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Mass balance of the Athabasca and Saskatchewan sectors of the Columbia Icefield, Alberta for 2015 and 2016

M. Ednie, M.N. Demuth, and B. Shepherd

2017

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Mass balance of the Athabasca and Saskatchewan sectors of the Columbia Icefield, Alberta for 2015 and 2016

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2017

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Summary

This Open File publication presents mass balance (summer, winter and annual mass balance), Equilibrium Limit Altitude and Accumulation Area Ratio data for the Athabasca and Saskatchewan Glaciers (Columbia Icefield, Jasper and Banff National Parks) for 2014-15 and 2015-16. The collection of glacier mass balance data on the Athabasca and Saskatchewan Glaciers is a joint effort between Jasper National Park and Natural Resources Canada/Geological Survey of Canada. Both glaciers experienced mass losses in both of the reported years with values in 2014-15 being more negative than in 2015-16. This result reflects the inter-annual variability observed for other glaciers in southwestern Canada and the northwest Pacific. Corresponding equilibrium line elevations were higher and accumulation area ratios were lower in 2014-15 as compared to 2015-16. When placed in context with geodetic estimates of mass change for the two glaciers since the mid-1960s, the 2014-15 and 2015-16 observations generally reflect large-scale regional glacier mass balance variability observed since the mid-twentieth century.

From Parker Ridge, AB, the eastern margins of the Columbia Icefield drape the landscape below Mount Castleguard (right). Michael N. Demuth photograph (2013-April-29).

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INTRODUCTION

The short and long-term changes in the mass of glaciers in many of Canada's Arctic and alpine regions play a significant role in regional and global sea-level change (f.ex., UNEP/WGMS, 2010; Zemp et al., 2015); and modulate mountain runoff that impacts natural and human system functioning (f.ex., for Canada's western Cordillera, see Moore and Demuth, 2001; Demuth et al., 2008; Comeau et al., 2009; Marshall et al., 2013). Employing its Reference Glacier-Climate Observing System (Appendix A), the Geological Survey of Canada (GSC) issues data reports and research on the state of Canada's glaciers. These efforts, in part, contribute to Canada's international commitments towards the goals of the United Nations Framework Convention on Climate Change.

As it concerns protected areas generally and Canada's system of National Parks and Reserves specifically, glaciers hold intrinsic landscape values and have public safety, visitor experience and ecological significance. The cool and turbulent waters derived from glacier melt and wastage exert a significant regulation of water quality for highly adapted biota, as well as a exerting a significant influence on stream morphometry and related habitat (Petts et al., 2006). Further, glaciers are significant to the distribution of grazing and predator species; their presence generating strong katabatic wind flow which helps to reduce insect harassment of ungulate populations. Glaciers that flow over significant topographic barriers may also provide travel corridors for wildlife and humans between valleys that are preferentially sought out during seasonal fluctuations in the weather (f. ex., Demuth et al., 2014).

Key measures of glacier health include the seasonal and annual "mass balance" and related glacier-climate indices such as the "equilibrium line altitude" and the "accumulation area ratio". Using methods outlined in Demuth and Ednie (2016) and Cogley et al. (2011), and measurement infrastructure and geomatics resources derived from companion research initiated in 2010 by the GSC-led project *Columbia Icefield Water for Life 2010-2015* (Demuth et al., 2012a, 2012b; and Persad et al., 2013), this report details the health of the Athabasca and Saskatchewan sectors of the Columbia Icefield for the 2014-15 and 2015-16 mass balance years.

1. DEFINITIONS - QUANTIFYING GLACIER FLUCTUATIONS

The fluctuation of a glacier under the influence of climate (precipitation, air temperature, solar radiation and cloud cover) can be described using various measures and metrics associated with its geometry (length, area and thickness), flow, surface facies expressions/glaciological zones, and mass change (*Figure* 1).

