009). Since the start of observations, the cumulative glacier-wide annual surface mass balance trends have been negative with exceptions in 1996, 2000 and 2012 (Figure 3) (Ednie and Demuth, 2016). The 1977-2016 average glacier-wide annual balance is -125 cm w.e. a^{-1}.

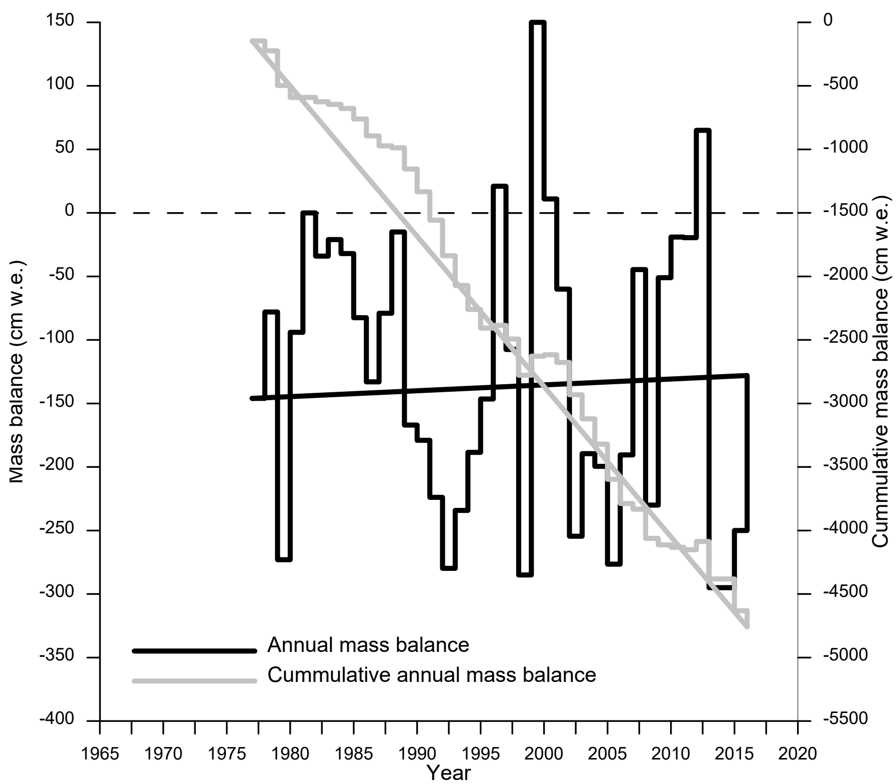

FIGURE 3. ANNUAL AND CUMMULATIVE MASS BALANCE AT HELM GLACIER.

2.2 Place Glacier

Place Glacier is located 19 km northeast of Pemberton, B.C in the Cayoosh Range in the southern Coastal Mountains (Figure 1). There are 13 mass balance stakes that are actively measured on Place glacier ranging from 1915 to 2351 m a.s.l. (Figure 4). Snow density data is collected at stake 100 at ~2298 m and at stake 40 at ~1961 m a.s.l. The glacier surface area has shrunk from 3.76 km^2 in 1981 (Moore and Demuth, 2001) to 3.09 km^2 as of summer 2015 (personal comm. Brian Menounos) and ranges in elevation from 1848 to 2540 m a.s.l. Place Glacier surface mass balance have been measured continuously since

1965 and is considered a reference glacier by the WGMS. Since the commencement of measurements, Place Glacier has experience negative annual surface mass balances in all years with exceptions in 1966, 1974 and 1976, 1999 and 2000 and for a 3 year period between 2010 and 2012 (Figure 5). The 1965-2016 average glacier-wide annual balance is -86 cm w.e. a^{-1}.

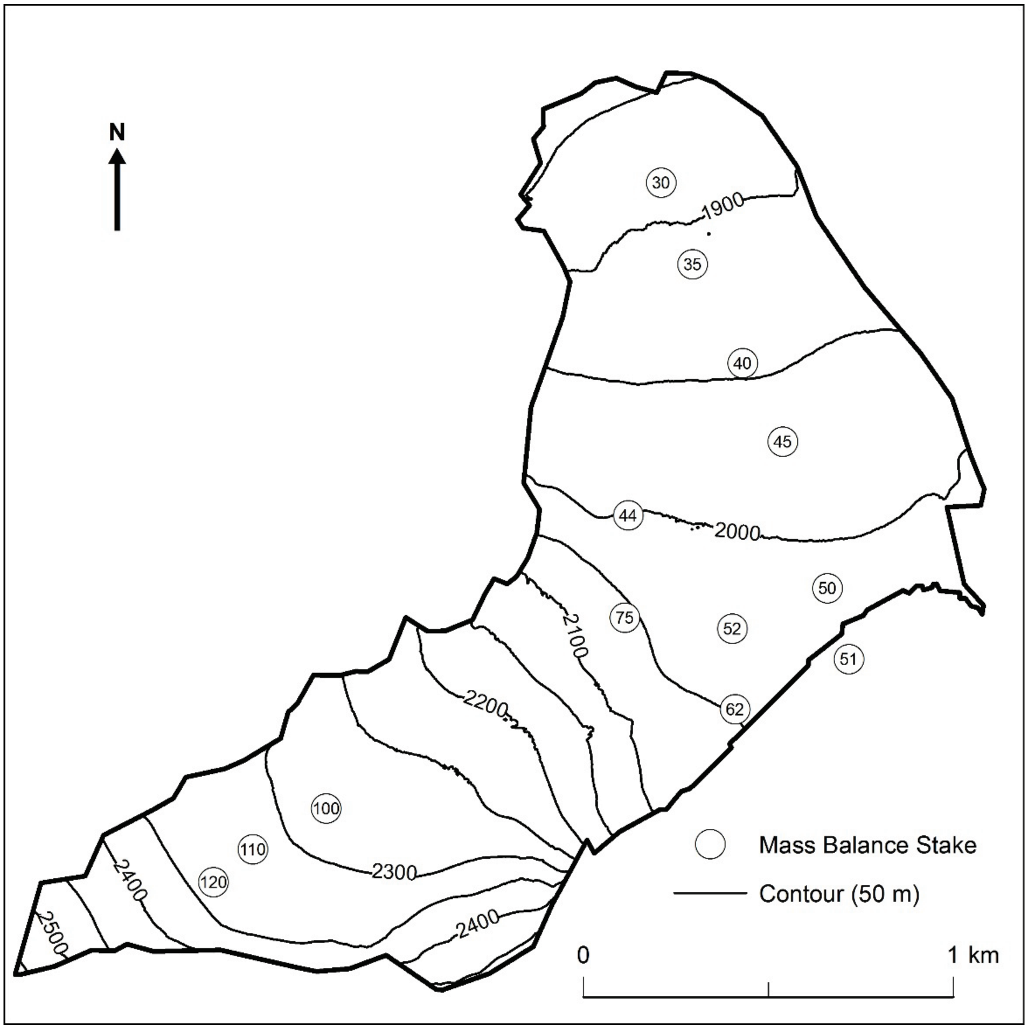

FIGURE 4. MASS BALANCE STAKE LOCATIONS AND GLACIER OUTLINE, PLACE GLACIER.

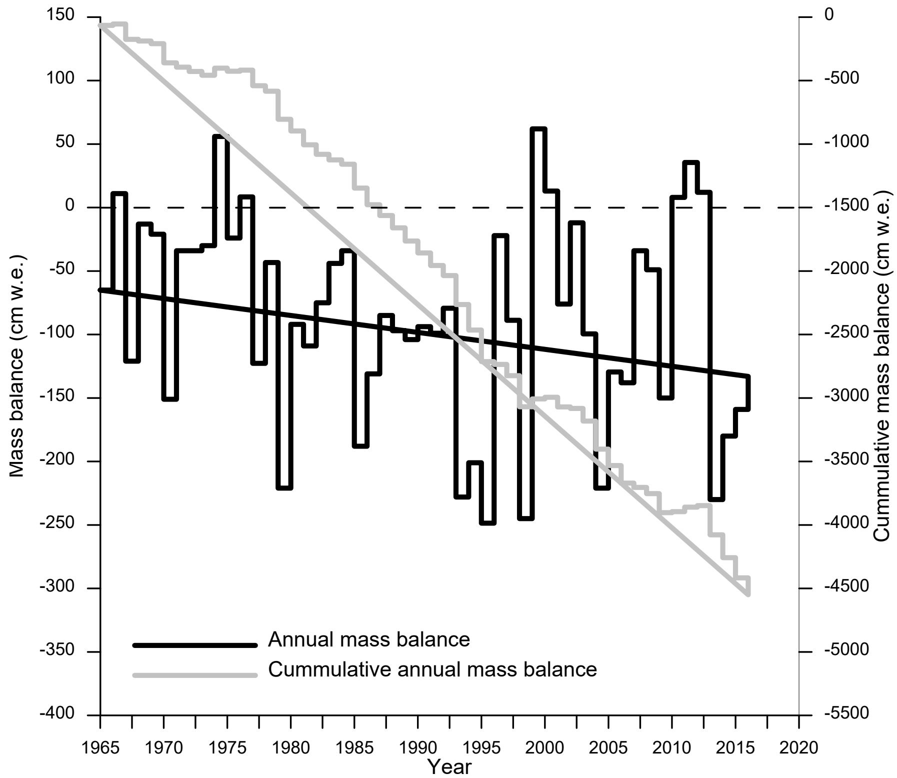

FIGURE 5. ANNUAL BALANCE AND CUMULATIVE BALANCE AT PLACE GLACIER.

2.3 Wapta Icefield

The Wapta Icefield straddles the Continental Divide in the Waputik Mountains of the Canadian Rockies along the Alberta-B.C. provincial border. The icefield is composed of a number basins and outlet glaciers, of which Peyto Glacier (Banff National Park) and Yoho glacier (Yoho National Park) are included in the glacier mass balance network. Peyto Glacier basin is 9.4 km^2 area and ranges in elevation 2163 m to 3031 m a.s.l. The Yoho glacier basin has a surface area of 17.9km^2 and ranges from 2071 m to 3126 m a.s.l. The combined mass balance network on the Wapta Icefield is composed of 23 mass balance stakes (Figure 6). A total of 15 stakes are situated on Peyto Glacier and the remaining 8 are on Yoho glacier. Snow pits are excavated annually at stake 180 (2647 m), stake 140 (2602 m), stake 85 (2174 m), stake 80 (2180 m) and stake 60 (2162 m) on Peyto Glacier. On Yoho Glacier, snow pits are excavated annually at