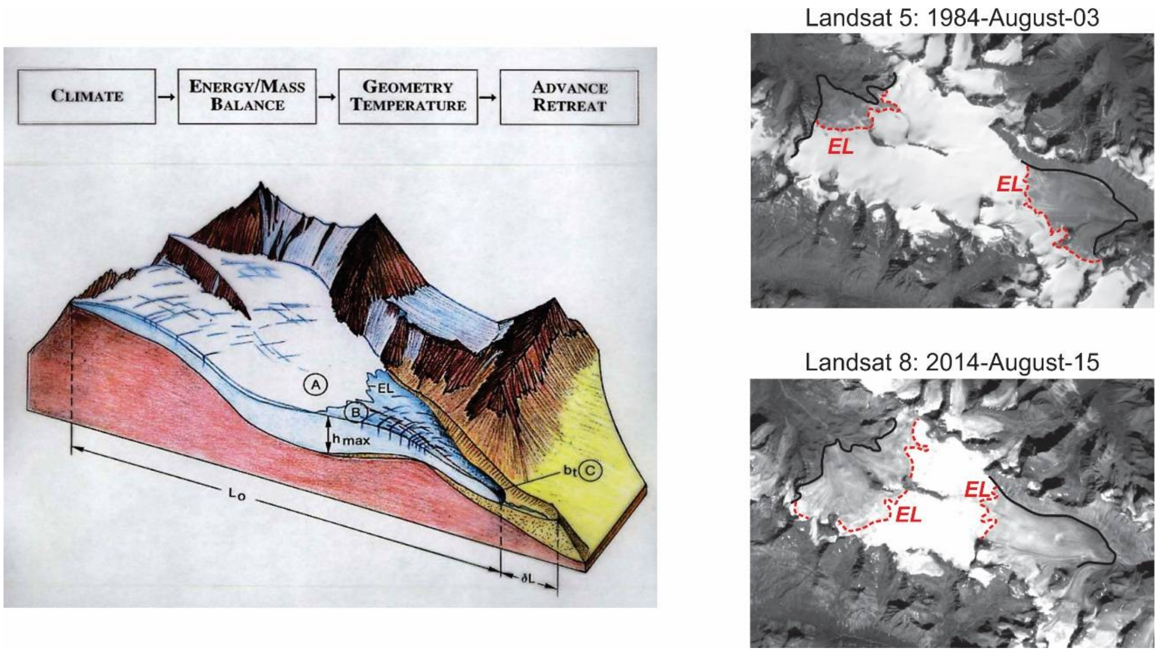

*FIGURE 1 A TYPICAL ALPINE GLACIER FEATURES NET ACCUMULATION AND NET ABLATION ZONES DIFFERENTIATED BY AN EQUILIBRIUM LINE (**EL**). ABOVE THE EL LAY THE SNOW AND FIRN FACIES OF THE ACCUMULATION AREA Ⓐ; BELOW IT THE ICE FACIES OF THE ABLATION AREA Ⓑ. LATE-SUMMER LANDSAT IMAGES OF THE BRINTNELL-BOLOGNA ICEFIELD IN NAHANNI NATIONAL PARK RESERVE ILLUSTRATE CONTRASTING FACIES CONFIGURATIONS AND ACCUMULATION AREA SIZES (DEMUTH AND EDNIE. 2016).*

Other relevant metrics include the Equilibrium Line Altitude (***ELA***) which, for temperate glaciers, generally corresponds to the maximum elevation attained by the seasonal snowline (see Demuth and Pietroniro, 1999 and the references therein) and the ratio of the *Accumulation Area* to the total area of the glacier, or the *Accumulation Area Ratio, **AAR***.

An important construct is that at the ***EL*** of the glacier, the net *mass balance* is zero; above it there is net mass gain; below it a net mass loss. Ice mass generated through the accumulation and densification of snow and firn above the ***EL*** will flow from the upper reaches of the glacier to its lower reaches where warmer conditions promote its ablation. Moreover, the apparent "retreat" of a glacier terminus (calving not withstanding) is due to "melt back" exceeding the down valley flux of ice. In general, a glacier will, under weather and climate forcing that places it in mass balance disequilibrium, constantly attempt to re-attain equilibrium by adjusting its area and thickness distribution through dynamic flow.

1.1 MASS BALANCE

The mass balance of a glacier is an accounting of how much mass is added and taken away by the processes of accumulation and ablation. Accumulation can result from precipitation, condensation, drift snow or avalanching; while ablation results from melt, sublimation, or avalanching (commonly ice calving from the glacier margins). In regions where the mass balance is primarily driven by climatic factors such as air temperature, precipitation, solar radiation and cloud cover, the measurement of mass balance provides a high-confidence, integrated indicator of the climate.

There are several methods and conventions for estimating the mass balance of a glacier. Three dominant methods are employed: i) traditional, *glaciological*, *direct*; ii) geodetic, *cartographic*, *topographic*; and iii) mass flux divergence (refer to Cogley et al., 2011 and Demuth and Ednie, 2016).

The tradition, "glaciological", or "direct" method is described herein. It is most commonly applied over simple mountain and outlet valley glaciers and results in an estimate of the "surface mass balance", ignoring processes whereby mass is exchanged internally and at the glacier base. The method generates both seasonal and annual balance (*b*) estimates at points after:

$$\boldsymbol{b_a} = \boldsymbol{b_w} + \boldsymbol{b_s} \qquad \textit{(EQN. 1)}$$

where subscripts *a, w, s* refer to the annual[1], winter and summer balances respectively.

[1] The *annual* mass balance is the mass balance of the glacier over a mass-balance year regardless of whether the fixed-date or the floating-date system is used. See Cogley et al. (2011; page 62-63) for further information on the ambiguity with the term "net" mass balance in relation to the stratigraphic system.

Point values are then integrated to generate the specific balance values over the whole glacier:

$$\boldsymbol{B} = \frac{\mathbf{1}}{\boldsymbol{S}} \int_{\boldsymbol{S}} \boldsymbol{b} \, \boldsymbol{ds} \qquad \text{(EQN. 2)}$$

This is equivalent to the cross product of the balance-altitude relationship, ***b(z)***, with the area-altitude relationship, ***s(z)***, all divided by the total glacier area, ***S***; and can be calculated using continuous numerical methods or in a discrete, step-wise tabular fashion.

Variations in the approach result from whether the distribution of mass balance is simple (f.ex., largely dominated by elevation) or compounded due to topographic influences that may justify integration over multiple dimensions. Where calving or contact of the glacier margins with water are involved, the considerations and resulting formulation become more complex (refer to Cogley et al., 2011; page 7).

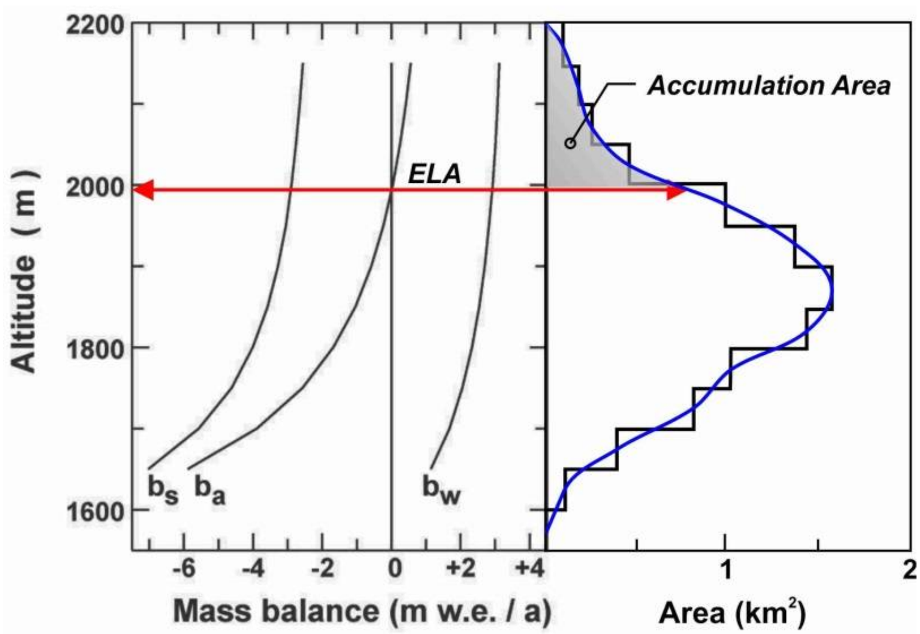

FIGURE 2 EXAMPLE OF MASS BALANCE-ALTITUDE (WINTER, SUMMER AND ANNUAL) AND AREA-ALTITUDE RELATIONSHIPS FOR AN ALPINE GLACIER IN NORTHWESTERN AMERICA. THE ONE-DIMENSION DETERMINATION OF THE EQUILIBRIUM LINE ALTITUDE (ELA) AND THE ACCUMULATION AREA IS ILLUSTRATED.

2. The Columbia Icefield – Athabasca and Saskatchewan Glacier Flowsheds

The Columbia Icefield is situated in the Park Ranges of the Canadian Rocky Mountains at 52.17° N latitude and 117.32° W longitude (*Figure* 3). The region is founded by folded and faulted Palaeozoic sedimentary bedrock, giving rise to an extensive network of benches that support several large icefields and numerous valley and mountain glaciers. In several instances, the icefields nourish outlet valley glaciers. The Columbia Icefield's configuration over the Continental Divide (demarcating the border between the provinces of Alberta and British Columbia) gives it the distinction of being the hydrological apex of Canada's mountain west.

Seven outlet glaciers currently drain the Icefield through flow into surrounding valley systems, while there are also broad terminal margins that extend across broad benches of bedrock. In addition, extensive high-elevation serac margins partition mass to several smaller glaciers laying beneath them.

A portion of the Icefield is located in the northwestern tip of Banff National Park (BNP) and the southern end of Jasper National Park (JNP). The Athabasca Glacier (in JNP) and the Saskatchewan Glacier (in BNP) are two of the major outflow glaciers draining the Icefield to the east and nourishing the Sunwapta-Athabasca River (Mackenzie Drainage Basin) and the North Saskatchewan River (Nelson Drainage Basin) respectively.

2.1 Study Site and Delineation

The Athabasca Glacier ranges in elevation from 1,965 to 3,463 m and covers an area of roughly 15 km^2. The Saskatchewan Glacier ranges in elevation from 1,784 to 3,322 m and covers an area of roughly 23 km^2. *Figure* 3 illustrates the Athabasca and Saskatchewan Glacier flowsheds. The flowshed outlines were delineated using the *hydrology basin function* in ArcGIS 10.2 using a digital elevation model (DEM; 1m resolution) derived from 2010 WorldView 2 imagery (Demuth et al., 2012b and Persad et al., 2013). The same DEM was used to create elevation contours and the 100 m interval hypsometry represented in *Figure* 4.

The glacierized terrain identified by the shaded area located to the north of the Saskatchewan Glacier was excluded from the flowshed as this region does not contribute mass flux to the main branch of the Saskatchewan Glacier[2].