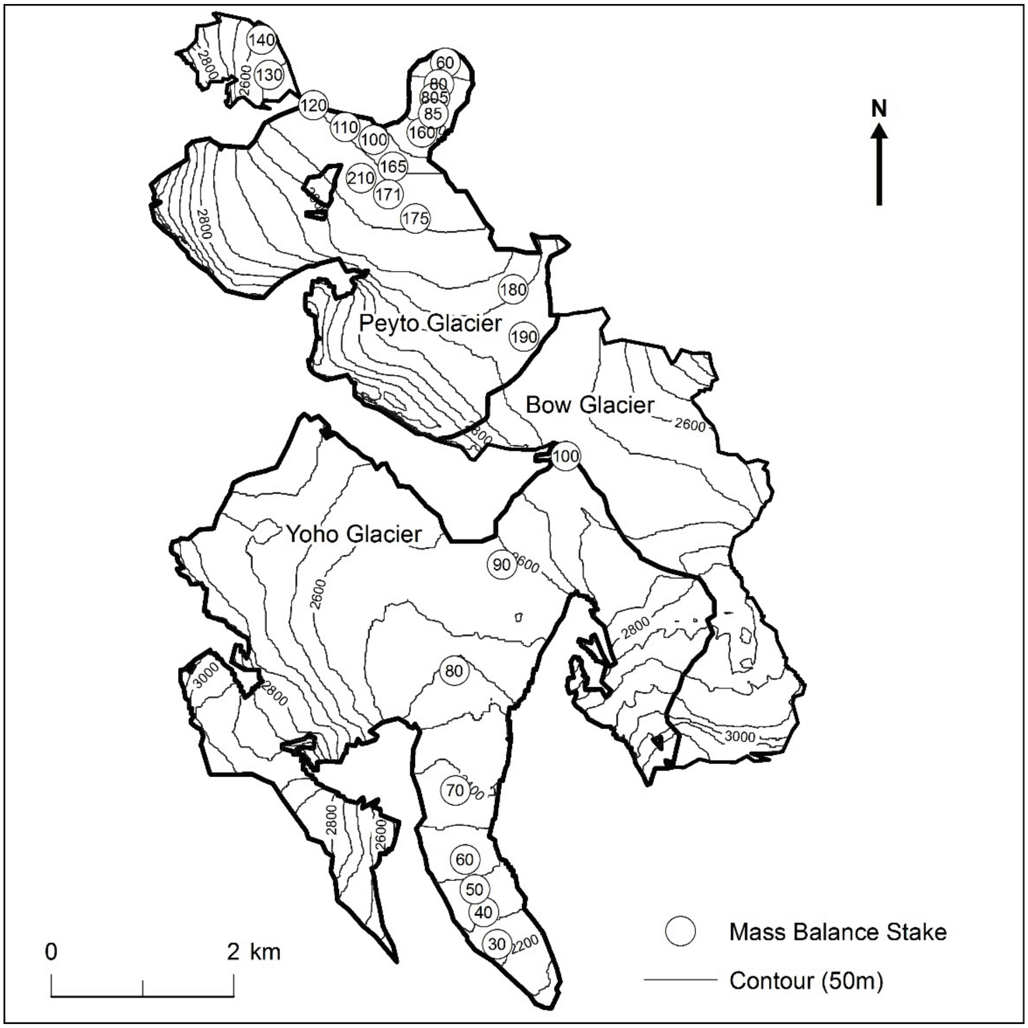

FIGURE 6. MASS BALANCE STAKE LOCATIONS AND GLACIER OUTLINE, WAPTA ICEFIELD (PEYTO AND YOHO GLACIERS).

stake 90 (2582 m) and at stake 40 (2134 m). Glacier surface mass balance has been measured on Peyto Glacier since 1966 (Østrem, 2006) and is considered a reference glacier by the WGMS . Kehrl et al. (2014) found that the lower glacier has decreased in volume at an annual rate of $3.3x10^6$ m^3a^{-1} and is predicted to retreat by ~1 km by 2019. Figure 7 shows that long term glacier-wide mass balance at Peyto glacier has been mostly negative with exceptions in the late 1960s and mid-1970s and in 2000 (Young, 1981; Demuth and Keller, 2006). The average glacier-wide surface mass balance for Peyto glacier is -63 cm w.e. a^{-1} (1966-2016). Mass balance measurements were initiated on Yoho glacier in 2012. Complete mass balance data for Yoho glacier for 2015 and 2016 balance years are not available due to technical and logistical issues associated with data collection and will not be presented in this Open File.

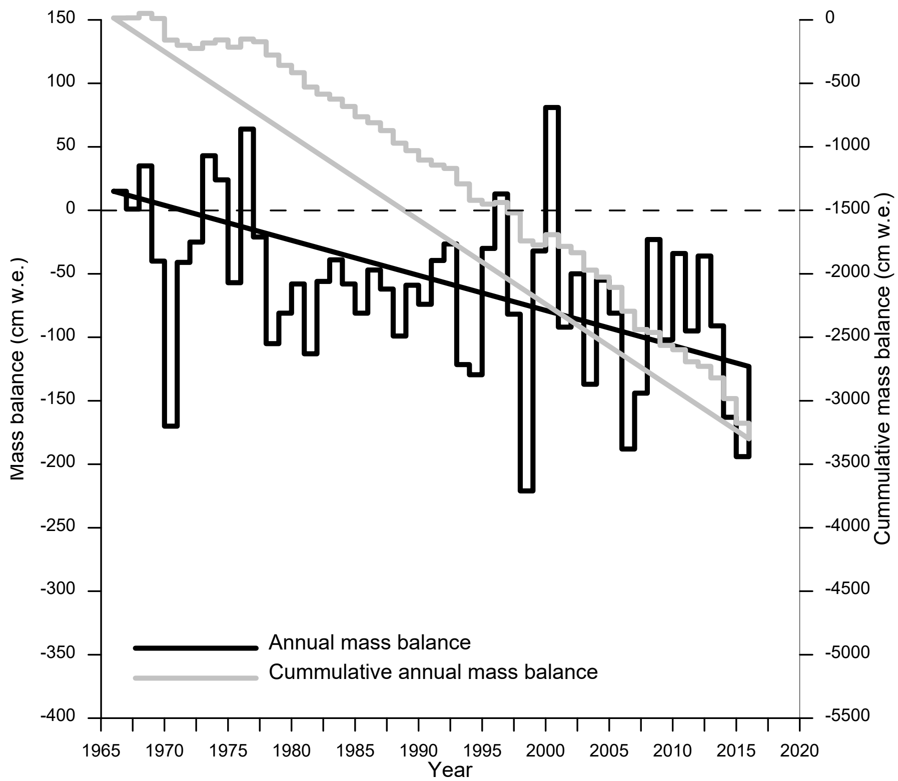

FIGURE 7. ANNUAL BALANCE AND CUMULATIVE ANNUAL BALANCE AT PEYTO GLACIER.

2.4 Columbia Icefield

The Columbia Icefield, the largest ice mass in the Canadian Rockies with surface area of 176 km^2, straddles the continental divide and is the apex of a triple watershed with water flowing north to the Arctic Ocean, east to Hudson Bay and west to the Pacific Ocean. Full site descriptions and glacier surface mass balance of the Athabasca and Saskatchewan Glaciers for 2015 and 2016 has been released in a separate Open File publication (see Ednie et al., 2017).