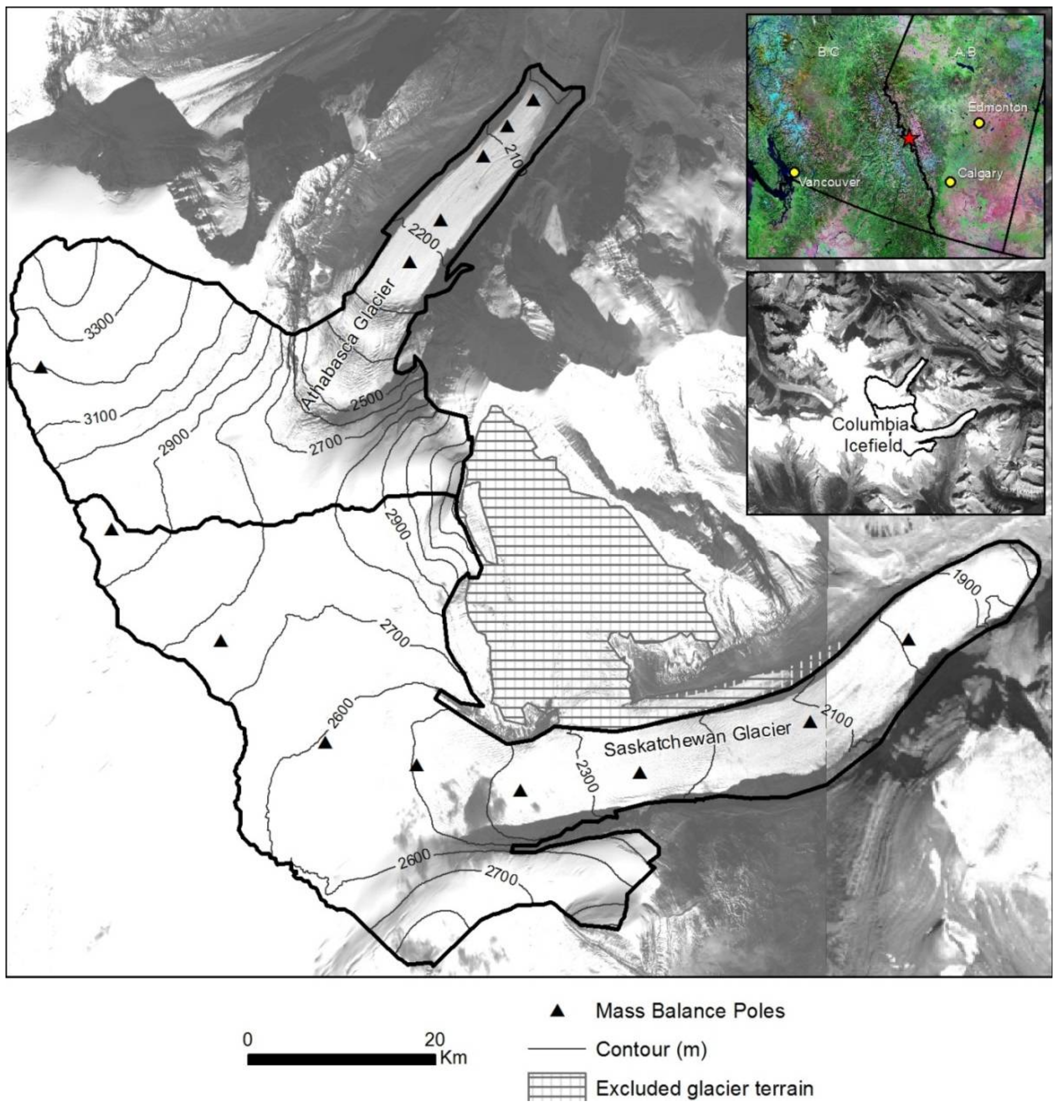

FIGURE 3 THE ATHABASCA AND SASKATCHEWAN GLACIERS FLOWSHED CONFIGURATIONS. THE SHADED GLACIERIZED TERRAIN WAS EXCLUDED FROM THE ANALYSIS; SEE TEXT FOR DETAILS. THE LOCATION OF MASS BALANCE STAKES IS INDICATED.

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[2] Ice flux from this region does not appear to contribute to the main body of the Saskatchewan Glacier as indicated from linear nature of the exposed medial moraine and is for the purposes of this analysis is excluded.

2.2 Measurement Infrastructure and Data Reduction

A network of mass balance stakes established in the April of 2010 extends along the major flowline profile of both the Athabasca and Saskatchewan Glaciers (*Figure* 3). For the Athabasca Glacier the flowline extends from the summit of Mount Snow Dome; for the Saskatchewan Glacier, from the plateau region immediately south of Mount Snow Dome.

The mass balance stakes on the Athabasca Glacier range in elevation between 1,983 and 2,225 m. The stake nearest the terminus (stake At10 and not included in *Figure* 3) melted out of the glacier in 2015 and was not reinstalled. Mass balance stakes are not maintained between 2,300 and 2,700 m a.s.l. as the heavily crevassed nature of the Athabasca's three distinct icefalls precludes easy access for measurement and maintenance purposes. Above the icefalls, there are two active mass balance stakes as well as a number of late winter snow probe transects.

The mass balance stakes on the Saskatchewan Glacier range in elevation between 1,920 and 2,951 m. Summer mass balance data was not collected between 2,400 and 2,800 m for the reported balance years due to the loss of stakes.

A network of snow pit and shallow snow and firn coring sites are established each measurement year to document snow and firn density and thereby convert stake and snow probe measurements into point water equivalence values over the ablation and accumulation zones within the flowshed.

These point values of are mapped over the flowshed in a 1-dimensional manner (*Figure 4 and Figure 5*) and the seasonal and annual specific mass balance computed using *Equation* 2.

Delineating the position of the ELA proved difficult on the Athabasca Glacier as there are no direct measurements with which to plot the annual balance – elevation curve over the equilibrium zone (f. ex. as shown in *Figure* 2) - the ELA for both years was situated above the mass balance stakes maintained by JNP and below the stakes maintained by GSC.

Determining the ELA for 2014-15 balance year for the Athabasca glacier was estimated (as in *Figure* 2) where the annual mass balance is zero, however, since there are relatively few mass balance stakes in the locale of the physical ELA, the annual balance – elevation curve is heavily extrapolated through this region and there could be considerable error in its value (± c. 50 m). For 2015-16 the location of the ELA was identified using a high-resolution Pleiades satellite image[3] (0.5 m resolution) acquired in mid-September, 2016 (f.ex.,Berthier et al., 2014). The elevation was obtained by georeferenceing the satellite image to the 2010 WorldView 2 DEM.

For both 2014-15 and 2015-16, the ELA for the Saskatchewan Glacier was directly observed during the final stake measurements completed at the end of the balance year.

3. Glacier Mass Balance 2014-15 and 2015-16

Glacier mass balance data were collected by JNP over the lower reaches of the Athabasca Glacier for the balance year 2014-15 and 2015-16. A total of 5 mass balance stakes were measured - all of which are located in the ablation region. The GSC collected mass balance data from 5 stakes on the Saskatchewan Glacier. For both the Athabasca and Saskatchewan Glaciers, an ensemble of stakes and snow probe transects were measured in their accumulation areas.

3.1 Results – Athabasca Glacier

Figure 4 illustrates that annual mass balance in 2014-15 ranged from -6.0 m water equivalence (w.e.) to -3.9 m w.e. in the ablation area of the Athabasca Glacier. In 2015-16, it ranged from -5.0 m w.e. to -4.0 m w.e. (as noted earlier stake At10 was removed in the 2015-16 mass balance year).

In the accumulation area of the Athabasca Glacier, there was greater annual mass balance gain in 2015-16 than in 2014-15. For example, in 2015-16 measurements at the two highest elevation stakes revealed an annual mass balance of 1.3 and 1.4 m w.e. while the same stakes in 2014-15 having an annual balance of 1.04 m w.e.

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[3] for a non-temperate glacier, the late summer snowline (LSS) approximately delineates the ELA (Østrem, 1973;, Demuth and Pietroniro, 1999), with the LSS elevation measured directly in-situ, or delineated from satellite imagery and elevations extracted from a suitable DEM.

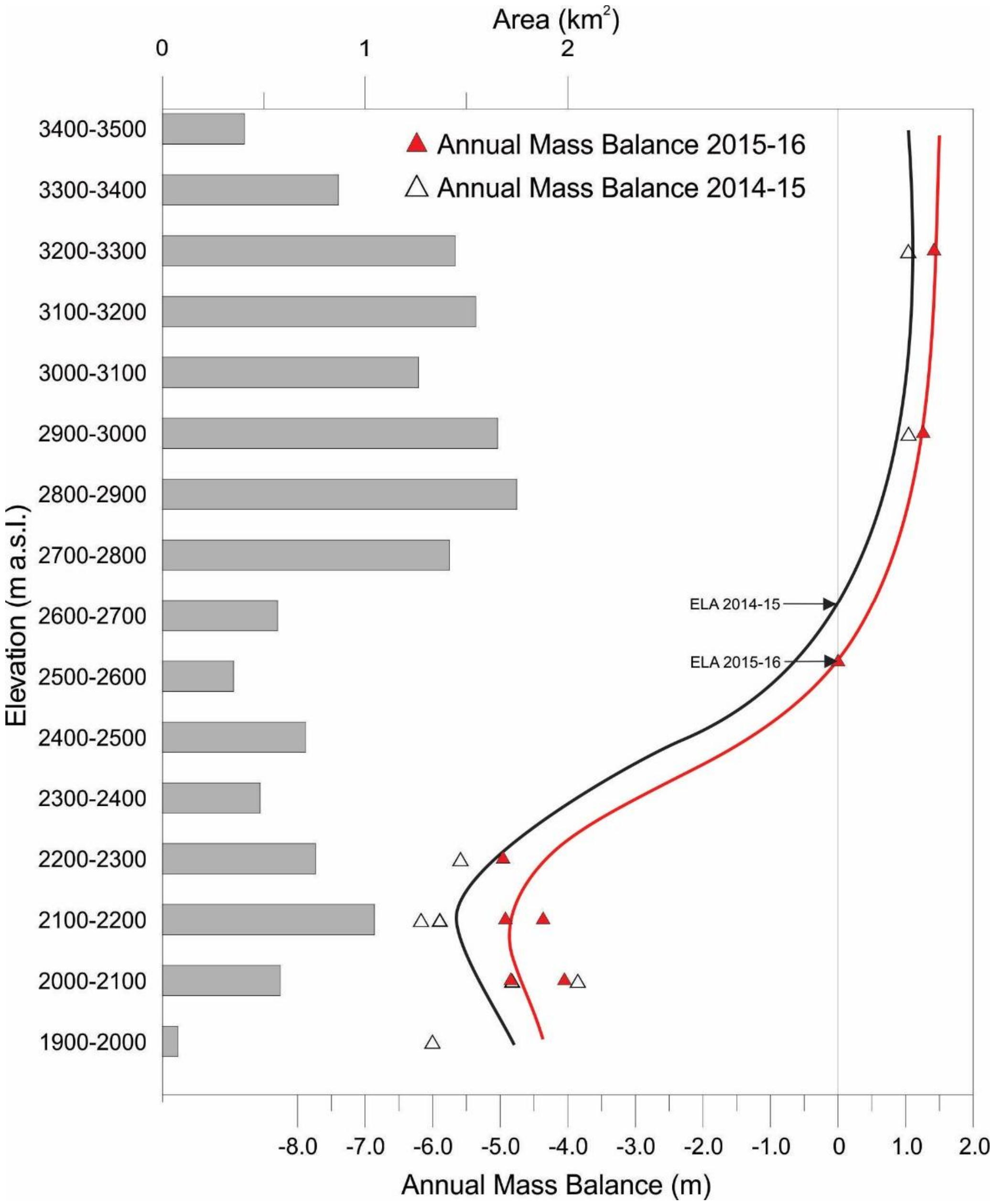

FIGURE 4 THE 100-METRE HYPSOMETRY AND ANNUAL BALANCE DISTRIBUTION OVER THE ATHABASCA GLACIER FOR THE 2014-15 AND 2015-16 BALANCE YEARS.

3.2 RESULTS – SASKATCHEWAN GLACIER

Figure 5 illustrates that the annual mass balance in the ablation area of the Saskatchewan Glacier ranged from -4.1 m w.e. to -3.1 m w.e. in 2015-16. In 2014-15, the same region had an annual mass balance of between -5.2 and -2.6 m w.e. The accumulation area in 2015-16 gained more mass as compared to 2014-15 balance year.