2.5 Bologna Glacier

The Brintnall-Bologna Icefield, with a surface area of 34 km^2, represents 17% of the 204.5 km^2 total glacier cover in the Nahanni National Park and Reserve, NT. The Bologna Glacier sector of the Icefield has shrunk from 17.8 km^2 in 1999 to 15.8 km^2 in 2017. The mass balance network consists of 12 stakes ranging in elevation from 1,841 m a.s.l. to 2,197 m a.sl. (Figure 8). Snow pits are excavated at stake 52 (2185 m), stake 12 (1,914 m), stake 30 (2,049 m), stake 10 (1,841 m) and stake 41 (2094 m).The majority of the 345 glaciers in the Ragged Range of the Selwyn Mountain are small alpine glaciers of less than 1.0 km^2. Between 2008 and 2017, the surface area of glaciers in the region has declined by approximately 30% with most the decline occurring in glaciers smaller than 0.01 km^2 (Ednie and Demuth, 2018, Demuth et al., 2014). Firn coverage has been reduced from 82% to 47% between 1984 and 2014 and is reported to have been completely absent in 2015 (Anderson, 2017). Bologna Glacier ranges in elevation from 1,694 m to 2,523 m a.s.l. Meltwater from the Bologna Glacier drains into the South Nahanni River and eventually into the Liard and Mackenzie Rivers. In collaboration with Nahanni National Park and Reserve, the Geological Survey of Canada established the network in 2006 (Figure 1).

3. METHODS

Glacier surface mass balances presented in this report are calculated following the traditional glaciological method (Østrem and Brugman, 1991; Cogley et al., 2011). Glaciers are visited a minimum of two times a year on roughly the same dates, once in spring (April/May) to collect snow depth measurements and snow density, and in fall (September/October) to measure maximum ice melt. Previous year ice melt data may also be collected during the spring fieldtrips.

Snow density data are collected from numerous snow pits and coring sites at multiple elevations along mass balance stake transects. Snow density data is used to convert snow depths measurements at stakes and snow depth transects to Snow Water Equivalence (SWE). At snow pit sites, snow density is collected at 10 cm increments to a depth of 150 cm or base of current winter snowpack. When snow depth extends below 150 cm, a 3” diameter Kovac’s coring kit is used to retrieve samples. The second data collection period coincides with estimated maximum ice melt in late summer to measure ice ablation, snow line elevation and perform maintenance on mass balance network and automated weather stations.

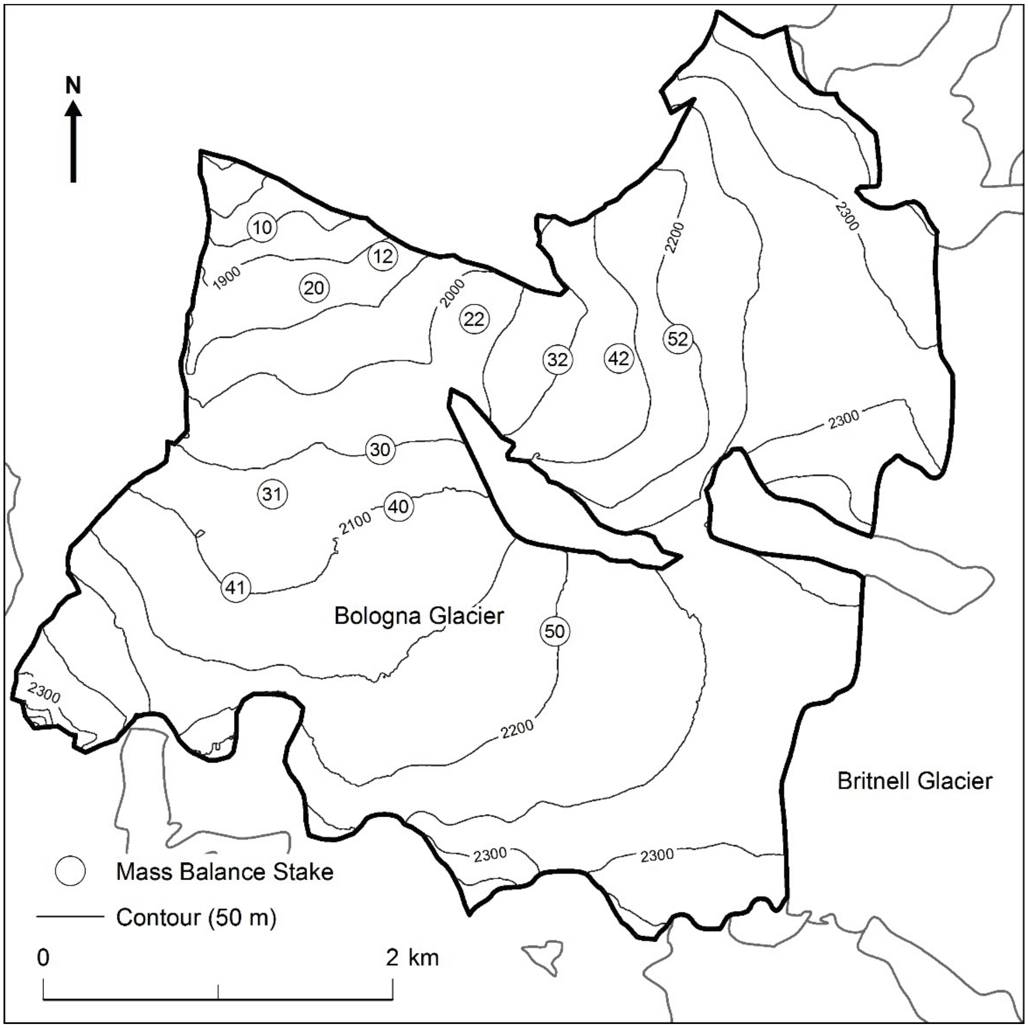

FIGURE 8. MASS BALANCE STAKE LOCATIONS AND GLACIER OUTLINE, BOLOGNA GLACIER.

This work is augmented by the use of satellite, airborne and UAV to derive complementary geodetic mass balances, surface facies configurations and periodic glacier inventory assessments. Landsat 8 L1TP type scenes, obtained from USGS Global Visualization Viewer (GloVis) courtesy of U.S. Geological Survey, were used to estimate late summer snow limit elevation for the 2015 and 2016 balance years on Peyto Glacier.

Winter (b_w) and summer (b_s) surface mass balances at each stake are calculated from winter accumulation and summer ablation data. These point values are integrated with glacier hypsometry to generate seasonal glacier-wide mass balances. For more information on the mass balance analysis techniques used by the GSC (see Cogley et al., 2011; Demuth and Ednie, 2016; Ednie and Demuth, 2017 for details).

4. Glacier Surface Mass Balance Results

4.1 Helm glacier

Stake measurements of annual balance at Helm glacier in 2015 ranged -404 cm w.e at 1873 m to -204 cm w.e. at 1940 m a.s.l. (Figure 9). The glacier-wide winter balance was 158 cm w.e., summer balance was -408 cm w.e., the annual balance was -250 cm w.e. and the ELA was higher than the uppermost elevation of Helm Glacier (Table 1). In 2016, only 3 stakes were measured as the 2 uppermost stakes (at 1970 m and 2004 m a.s.l) had melted out of the ice during the ablation period and the surface ice reference point was lost. Where data was collected, the annual balance ranged from -236 cm w.e. at 1831 m to -89 cm w.e. at 1940 m a.s.l. (Figure 9). Ablation at the missing stakes was estimated using a mass balance gradient generated by fitting a polynomial curve to stake data from the past 12 years (2003-2015) (Van Beusekom, 2010). The resulting mass balance gradient was modified to reflect the current year measured mass balance values. The glacier-wide winter balance was 169 cm w.e., the estimated summer balance was -297 cm w.e and the estimated annual balance was -128 cm w.e. The estimated ELA was 2140 m a.s.l. and the AAR was 2% (Table 1).

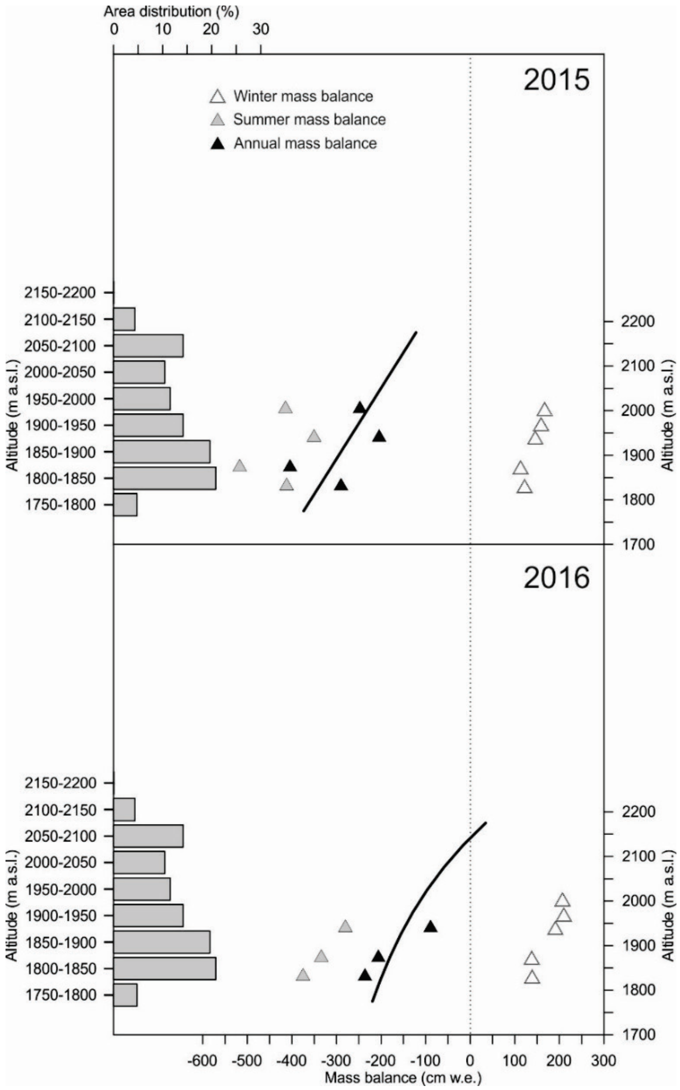

FIGURE 9. WINTER, SUMMER AND ANNUAL BALANCE FOR 2015 (TOP) AND 2016 (BOTTOM) BALANCE YEARS FOR HELM GLACIER.

4.2 Place Glacier

In 2015, the annual surface mass balance ranged from -370 cm w.e. near the glacial terminus to -70 cm w.e at the highest measured stake at 2305 m (Figure 10). Place Glacier experienced a glacier-wide winter balance of 145 cm w.e., a summer balance of -304 cm w.e and an annual balance of -159 cm w.e in 2015. The ELA was 2470 m with an AAR of 0.6% (Table 1). In 2016, Place glacier had an annual surface mass balance ranging from -313 cm w.e. at 1915 m a.sl. to -43 cm w.e. at 2351 m a.s.l. (Figure 10). The glacier-wide winter balance was 153 cm w.e., summer balance was -291 cm w.e and the annual balance was -137 cm w.e (Table 1). The ELA for Place Glacier in 2016 was slightly lower than in 2015 at 2450 m a.s.l. leading to a AAR of 3.1%.

TABLE 1. WINTER BALANCE, SUMMER BALANCE AND ANNUAL BALANCE, EQUILIBRIUM LIMIT ALTITUDE AND AREA ACCUMULATION RATIO FOR ALL GLACIERS IN NETWORK. INCLUDING ATHABASCA GALCIER AND SASKATCHWEAN GLACIER DATA FOR REFERENCE (EDNIE ET AL., 2017).