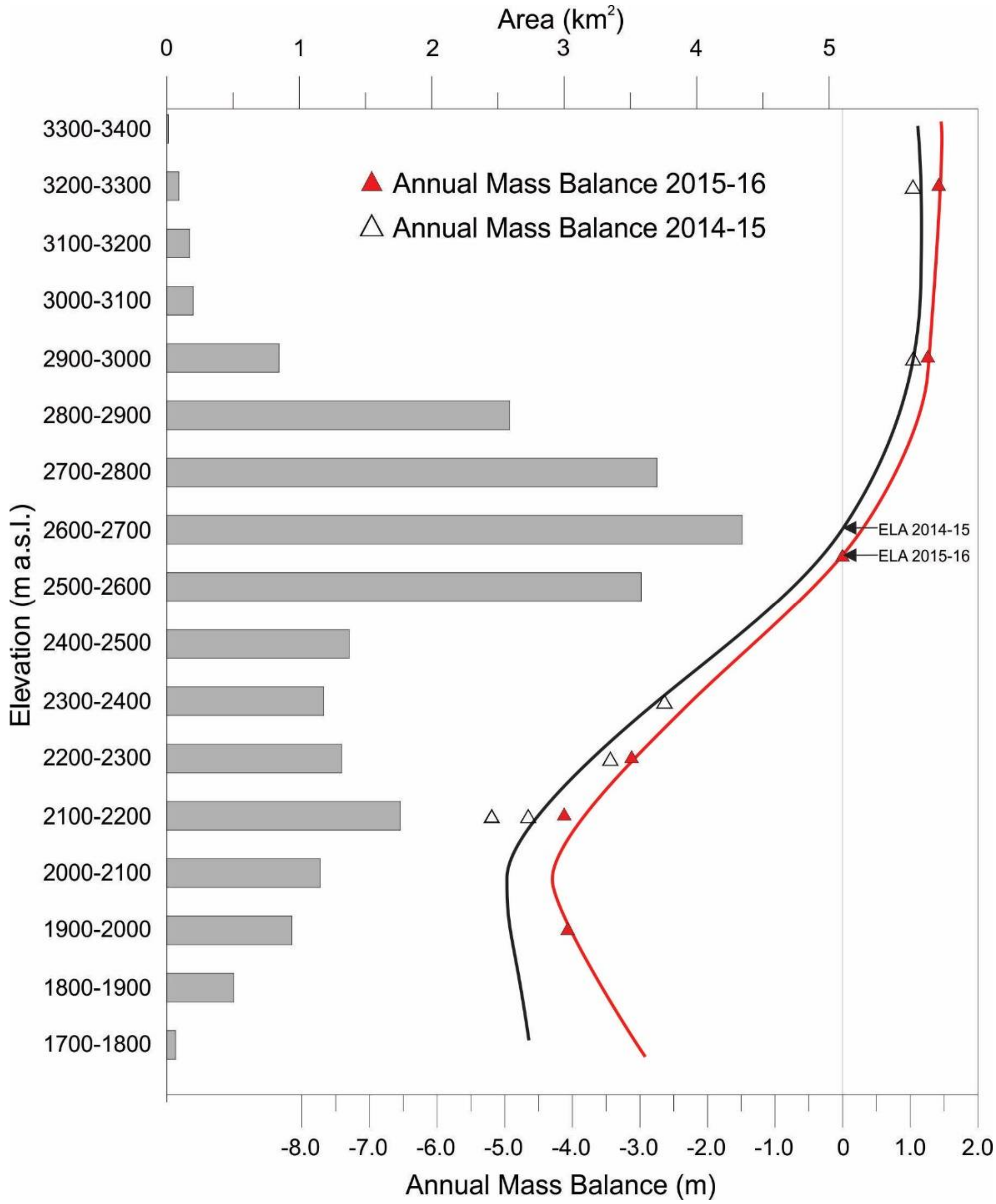

FIGURE 5 THE 100 METRE HYPSOMETRY AND ANNUAL BALANCE DISTRIBUTION OVER THE SASKATCHEWAN GLACIER FOR THE 2014-15 AND 2015-16 BALANCE YEARS.

Table 1 presents the winter, summer and annual mass balances for 2014-15 and 2015-16 balance years for the Athabasca and the Saskatchewan Glaciers in meters of water equivalence. The table also includes the Equilibrium Line Altitude (ELA) in meters above sea level and the Accumulation Area Ratio (AAR) as a percentage.

TABLE 1 WINTER, SUMMER AND ANNUAL BALANCE, EQUILBRIUM LINE ALTITUDE AND ACCUMULATION AREA RATIO FOR ATHABASCA GLACIER AND SASKATCHEWAN GLACIER FOR 2014-15 AND 2015-16.

	Athabasca Glacier		Saskatchewan Glacier	
	2014-2015	2015-2016	2014-2015	2015-2016
Winter balance (m w.e. a^{-1})	1.17	1.22	1.31	1.14
Summer balance (m w.e. a^{-1})	-1.76	-1.35	-2.54	-1.97
Annual balance (m w.e. a^{-1})	-0.60	-0.13	-1.22	-0.84
ELA (m a.s.l.)	2,650	2,550	2,650	2,620
AAR (%)	72.0	74.2	40.4	45.9

Overall, the Athabasca Glacier experienced a greater annual balance (-0.13 m w.e.) in 2015-16 balance year compared to the previous year (-0.60 m w.e.). The winter balances between the two study years were similar with a slightly greater winter balance in 2015-16. There was a greater loss of mass during the melt season in 2014-15 (-1.76 m w.e.) than in 2015-16 (-1.35 m w.e.). The ELA for 2015-16 was 100 m lower resulting in a greater Accumulation Area Ratio (i.e., from 72.0 to 74.2 %).

The Saskatchewan Glacier's winter balance was greater in 2014-15 than in 2015-16. The loss of snow and ice throughout the summer melt period in 2015-16 (-1.97 m w.e.) was less than that in the previous year (-2.54 m w.e.). The Saskatchewan Glacier annual balance in 2014-15 was -1.22 m w.e. while in the 2015-16 balance year it was -0.84 m w.e. The ELA descended about 30 m between 2014-15 and 2015-16 resulting in an increase in the AAR from 40.4 % to 45.9%.

For both glaciers, it should be noted that the current fluctuation of the ELA within the area-elevation distribution results in relatively small corresponding fluctuations of the AAR. As the ELA rises out of the region where the Icefield transitions into its outlet glaciers (as is forecast to occur over the medium to long term; see Clarke et al. 2015), AARs should diminish proportionately.

4. COMMENTARY AND SYNTHESIS

4.1 SEASONALITY INFLUENCES

As it concerns seasonality and the health of the Columbia Icefield, there is currently insufficient data to determine the relative role of summer versus winter conditions on the overall annual balance of the eastern portion of the Columbia Icefield (Athabasca and Saskatchewan flowsheds). Zemp et al. (2015; Figure 5 - refer to "WNA") note, however, that annual mass balances in western North America are generally determined by ablation in summer; though Demuth and Keller (2006) and Demuth et al. (2008) note that during certain periods in the 20th century, winter conditions (accumulation) were just as or more important in determining the outcome of the annual balance of glaciers in the western Cordillera.

As it concerns broad-scale spatial variability of winter accumulation over the Icefield, there is only anecdotal knowledge that winter accumulations are higher over the western sector of the Icefield compared to the eastern sector within which the Athabasca and Saskatchewan Glacier flowsheds are situated. This is likely the result of enhanced orographically-generated precipitation over the former region as moisture leaves the interior ranges and impinges on the western slopes of the Rocky Mountains. Notable though is that "upslope conditions" in winter and spring often augment snow water equivalence over broad swaths of the southern eastern slopes of the Canadian Rocky Mountains. Moreover, wind scour is a major agent of variability and should guide an augmentation of the Icefield's mass balance measurement infrastructure.

4.2 TEMPORAL CONTEXT

To establish a temporal context for the 2014-15 and 2015-16 observations reported herein, long-term, multi-annual estimates of the geodetic mass balance were generated using the cumulative geodetic balances reported by Tenant and Menounos (2011, Figure 8). This was accomplished be de-convolving the cumulative record into a serial record for the same time periods (Demuth and Horne, 2017).