	Helm Glacier		Place Glacier		Wapta Icefield (Peyto Glacier)		Bologna Glacier		Athabasca Glacier		Saskatchewan Glacier	
Year	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Winter balance cm w.e. a^{-1}	158	169	145	153	85	96	n/a	88	110	122	131	114
Summer balance cm w.e. a^{-1}	-408	-297	-304	-291	-279	-218	n/a	-146	-176	-135	-254	-197
Annual balance cm w.e. a^{-1}	-250	-128	-159	-137	-194	-122	-115	-58	-66	-13	-123	-83
ELA m a.s.l.	>2150	2140	2470	2450	2950	2850	2450	2300	2650	2550	2650	2620
AAR %	0	2.0	0.6	3.1	1.0	6.3	0.4	6.1	72.0	74.2	40.4	45.9

4.3 Peyto Glacier

In 2015, the annual balances at the stakes ranged from -646 cm w.e. at 2162 m to -121 cm w.e. at 2423 m a.s.l. (Figure 11) A Landsat 8 L1TP type scene (path 44, row 24) acquired on August 08, 2015 was used to estimate the annual ELA. The glacier-wide winter balance was 85 cm w.e. and the summer balance was -279 cm w.e. with an annual balance of-194 cm w.e. (Table 1). The ELA was estimated to be 2950 m a.s.l. and the AAR was 1.0%. In 2016, annual surface mass balance ranged from -591 cm w.e. at 2263 m to -183 cm at 2464 m (Figure 11). A Landsat 8 L1TP type scene (path 44, row 24) acquired on August 30, 2016 was used to estimate the annual ELA. The glacier-wide winter balance was 96 cm w.e., the summer balance was -218 cm w.e. and the annual balance was -122 cm w.e. (Table 1). The ELA was calculate to be 2850 m a.s.l. and the AAR was 6.3%.

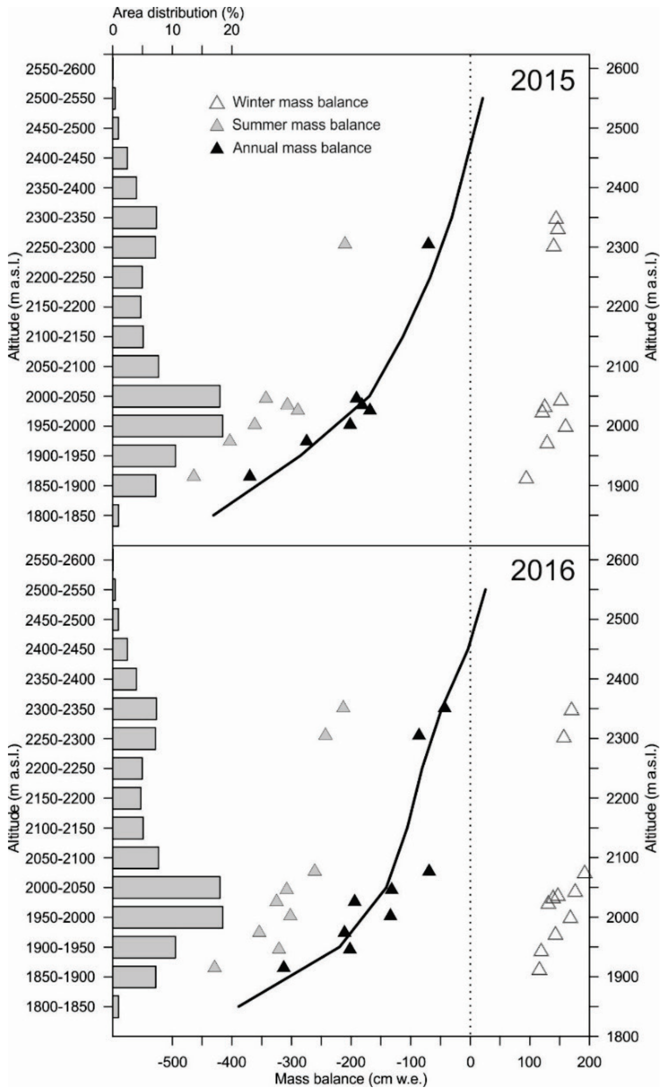

FIGURE 10. WINTER, SUMMER AND ANNUAL BALANCE AT EACH STAKE FOR 2015 (TOP) AND 2016 (BOTTOM) BALANCE YEARS FOR PLACE GLACIER.

4.4 Bologna Glacier

In 2015, the annual balance ranged from -239 cm w.e. at 1935 m to -116 cm w.e. at 2194 m a.s.l (Figure 12). The glacier-wide annual balance was -115 cm w.e., the ELA was 2450 m a.s.l. and the AAR was 0.4% (Table 2). Bologna glacier was not visited in spring 2015 and therefore winter and summer balances at each stake and for the entire glacier could not be calculated for 2015. Annual balance for 2015 was calculated using stake data from 2014 and 2015 summer visits.

Annual balance in 2016 ranged from -242 cm w.e. at 1826 m to -49 cm w.e. at 2193 m (Figure 12). Glacier-wide mass balances were 88 cm for winter, -146 cm for summer and an annual balance of -58 cm w.e. (Table 1). The ELA was 2300 m and as a consequence the AAR was 6.1 %.

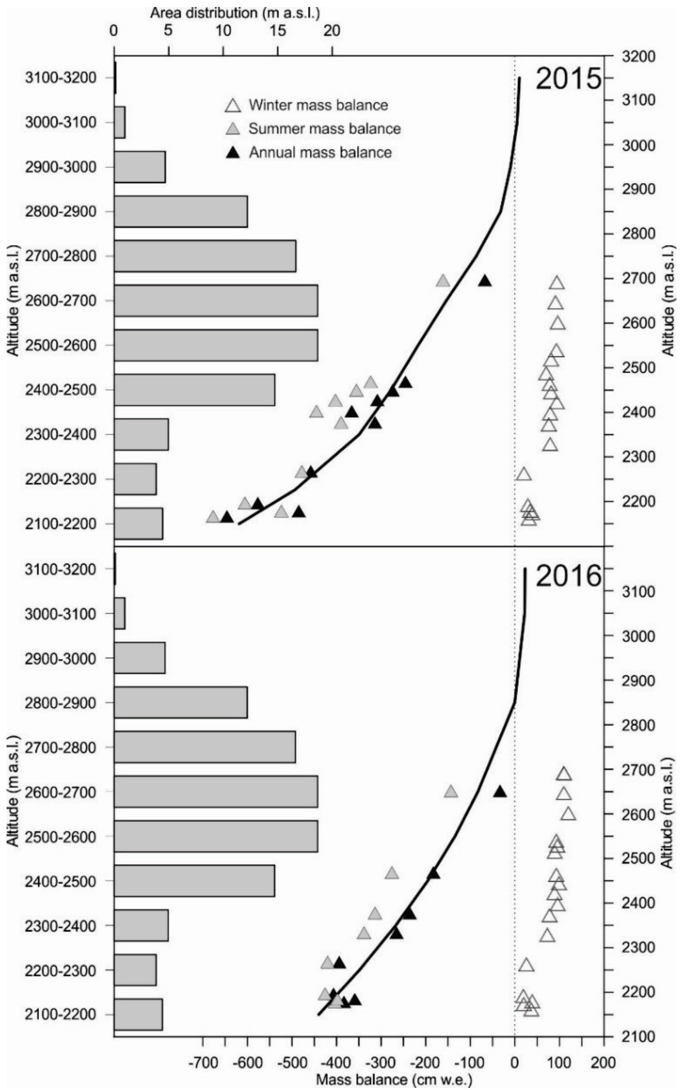

FIGURE 11. WINTER, SUMMER AND ANNUAL BALANCE AT EACH STAKE FOR 2015 (TOP) AND 2016 (BOTTOM) BALANCE YEARS FOR PEYTO GLACIER.

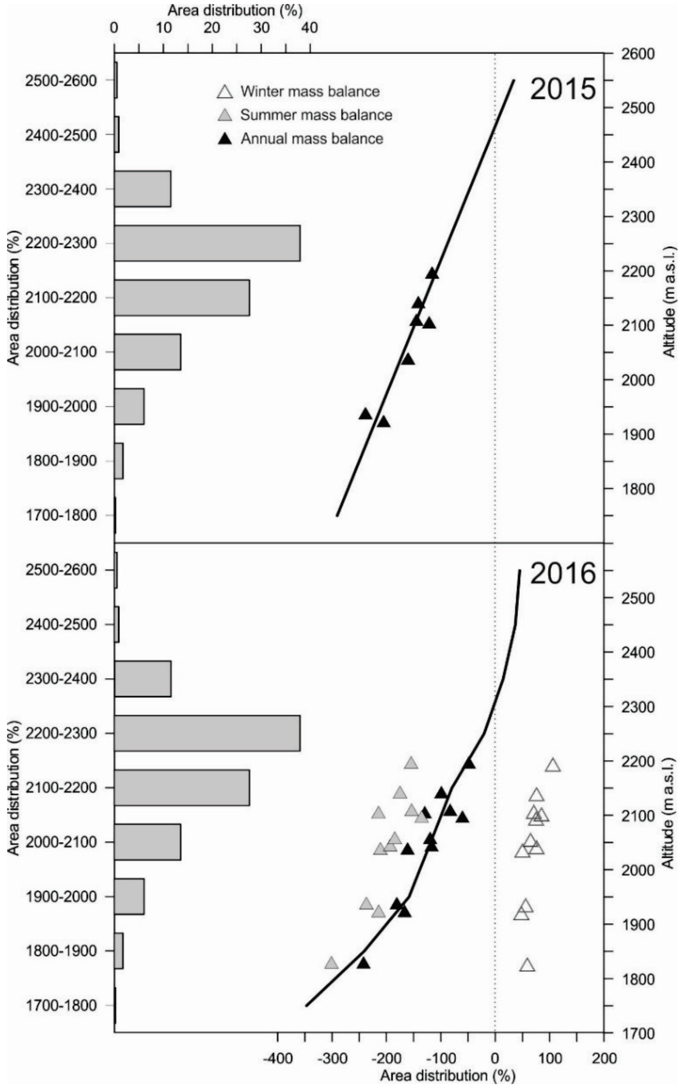

FIGURE 12. WINTER, SUMMER AND ANNUAL BALANCE AT EACH STAKE FOR 2015 (TOP) AND 2016 (BOTTOM) BALANCE YEARS FOR BOLOGNA GLACIER.

5. SUMMARY

Negative annual surface mass balances were observed at all glaciers in the network for both 2015 and 2016. Extremely negative annual balances were recorded in 2015 at Helm, Place and Peyto Glaciers when compared to the long-term averages (Table 2). For example, net loss at Peyto Glacier for 2015 was almost three times the long-term average and was the 2nd most negative year since 1966. In 2016, annual balances for Helm and Place Glaciers were closer to the long-term averages but Peyto Glacier continued to experience a highly negative annual balance.

TABLE 2. HISTORICAL GALCIER-WIDE ANNUAL BALANCE COMPARED TO 2015 AND 2016 BALANCES AT PEYTO GLACIER, HELM GLACIER AND PLACE GLACIER.

	Helm Glacier *n= 39 years*	Place Glacier *n= 51 years*	Peyto Glacier *n= 50 years*
Historical annual balance (cm w.e.)	-125	-86	-67
2015 glacier-wide annual balance (cm w.e.)	-250	-159	-194
2016 glacier-wide annual balance (cm w.e.)	-128	-137	-123

6. Future Work

The current distribution of mass balance stakes on glaciers in the network is skewed towards lower elevations resulting in a greater emphasis on data from the ablation zone with less information from areas of accumulation. This has been an issue for Peyto Glacier in particular since its steep upper reaches preclude reliable stake measurements and present hazards particularly in late winter. Errors may be introduced when extrapolating mass balance gradients to elevation zones where observations are limited or non-existent (Shea et al., 2013). This lack of information applies mainly to summer melt balance gradients as during winter month's relatively comprehensive snow depth and snow pit surveys are conducted throughout most elevations except for Peyto Glacier. In the future, these errors may be compounded due to the upward movement of the ELA and shrinking AAR observed on glaciers in the network and globally (Mernild et al., 2013; McGrath et al., 2017). The planned addition of new mass balance stakes in the accumulation region on glaciers will reduce the potential error associated with the lack of high elevation mass balance data.