Figure 6 illustrates the long-term fluctuation of the annual mass balance for the Athabasca and Saskatchewan Glaciers for varying time periods during the interval 1964-2009. The 2014-15 and 2015-16 annual balances are plotted as open and closed circles for the Athabasca and Saskatchewan Glaciers respectively. Uncertainty of the annual mass balances derived from the geodetic method is represented by the thickness of the line (c. 0.1 m w.e. for both glaciers). The uncertainty for the 2014-15 and 2015-16 mass balances is represented by the error bars. The uncertainty for the Athabasca Glacier is estimated to be 0.4 m w.e.; and for the Saskatchewan Glacier it is 0.2 m w.e.

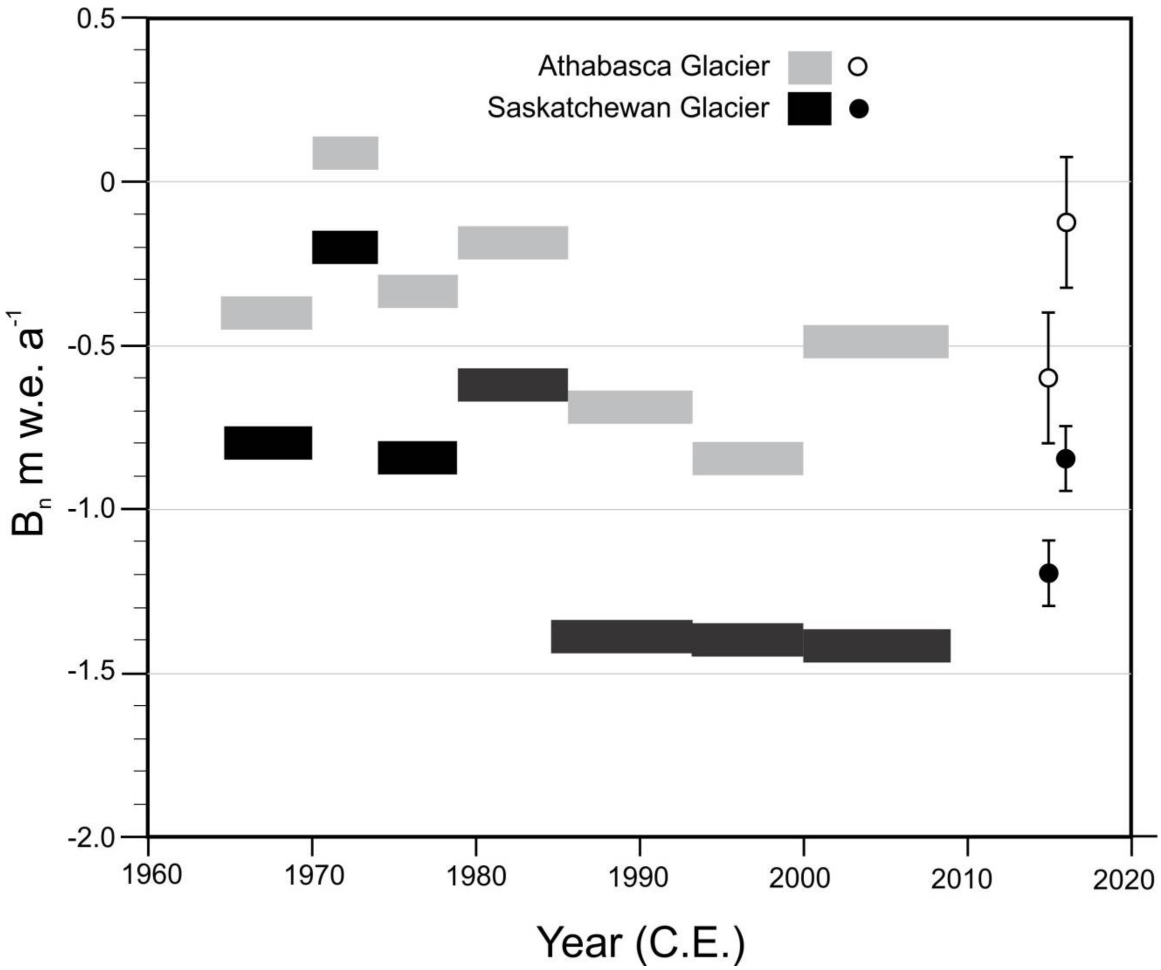

FIGURE 6. THE 2014-15 AND 2015-16 ANNUAL MASS BALANCES FOR THE ATHABASCA AND SASKATCHEWAN GLACIERS ARE ILLUSTRATED IN COMPARISON WITH THEIR GENERAL MASS FLUCTUATIONS SINCE THE MID 1960S; ADAPTED FROM DEMUTH AND HORNE (2017) (DETAILS IN THE TEXT).

The temporal pattern revealed in *Figure* 6 has features of the well documented shift after 1976 to more negative glacier mass balances due to lower end-of winter snow water equivalence over southwestern Canada and the Pacific northwest generally (f.ex., Moore and McKendry, 1996), and lower winter glacier mass balances specifically (f.ex., McCab and Fountain, 1995; Demuth and Keller, 2006; Demuth et al., 2008).

The 1976 shift (and others before it) have been associated with the so-called “Pacific Decadal Oscillation” (PDO) and its “warm” and “cold” phases. Whitfield et al. (2010)

summarize and update the nature and role of the PDO on hydro-climatic phenomenon associated with a modulation the Pacific North American (PNA) circulation pattern governing, in part, the advection of moisture-bearing storm tracks into the region. In particular they discuss the PDO being in and out of phase with the influences of the El Nino Southern Oscillation (see also Fisher et al., 2008).

Notably, after 1990, the region appears to have entered a “mixed” phase from its preceding post 1976 “warm” phase. A persistent period of higher variability has indeed been documented to have taken hold after 1990 (see f.ex., Zemp et al. 2015: Figure 5 - refer to “WNA”; Demuth and Ednie, 2016: Figure 9; Demuth and Horne: Figure 6) where near record mass losses of glaciers occurred in 1998 followed by two years of mass gains – one of which (2000) was a record mass gain.