7. CONCLUSION

GSC Open File 8503 presented results from glacier mass balance survey conducted as part of the Geological Survey of Canada's Glacier-Climate Observing System in the Cordillera for balance years 2015 and 2016. The data indicate that all the glaciers in the observing system experienced negative glacier-wide annual balances during both years reported with 2015 being more negative than 2016. At observing sites, annual balances in 2015 were significantly more negative than long-term averages while in 2016 the annual balance at Helm Glacier was similar to the long-term average but Place and Peyto Glaciers continued to have highly negative annual balance. Results from this observing network provides essential information on the current state of glaciers in Canada's western and north-western Cordillera.

8. Acknowledgments

This work was conducted under a combination of Parks Canada Agency research and collection permits (JNP-2010-4694; NAH-2015-18573) and British Columbia Ministry of Environment science license #107995. Logistical support for the Bologna Glacier component provided by Polar Continental Shelf Project (project #00715 and #00516). The authors would like to thank Emily Anderson, David Aktinson, Steve Bertollo, Eric Courtin and Jason VanderSchoot for assistance in data collection.

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Appendix A. Geological Survey of Canada's Glacier-Climate Observing System in the Cordillera.

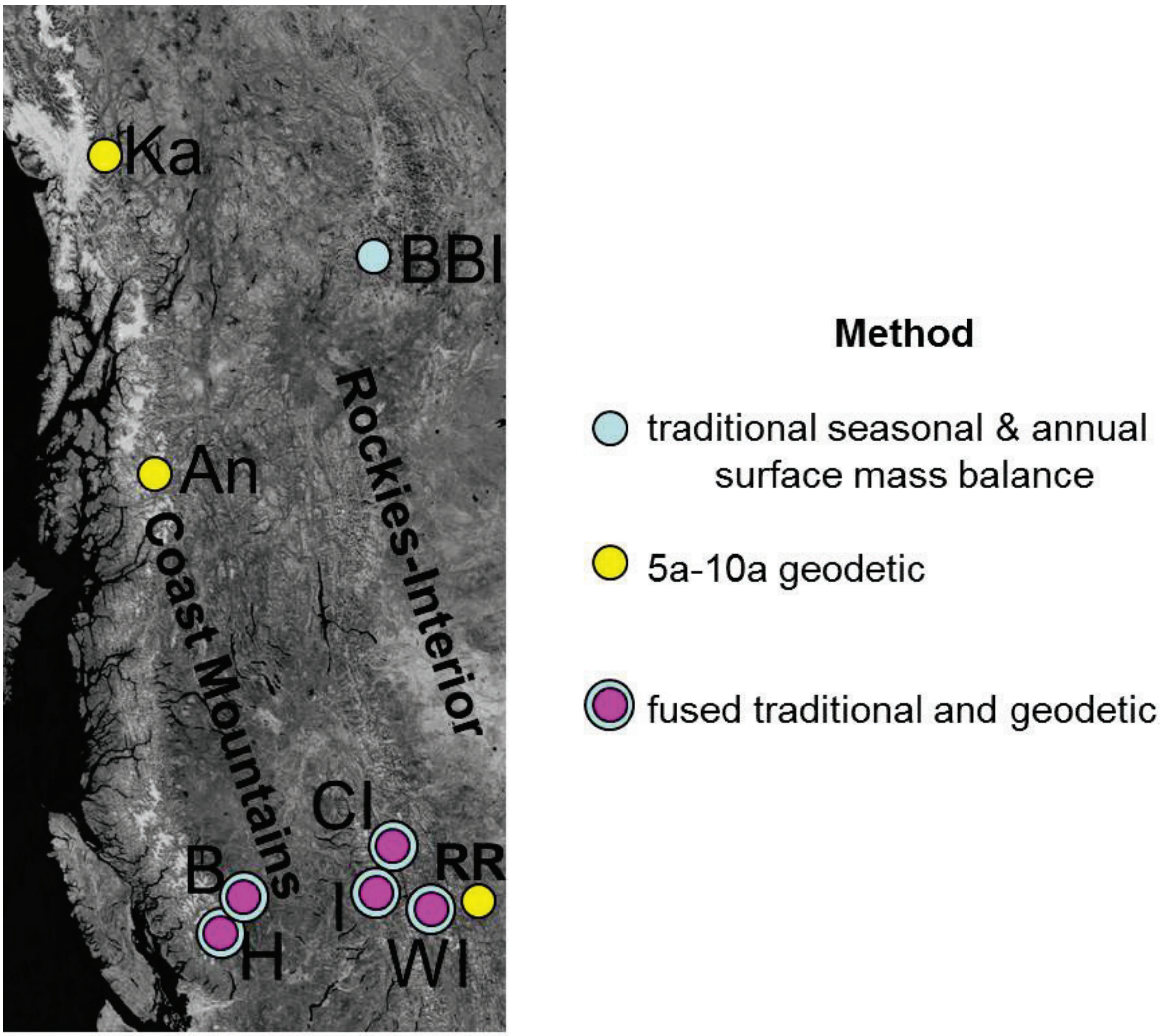

Figure A 1. Mass balance observing sites for the Cordillera: WI = Wapta Icefield (Peyto and Yoho); RR = Ram River; CI = Columbia Icefield (Athabasca and Saskatchewan); I = Illecillewaet; BBI = Brintnell-Bologna Icefield (Bologna); KA = Kaskawulsh; AN = Andrei; B = Place; H = Helm.

Mountain National Parks:

Wapta Icefield is located in ***Banff*** (Peyto Glacier) and ***Yoho*** (Yoho Glacier) *National Parks*.

Columbia Icefield is located in ***Jasper*** (Athabasca Glacier) and ***Banff*** (Saskatchewan Glacier) *National Parks*.

Illecillewaet Glacier is located in ***Glacier and Mount Revelstoke National Park***.

Northern Bioregion Parks and Reserves:

Kaskawulsh Glacier is located in ***Kluane National Park Reserve***.

Brintnell-Bologna Icefield (Bologna Glacier) is located in ***Nahanni National Park Reserve***.

British Columbia Provincial Parks:

Helm Glacier is located in ***Garibaldi Provincial Park***

Metadata for each glacier/icefield site, including details on observing and research partnerships, measurement infrastructure and First Nations territorial references, are available from: mark.ednie@canada.ca