The notion of higher variability at the scale of glacier mass fluctuations is also evident in the measured record mass losses experienced in 2014-15 by most glaciers in southwestern Canada and the Pacific northwest (Brian Menounos et al., 2015. personal communication; Demuth and Ednie, 2016; Demuth and Horne, 2017), followed by much more modest losses in 2015-16. This is reflected in the recent short records reported herein for the Athabasca and Saskatchewan Glaciers.

CONCLUSIONS

This GSC Open File has presented mass balance, ELA and AAR data for the Saskatchewan and the Athabasca Glaciers for the balance years 2014-15 and 2015-16. The annual mass balances for the two glaciers for both years were negative with a smaller annual mass loss in 2015-16 compared to 2014-15. Other key measurements of the glaciers’ overall health such as ELA and *AAR* fluctuated correspondingly according to the controls exerted by the hypsometry of the Icefield. These short observations were placed in a larger temporal and regional context, and suggest that the mass changes recently observed by the Athabasca and Saskatchewan Glaciers, while specifically influenced by their upland icefield origins, generally reflect the large-scale regional fluctuations in hydro-climatology documented since the mid-twentieth century.

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

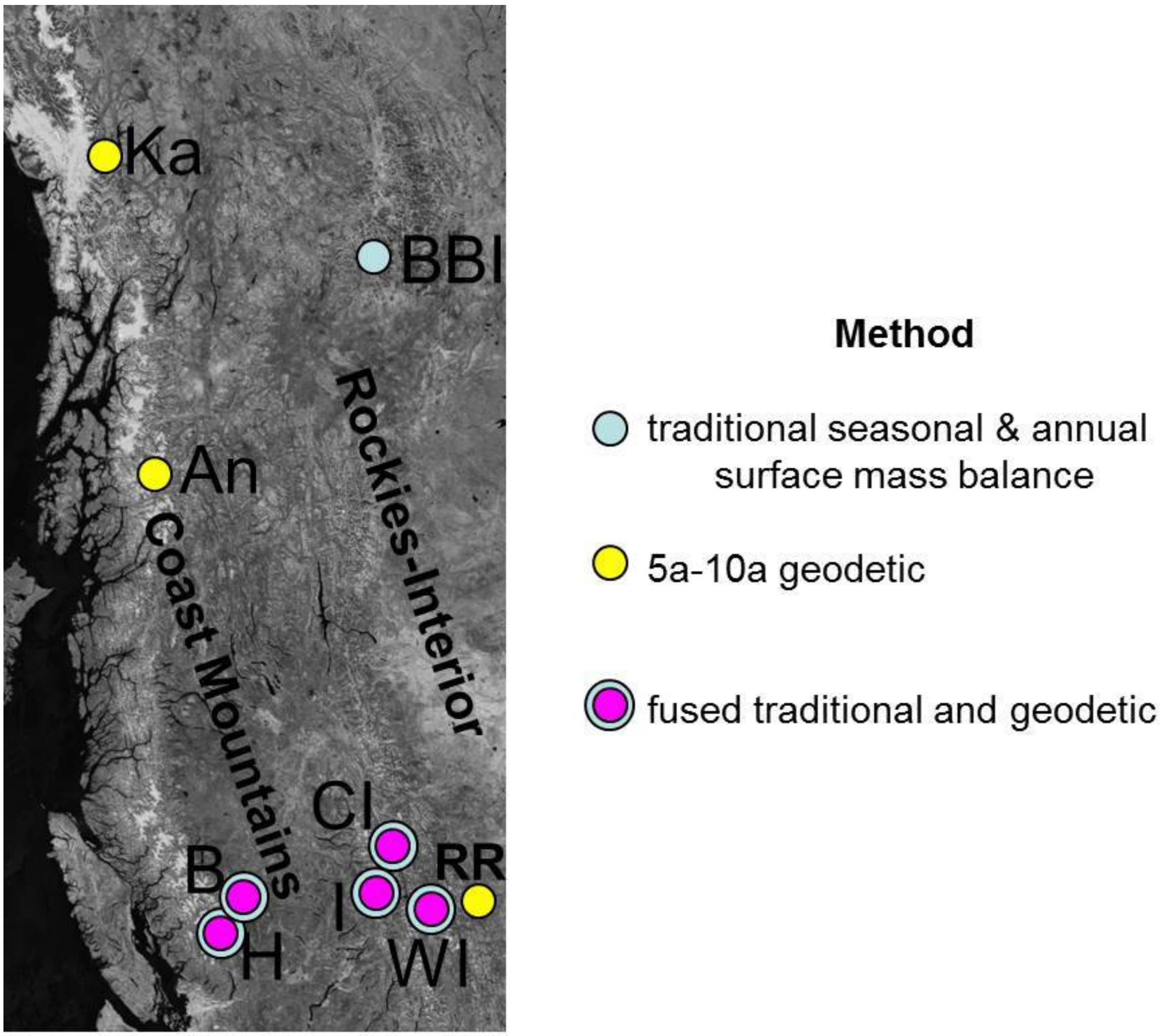

FIGURE A 1 REFERENCE MASS BALANCE OBSERVING SITES FOR THE CORDILLERA: WI = WAPTA ICEFIELD (PEYTO AND YOHO); RR = RAM RIVER; CI = COLUMBIA ICEFIELD (ATHABASCA AND SASKATCHEWAN); I = ILLECILLEWAET; BBI = BRINTNELL-BOLOGNA ICEFIELD (BOLOGNA); KA = KASKAWULSH; AN = ANDREI; B = PLACE; H = HELM.

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

ACKNOWLEDGEMENTS

The authors thank and acknowledge the support of the Parks Canada Agency and its resource conservation specialists, managers and scientific directors who have all maintained a long view and a philosophical and practical interest in this work and the relevance it has for assessing protected area functioning. In particular, we thank Brenda Shepherd, Derek Petersen, Greg Horne and John Wilmshurst. Brenda Shepherd, Steve Bertollo (Nunatak Research) and Eric Courtin (University of Victoria) participated in the conduct of mass balance measurements during the 2014-15 and 2015-16 mass balance years. The Pléiades satellite imagery used in this study were provided to the Pléiades Glacier Observatory project via the French Space Agency's (CNES) ISIS programme.

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